Regional Atmospheric Carbon Budget in Amazonia
Balanço Atmosférico Regional de Carbono na Amazônia - BARCA

1. Scientific Rationale

The Amazon Basin accounts for ~10% of global terrestrial net primary productivity [*Melillo et al.*, 1993] and contains one-half of the world's undisturbed tropical forest, 5.8×10^6 km^2, and extensive areas of tropical savanna [*FAO*, 1993]. Current estimates of CO_2 fluxes over Amazônia are subject to large uncertainties that propagate into the global carbon budget. Huge net sources of CO_2 are usually attributed to the region, due to deforestation and agricultural development. However recent eddy flux data have been reported to show large net uptake in the tropical rainforest that, if extrapolated regionally, provide a strong carbon sink [*Malhi and Grace*, 2000]. Scaling up from a few eddy flux sites to the entire Basin is difficult without complementary data and an integrating framework. The proposed combination of observations and analysis framework is intended to address the question of Basin-scale sources of CO_2, a central issue of the Brazilian Millenium Institutes and the Large-scale Biosphere-Atmosphere (**LBA**) program.

A number of studies have been carried out as part of the LBA program on local scales, greatly expanding the previous scientific knowledge on carbon dynamics, soils, species distributions, and vegetation age structure. **Time is ripe for an integrative study synthesizing the information available from the LBA studies with new aircraft observations to quantify Basin-scale carbon fluxes**.

BARCA (Balanço Atmosférico Regional de Carbono na Amazônia) proposes intensive aircraft observational campaigns which will collect data that are *quantitatively and qualitatively different from current data,* with atmospheric concentrations measured over the entire continent and adjacent waters. An integrative modeling framework designed to *determine spatially resolved sources and sinks of* CO_2*, CO, and other gases at short and long time scales* will be applied, which combines high-resolution atmospheric transport with models of surface fluxes. The integrative modeling framework will be merged with observations in "Model-Data-Fusion" to derive the state of the atmosphere and the carbon cycle that is consistent with the aircraft observations as well as a variety of other datastreams, such as soil properties, remotely-sensed vegetation data, and long-term flux measurements. These optimally constrained models will provide the most reliable diagnostic and predictive capability for surface-atmosphere fluxes of CO_2 and CO in the data-rich environment of the LBA.

BARCA addresses the "missing scale" for measurements of CO_2 fluxes, intermediate between local and global. Process- and ecosystem-level studies, such as continuous eddy correlation fluxes [*Goulden et al.*, 1996; *Jarvis et al.*, 1997], provide detailed information about carbon exchange by a patch of forest. Inverse studies couple marine boundary-layer observations and atmospheric transport models to yield carbon fluxes at global or hemispheric scales [*Tans et al.*, 1990], but have not succeeded at regional to continental scales due to lack of data over continents and uncertainties in modeling transport [*Gloor et al.*, 1999]. The proposed atmospheric observations in Amazônia are intended to address the gap between the local studies and the global inverse studies.

Extensive airborne measurements over Amazônia are envisioned to cover horizontal scales of 100~1000 km, altitudes 0.15-12 km, and most daytime hours, closely coordinated with ground measurements at LBA towers and at a coastal station (INPE-Natal). Flight planning will be guided by transport simulations using high-resolution assimilated meteorological fields, currently under development at the Universidade de São Paulo (USP). In this way, BARCA will:

- directly quantify regional to Basin-scale fluxes in Amazônia using airborne measurements of CO_2 and other tracers in and above the planetary boundary layer (PBL);
- establish relationships between vertical concentration gradients and exchange fluxes observed at the eddy flux towers in LBA and over adjacent regions;
- test hypotheses central to LBA and the Millenium Institutes that Amazônia is a major net source or sink for CO_2;
- characterize horizontal and vertical distributions of atmospheric CO_2 over Amazônia for the purposes of planning remote sensing instrumentation

BARCA plans to conduct airborne measurements during both the wet and dry seasons to characterize the seasonal variability of carbon fluxes. Proposed regional experiments over natural and disturbed ecosystems will deliver regional carbon fluxes over different land surfaces, especially the developed and undeveloped districts of Rondônia, while the large-scale transects yield Basin-scale flux over the whole of Amazônia.

