*Research Project submitted to the FAPESP Global Climate Change Program – Nov 2008*

# AEROCLIMA - Direct and indirect effects of aerosols on climate in Amazonia and Pantanal

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Proposed start date: April 2009, duration: 48 months.

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## 1 – Summary

The proposal AEROCLIMA will work on an integrated strategy to enhance the knowledge on the direct and indirect effects of aerosols on climate for the Amazonia and Pantanal regions. The basic concept for AEROCLIMA is of an integrated study, combining field studies with intensive in-situ measurements, remote sensing and regional and global modeling. The idea is to reduce uncertainties on direct and indirect aerosol radiative forcing and to evaluate the impact of aerosols on the ecosystem, including into the hydrological cycle trough an approach with detailed aerosol and radiation measurements in several sites, coupled with a modeling component with 1D and regional climate models approach. Key aerosol properties such as aerosol size distribution, mass, elemental and ionic composition, light scattering and absorption, CCN activity, and others will be

measured for one year in each of 3 aerosol sampling stations: North of Manaus (pristine natural biogenic emissions), Alta Floresta (biomass burning aerosols) and Campo Grande at the Pantanal region. Intensive measurements campaigns such as CLAIRE 2010 will use aerosol mass spectrometers and advanced instrumentation to better characterize aerosol properties. We will also have aerosol vertical profiles with continuous Raman Lidar measurements as well as 7 AERONET sun photometers and radiometers in continuous operation for model validation. Airborne measurements using an instrumented aircraft (INPE Bandeirante) will explore the large scale aerosol properties and distribution over Amazonia and Pantanal. The large scale aerosol and cloud properties and distribution will be observed with the use of MODIS, CALIPSO, CloudSat, AIRS, TRMM and other sensors. Novel remote sensing instruments will be developed to measure cloud water phase, as well as cloud droplet size distribution.

The modeling component will use and develop CATT-BRAMS and WRF-Chem to study the regional aerosol distribution, properties, impacts and radiative forcing. LES and cloud resolving models will be used to study aerosol-cloud interactions. The development effort on these regional models will be implemented at the existing CPTEC GCM, and further implemented in the future Brazilian Model of the Global Climate System (BMGCS). We will help to build the radiation code at the BMGCS based on data and parameterizations obtained in this proposal. The different models will also be used to perform sensitivity studies to investigate the most relevant parameters on the direct and indirect aerosol effects on climate.

The joint use of a integrated approach with extensive measurements, remote sensing and modeling will allow a new and more complete vision of the impact of aerosols on climate, particularly over South America. The results should be applicable over other tropical areas (Africa and Southeast Asia), with partnership to be developed with other similar studies in these regions. This proposal will address a key issue to the FAPESP Global Climate Change Program.

## 2 – Results from previous or ongoing funding by FAPESP:

Paulo Artaxo have coordinated in the last 8 years (2000-2004, 2004-2008) two very large Millennium Institute projects, from the Ministry of Science and Technology (MCT), with a budget of more than R$4.000.000,00 each one. The scientific focus was in the atmospheric chemistry component of the LBA (The Large Scale Biosphere-Atmosphere Experiment in Amazonia) Experiment. He was also co-PI of 2 large research projects funded by the EU: SMOCC (PI: Andi Andreae) and EUCAARI (PI: Markku Kulmala). Additionally, he coordinated 4 FAPESP projects:

**1) FAPESP Thematic project 1997/11358-9**. Title: Physical and chemical interactions between the biosphere and the atmosphere in Amazonia at the LBA Experiment. Started at 15/07/1998, ended at 28/02/2003. **Abstract:** This proposal implements studies on the physical and chemical interactions at the biosphere-atmosphere interface in Amazonia. It is an integrated part of the

"Large Scale Biosphere-Atmosphere Experiment in Amazonia - LBA". It is one of the five components of LBA: 1) Physical climate; 2) Carbon cycle and biogeochemistry; 3) Chemistry and physics of the atmosphere; 4) Hydrology and water chemistry; 5) Numerical Modeling. We are proposing to install and operate continuously for four years three atmospheric monitoring stations at: 1) Tapajós National Forest; 2) Manaus; 3) São Gabriel da Cachoeira. These sites will have towers from the LBA experiment. At these sampling stations we will measure several trace gases, including $CO_2$, $CH_4$, $N_20$, CO, VOC, HC, $NO_x$, $NO_y$ and $O_3$. Aerosol particles will be studied in detail, with measurements of aerosol composition and ionic content, size distribution and optical properties, as well as organic and elemental carbon. In addition, precipitation composition in terms of trace elements, ionic content, dissolved and total carbon will be measured, in order to obtain the wet deposition fluxes of essential nutrients. Continuous measurements of aerosol optical thickness with sun-photometers will allow a detailed study of the influence of aerosol particles on the atmospheric radiation budget. Large-scale experiments using aircraft will allow basin-wide studies on the atmospheric composition and properties. The atmospheric chemistry of VOC, $NO_x$ and several oxidants will be studied from the point of view of photochemistry processes and atmospheric carbon cycling. Chemical-dynamic transport models will be developed for the Amazon Basin, to integrate the atmospheric chemistry measurements with the large-scale transport.

**2) FAPESP project 1996/02672-9**. Research project: Atmospheric aerosols in Amazonia: Long term measurements and long range transport. Project run from 17/05/1996 to 25/11/1999. This project was aimed at the operation of aerosol collection and analysis in Alta Floresta, Cuiabá and Santarem for 2 years. This was done, and about 10 papers were published in this project. It was partially done in partnership with Willy Maenhaut and Rene Van Grieken, from Belgium

**3) FAPESP infrastructure grant 1996/10261-9**. Determination at ultra trace level of the elemental composition of aerosols trough PIXE and ICP-MS. Project run from 04/06/1997, ended at 04/09/1999. This project was aimed at buy equipment to perform ICP-MS and PIXE analysis of aerosols. It was fully implemented, and the methods are available and in use today.

**4) FAPESP Infrastructure multi-user grant, number 2004/08865**, with the title: The role of the Amazonian fluvial systems on the regional and global carbon cycling: $CO_2$ emissions and interactions between aquatic and terrestrial ecosystems. PI: Reynaldo L. Victoria, CO-PI: Paulo Artaxo, Evelyn Novo. Duration: 04/2005 to 08/2007. This project implemented the analysis of $CO_2$ evasion from rivers in Amazonia, and had several publications listed at the CV attached to this proposal.

Additionally, a large number of projects involving PhD students were supported by FAPESP in the last 10 years. Between them the FAPESP PhD scholarships for: Theotonio Pauliquevis, Luciana V. Rizzo, Silvia de Lucca, Andrea D. de Almeida Castanho, Aline S. Procópio, Ana Maria Córdova Leal, and Fábio Gerab. Also FAPESP funded two Pos Doc grants: José Vanderlei Martins, Márcia A. Yamasoe. FAPESP recently funded the visiting scientist grant for Scot T. Martin, Harvard University, (FAPESP project 2007/03300-4) during 2007 and 2008.

The listing of papers produced from these FAPESP grants is far too big to be listed here. Paulo Artaxo published a total of 142 papers from 1999 to 2008, and most of the papers are linked to one of these grants that provided support for the field research or students. These include two papers published in Science, and other 2 submitted to Nature in late 2008.

Maria Assunção Silva Dias coordinated several projects from FAPESP that supported important field campaigns in the Amazon as part of the LBA Experiment (more details in http://www.master.iag.usp.br/lba/index.php). The main ones are:

(1) **FAPESP 1997/09926-9** Biosphere Atmosphere Mesoscale Interaction in the Amazon - This project involved the WETAMC/LBA (Wet Season Atmospheric Mesoscale Campaign) that focused on the biosphere impact on convection. The campaign was simultaneous to TRMM/LBA and generated original results on the interaction between landscape (forest vs. pasture) aerosol and convective activity in two different modes of large scale circulation known as easterlies and westerlies or as break and monsoon phases. A special issue of JGR for LBA in October 2002 has the main results.

