Spatial Integration of Regional Carbon Balance in Amazônia

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Abstract

We propose a three-year research program to estimate the basin-scale carbon balance of Amazônia, using a combination of data collected by flux towers, atmospheric data collected from light rental aircraft, numerical modeling of ecosystem carbon flux and regional atmospheric circulation, remote sensing, and geographic information systems. Tower flux data from sites in intact forest, regrowing forest, pasture, and savanna, will be used to calibrate a model of ecosystem physiology and biogeochemistry (based on the component models SiB2 and CASA) for each major cover type in the region. This model will be coupled to a mesoscale atmospheric model (RAMS), to investigate the propagation of the "signal" of terrestrial carbon flux into the local and regional atmosphere. Light aircraft will be used to estimate local boundary-layer budgets of CO_2 and its stable isotopes, and these data will be used in conjunction with the model to estimate carbon budgets of each cover type over much larger areas than is possible from the towers. An improved ecosystem model will then be applied across the basin using remotely sensed data and a GIS, to calculate the spatial structure of ecosystem carbon flux throughout the year. These estimated fluxes will be used in the mesoscale atmospheric model to predict 3-dimensional fields of CO_2 and $\delta^{13}C$, which can be compared to data collected by later aircraft campaigns such as LBA-CLAIRE or TRACE-B, when they become available. It is hoped that our results will allow reliable carbon budget estimation in other regions from EOS data in the future using relatively inexpensive aircraft sampling programs.

Introduction

The tropical land surface plays a crucial role in the global carbon cycle. The region contains the most active ecosystems in the world, exchanging as much as 5% of the mass of atmospheric CO_2 every year. In the annual mean, large opposing fluxes due to deforestation, forest regrowth, and possibly CO_2 fertilization complicate the interpretation of the regional carbon budget. Recent changes in land use have contributed to the release of CO_2 to the atmosphere, accounting for a significant fraction of the global anthropogenic flux (Houghton *et al*, 1987; Schimel *et al*, 1996). In addition to these regional issues, quantification of tropical carbon fluxes is a key "missing link" in our understanding of the *global* carbon cycle. Rayner *et al*. (1996) used a tracer transport model to invert atmospheric data, and calculated the locations of stations which would best reduce uncertainty in atmospheric CO_2 exchange with the oceans. They found that the existing observational network would best be extended by adding data over the Amazôn, because uncertainties in tropical ecosystem fluxes are among the most significant uncertainty terms in the inversion budgets.

Ecological and biogeochemical factors affecting the carbon balance of terrestrial ecosystems are heterogeneous in both space and time, complicating regional integration from site-based measurements. Spatial and temporal changes in the concentration and stable isotopic composition of atmospheric CO_2 contain information that can used to extrapolate local ecological measurements to larger scales. This information can be used to infer the properties of the underlying ecosystem, so that measurement of atmospheric properties can serve as a kind of "remote sensing" of ecosystem function. Eddy flux towers, for example, can provide estimates of ecosystem carbon balance over areas of several hectares, assuming the surrounding terrain is relatively flat and homogeneous, and there is negligible canopy storage or nocturnal drainage flow. These studies are invaluable in terms of constraining process-based models of carbon exchange, but in general such results cannot be extrapolated to larger spatial scales because the representativeness of the tower flux site is unknown and unknowable.

At the other end of the spatial continuum, atmospheric data collected by the global flask network (Conway *et al*, 1994; Keeling *et al*, 1989a; Francey *et al*, 1995) have been used to constrain carbon budgets by performing inversions using tracer transport models (Tans *et al*, 1989; Enting and Mansbridge, 1989; keeling *et al*, 1989b; Tans *et al*, 1990). This technique is most useful in estimating zonal mean fluxes over wide latitude ranges. Unfortunately, this approach provides almost no constraint at all on tropical carbon exchange, because the intensity of deep tropical convection and the seasonal shift in cross-equatorial transport allow the "signal" to propagate quickly and evenly into both hemispheres (Plumb and McConalogue, 1988). Thus the tropical terrestrial flux due to land use changes and possible fertilization is commonly either prescribed *a priori* or treated as a residual in global inversions (Denning, 1994).