BARCA is inherently a collaborative effort, combining a range of disciplines and spans multiple spatiotemporal scales. The Millennium Institutes, with a tradition of cross-discipline, cross-border collaborations, will provide the institutional backbone for such collaborations. Furthermore, BARCA will enhance and be enhanced by a wide range of LBA projects. Eddy covariance data from LBA towers provide continuous time series of fluxes and concentrations, allowing correction for the fair-weather bias inherent in low-level aircraft operations and to generalize conclusions based on two seasonal studies. Conversely, direct measurements of regional and Basin-scale exchange fluxes evidently aids scaling up of LBA results. Information on the vegetation type, land use/land cover, aboveground biomass, and phenology in the study regions will come from LBA remote sensing.

2. Summary of Aircraft Mission

Sources and sinks of carbon impart their signatures on the atmospheric concentration distribution, subject to modifications by atmospheric transport processes such as advection, turbulent mixing, and cloud venting. In particular, atmospheric winds typically advect air parcels across hundreds of km over a day, so the atmospheric distribution of CO_2 yields unique information on regional to Basin-scale fluxes once atmospheric transport is accounted for.

The aircraft is the only means to observe the three-dimensional tracer distribution in the atmosphere at high-resolution. Thus the important observational needs of research in the LBA program can only be met through measurements made from aircraft. Within LBA local-scale measurements and results of process studies are being combined with remotely sensed data and other geographically extensive data sets to derive regional-scale understanding. Airborne observations will play a key role in the synthesis effort designated "IntegraLBA" by providing an intermediate-scale of measurement in scaling-up site-specific information. The goal is to unify bottom-up and top-down determination of Basin-wide budgets for CO_2, CO, aerosols, and other species, using in situ aircraft data, tower site flux and concentration data, and satellite measurements, combined through the use of high-resolution assimilated wind fields and land surface models.

The airborne observations will fill key data gaps and reduce major scientific uncertainties in the understanding of regional carbon balance and trace gas fluxes. Carbon dioxide measurements from this aircraft will provide essential information for evaluating approaches to quantify vegetation recovery and biomass change following forest clearing and various forms of land use. They also will enable more accurate biophysical parameter assessments over regions and enable validation of satellite algorithms for deriving these parameters.

The BARCA aircraft missions will deploy two Brazilian aircraft in Brazil, tentatively identified as the INPE Bandeirante and a leased Lear 35 or 55. The measurements onboard the two aircrafts are the following:

Lear 55 (leased)

Measurements	Source (provisional)	Comments/action item
H_2O, P, T	Jena/Lloyd	Feasibility action item
Lat/Lon/GeoAlt	USP/Artaxo	new GPS unit, antenna on window?
CO	Harvard/	VUV
CO_2	Harvard	Licor/
Flasks	CMDL+USP	Medusa/Miller or suitcases/Gatti
O_3	Birks/2B	Scientist attend?

INPE Bandeirante

Measurements	Source (provisional)	Comments/action item
H_2O, P, T	Jena/Lloyd	has been flown before
Lat/Lon/GeoAlt	USP/Artaxo	has been flown before
CO	Mainz	VUV
CO_2	CMDL Tans/Artaxo	New unit/Tans
CO_2	Jena/Lloyd/Artaxo	Has been flown before
Flasks	CMDL+USP	Medusa/Miller or suitcases/Gatti
O_3	Birks/2B	scientist attend?
TSI Nephalometer	Artaxo	has been flown before
MobPartAnal	Artaxo	has been flown before

PTRMS	Guenther/Artaxo	availability uncertain; has flown
FTIR	Yokulson/Artaxo	availability uncertain; has flown

We plan two campaigns of 6 weeks duration each to cover the dry season in 2002 and the wet season either in 2002 or in 2003. The dates for the campaigns will be chosen to maximize overlap with the airborne remote sensing periods, for scientific reasons (detailed analysis of surface conditions and vegetation) and logistical advantages (a single MOU for airborne observations, facilitate customs issues).

The BARCA flight strategies can be divided into the following two categories:

1. **Lagrangian regional experiments**: diurnal airborne measurements of CO_2, CO, and H_2O within and above the PBL in an airmass-following framework which provide tight constraints on regional fluxes and their variations across different disturbance regimes.
2. **Large-scale surveys**: sampling of large-scale CO2 distribution along the synoptic flow pattern gives Basin-scale flux constraints

Details regarding the regional experiments and large-scale surveys are included in section 4.