(2) **FAPESP 2001/06908-7** Thematic Grant "Radiation, Cloud, and Climate Interactions in the Amazon during the DRY-TO-WET Transition Season/LBA RACCI/LBA" An atmospheric mesoscale campaign in the transition from dry to wet season was carried out involving a RACCI component funded by FAPESP and a SMOCC component funded by the European Community. Both resources helped fly a microphysical airplane that lead to original data and results on cloud microphysics and the role of aerosol on cloud development in the Amazon region. Articles in Science and JGR show the main results.

Márcia Yamasoe have an ongoing FAPESP project: FAPESP – Research Grant Process 2006/56550-5 – ongoing (from February 2007 to January 2009). Studying the influence of aerosol particles emitted by fires on the vegetation photosynthesis in the Amazon. PI – Marcia Yamasoe. Biomass burning emits large amount of gases and aerosol particles to the atmosphere. Aerosol particles interact with solar radiation through scattering and absorption processes, which decrease the total amount of solar radiation available at the surface and can increase the diffuse fraction. Those changes in the radiation profile modify surface turbulent sensible and heat fluxes and can affect vegetation photosynthesis. This project aims to study the effect of aerosol particles emitted from fires on the vegetation photosynthesis of a tropical rainforest located in the Southwestern portion of the Amazon Basin.

## 3 - Statement of scientific problems to be tackled by the proposed project.

Amazonia is a region that is going trough important changes and is a critical region from the point of view of effects of climate change (Mahli et al., 2008). Andreae et al. (2002) proposed a linkage between natural biogenic emissions, especially primary biological particles, and the water cycle in Amazonia. Kulmala et al. (2004) and Oliveira et al., (2007) noted that this linkage also extends to the carbon cycle. It is critically important to reduce the current uncertainty of the impact of aerosol particles on climate (Ramanathan et al., 2008), and Amazonia is an important region to study these issues for a number of reasons (Koren et al., 2004, 2008). It is important to identify and quantify the processes and sources governing global and regional aerosol concentrations, to better quantify the physico-chemical properties of atmospheric aerosols and to quantify the feedback processes that link climate change and atmospheric aerosol concentrations with emphasis on the production and loading of natural aerosols and their precursors. Direct and indirect aerosol radiative forcing is the largest uncertainty in the global climate change issue (Lohmann and Feichter, 2001, 2005, Hansen et al., 1997, 2007). Figure 3.1 show the radiative forcing of the Earth climate system, were it is easy to observe that the cooling effects of aerosols both directly and indirectly are critically important for the total net forcing (Forster et al., 2007).

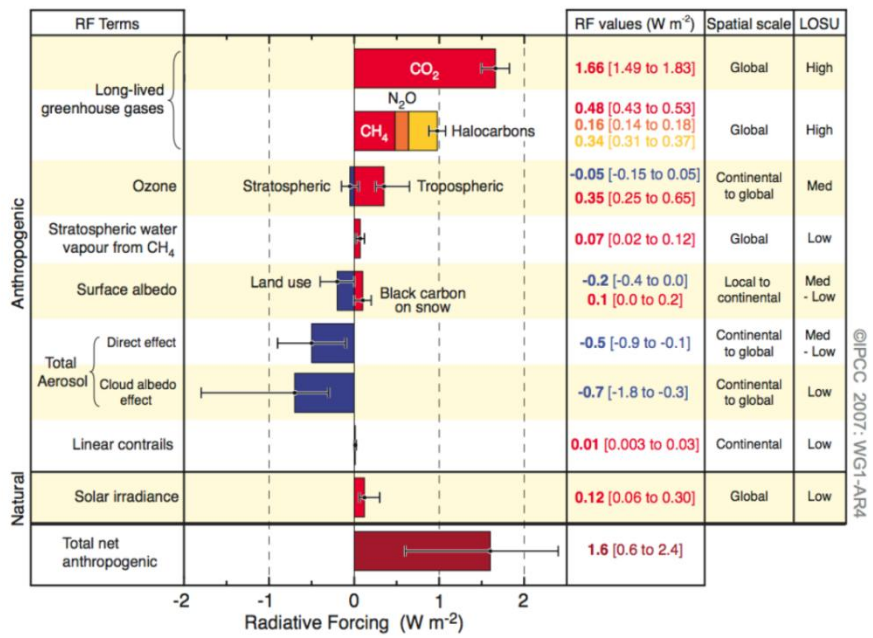



Figure 3.1 – Radiative forcing of the Earth climate system. It is clear from this plot that the cooling effects of aerosols both directly and indirectly are critically important for the total net forcing (Forster et al., 2007).

The uncertainties in the cooling effects of aerosols are much larger than the uncertainties in the forcing of long lived greenhouse gases or other forcings (IPCC, 2007). Figure 3.2 shows the direct and indirect forcing simulated by all IPCC AR4 models, indicating the very large uncertainties in the direct effect (plot on the left) and in the cloud albedo effect (plot on the right).

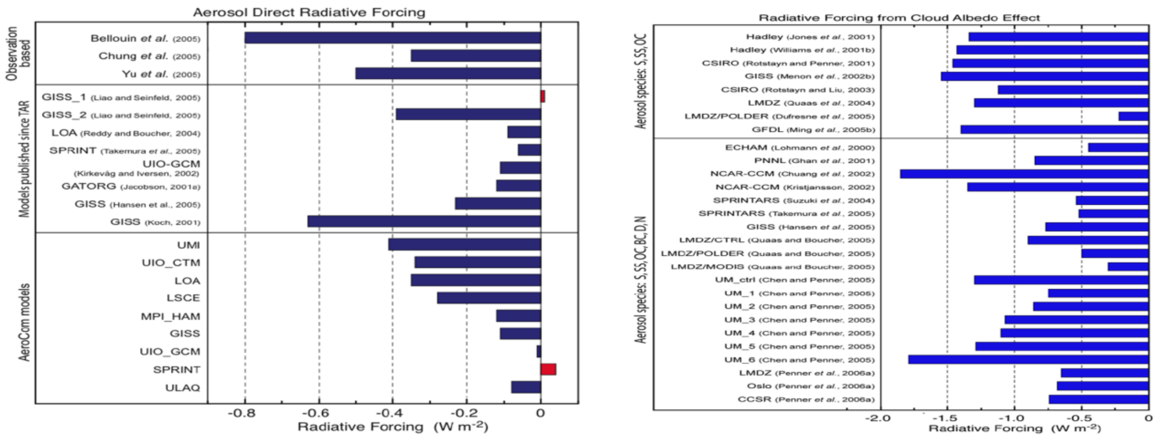



Figure 3.2 - Variability in the aerosol direct radiative forcing and cloud albedo forcing simulated by all IPCC AR4 models, indicating the very large variability in the direct effect (plot on the left) and in the cloud albedo effect (plot on the right). This is the large source of climate uncertainty in the IPCC, and how biomass burning and natural biogenic aerosol are treated in models is important.

Modeling the direct and indirect effect of aerosols on climate is a challenging task that has been tackled by many research groups around the world and many feedbacks and dependencies still need to be better understood to be accounted for in models (Penner et al, 2006). One of the main reasons for this lack of knowledge is that models are not yet well constrained by observations. While cloud-resolving models with explicit microphysics have been used effectively to explore indirect effects (*Guo et al, 2007*), uncertainties associated with turbulence, entrainment, and sub-grid variability in cloud microphysics, which are critical challenges for all cloud parameterizations, impose strong limitations to the models' results (*Lohmann and Feichter, 2001, 2005*).