The relative abundance of the stable isotopes ^{13}C and ^{12}C provide a powerful constraint to transport inversion calculations, because photosynthesis discriminates strongly against the heavier isotope. In contrast, dissolution of CO_2 into surface ocean waters is associated with relatively little isotopic fractionation, so transport inversions of CO_2 and its isotope ratio $\delta^{13}C$ can distinguish between marine and terrestrial exchange within a given latitude zone (Keeling *et al*, 1989b; Enting *et al*, 1995; Ciais *et al*, 1995). Application of this technique has led to the suggestion that interannual variability in the natural carbon cycle in response to ENSO events is associated with large opposing anomalous CO_2 fluxes at the air-sea and air-land interfaces. This interpretation is complicated by the fact that much of the interannual variability in tropical ecosystems is associated with C_4 photosynthesis, with much less isotopic discrimination than C_3 plants. In terms of its effect on atmospheric $\delta^{13}C$, C_4 photosynthesis (discrimination $\Delta = -4.4‰$) behaves more like air-sea exchange ($\Delta \approx -2$ ‰) than it does like C_3 photosynthesis ($\Delta = -27‰$) (Berry, 1989; Fung *et al* , submitted). It is quite possible that inversions of the global distribution of CO_2 and $\delta^{13}C$ have misinterpreted changes in tropical C_4 photosynthesis as changes in the tropical oceans. This is especially problematic given that the dominant land use change in the tropics is from C_3 forest to C_4 pasture!

Tracer transport inversions of the large-scale atmospheric CO_2 observations are also subject to significant uncertainty resulting from the importance of unresolved sub-grid scale vertical transport. Over vegetated land surfaces, photosynthesis and vertical atmospheric motion are strongly correlated because they are both driven by solar radiation: photosynthesis is associated with strong thermally-driven turbulence and deep convection. This correlation "*rectifies*" the atmospheric response to terrestrial forcing, retaining the respiration "signal" near the surface and ventilating the photosynthesis signal into the free troposphere. Atmospheric rectification of just the seasonally balanced exchange of CO_2 with the terrestrial biota may produce a meridional gradient in annual mean concentration that is half as strong as the signal produced by fossil fuel emissions (Denning *et al* , 1995, 1996a,b). This rectifier effect is strongest over the tropical continents, where both ecosystem productivity and moist convective transport are strongest.

Atmospheric CO_2 and isotopic data can thus be used to deduce the exchange of carbon with terrestrial ecosystems at very large scales and at very small scales, but the overall constraint is still rather weak. Tropical fluxes produce only very weak spatial structure at the largest scales, the isotopic signal is complicated by the fact that land-use change has a similar signature to air-sea exchange, and very strong vertical transport by tropical deep convection complicates model inversions. The key to eliminating much of the uncertainty in the global carbon cycle is to quantify tropical fluxes associated with deforestation, forest regrowth, and carbon fertilization, yet isolated flux towers cannot hope to represent the full range of spatial variability.

We propose a multistage program of research intended to bridge the spatial gap between flux towers and the flask network to provide mesoscale and regional estimates of the carbon balance of Amazônia. The proposed study will involve the development of semi-mechanistic models of ecosystem carbon flux for several land-use types; coupling of these site-calibrated models to a mesoscale atmospheric transport model to quantify interactions among ecosystem metabolism, boundary layer turbulence, deep convection, and the propagation of the terrestrial signal into the troposphere; a field campaign with light rental aircraft to measure boundary-layer budgets of CO_2 and estimate the carbon balance of the various cover types over large areas; and a basin-scale integration component using remote sensing and GIS technologies to parameterize the ecosystem models, and the atmospheric transport model constrained by regional meteorological data to provide estimates of the 3-dimensional distribution of CO_2 and $\delta^{13}C$ for comparison to the results of the European aircraft campaigns. The proposed study will require three years of support, and will involve extensive collaboration with other LBA investigations, with Brazilian scientists at the Universidade de São Paulo, and with members of the Randall (Sellers-Mooney) EOS-IDS team.

Project Objectives

1. Extend surface carbon balance estimates from flux towers to larger areas of intact forest, regrowing forest, pasture, and savanna, using a model of terrestrial ecophysiology, a mesoscale atmospheric model, and a sampling program using light rental aircraft.
2. Estimate seasonal carbon fluxes across the basin using GIS and remote sensing to extrapolate smaller scale results based on land-surface classification and MODIS data.
3. Predict seasonal 3-D structure of CO_2 and stable isotopes across Amazônia for comparison to aircraft data from LBA-CLAIRE. This will allow validation of spatially explicit carbon budgets from step 2.