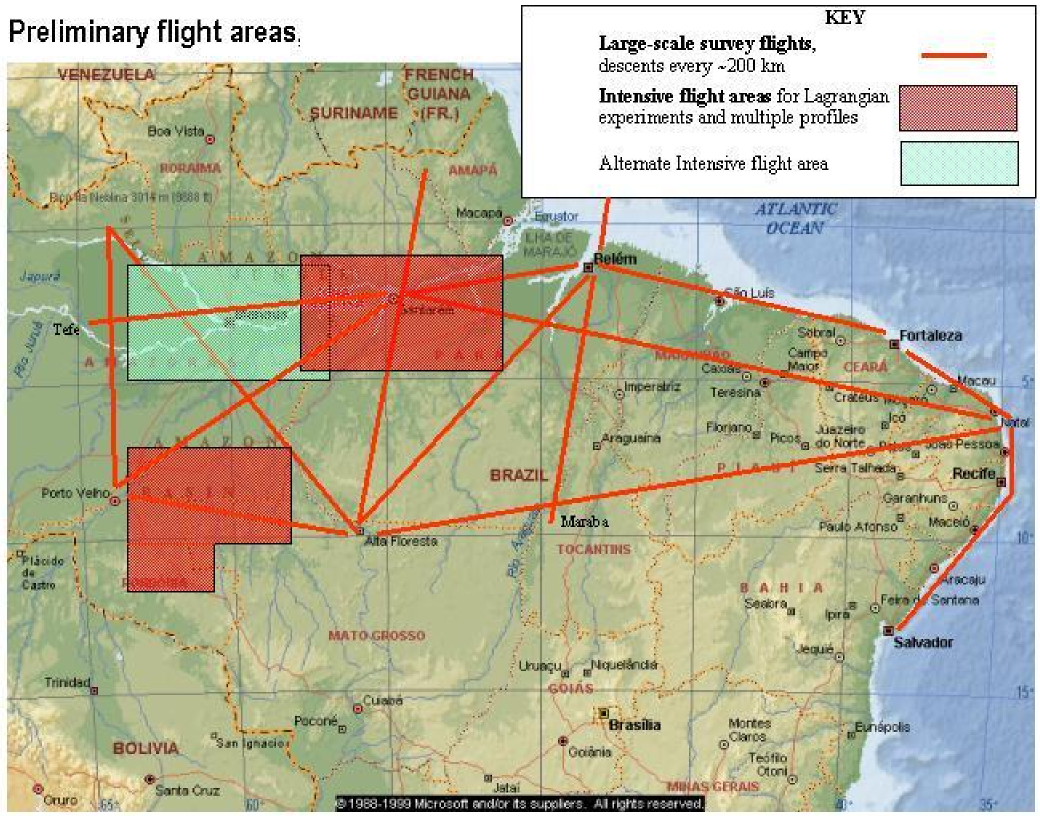
The planned operational areas for the aircrafts are drawn on the attached map. The main features include:

Large-scale surveys: Inflow airmass characterization (Atlantic coast), basin scale cross-sections at different distances from the coast; these flights will take place in the middle of the campaign period, roughly the 3rd week of November.

Santarém intensive flight area: Lagrangian experiments and multiple diurnal profiling, covering the area around Santarem, including Tapajós National forest, Tapajós River, and Amazon River. We plan to do these experiments around the first 1.5 weeksof the mission.

Rondônia intensive flight area: Lagrangian experiments and multiple diurnal profiling, covering the area east of Porto Velho. We plan to do these experiments around the last 1.5 weeks at end of November.

Western Amazon intensive flight area: A flight segment to Saõ Gabriel may be flown if operational conditions are within limits (not shown on the map).



3. Integrative Framework for Model-Data Fusion

The BARCA integrative framework provides an internally consistent representation of the atmosphere and the biosphere, critical for learning about carbon sources/sinks through aircraft observations and other datastreams. The role of the integrative framework can be understood from the following formal representation linking a CO_2 observation at location $\mathbf{x}_r$ and time t_r, to sources/sinks $S(\mathbf{x}, t)$ [*Gerbig et al.*, 2003]:

$$CO_2(\mathbf{x}_r, t_r) = \underbrace{\int_{t_0}^{t_r} dt \int_V d^3x\, I(\mathbf{x}_r, t_r \mid \mathbf{x}, t) S_{veg}(\mathbf{x}, t)}_{\Delta CO_{2veg}(\mathbf{x}_r, t_r)} + \underbrace{\int_{t_0}^{t_r} dt \int_V d^3x\, I(\mathbf{x}_r, t_r \mid \mathbf{x}, t) S_{foss}(\mathbf{x}, t)}_{\Delta CO_{2\,foss}(\mathbf{x}_r, t_r)} + \underbrace{\int_V d^3x\, I(\mathbf{x}_r, t_r \mid \mathbf{x}, t_0) CO_2(\mathbf{x}, t_0)}_{CO_{2up}(\mathbf{x}_r, t_r)} \quad (1)$$

where $I(\mathbf{x}_r, t_r|\mathbf{x}, t)$ encapsulates the effect of atmospheric transport, specifying the fraction of a fluid element found at $\mathbf{x}_r$ and time t_r, given that the fluid element was at $\mathbf{x}$ and time t and is analogous to a Green's function. The first two terms on the RHS of Eq. 1 specifies the contribution of biospheric and fossil fuel fluxes to changes in CO_2 at ($\mathbf{x}_r$, t_r), respectively, in domain V during the time interval between initialization time t_0 and t_r. The third term refers to the contribution to the observation due to advection of CO_2 from the initial field $CO_2(\mathbf{x}, t_0)$.

The atmospheric model in the integrative framework provides $I(\mathbf{x}_r, t_r|\mathbf{x}, t)$, linking the sources/sinks with the atmospheric tracer observations. The integrative framework further includes representations of sources/sinks $S(\mathbf{x}, t)$ that are implicit functions of other variables $\boldsymbol{\lambda}$ which depend on $\mathbf{x}$ and t (e.g., solar radiation, temperature, population density). In particular, the biospheric model $S_{veg}(\mathbf{x}, t;\ \boldsymbol{\lambda})$ includes $\boldsymbol{\lambda}$ that are thought to affect carbon fluxes: e.g., solar radiation, leaf area, temperature, and biomass. Numerous datastreams from multiple scales will be necessary to provide values for $\boldsymbol{\lambda}$ in order to generate $S_{veg}(\mathbf{x}, t;\ \boldsymbol{\lambda})$.

The model-data fusion step entails the use of the observational constraint from $CO_2(\mathbf{x}_r,t_r)$ and $CO_2(\mathbf{x},t_0)$, combined with the atmospheric model to generate $I(\mathbf{x}_r, t_r|\mathbf{x}, t)$, in order to adjust $\boldsymbol{\lambda}$ in the biospheric model such that the modeled CO_2 is optimally consistent with the observed values. The optimized $S_{veg}(\mathbf{x}, t;\ \boldsymbol{\lambda})$ would then incorporate information from the combination of atmospheric, ground-based, and remote-sensing observations, representing the best guess regarding the carbon fluxes at the regional to Basin-scales.

Special attention has to be given to the development of an atmosphere-biosphere modeling framework: too much complexity (involving too many parameters) will prohibit finding an optimal state (set of parameter values), while too much simplicity might prohibit capturing much of the processes involved and will not have predictive skills. A balance has to be found in which the model is capable to describe the emergent properties of the system on relevant spatial and temporal scales.

Atmospheric Model

The representation of atmospheric transport in the modeling framework has to properly take into account processes such as turbulent mixing and vertical transport through shallow and deep cumulus convection. The challenge will be to reduce any biases associated with inappropriate representation of mixing near the surface, especially when dealing with fluxes that strongly vary on diurnal timescales ("rectifier-effect") [*Denning et al.*, 1996]. The airborne observations with nearly complete tropospheric coverage in the vertical will provide a strong diagnostic check on the transport representation, and will provide guidance with regard to required model improvements.

The Stochastic Time-Inverted Lagrangian Transport (STILT) model [*Lin et al.*, 2003] has been developed to compute atmospheric transport backward in time and determine $I(\mathbf{x}_r, t_r|\mathbf{x}, t)$, the influence of upstream fluxes on atmospheric observations. STILT simulates the motions of particles—representing air parcels—backward in time, advected by mean wind velocities as well as stochastic velocities representing turbulent eddies that are particularly important in the PBL. The backward-time formulation significantly reduces computation needed to derive $I(\mathbf{x}_r, t_r|\mathbf{x}, t)$. The Lagrangian formulation reduces numerical diffusion and errors associated with comparisons between coarse, grid-averaged values and point data [*Stohl*, 1998].