# 4 - Justification and rationale

Changes in climate are driven by natural or human-induced perturbations of the Earth's energy balance. These climate drivers or "forcings" include variations in greenhouse gases, aerosols, cloud cover and properties, land use, and many other factors. A *climate forcing* is an energy imbalance imposed on the climate system either externally or by human activities. A *climate feedback* is an internal climate process that amplifies or dampens the climate response to a specific forcing (IPCC 2007). Climate forcings are usefully subdivided into direct radiative forcings, indirect radiative forcings, and nonradiative forcings. Direct radiative forcings directly affect the radiative budget of the Earth; for example, aerosol particles scattering radiation back to space. Indirect radiative forcings create an energy imbalance by first altering climate system components (e.g., cloud properties), which then lead to changes in radiative fluxes. Non-radiative forcings create an energy imbalance that does not directly involve radiation; an example is the change in evapotranspiration flux resulting from land use change. (*NAS-US, 2005*).

The traditional global mean TOA radiative forcing concept has some important limitations, which have come increasingly to light over the past decade and are discussed in the latest IPCC report (*Hansen et al., 1997, IPCC, 2007*). The concept is inadequate for some forcing agents, such as absorbing aerosols and land-use changes (*Ramanathan et al., 2008*), that may have regional climate impacts much greater than would be predicted from TOA radiative forcing. Also, it offers little information on regional climate change or precipitation. In particular, the concept needs to be extended to account for (1) the vertical structure of radiative forcing, (2) regional variability in radiative forcing. This proposal will address both issues and one of the focus will be on surface regional aerosol forcing. Regional variations in radiative forcing may have important regional and global climatic implications that are not resolved by the concept of global mean radiative forcing. Tropospheric aerosols and surface albedo changes have particularly heterogeneous forcings. Several types of forcings—most notably aerosols, and land-use change, and modifications to biogeochemistry, impact the climate system in nonradiative ways, in particular by modifying the hydrological cycle and vegetation dynamics. Aerosols exert a forcing on the hydrological cycle by modifying CCN, ice nuclei, precipitation efficiency, and the ratio between solar direct and diffuse radiation received. In Amazonia, emissions of VOC are very heterogeneous and with high seasonal variations (Guenther et al., 1995), and this affects aerosol and CCN production. It is important to improve the understanding and parameterizations of aerosol-cloud thermodynamic interactions and land-atmosphere interactions in climate models in order to quantify the impacts of these climate forcings on both regional (Amazonia and Pantanal regions) and global scales.

The radiative forcing since preindustrial times by well-mixed greenhouse gases is well understood. However, there are major gaps in understanding of the other forcings, as well as of the link between forcings and climate response. Error bars remain very large for current estimates of radiative forcing by aerosols, ozone and other critical components. The most important step for improving understanding of radiative forcings is to obtain a robust and detailed record of radiative forcing variables. The observational evidence needs to be more complete both in terms of the spatio-temporal and electromagnetic spectral coverage and in terms of the quantities measured (*Andreae, 2007, Anderson et al., 2003*).

The interaction between aerosol particles and clouds can lead to a number of indirect radiative effects that arguably represent the greatest uncertainty in current radiative forcing assessments (Albrecht, 1989). In the so-called first indirect aerosol effect, the presence of aerosols leads to clouds with more but smaller droplets, and such clouds are more reflective and therefore have a negative radiative forcing (McFiggan et al., 2007). These smaller cloud droplets can also decrease the precipitation efficiency and prolong cloud lifetime; this is known as the second indirect aerosol effect. The so-called semi direct aerosol effect occurs when absorption of solar radiation by soot leads to an evaporation of cloud droplets. It is essential to perform fundamental research on the physical and chemical composition of aerosols, aerosol activation, cloud microphysics, cloud dynamics, and sub grid scale variability in relative humidity and vertical velocity, among other variables. Physical and chemical properties of CCN particles is also a critical issue (Rosenfeld, 2008, Andreae et al., 2008). It is important to improve representation in 1D, regional and global models of aerosol microphysics, growth, reactivity, and processes for their removal from the atmosphere through laboratory studies and field campaigns (Rosenfeld, 2008). Uncertainties in relating aerosol to cloud droplet populations seriously limits our ability to quantify the indirect aerosol effects (McFiggan et al., 2007). To treat cloud droplet formation accurately, the aerosol number concentration, its chemical composition, and the vertical velocity on the cloud scale need to be known (Menon et al., 2002). Nenes and Seinfeld (2003) developed a parameterization based on the Köhler theory that can describe cloud droplet formation for a multimodal aerosol, including kinetic effects. Albrecht (1989) studied the narrowing on the droplet size distribution induced by aerosols, suppressing precipitation and extending cloud lifetime. Hansen et al. (1997) suggested an alternative path by which radiation-absorbing aerosol can decrease cloud lifetime by heating cloud layers. Rosenfeld (2000) proposed the inhibition of deep convective precipitation by urban pollution aerosols, decreasing cloud droplet size and delaying the onset of freezing.

Aircraft in situ measurements can measure cloud droplet profiles with height, and Andreae et al. (2004) showed strong influence of biomass burning aerosols on cloud droplet size. Satellite remote sensing measurements have provided new information about cloud-aerosol interactions (Rosenfeld and Lensky, 1998). Koren et al. (2004) observed quantitatively the inhibition of certain types of clouds in the Amazon due to the presence of heavy smoke and more completely, Koren et al. (2008) shows the superposition of two aerosol effects acting on cloud microphysics and on the thermodynamic structure of the atmosphere through aerosol absorption. However, all these satellite inferences have been based on 1 to 2 km resolution of single snapshots of the cloud tops, or large statistics on 1 x 1 degree resolution MODIS data (Kaufman et al., 2005, Koren et al., 2005). The satellite-derived vertical evolution is a composition of many cloud pixels at different degrees of evolution, assuming the ensemble represents the evolution of a single cloud with height and time. While this method of inferring vertical evolution is useful, it relies on strong assumptions and limitations that do not occur for the methodology proposed in this research component.

Most of the Amazon Basin has a well marked yearly cycle of rainfall with a short dry season, a long wet season and short transitions between the dry and the wet seasons and vice-versa. In the dry season and in the transition to the dry season, the biomass burning takes place mainly at the southern and eastern sectors of the Amazon Basin and provides a ten-fold increase in background number concentration of aerosols and of the cloud condensation nuclei (Williams et al 2002). In the wet season, the main source of aerosol and of CCN is biogenic, including primary biogenic aerosol, biogenic secondary aerosol, small amount of sulfate deposition on new particles, and small debris from decaying vegetation (Artaxo et al, 2001, 2002, Guyon et al 2004).

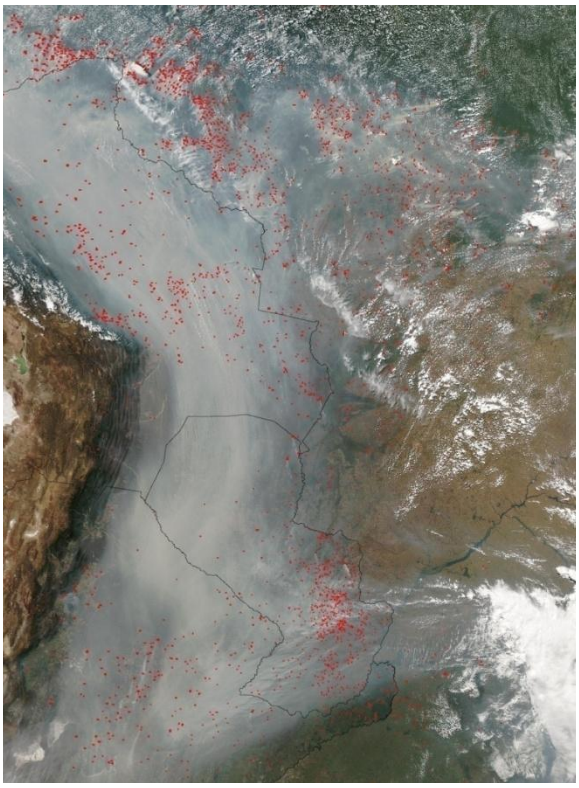
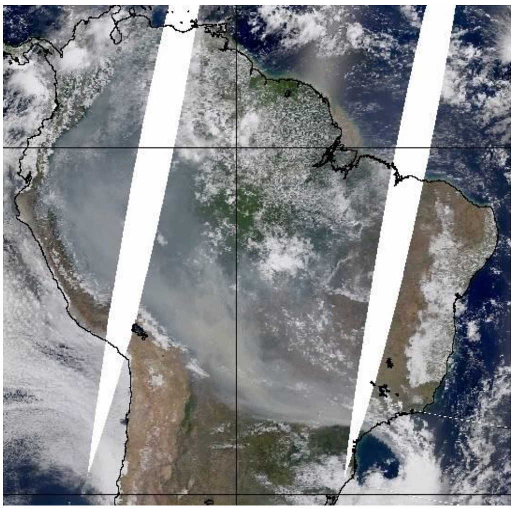


Figure 4.1 - Large scale aerosol plumes from biomass burning in Amazonia measured with the MODIS sensor shows continental scale aerosol distribution and impacts on the radiation balance and hydrological cycle.