Technical Plan

1998: Model development and calibration

The Simple Biosphere Model (SiB2)

The Simple Biosphere (SiB) Model, developed by Sellers *et al*. (1986), has recently undergone substantial modification (Sellers *et al*., 1996*a*, *b*, *c*), 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 rather than prescribed from the literature. The vegetation canopy has been reduced to a single layer. 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, making possible the calculation of CO_2 exchange between the global atmosphere and the terrestrial biota on a timestep of several minutes (Denning *et al*, 1996a,b; Zhang *et al*, 1996). Photosynthetic carbon assimilation is linked to stomatal conductance and thence to the surface energy budget and atmospheric climate by the Ball-Berry equation (Ball, 1988; Collatz *et al*., 1991, 1992; Sellers *et al*., 1992*a*, *b*, 1996*a*), which is the basis for the ability of the model to calculate the climatic effects of physiological responses to elevated CO_2 (Sellers *et al*, 1996*c*).

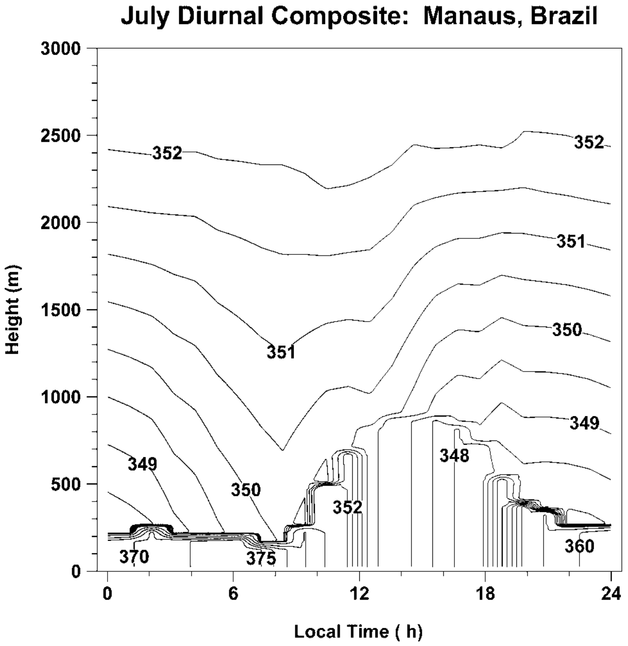

Figure 1: Diurnal time-height cross-section of CO_2 concentration as simulated by SiB2 in the CSU GCM (Denning *et al*, 1996*b*)

Denning (1994; see also Denning *et al*, 1995, 1996a,b) has coupled the ecosystem carbon flux calculation in SiB2 to global-scale atmospheric transport to predict the 3-dimensional concentration field of CO_2 in the Colorado State University (CSU) General Circulation Model (GCM). The high time resolution of the simulation (6 minutes) relative to previous global studies, along with embedded parameterizations of PBL turbulence and deep cumulus convection, produced very reasonable predictions of the diurnal cycle and vertical structure of CO_2 concentration in the few areas where data area available (Denning *et al* , 1996*b,c*), including Amazônia (Figure 1).

Photosynthesis, PBL turbulence, and atmospheric convection over land are all forced by solar radiation at the surface, so they are strongly correlated in nature, with strong ventilation and deeper mixing of CO_2-depleted air during the day and the growing season, and systematic retention of CO_2-enriched air under the nocturnal inversion and during the transition seasons (Fig. 2). In global simulations with SiB2 coupled to the CSU GCM, we found that the covariance between terrestrial photosynthesis, PBL structure, and cumulus convection produces a "rectifier effect," which results in a vertical gradient of several parts per million (ppm) in the annual mean CO_2 concentration over land (Denning, 1994, Denning *et al* , 1996*b,c*). The simulated diurnal rectifier is strongest over the tropical continents where net ecosystem exchange (NEE) is strongest. One of the major objectives of the research proposed here is to test this prediction with more detailed models at spatial scales that can be observed in nature.