The STILT model will be driven with mesoscale meteorological fields from the Regional Atmospheric Modeling System (RAMS), [*Pielke et al.*, 1992] developed at Colorado State University as a multi-purpose, non-hydrostatic mesoscale model to allow for simulation of atmospheric circulations that range from eddies to hemispheric scale phenomena [*Cotton et al.*, 2003]. A version of RAMS designed for climate simulations [*Liston and Pielke*, 2001] enables simulations to be carried out at multi-year timescales. RAMS has nesting capabilities that allow atmospheric phenomena to be resolved at fine scales in target regions and to dynamically interact with the rest of the model domain, resolved at coarser scales. The RAMS convective parameterization has recently been upgraded to include schemes—e.g., the Grell scheme [*S. Freitas*, personal communication] and the Kain-Fritch scheme [*Castro et al.*, 2003]—which produce convective mass fluxes, enabling detailed vertical redistribution of tracers, aerosols, and hydrometeors.

A version of RAMS developed in Brazil (BRAMS) is already being used at USP for operational forecasting covering the South American region [http://www.master.iag.usp.br]. The operational system includes aerosol forecasts that are based upon predicted areas of biomass burning [*S. Freitas*, personal communication].

The atmospheric model involving RAMS and STILT will also be essential in planning flight tracks as part of the Lagrangian regional experiments (see section ???). In this case, STILT will be driven with meteorology from the RAMS operational forecasts at USP.

Biospheric Model

The Ecosystem Demography (ED) model [*Moorcroft et al.*, 2001] is a mechanistic representation of the terrestrial biosphere designed to simulate vegetation dynamics from hourly to decadal timescales. The explicit linkage in ED between processes operating at a wide range of temporal scales is unique amongst terrestrial biosphere models. ED incorporates leaf-level physiological processes (hourly timescale) that dynamically interact with the atmosphere to determine the transfer of energy, water, momentum, and CO_2 and thus control the response of the land surface to aerosols in smoke plumes. ED further includes a novel, stochastic formulation of the ensemble dynamics of individual trees that simulates processes such as fire disturbance, competition, recruitment, and mortality (monthly to multi-year timescales). Such land surface processes operating at timescales greater than a week have been demonstrated to be critical for understanding the climate [*Bonan*, 2002]. The individual tree-based approach that lies at the heart of ED in lieu of the "big-leaf" approach [*Sellers et al.*, 1997] commonly taken by land surface models means that ED predicts sub-gridscale distributions of vegetation properties which are important to represent land-atmosphere interactions [*Moorcroft*, 2003; *Pielke*, 2001].

Additional Datastreams

The datastream ingested by the modeling framework will include atmospheric observations from airborne intensives and from long-term monitoring sites such as the NATAL site and flux towers with accurate CO_2 calibrations, ecosystem exchange fluxes measured by the network of eddy flux towers, and remotely sensed vegetation parameters.

4. Flight Strategy

4.1 Regional experiments

Regional budget studies over the Amazon will focus on the Primary LBA Transects (Fig. 12). Budget studies in the vicinity of principal LBA flux tower sites will help us to develop methods to scale up the ground-based measurements from the flux footprint to the regional scale. Likewise, the flux measurements at nearby tower sites will allow us to correct the budget results for biases associated with weather requirements for airborne sampling.

During the first half of each campaign we plan to operate the Lider Lear 35a from Manaus, conducting regional experiments over the northern Primary LBA Transect and Central Amazonia.

Flights in regional budget studies will sample cross-sections following an airmass over 24 hours as it moves toward the location of the receptor cross-section, as well as sampling repeatedly over the LBA tower sites for the Eulerian analysis. The location of the airmass of interest will be forecast using the STILT model driven by forecasted wind fields from the Eta model at CPTEC, run in operational mode [*C.S. Chan,* personal communication]. Flight patterns will be similar to COBRA-2000 (Fig. 5): a late afternoon flight on the first day, followed by three flights on the second day, early morning, noon, and late afternoon. An additional sawtooth pattern will be flown perpendicular to the cross-sections, along the mean wind direction, to characterize the 3-D tracer distribution and provide context for the Eulerian analysis. Cross- sections will be sized generously to maximize tolerance for errors in the forecasted winds. The along-wind cross-section helps to match upstream and downstream measurements in the presence of wind shear. We plan 46 flight hours for ~5 regional experiments during each campaign.