Claeys et al (2004) analysis of natural wet season aerosols from the forest in the Amazon Basin shows that considerable quantities of organic compounds originated from the oxidation of isoprene getting deposited into preexisting particles and constitute between 5 to 25 % of secondary organic aerosol. Roberts et al (2002) analyzed the effect of sulfate – from decaying organic matter -

deposition on pre-existing particles on their capacity to become cloud condensation nuclei showing that the amount of sulfate on the particle was directly related to the activation fraction of the aerosol for a given supersaturation.

Due to the prevailing atmospheric circulation, aerosols originated in the Amazon Basin spread throughout a large part of South America (Freitas et al 2000, 2005, 2007) transported throughout the depth of the atmosphere by clouds and modified by mixing with other air masses. Of particular interest is the trajectory of air parcels due south going over the Pantanal ecosystem and reaching subtropical South America. In spring time, at the peak of biomass burning in the Amazon Basin, convective activity over south-southeastern Brazil, northern Argentina, Paraguay and Uruguay is characterized by mesoscale convective systems that are quite strong (Zipser et al 2006) and receive an input of moisture and aerosol from Amazonia.

During the transition season from dry to wet in 2002, an LBA intensive field campaign was conducted in SW Amazon Basin to measure the impact of aerosol on clouds with an airplane instrumented to measure cloud microphysics. Andreae et al (2004) describe the first results which show a well defined shift of the drop size spectra to larger droplets from cloud base to middle levels in clouds inside the polluted air mass when compared to those in cleaner environments, indicating basically that larger droplets are suppressed in lower levels in the presence of large number of aerosols due to the competition by the available moisture. Williams et al. (2002) noted that in the transition season from dry to wet season, the convective systems in the Amazon had the typical features of continental thunderstorms with plenty of lightning (c.f. Petersen et al 2000), damaging winds and eventually hail. The triggering of deep convection in a scenario of cooler surface, enhanced CCN number concentration, and absence of frontal systems, would be possible by either forced uplift over topography, or in selected spots with large sensible heat flux such as in slopes, deforested areas or bare soil areas (Souza et al 2002). In this case, the process of rain formation would have to be through the ice phase which explains the enhanced lightning in the dry to wet season (Petersen et al. 2000). During the wet season, the low number of lightning discharges (Petersen et al. 2004) indicates a more oceanic behavior of convection although significant intraseasonal variability is observed (Jones et al 2000). Carvalho et al (2002) and Laurent et al (2002) showed that showed that during easterlies winds the clouds were more isolated and deeper while Anagnostou and Morales (2002) and Rickenback et al (2002) indicate that rainfall had larger convective fraction during easterlies winds. Aerosol concentration varied accordingly with low concentrations during the westerlies when the systems were larger in area. Silva Dias et al (2002) discussed the possible feedback of clouds and aerosol in the wet season suggesting that the main effect could be in the local recycling of biogenic material during the westerlies and an export of biogenic material during the easterlies through the enhanced vertical transport to upper levels. A consequence of the long range transport of aerosol as seen by convective trajectory calculations (Freitas et al, 2000 and Andreae et al 2001) may affect the surface budget in remote areas through the radiative forcing of aerosol with the possibility of having an impact of rainfall development in these remote areas (Longo et al, 2006).

Modeling the interaction between aerosols and cloud microphysics involves different processes as the atmosphere evolves from very clean to much polluted conditions (Lohmann and Feichter, 2004, 2005). Numerical simulations of aerosol impact on Amazon rainfall have been carried out by Martins et al (2008) and the results presented considerable sensitivity to changes in cloud condensation nuclei (CCN) and cloud size distribution properties. High CCN concentrations, typical of polluted days, were found to result in increases or decreases in total precipitation, depending on the level of pollution used as a reference. The main consequence of the increased pollution was a change from a warm to a cold rain process. Under polluted conditions, cloud cover diminished, allowing greater amounts of solar radiation to reach the surface**.** Li et al (2006) show similar results from an analysis of satellite data over the Amazon. Koren et al (2008) investigated the relationship between clouds and aerosol also using satellite data and point out to the same sort of non-linearity showing a smooth transition between two opposing effects of aerosols on clouds: the microphysical and the radiative. Cloud resolving models use two basic types of microphysics parameterization: bulk microphysics (for BRAMS, Pielke *et al*., 1992; Walko *et al*., 1995) and spectral bin microphysics (Hall, 1980; Kogan *et al*., 1984; Flossman *et al*., 1985; Kogan, 1991; Costa *et al*., 2000a, 2000b, Saleeby and Cotton, 2005). Models of spectral bin microphysics are very time consuming but allow a realistic process simulation that can be used as framework for the more simple bulk microphysics used by mesoscale or global models.

The cloud modeling component of this project proposes a multi-scale approach, ranging from single column radiative transfer codes to address mainly sensitivity studies, large eddy simulations (LES), and regional and global circulation models. We believe that this broad scales range will be more appropriate for the understanding and quantification of the direct and indirect effects of aerosols on the climate system, particularly over Brazil. Naturally, the numerical models to be used must account for the direct and indirect effect of aerosols, the impacts on hydrological cycle and thermodynamic properties of the planetary boundary layer. For this multi-scale inter-comparison to be worth and profitable it will be mandatory to have measurements that provides, for instance, aerosols and clouds vertical structures and their optical properties. They will also provide the forcing needed to drive simulations by single column models, large eddy simulations, regional and global models.

Koren et al (2008) showed important results that aerosol particles in Amazonia can both enhance and reduce cloud cover due to the competition between cloud microphysics and radiative effects. It was the first time that cloud fraction enhancement was measured in Amazonia for small increases in AOT. Figure 4.2 bellow shows clearly the changes in cloud fraction and cloud top pressure due to increase in aerosol loading in Amazonia. We will continue these studies, separating the different Amazon regions, because western Amazonia could have different properties from

Eastern Amazonia, because each has different water vapor amounts and aerosol loadings.