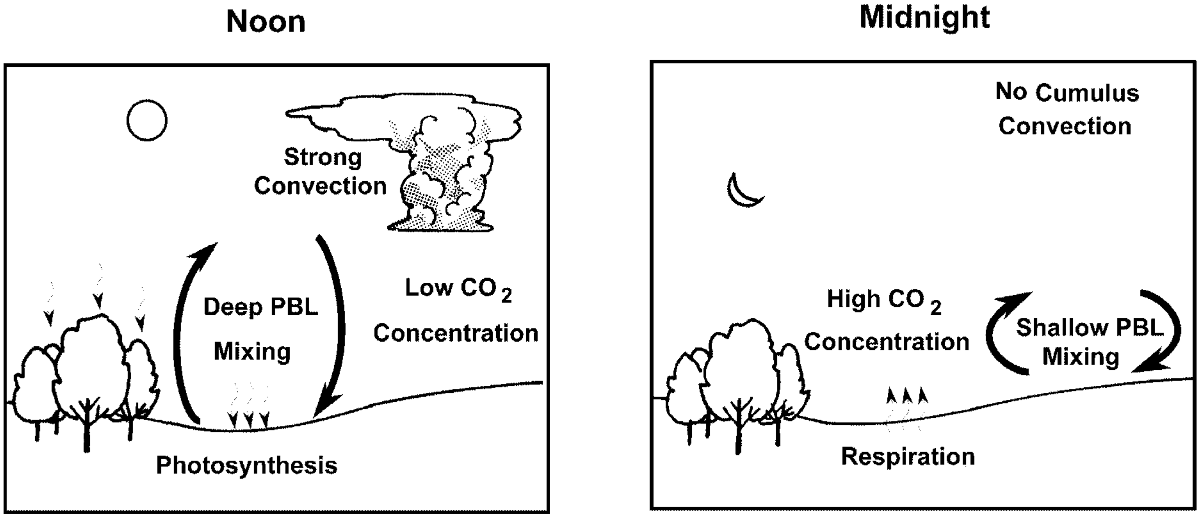

Figure 2: The diurnal atmospheric CO_2 rectifier effect.

Important developments are now underway which will significantly improve the ability of SiB2 to simulate ecosystem carbon balance for LBA. A multilayer soil thermodynamics parameterization has been implemented, based on the work of Bonan (1996), which greatly improves the prediction of deep soil temperature and moisture content (Denning *et al* , 1996*d*). The model currently uses 6 to 10 layers, with a zero-flux lower boundary at 6 meters depth. An explicit litter layer provides physical realism and allows litter decomposition to be decoupled from root metabolism. This new soil physics code also paves the way for improved representations of root distribution and root and microbial respiration, because these ecological variables depend sensitively on accurate moisture and temperature profiles in the soil.

A parallel effort at the Carnegie Institution of Washington and Stanford University (Joe Berry, Chris Field, and Joerg Kaduk, personal communication) has produced a new parameterization of carbon allocation, growth and maintenance respiration, and microbial decomposition based in part on the CASA model of Potter *et al* (1993). This parameterization, which uses the multilayer thermodynamics and hydrology described above, is already being implemented and tested in SiB2, and will be used in the work proposed here.

Under separate funding, algorithms for predicting the fractionation of stable carbon isotopes during photosynthesis and the isotopic disequilibrium of respired CO_2 are now being implemented in SiB2 (Fung *et al* , submitted). Photosynthesis discriminates against the heavier ^{13}C during both diffusion into stomatal pores and biochemical fixation by carboxylation (Berry, 1989). The relative contribution of diffusion and carboxylation to this process, and hence the overall effect on the $\delta^{13}C$ of atmospheric CO_2, depend on the local environment of the plant (humidity at the leaf surface, stomatal conductance, illumination, etc), which is predicted on a minute-by-minute basis in SiB2. C_4 plants such as tropical grasses have a biochemical mechanism that concentrates CO_2 near the carboxylation site, so the fractionation process is dominated by diffusion, which has a weaker ^{13}C signature. The predominant land use perturbation in Amazônia is from C_3 forest to C_4 pasture, so the ability to predict these fractionation effects will allow quantification of the effects of deforestation "at a distance."

Under a separate proposal to the LBA-Ecology program, Joe Berry, Chris Field, and Humberto Rocha plan to perform site calibration of the revised SiB2 model for sites in intact forest, secondary forest, pasture, and savanna. Initial calibration would be performed using pre-existing data sets such as from the ABRACOS study (Gash *et al* , 1996), and from data collected over tropical species in Biosphere2. SiB2 has already been calibrated for tropical forest and pasture ecosystems of Amazônia (Rocha *et al* , 1996). In addition, they would travel to Brazil to perform ecophysiological measurements and measure carbon pools in the soil. Their goal is to have site-calibrated simulations with SiB2 working before the LBA flux towers are operational, and to then use the flux tower data to validate and test the model.