Spatial coverage of the regional budget

Regional study areas will have horizontal dimension of 100-300 km. Mean wind speeds in the mixed layer at 950 mbar average 3-4 m/sec (Fig. 13), predominantly easterly in Santarèm and southeasterly in Rondônia. Thus an airmass moves ~300 km during the 24 hours of each experiment. The separation between the individual cross-sections will be about 200 km between the late afternoon and early morning flight, and will be about 50 km between the daytime cross-sections. From the regional experiments conducted during COBRA-2000 we anticipate being able to resolve surface fluxes on the scale of 50km perpendicular to the mean wind. Some regions will be chosen to sample developed agricultural areas that can be contrasted with undeveloped primary forests, in support of the LBA goal to delineate land use effects.

By following a single airmass over a 24 h period, the budget method will give nighttime respiration and daytime uptake fluxes for different geographical areas (Fig. 5). Both nighttime and daytime fluxes can be derived for the same area by following separate airmasses over the same region during the day and the night. Because of minimum altitude requirements, the aircraft cannot fly below the nighttime mixed layer top. Therefore the signal from the nighttime respiration will be extracted from the early morning measurements in the growing mixed layer, into which the accumulated nighttime CO_2 is diluted (see Fig. 5), supplemented by tower data and missed approaches. The experiment can be moved to any area within flight range. Locations such as rural airports suitable for "missed approaches", and LBA towers and surface sites, will be favored. We can adapt to changes in forecasted winds between the first and second day of the regional experiment by moving the receptor to the revised location of the region that is downstream of the area sampled during the first day.

CO as tracer

Concurrent *in situ* measurements of CO help determine regional budgets of CO_2 in several ways:

i) The spatial variability in the CO cross-section above the PBL helps to assess whether the same airmass was in fact followed as forecasted by the flight-planning tool. Concentrations just above the PBL, not under direct influence from turbulent mixing and removed from surface fluxes, will tend to maintain vertical layering and horizontal gradients, subject to subsidence and wind shear. Thus comparisons of consecutive cross-sections helps to test values for the shear and subsidence from Eta as well as checking the mean transport trajectory.

ii) If there are localized sources of CO_2 from biomass burning or fossil fuel emissions between two consecutive cross-sections, the downstream cross-section will reveal a spatially limited change in the amount of CO, since the emission will not be dispersed over the whole cross-section over half-day time scales. In this case the budget of CO will allow estimation of this surface source. The inferred CO_2 flux can then be corrected for this fossil or biomass burning source by applying known or observed emission ratios [*Andreae et al.*, 1988]. The spreading of a point source in the domain would provide a test of the STILT model.

During the dry season, the spatial variance of CO is large [*Sachse et al.*, 1988] and CO data help validate trajectories, but budgets are poorly constrained. During the wet season, CO exhibits less variability [*Harriss et al.*, 1990], so approach i) should be practical.

H_2O as tracer

Water serves as a useful transport tracer under non-precipitating conditions. The PBL height can be determined from the sharp gradient in water content between air in the PBL and free troposphere. The subsidence rate, generally measured with difficulty because of its small value, can be quantified from vertical shifts in layers of humid or dry air between two cross-sections. This appears to be an especially useful datum for COBRA-BRAZIL. The principal source of water over the forest is co-located with sinks of carbon in the leaves, so water potentially serves as a valuable tracer to help determine carbon fluxes, particularly in the Amazônian dry season, when 90% of total evaporation is derived from transpiration through the stomata [*Shuttleworth*, 1988]. Regional-scale evaporation estimates provided by a Lagrangian water budget, calculated in an analogous fashion to a carbon budget described above, can be compared with bottom-up estimates generated from the numerous ground measurements of water fluxes by other LBA investigators using eddy covariance, sap flow, and branch-level chambers. Thus the water budget serves as an additional constraint on scaling-up methods, which have to yield regional fluxes comparable with the Lagrangian method for both CO_2 and water.

Use of remote sensing data

Information from airborne and spaceborne remote sensing platforms will help place the observed fluxes in a biological context. Variables including land use, vegetation type, above ground biomass (AGB), phenology (temporal change in leaf area index (LAI)), and fractional photosynthetically available radiation (FPAR) are important to understand the drivers of CO_2 exchange. It may be possible to test estimates of CO_2 release due to deforestation using Landsat imagery by comparing aircraft-derived carbon fluxes for developed and undeveloped areas. Since our campaigns will coincide with LBA airborne remote sensing, these data will be available during COBRA-BRAZIL. The footprint area provided by the transport model can be combined with maps of these variables to assess the influences of vegetation and land use types on CO_2 fluxes. The goal is to combine information from remote sensing with the observed regional flux budgets to advance development of methods for scaling-up.