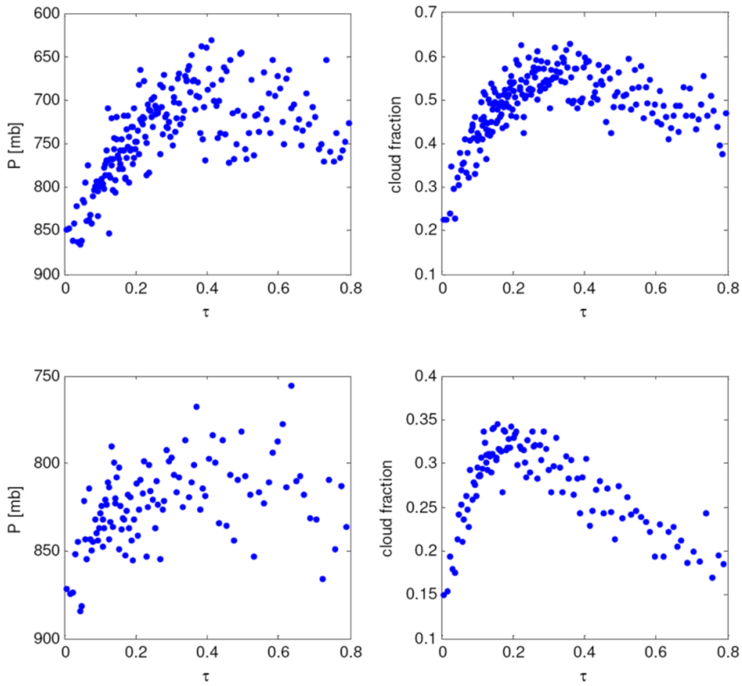



Figure 4.2 - Left – cloud top pressure (P) vs. AOD. Lower P may indicate taller convective clouds that reach to higher levels of the atmosphere. Right – cloud fraction vs. AOD. The upper row is for all data and the lower row is for data restricted to cloud fraction less than half. From Koren et al., Science, 2008.

## 4.1 - Modeling Framework - Radiative single column codes

The aerosol optical properties will be used as input in the different radiative transfer code for intercomparison and sensitivity study tests. Lidar system will provide vertical profile of aerosol and water vapor and cloud basis height. Other radiometric measured data will be used to validate model results. The idea is to simulate different scenarios such as clear and very clean sky (AOD(@500nm) < 0.1), moderately hazy (AOD around 0.5), extremely hazy (AOD > 2.0), cloudy, and mixed cloudy and hazy days chosen according to real measurement data.

### Radiative transfer (RT) codes that will be used in this proposal

- SBDART 2.4 (Santa Barbara DISORT Atmospheric Radiative Transfer) (Ricchiazzi et al., 1998) (http://www.crseo.ucs-b.edu/esrg/pauls_dir). It is based on the DISORT multiple scattering radiative transfer module. It includes many optical models for clouds and aerosol, and allows users to input their own model.

- LibRadtran (Kylling and Mayer, 1993-2004, Mayer and Kylling, 2005). With this package the user can choose different solver for the radiative transfer problem, e.g. a fast two-stream code to calculate approximate irradiance or a discrete ordinate code to accurately simulate radiances, with or without polarization. Users can also input their own model for aerosol and cloud properties.

- BRASIL-SR model BRASIL-SR, developed by CPTEC/INPE and LABSOLAR/UFSC (Martins et al., 2007) based on GKSS model described in Stuhlmann et al. (1990). The model BRASIL-SR provides solar irradiation estimates using the ''Two-Stream'' approach to solve the atmospheric radiative transfer equation, the GOES-EAST satellite images and a climate database which includes temperature, surface albedo, relative humidity and visibility data.

Sensitivity studies using this set of radiative transfer codes, together with standalone versions of the radiative transfer codes of the regional and global models in the framework of this project (described below), using aerosol and cloud optical properties from direct observations and satellite retrievals will be performed. These studies aim to drive the development of suitable parameterization for the Amazon basin and Pantanal regions to account for the aerosols-clouds-radiation interaction. Those will be later implemented in the regional and global models. As standards for comparison and validation we intend to use both the line by line results from the Continuous Intercomparison of Radiation Codes (CIRC) project (Oreopoulos et al., 2008) and the results of the field experiments conducted in the framework of this project.

## 4.2 Regional scale and global circulation models

We propose the use of two regional scale models and a global circulation model (GCM) in the framework of this project, as described below:

### The CCATT-BRAMS Regional Model

The Eulerian chemistry–transport model CCATT-BRAMS (Coupled Chemistry-Aerosol-Tracer Transport model to the Brazilian developments on the Regional Atmospheric Modeling System, Freitas et al., 2005, 2006, 2007, Longo et al., 2006, 2007, 2008), suitable to study and provide a high spatio-temporal resolution of non-$CO_2$ gaseous species and aerosols distribution and its linkage with atmospheric dynamics over the Amazon basin. The CCATT system is on-line and fully coupled with the atmospheric dynamics core of BRAMS. The sub-grid transport parameterizations include diffusion in PBL, shallow and deep convection and plume rise for biomass burning emissions. The atmospheric model has a complex and state-of-the-art set of parameterizations to simulate surface-atmosphere exchanges, boundary layer development, cloud microphysics and cumulus convection. The radiative parameterization takes into account the interaction between aerosol particles and short and long wave radiation. The system may be virtually configured with any chemical mechanism using SPACK (Simplified Preprocessor for Atmospheric Chemical Kinetics, Djouad et al., 2002) pre-processor. Photolysis rates are calculated on-line using the FAST-TUV model. Dry deposition follows the resistance formulation and accounts for the aerodynamic, quasi-laminar layer and canopy resistances (Wesely, 1989, Seinfeld and Pandis, 1998). Wet deposition is parameterized following Berge (1993) for PM2.5, Henry's law for gaseous and is fully coupled with the convective scheme. The direct effect of aerosol is accounted according to a dynamic aerosol model, that was derived using measurements based on AERONET observation for South America.

Aerosol loading retrievals from satellite observations will also be considered in this regional modeling component. A data assimilation approach will be used to integrate observational information into CCATT-BRAMS. The assimilation scheme that is coupled to the CCATT-

BRAMS model is based on a 3D-VAR code (three dimensional variational data assimilation), developed by RIU (Rhenish Institute for Environmental Research) (Elbern and Strunk, 2005. 3-DVAR allows for assimilation of observations that are not a direct variable of the model. This method has the flexibility to account for the anisotropic and inhomogeneous characteristics, for example of fire plumes, if a suitable technical formulation of the Background Error Covariance Matrix (BECM) is provided (Hoelzemann et al., 2001). The 3D-VAR code from RIU includes the Weaver and Courtier (2001) diffusion approach which has sufficient flexibility to account for these problems. The first version of the 3D-VAR code from RIU has already been implemented into CCATT-BRAMS. Initial and boundary conditions for chemistry fields are obtained from MOCAGE-MeteoFrance global chemistry model through a set of tools for data manipulation, assimilation and ingestion using 4DDA (Newtonian relaxation).

Sources emission for anthropogenic (industrial, urban, transportation, biomass burning, charcoal production, waste burning, etc) and biogenic processes uses a set of published data and methodologies (e.g., RETRO, EDGAR, GEIA-POET, 3BEM). A numerical tool was developed to generate the emission data using several types of grid projection for global and regional models. This system has been validated using surface and airborne measurements from SMOCC/2002 and CLAIRE/1998 field campaigns as well as data retrieved from AIRS, MOPITT and MODIS.

## The regional model WRF-CHEM

The Weather Research and Forecasting (WRF) and Chemistry (WRF/Chem) model is based upon the non-hydrostatic global to urban WRF community model maintained at NCAR (National Center for Atmospheric Research) [http://www.wrf-model.org]. Details of WRF/Chem can be found in Grell et al. [2005] and Fast et al. [2006]. Real-time forecasts can be found at Internet web-address [http://www.wrf-model.org/WG11].

This model system is "online" in the sense that all processes affecting the gas phase and aerosol species are calculated in lock step with the meteorological dynamics. Gas-phase chemistry modules are created by the Kinetic PreProcessor (KPP). As of now three aerosol modules are available. The first choice for the user is the simple aerosol and chemistry modules from the Goddard Chemistry Aerosol Radiation and Transport model (GOCART). The second choice is a modal representation based on the Modal Aerosol Dynamics Model for Europe (MADE, Ackermann et al., 1998) which itself is a modification of the Regional Particulate Model (Binkowski and Shankar, 1995). Secondary Organic Aerosols (SOA) has been incorporated into MADE by Schell et al., (2001), by means of the Secondary Organic Aerosol Model (SORGAM). Finally the user may choose a sectional approach, where the aerosol specie size distributions are broken into bins. Here the Model for Simulating Aerosol Interactions and Chemistry (MOSAIC, Zaveri et al. 2005a, 2005b, 2008) has been implemented into WRF/Chem. MADE/SORGAM as well as MOSAIC both allow for the interaction of aerosols with the radiation schemes (direct and semi-direct effect) as well as the interaction with the microphysics scheme (indirect effect). Work is currently in progress to implement these interaction processes also for the GOCART approach. Three photolysis options are also available to the user. For a more detailed description of the current modeling system, see also http://ruc.fsl.noaa.gov/wrf/WG11/tutorial2008.htm.