In addition to calibrating the ecophysiological parameters of SiB2 for the various tropical ecosystems, Berry *et al* will characterize the isotopic signatures associated with photosynthesis and respiration at each site. For example, the effect of respiration on $\delta^{13}C$ depends on the age structure of soil organic matter, and the effects of photosynthesis depend on the photosynthetic pathway (C_3 vs. C_4) and on environmental stresses that determine the relations between stomatal function and carboxylation. This information will be extremely valuable for the later aircraft sampling program (to be performed in 1999) proposed here, and will constrain the model simulations.

The Regional Atmospheric Modeling System – RAMS

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*).

The RAMS system has already been in use by Brazilian investigators for a number of years (e.g., Rocha *et al* , 1996). Prof. Humberto Ribeira da Rocha has already begun coupling SiB2 to RAMS to investigate micrometeorological coupling between the forest and the atmosphere. We will work with Drs. Pedro Silva Dias, Maria Assuncao F. Silva Dias, and Humberto Ribeira da Rocha in 1998 to develop a common modeling platform that includes our improved carbon calculations, which will be implemented at both UCSB and at the Universidade de São Paulo. They have agreed, under a subcontract (see attachments) to perform simulations of atmospheric circulation as part of the LBA 4DDA program, which they will produce using the nested grid feature of RAMS. Weather data will be assimilated on a grid of order 10's of km, and 6 levels of nested fine scale grids will be used to produce simulations of the atmospheric circulation down to the scale of a large eddy simulation (LES) in the immediate vicinity of the flux towers chosen for this study (order a few 10's of meters).

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 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.

1999: Aircraft measurement of large-scale fluxes and isotopes

The coupled SiB2-RAMS model developed in 1998 will be capable of predicting ecosystem metabolism, carbon isotopic fractionation and disequilibrium, the surface energy budget, the structure of atmospheric turbulence, and the transport of CO_2 and $^{13}CO_2$ in the local and regional atmosphere. These simulations will be driven by regional meteorological observations assimilated in the LBA 4DDA system, and by MODIS data used to specify vegetation activity. The coupled nature of the modeling system means that the simulated physics, biogeochemistry, and trace gas transport are mutually consistent, so that meaningful interactions such as PBL rectification of the ecosystem signal are captured. In 1998 we will apply this modeling system to simulate the atmospheric environment surrounding the tower sites, and will use atmospheric sampling from light aircraft to validate and test the model predictions. Our goal is to use the simulations to inform the flight plans, and the data collected by the aircraft to construct PBL budgets that are representative of much larger areas than can be sampled by the flux towers.

We propose to obtain a series of vertical profiles of CO_2, H_2O and air temperature up to a height of at least 3 km with a LiCor and a Campbell CR-10. The experimental apparatus is shown schematically in Figure 3. It is important to go this high in order to quantify turbulent entrainment at the PBL top. We will measure the change in CO_2 concentration as we follow the airmass and the change in CO_2 at one location by doing several transects to determine the influence of advection. We also have a GPS system, which allows us to make a rough estimate of the mean wind speed as well as the location of our flight path. By doing frequent calibrations we will measure the CO_2 concentration with an accuracy of 0.1 ppmv. Simultaneously, we will collect flasks for isotopic analysis. The flasks will be sent to NOAA CMDL for analysis of CO_2 and stable isotopes ^{13}C and ^{18}O, as well as other trace gases. The analysis of these flask samples will be on the same instruments and according to the same procedures and internationally accepted calibration standards as the global flask network, so intercalibration between our boundary-layer budget data and other CO_2 and trace gas data will be accomplished. Measurement of the isotopic composition of CO_2 is a key component of these flights, since it is a sensitive indicator of land use conversion from C_3 forest to C_4 pasture.