Assessment of feasibility for the Lagrangian experiments

The feasibility of Lagrangian regional experiments at various locations will be assessed prior to the mission by examining the upstream influence areas predicted by the STILT model, using archived assimilated winds. Particle ensembles will be started at Santarèm and Porto Velho, and the particle locations after 24 hours will determine the size of cross-sections necessary to characterize airmasses and the distance over which the airmass will be advected. The simulations will be conducted for many days in both wet and dry seasons to construct a climatological picture of likely flight scenarios. Particular attention will be paid to the character of the footprint, and we will avoid areas with strong admixture of large rivers, forests, and agricultural land in favor of relatively uniform land surface types in a particular footprint.

Visual Flight Rules (VFR) are needed for most of the regional scale missions. By adding satellite products of cloud cover for the different regions to the flight scenario climatology, we can assess the likelihood for VFR conditions. In case of cloudy conditions, the flight pattern for the cross-sections can consist of horizontal legs at different altitudes with ascents and descents at each end, and "missed approaches" to airports with ILS.

Flight planning

Collaborators at CPTEC will provide forecast products from the Eta model over South America. At the operational center (either Santarèm or Porto Velho) these data will be downloaded and used to drive the STILT model to forecast airmass motion for flight planning.

Analysis of observations

We will draw upon the expertise of researchers at CPTEC and USP in understanding the meteorology and convective systems of the Brazilian Amazon [*Bonatti and Rao*, 1987; *Silva Dias et al.*, 1987; *Freitas et al.,* 2000]. Both of these institutions will provide mesoscale meteorological fields in post-flight analyses to derive flux on the regional and Basin-scales. High-resolution RAMS assimilations will be performed by USP to provide winds for the regional Lagrangian budget experiments. Meteorological fields from mesoscale reanalysis using RAMS (USP) and Eta (CPTEC) will be used to drive transport models like STILT for the large scale experiment and for interpretation of the data collected in the Eulerian approach.

4.2 Large-scale surveys

We propose to conduct large-scale surveys to estimate Basin-wide net CO_2 exchange. The dominant wind direction for the Amazon Basin is easterly, with a seasonal dependence induced by the shift of the ITCZ (Fig. 13). A CO_2 cross-section in the inflow area will be established by sampling along the coastline of the Amazon Basin (Figs 12, 13 and 14), including over the continuous CO_2 station being established under LBA at Natal. Three further large-scale CO_2 cross-sections will be measured over regions further inland and downstream along the general flow direction. The location for the cross-sections will be adjusted by using forecasts of back trajectories at the time of the mission. The horizontal extent of the cross-sections is controlled by synoptic-scale convergence and will be about 1000-2000 km (Fig. 12, 13). Four large-scale cross-sections will be constructed with 7-8 flights with numerous vertical profiles, total flight time of 21 hours over ~6 days.

Signals of surface fluxes are most strongly reflected at the inland region in air parcels lower in the atmosphere, labeled **blue** in Fig. 14. The difference in CO_2 concentration in these air parcels between their downstream value at the inland region and upstream value at the inflow area reveals Basin-scale fluxes. Concentrations of CO and CO_2 up to 10 km, combined with transport rates from the Eta and RAMS assimilations, should allow us to compute the Basin-scale flux. If deep convection is absent from the domain, vertical transport is dominated by large-scale subsidence. The expected subsidence will be 3-6 km during their transport between the first and the last cross-section, assuming an average wind speed of 3.5 m/s and subsidence rates of 0.5-1 km/day (typical values from the NCEP re-analysis). Thus the principal influences on the lower portion of the inland cross-section are captured by flights sampling up to 10 km.

Deep convective systems modify the transport of air parcels arriving lower in the atmosphere at the inland region (**blue** arrows in Fig. 14). According to *Scala et al.* [1990] there are distinct transport pathways in deep convective systems in Amazônia. Some air is pumped from the lower atmosphere to the cloud top region in the upper troposphere (labeled **green** in Fig. 14). However, there is no analogous path to transport air from the upper troposphere to the PBL. Mesoscale downdrafts bring air from ~6km to the lower atmosphere (**blue**) [*Scala et al.*, 1990], but generally not from cloud-top altitudes. An inflow cross-section with a vertical extent of about 10 km altitude should allow us to capture these upstream air parcels, to compute fluxes within the accuracy of the representation of large-scale subsidence and mesoscale downdrafts in the mesoscale assimilations by RAMS and Eta. Thus even in the presence of convective systems, the maximum sampling altitude needed for the Basin budget is in the range of the Lear 35a.