Biogenic emissions of isoprene, monoterpenes, other VOC (OVOC), and nitrogen emissions by the soil are specified at reference temperature and PAR (photosynthetic active radiation) according to Guenther et al. [2005] for deciduous, coniferous and mixed forest, and from Schoenemeyer et al. [1997] for agricultural and grassland. Emissions are applied over a surface grid according to the single WRF land-use category assigned to that grid, and the temperature dependence of the emissions is tied to the surface temperature.

## The global models CPTEC-AGCM and BMGCS

The purpose of working with a GCM within the context of this proposal is twofold. First, we need boundary conditions for the high resolution regional models, and these must come preferentially from a GCM with similar physics as the regional model. Second, we need to implement in a GCM what we have learned from higher resolutions models, i.e., the developed parameterizations for the cloud-aerosol-radiation interaction, which should help reducing the uncertainty in simulated direct and indirect effects in global models over the South America and hence also in the simulated Earth's energy balance in future climate's predictions.

The present version of the AGCM model available at INPE is the so called CPTEC AGCM, which was developed at the Brazilian Center for Weather Forecast and Climate Studies (CPTEC) based on the CPTEC/COLA (Center for Ocean-Land-Atmosphere Studies) GCM described by Cavalcanti et al (2002). It was shown that the model simulates reasonably well the main features of global climate, as well as the seasonal variability of the main atmospheric variables. The CPTEC GCM is used for weather and climate forecast since 2004 and more recently it is also used for providing boundary condition of CPTEC's air quality forecast system, which is based on CCATT-BRAMS described above. The CPTEC AGCM has a new dynamical formulation that made explicit the advection terms in the equations allowing the use of a semi-lagrangian scheme and hence the transport of scalar quantities such as mixing ratios of aerosols and trace gases. Physical parameterizations of the sub-grid scale processes include the vegetation scheme (Xue et al. 1991); second-order closure turbulent vertical diffusion (Mellor and Yamada, 1982); shallow cumulus effects following Souza (1999); Grell & Devanni (2002) deep cumulus convection ensemble scheme (Figueroa et al 2006); large scale precipitation produced from removal of supersaturation; Edwards and Slingo (1996) short and longwave radiation (Chagas and Barbosa, 2006, 2008); and the cloud scheme of Slingo (1987) and Hou (1990).

It is important to emphasize that this proposal is in the context of the development plans of a Brazilian Model of the Global Climate System (hereafter, BMGCS). Another proposal to sustain the building of the BMGCS is under discussion within INPE and will soon be submitted to FAPESP as a response to a call of proposals parallel to this one, which will develop and implement a complex model of the global climate system. FAPESP will grant R$2.6 millions to the selected proposal which will develop and implement a complex model of the global climate system. It has been planning that BMGCS should be able to simulate the response of the Earth system to the various forcing mechanism, especially changes in the atmospheric greenhouse gases and aerosols budget, variations in the solar constant and land-use changes, in a scale of decades to centuries and in a spatial scale adequate for studies of impacts, adaptation and vulnerability. Special emphasis will be paid to reducing the uncertainties of future climate projections in relation to those generated by current global climate models. As it becomes available, the BMGCS will work in parallel with the CPTEC AGCM for testing purposes, and will later replace this model.

## 5 - Significance and relevance for the FAPESP PFPMCG Program

The FAPESP PFPMCG Program emphasizes the importance of detailed and reliable measurements of variables that are relevant to the impact of changes on climate. This is explicit in the program objectives. Measuring the aerosol direct and indirect effect and cloud microphysical response to varying aerosol conditions in Amazonia and Pantanal, in high spatial and temporal resolutions, is essential to expand our knowledge about the climatic consequences of cloud-aerosol interactions. Clouds and precipitation processes are the basic building blocks of the water and energy cycle. One simply cannot understand clouds, water or the release of latent heat in the atmosphere without understanding how the aerosol modifies these parameters at the microphysical level. Likewise it is necessary to *measure* the cloud response to differing aerosol environmental conditions in order to understand the fundamental processes occurring in clouds in tropical regions.

Tackling this issue as proposed here is directly related to FAPESP's Program on Global Climate Change since it will advance our knowledge in the areas of Atmospheric Radiation Balance, Aerosols, and the Water Cycle. It will contribute to reduce the uncertainty of the aerosol role in the hydrological cycle, which is one of the key goals of the Program. It will also help advancing the quantification and separation of a potential climatic signal over the Amazon by detection of cloud-aerosol effects and attribution of causes, in the same direction as one of the overarching scientific questions expressed in FAPESP's Program on Global Climate Change. In addition to that, this research component will foster networking and integrating science performed in the State of São Paulo with the research objectives of international partners such as the University of Maryland, NASA, Max Planck Institute, Harvard University, Stockholm and Helsinki Universities and others.

In this proposal we are working on an integrated study using direct and remote sensing observations and numerical modeling of the physical and chemical processes involved. The strong experimental component of this proposal aims to fulfill the lack of relevant information over South America, while the modeling component aims to quantify and reduce the uncertainties associated with the direct and indirect effects of aerosols on local, regional and global scales. It is worth noting that the development of BMGCS, which will be also proposed to FAPESP, will benefit from our state-of-the-art measurements over South America and this multi-scale modeling inter-comparison exercise. Conversely, the modeling component will benefit greatly from having the developers strong participation in the BMGCS proposal.

# 6 - Specific aims

The overall objective of AEROCLIMA is to *investigate the connection between the concentration and physico-chemical properties of biogenic and biomass burning aerosol in the radiation balance and climate, including effects on cloud development and microphysics for two important regions in South America: Amazonia and Pantanal*. The basic concept for AEROCLIMA is that of an integrated study, combining field studies, remote sensing and modeling. To achieve this goal, we will perform the following tasks:

1. Calculate long term direct and indirect radiative forcing of aerosols in Amazonia and Pantanal, using a combination of measurements and modeling tools.

2. Characterize in detail physico-chemical properties of aerosol particles that are relevant for their impact on the environment and climatic effects.

3. Install and operate three aerosol field measurement stations that for one year will study detailed properties of aerosols: size distribution, absorption, scattering, composition, CCN activity and others. Aerosol and water vapor vertical profiles will be measured with a Raman Lidar. These stations will be installed at: North of Manaus, Alta Floresta (biomass burning region) and Campo Grande (Pantanal).

4. Implement intensive measurement programs such as the proposed LBA/CLAIRE2010, were more detailed aerosol properties will be measured including aerosol mass spectrometry, ion cluster measurements and detailed organic aerosol composition, VOC concentrations, among others.

5. Perform large scale aircraft measurements using the INPE Bandeirante aircraft to measure the large scale and vertical distribution of aerosols. Develop innovative instrumentation to measure water phase and cloud droplets in convective and stratus clouds.

6. Use remote sensing measurements with MODIS, CALIPSO and CERES to study large scale and long term aerosol and radiation fields in Amazonia and Pantanal. This will be used to quantify the effect of smoke aerosol on cloud properties.

7. Develop and evaluate semi-empirical parameterizations for the cloud-aerosol-radiation interaction suitable for the Amazon basin and Pantanal region for different aerosol burden regimes.

8. Model the effect of biogenic and biomass burning aerosol on cloud microphysics at the individual cloud and at regional level with spectral bin microphysics coupled to BRAMS. Perform sensitivity studies to investigate the relative importance of each variable.