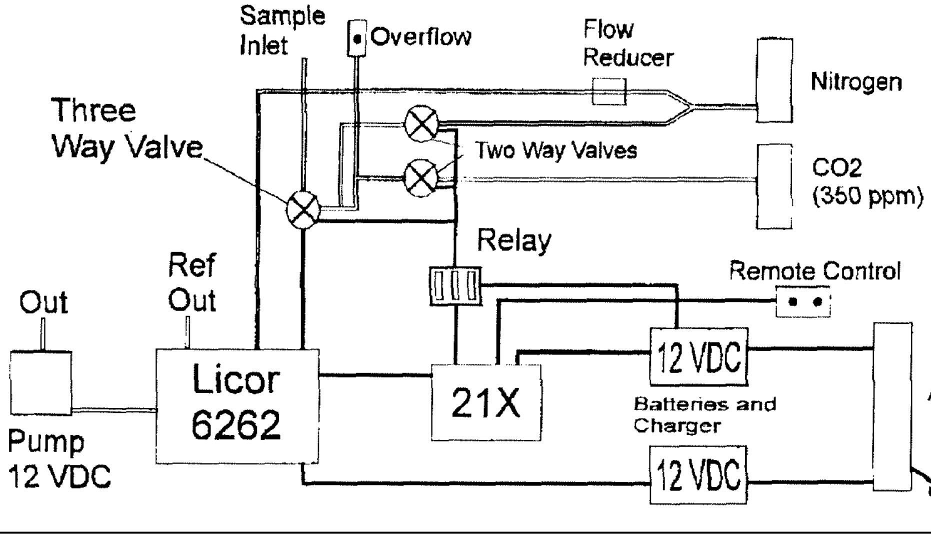

Figure 3: Schematic of aircraft instrument package to be used for PBL budget studies.

Following Raupach (1991), the conservation equation for scalars in the CBL can be written as

$$\frac{dC}{dt} = \frac{F_C}{h} + \frac{C_t - C}{h}\frac{dh}{dt} + advection \qquad (1)$$

where C is the mean scalar concentration in the PBL, t is time, F_C is the flux of carbon into the atmosphere from the surface (equal to the net ecosystem exchange, NEE), h is the depth of the PBL, and C_t is the mean value of C just above the PBL.

Rearranging the terms in equation 1 leads to:

$$Fc = h\frac{dc}{dt} - (C_t - C)\,\frac{dh}{dt} - advection \qquad (2)$$

We propose to estimate the NEE (F_C) by quantifying each term on the right-hand-side of equation (2) by aircraft sampling, as has been done by Desjardins *et al* (in prep) in the BOREAS 96 campaign (Figure 3). The experimental design is a compromise between the conflicting requirements of (a) quantifying the concentration over the entire PBL, and (b) quantifying advection using horizontal transects.

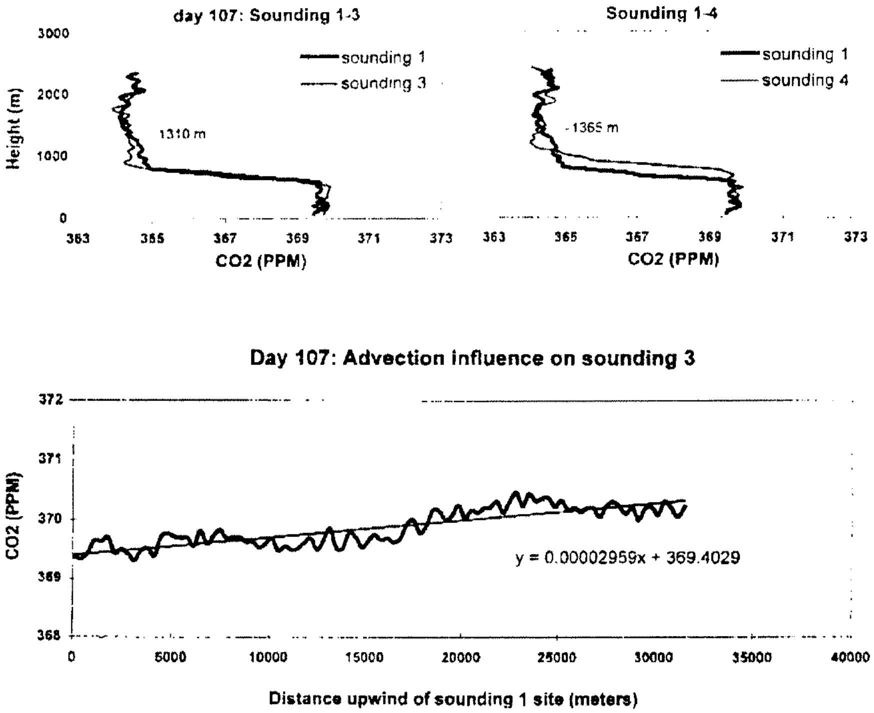

Figure 4: Vertical profiles and horizontal transect of CO_2 concentration measured over the BOREAS study area in 1996. Desjardins *et al* (in prep).