We will use operational forecasts of back trajectories from the MRF model to help optimize timing and location of cross-sections, to avoid poor flying weather and major disturbances. Prior to COBRA-BRAZIL missions, studies using archived data will be undertaken to develop sampling strategies for likely synoptic conditions, including selection of airports.

Derivation of large-scale fluxes

Measured CO_2 fields will be analyzed using the STILT model to derive surface fluxes of CO_2 as currently in progress for COBRA-2000 large-scale experiments. Diurnal information from the Eulerian experiments provides a first-order correction to account for the daytime variations present in the large-scale concentrations. The STILT model will be driven by RAMS assimilations provided by USP [*M.A.F. Silva Dias* and *P.L. Silva Dias*, collaborators] and by assimilated winds from the Eta model (CPTEC collaborators), both of which have high spatial resolution.STILT will be combined with surface grids for vegetation type and land use/land cover, and net fluxes derived using guidance from LBA tower data and ground-based studies.

Surface measurements of CO_2 and CO at a new coastal station (INPE-Natal) in the inflow-area, as well as flask data from vertical profiles using a small aircraft (LBA-Ecology investigation TG-06) will augment COBRA-BRAZIL data. By including these measurements, it will be possible to assess the variability of CO_2 during the period of the large-scale experiment.

Advantages of the proposed program to measure large scale net flux of CO_2

The proposed techniques to quantify fluxes of CO_2 in the Amazon Basin have these advantages:

- The Lagrangian regional budget technique provides surface fluxes of CO_2 based on accurate column measurements in the same airmass, minimizing contributions from advection terms.

  -The horizontal extension of about 300km*300km, resolving fluxes at about 50km*50km, can not be covered by any other experimental technique currently available.

  -Following airmasses over a full 24-h period allows precise estimates of nighttime respiration and daytime photosynthesis.
- The proposed large-scale surveys will provide an estimate of the net source/sink at the scale of the Amazon Basin which is much more precise than inverse studies using marine boundary-layer measurements can deliver. The signature of major net sources or sinks should be clearly resolved.
- Results from the Lagrangian and large-scale experiments will help us evaluate flux estimates from Eulerian methods, which can be applied routinely using cheaper aircraft and instrumentation

Instrumentation

Airborne platform

The Lear 35a owned and operated by Lider Air Taxi is a twin-engine fanjet with an operating ceiling of 39,000 feet (11 km). It is an air ambulance that can be operated out of relatively short airstrips and to be flown at slow speeds down to 140 kts (72 m/s). It can cruise at 340 knots (175 m/s). The Lear is well suited for intensive vertical profiling of the entire atmosphere including the PBL and covering large areas. The endurance is 3.5-4 hours, allowing coverage of continental scales.

Meteorological parameters

The basic instrumentation package of the Lear measures temperature, dew point, pressure, winds (*u, v, w*), and aircraft position, altitude, and performance.

CO_2 instrument

The *in situ* CO_2 analyzer is a non-dispersive infrared gas analyzer based on the Harvard University ER-2 CO_2 analyzer [*Daube et al.*, 2002], which has an uncertainty <0.1 ppmv for more than 150 flights. The COBRA instrument has 8 stratospheric balloon flights and more than 30 flights aboard the UND-Citation during COBRA-2000. In-flight and laboratory calibrations indicate that the uncertainty of the CO_2 observations during COBRA-2000 was ±0.25 ppmv, with increased uncertainty vs. the ER-2 instrument primarily associated with configuration issues (water trap too large, reference gas drift) which are readily resolvable for COBRA-BRAZIL.

CO instrument

The VUV-Fluorescence instrument is capable of measuring CO at 1 Hz resolution with a precision of 2 ppb, and a long-term accuracy of 3 ppb [*Gerbig et al.*, 1999]. It was operated during the more than 30 flights of COBRA-2000 aboard the UND Citation with data coverage close to 100%. A similar instrument showed excellent agreement in an airborne intercomparison, the observed differences were consistent with the estimated precision [*Holloway et al.*, 2000].

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