9. Implement regional models with full aerosol microphysics, developed based on measurements in this project. The regional models will be based on CATT-BRAMS and WRF-CHEM models.

10. To contribute to the BMGCS development, taking advantage of all expertise gained in the context of this proposal on the parameterizations for aerosol-cloud-radiation interactions and gaseous and aerosol chemistry.

# 7) Expected results

We will disseminate the knowledge on the effects of aerosols on the ecosystem that influence not just radiation field, photosynthesis, precipitation, but also nutrient cycles and carbon uptake by the forest. The spatial and temporal distribution of aerosol particles is critically important for the carbon balance of the forest (Davidson and Artaxo, 2004, Oliveira et al., 2006, Ometto et al., 2005), and we will work together with other LBA researchers to disseminate these results to allow a more realistic carbon uptake in the models.

One of the key products of this project is to provide a more realistic parameterization for regional and global models of aerosol forcing. Additionally, the knowledge of the processes on how and when aerosol influences cloud microphysics will be important for the hydrological studies of Amazonia. The aerial distribution of aerosols will be important for researchers working with health impacts. A large set of researchers from FIOCRUZ group worked with this issue as part of the LBA Millennium Institute, and concentrations of $PM_{10}$ as high as 300 µg/m³ were associated with high hospital admissions in Alta Floresta. We need more accurate large area $PM_{10}$ distribution to allow assessment of the health impacts over other sites in Amazonia. This project will provide this product to the FIOCRUZ group and we will work together with them aiming to help assessing the health impacts of aerosols in the Amazonian population.

The Cloud Scanner and the Rainbow Camera were flown in the INPE Bandeirante aircraft in two experiments during January-February 2005 and October-November 2007, both in Brazil, and also in other experiments in the USA and Chile. During the Brazilian experiment in 2007 the Cloud Scanner was mounted in two lateral aft windows in the aircraft allowing for the measurement of cloud side radiances, while the Rainbow Camera was mounted in a dorsal aircraft window to measure cloud top radiances and aerosols. Figure 7.1 shows an example of the expected results to be obtained by this research component. This figure shows the result from cloud side measurements on board the Bandeirante aircraft over the Amazon Basin in 2005. The central panel in Figure 7.1 shows the actual picture of the cloud under study, while the left panel shows the brightness temperature image overlaid by a temperature profile (white plot) in the center of the cloud. The right panel exemplifies the result of an algorithm separating the ice and water components in the cloud. The red dashed horizontal line represents the zero Celsius mark where also the mixed phase starts on the right panel.

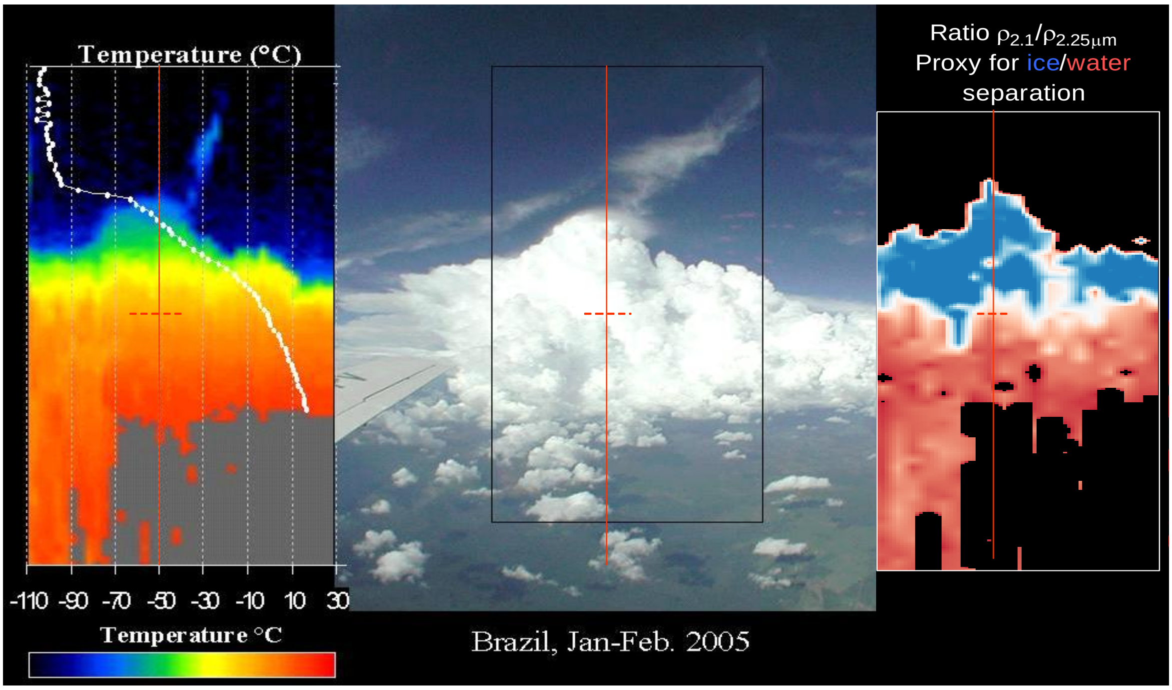



Figure 7.1 – Cloud side measurements performed with the Cloud Scanner instrument. The left panel shows the temperature profile, the center panel shows the actual picture of the cloud being observed, and the right panel shows and image of the ratio of reflectances at 2.10/2.25 µm, which represents the separation between ice and water particles in the cloud (Martins et al., 2007).

The vertical profile of effective radius adds very important information on the effect of the aerosols on cloud droplets and on the cloud microphysical processes driving the initiation of precipitation. Figure 7.2 (left panel) gives an example of effective radius retrieval to be obtained, showing warm cloud processes near cloud base where droplets grow by diffusion and collision-coalescence, and the mixed phase processes where the droplets grow faster. The mixed phase processes take place until a temperature of about -37°C is reached, causing the droplets to increase up to 37 µm effective radius. The ice phase shows the effective radius decreasing with height.

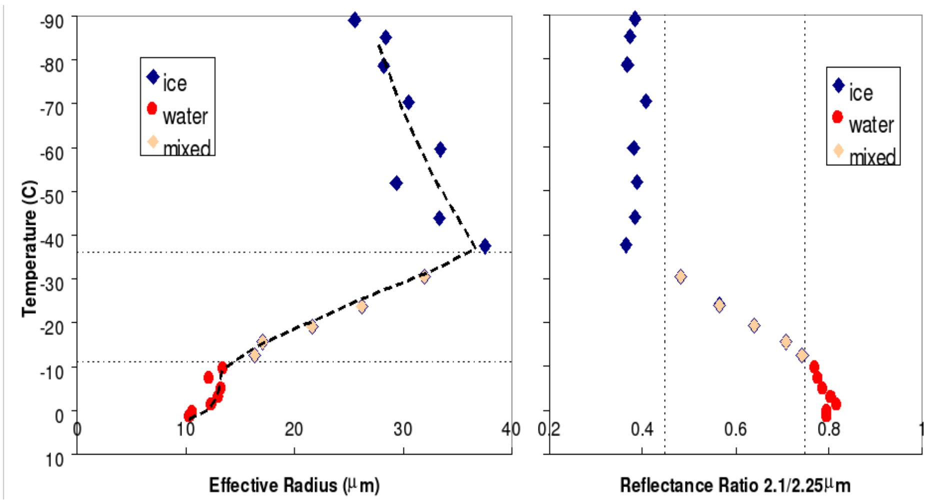



Figure 7.2 – Effective radius and separation between ice and water as a function of the vertical profile along the cloud side. At left is the derived effective radius and its temperature profile. At right is how the ratio between reflectances 2.10/2.25 µm can clearly separate ice (blue), mixed phase (pink), and water phase (red).

A completely independent measurement of the droplet thermodynamic phase is shown in the right panel of Figure 7.2. This panel shows the ratio between reflectances at 2.10/2.25 µm which is a proxy for water, ice, or mixed phase present inside the cloud. It is important to notice that the mixed phase identified in the reflectance ratio 2.10/2.25 µm corresponds unequivocally with the mixed phase droplet growth identified in the effective radius profile. This remarkable agreement once again indicates the power of the cloud side measurements in identifying the cloud microphysical processes inside the cloud.