The locations of the LES simulations and the aircraft sampling will be determined according to the final placement of the LBA tower flux sites. We suggest that our objectives would be met if the tower cluster near Santarém included sites in all the major vegetation/land use types. This site is the subject of a proposal by David Fitzjarrald at SUNY/Albany and colleagues. We would be happy to work with them and provide any modeling support and collaboration deemed appropriate. The Amazôn River is particularly broad in that area (several km), acting in effect much as an inland lake in terms of its effects on atmospheric transport and CO_2 concentrations. On relatively quiet days a gradient in sensible heat flux will be generated by the juxtaposition of the cool water and the warmer forest, so that air will be drawn "inland" form the river shore across the forest. In such conditions, an "internal" boundary layer is generated over the forest which grows with distance from the river. Aircraft sampling in such a layer can be done to estimate the net ecosystem exchange of CO_2 with the underlying forest.

By careful choice of sampling locations to coincide with flux tower clusters representing major vegetation cover types in Amazônia, we hope to provide net fluxes over large areas of intact forest, secondary forest, pasture, and savanna. The aircraft PBL budgets will be centered on the flux towers, so that the tower data can be used to provide information about seasonal and diurnal variations. The NEE data obtained from the aircraft sampling program will extend the tower flux data to larger scales, and will be used to improve the model parameterizations, increasing our confidence in carbon flux estimates extrapolated using the models in areas not covered by the flux towers.

Another LBA proposal by Tans, Bakwin, and Artaxo will provide weekly analyses of CO_2 and its stable isotopes in vertical profiles over the Atlantic near Belém, near the mouth of the Amazôn, and over the middle of the basin, near Manaus. These profiles will allow quantification of the PBL integral of CO_2 and isotopic composition in the inflow air to the basin and after the PBL air has made a transit over about 1000 km of forest. From these data, Tans *et al* hope to constrain the overall exchange of CO_2 between the forest and the atmosphere over a large fraction of Amazônia throughout the year. Our proposed PBL budget experiments are centrally located along this transect (near Santarém). The weekly endpoints measured by Tans *et al* will provide context for our PBL budgets, and our PBL flights will provide mechanistic detail in the middle of their large-scale transect. We view the two proposals as complementary, and hope that the mesoscale atmospheric modeling will provide the "glue" to allow meaningful interpretation of the relationship between weekly vertical profiles and the intensive campaign near Santarém. In the event that the Tans *et al* proposal is *not* funded, we will be unable to carry out the flask sampling program, because the flask sampling apparatus will be constructed using LBA funds. We would still plan to conduct the PBL budget campaign, however.

2000: Basin-scale integration

In 2000, we will apply the improved models of land surface carbon exchange to the entire Amazôn basin using a number of data sources. Surface land use will be specified from a land cover database product (either the new 1 km AVHRR land use classification being developed for MODIS, or a successor to this product, or preferably a regional product developed by LBA in conjunction with INPE scientists). The land use and land cover data used in the model will also include specification of historical land use, which will allow the specification of carbon and nutrient pools according to the age structure of the landscapes across the basin. These data will be used in the carbon cycle model developed by Field *et al* to estimate the contribution of land use conversion and reversion to the local fluxes. High-resolution imagery from MODIS will be used to specify canopy structure and function in the hybrid SiB2-CASA model, and surface climate will be specified from the regional atmospheric model RAMS, which will be forced using the LBA 4DDA system to apply the maximum possible constraint from observed climate and meteorological data. If the proposal by Tans *et al* is funded, their data will provide the inflow boundary condition (off the coast near Belém) for the regional simulations, and another anchor point near Manaus, for both CO_2 and $\delta^{13}C$. Further validation/calibration points will be provided by the tower flux sites. The hybrid model, calibrated from field and aircraft data over the various component ecosystem types, will produce basin-wide estimates of carbon flux and isotopic discrimination and disequilibrium that are consistent with the surface energy budget and hydrologic interactions in the soil-forest-atmosphere system.

The NEE fluxes produced in the basin-wide simulations described above will then be fed into the tracer transport code in RAMS to predict the full 3-dimensional concentration and isotopic composition field of CO_2 over Amazônia for the full year. Ideally, these 3-D estimates would be applied in a synthesis inversion of deep aircraft data collected by TRACE-B, but these data may never become available. We are optimistic that the European LBA-CLAIRE program will provide at least some deep 3-D concentration data for CO_2. Our simulated 3-D CO_2 fields will predict the results of these experiments in advance, and should be very valuable in planning for such missions. As data become available for 3-D CO_2 from either CLAIRE or TRACE-B, they will be compared to the simulated concentration field to test the models used in this study. In addition, these simulations and data will be an excellent test of the regional-scale effects of the atmospheric CO_2 "rectifier" and its impact on global carbon budget inversions (Denning *et al* , 1995, 1996b). We further hope that the simulated 3-D distribution of the isotopic composition of CO_2 over the Amazôn will allow the development of inexpensive observational strategies to monitor the effects of land use conversion (from C_3 forest to C_4 agriculture) through atmospheric data.

One of the most important results of the research outlined here would be a well-understood and well-constrained estimate of the basin-wide net annual exchange of CO_2 between the Amazôn and the atmosphere. This is a central goal for LBA. A second benefit would be the development of modeling technology to leverage EOS data with relatively inexpensive light aircraft, which could be applied to obtain regional carbon budgets in other areas as well. We would use this information in our ongoing efforts to calculate the global carbon budget of the atmosphere in the CSU GCM by inversion of the global flask observing data.

Education and Training

The proposed project will contribute to NASA's goals of education and training in several ways. We will recruit and train a Ph.D. student (Lara Prihodko) and a PostDoctoral researcher (to be named), who will gain valuable skills in modeling of land-surface atmosphere interactions, carbon cycles, and the coupling of remote sensing to ecological and atmospheric processes. We will exchange models, data, and expertise with Brazilian scientists at USP and INPE, and their students and colleagues (please see attached letters of collaboration). We will engage in scientific exchange of visitors with Brazilian institutions: a Ph.D. student from UCSB will visit the Universidade de São Paulo for one month, and two USP scientists would UCSB.

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Data Plan

We plan to share any and all data and model results through an LBA data management system, by means which will have to be determined when such a system is designed. We would be happy to participate in the design of such a system, if this proposal is funded. We will produce the following types of data:

- Atmospheric CO_2 and $\delta^{13}C$ fluxes and concentrations over a radius of several km around several flux towers, on a spatial scale commensurate with LANDSAT imagery
- Vertical profiles and transects of atmospheric CO_2 concentration measured by the proposed light aircraft sampling program
- Basin-wide estimates of carbon flux throughout one year, on a spatial scale commensurate with MODIS imagery
- 4-dimensional estimates of CO_2 concentration and $\delta^{13}C$ in the atmosphere above Amazônia during 2000, produced in RAMS for comparison with CLAIR and TRACE-B.

We anticipate exchange of input data and model output with the Silva Dias group at USP, with Berry and Field at Carnegie, and with Tans *et al* at NOAA/CMDL, on a weekly basis. This will be accomplished over the internet via ftp. We agree to provide these data to the

LBA data management system within 6 months of producing them, allowing time for quality assurance, data reduction, and documentation.

Management Plan

Personnel

The Principal Investigator (Denning) will plan and managing the project, coordinating the modeling efforts and data analysis. In addition, Denning will manage the extensive collaborative outreach proposed with other projects. He will also serve as a mentor for both the Post Graduate Researcher and the Ph.D. student, as well as teach formal courses to the Ph.D. student. He will advise the scientific visitors from Brazil on the use of the modeling system and its interface to the available data.

Dr. Ray Desjardins will coordinate the aircraft sampling program in 1999. Desjardins is an internationally renowned micrometeorologist who has extensive field experinece in collecting and analyzing the type of data we propose to collect.

A Post Graduate Researcher will perform most of the model development and model experiments in the project. He or she will be recruited nationally, and will have expertise in both the use and programming of the RAMS model and ecosystem metabolism.

A Ph.D. student, probably Lara Prihodko, will be supported under the project. She has expertise in both bio-optical remote sensing and geographic information systems and in numerical simulation of the soil-vegetation-atmosphere system (see enclosed CV). She will be responsible for basin-scale parameterization of the ecosystem models from geographically-referenced data.

A Programmer/Analyst will be recruited to manage the computer systems required for this project. He or she will be supported largely through funds from other grants, but will contribute about 25% of his or her time to this project. Support required includes system administration, data management, and scientific programming.