From the intercomparison of radiative single column codes proposed we expect: first, to learn how well radiative transfer codes worldwide reproduce observations over South America, and second, we expect to contribute to the reduction of uncertainties over South America in regional models and global models that will be used in the next IPCC assessment report.

Both regional models have been broadly used and validated regarding their ability to forecast atmospheric chemistry composition in many opportunities. For example, the CCATT-BRAMS system has been validated using near surface and airborne measurements from SMOCC/2002 and CLAIRE/1998 field campaigns as well as data retrieved from AIRS, MOPITT and MODIS sensors [Freitas et al., 2005]. However, to correctly evaluate the atmospheric feedback due to atmospheric chemistry composition changes, especially aerosols, is a much more challenging task. Assessing the radiative forcing of biomass burning aerosols, the CCATT-BRAMS model indicates a significant impact on the energy budget, with the reduction of solar radiation reaching up to 40% and consequent reductions of the evapotranspiration and sensible heat, and an increase of the near surface temperature (Figures 7.3 a and b). The observed climatology between 1979-1995 and the observed rainfall for 2002, shows some association between aerosols and reduction in rainfall for this time period. However, due to data scarcity in this region, we cannot firmly state that this reduction was associated to the aerosol effect or an internal variability of local climate.

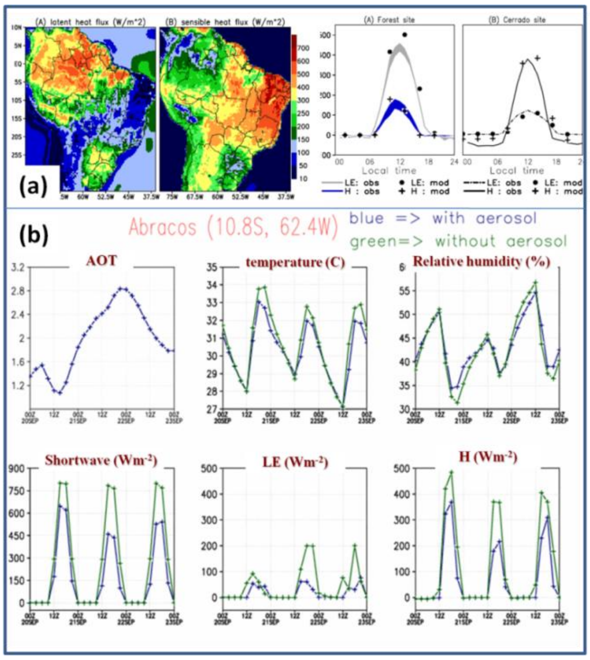



Figure 7.3: (a) CCATT-BRAMS model results for sensible and latent heat (mean values for Aug-Sep-Oct/2002 – 1500UTC) and their evaluation against observation. (b) Smoke aerosol impact on the energy budget and boundary layer thermodynamic properties.

Although the direct effect of aerosols in the radiative budget and respective heating rates are already taken into account in both regional models in the framework of this project, the indirect effects still remains to be developed and implemented. We plan to insert a cloud microphysics scheme with autoconversion dependent on the CCN (Berry, 1968) into the convective parameterization, which is which is presently the same in both regional models (Grell and Devenyi, 2002). The CCN input for this cloud microphysics scheme will be estimated at each model time-step from the AOT simulated via the relationship observed between CCN and AOT following Andreae et al. (2008). The biggest challenge however, will be to include the cloud optical properties dependent of CCN in the models. This will require an intricacy statistical analysis of the cloud optical properties derived from remote sensing over the Amazonian region and sensitivity studies with single column radiative transfer code. Also, we acknowledge that it will be challenging to handle all the inherent uncertainties of these retrievals, which reinforce that extensive and long term measurements over South America are crucial.

The CPTEC AGCM still lacks the gaseous and aerosol chemistry, nevertheless their direct effects are taken into account by prescribing three dimensional fields of aerosol mass mixing ratios. One objective of this proposal is to implement the chemistry module from CCATT-BRAMS into the CPTEC AGCM allowing a more consistent evaluation of the direct effects on climate. Also, we will need to improve the microphysics treatment in the AGCM in order to allow prognoses of droplet and ice-crystal numbers, which are indeed necessary for estimating indirect effects of aerosols. The technical results from this modeling effort will be shared with the FAPESP PFPMCG proposal for the development of the BMGCS.

# 7a) Preliminary results

The group involved in this proposal has extensively worked with aerosols in the Amazon basin for the last 20 years, with a very large publication record in this issue. A large and solid amount of science was produced as a result of this work, in partnership with groups from Max Planck Institute, NASA, Harvard, Lund and Helsinki Universities among others. The SMOCC experiment, as well as the LBA-CLAIRE 98, 2001 and EUSTACH experiments were good examples of collaborations that produced a large set of knowledge on Amazonian aerosol (Andreae et al., 2002, Artaxo et al., 2002, 2007). The recent AMAZE experiment coordinated by USP and Harvard research groups also advanced significantly the knowledge on aerosol properties in Amazonia. The CLAIRE 2010 experiment will continue this tradition of large scale aerosol experiments in Amazonia.

Large seasonal variability occurs in Amazonia in terms of aerosol concentrations. Figure 7.1 shows the time series of fine and coarse mode aerosols in Alta Floresta for about 13 years (1992 to 2005) of continuous measurements. The very high concentrations (200-600 ug/m³) during biomass burning season are evident. These translate to very high AOT of 3-4 at 500 nm. Only aerosol mass and elemental composition was measured for these sites over the last years, and now we are proposing to include measurements of detailed optical properties, CCN activity and vertical profiling with Raman Lidar. Radiometers and sun-photometers will complete the set of measurements. For a description of some of these results, please see Artaxo et al., 1988, 1994, 2002, and Echalar et al., 1998.

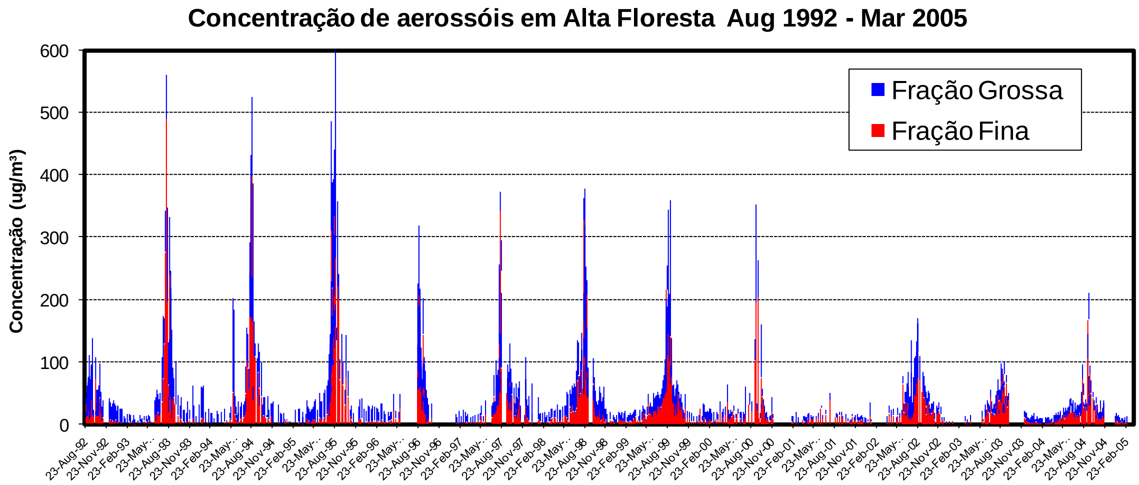



Figure 7.1a - Time series of fine and coarse mode aerosols in Alta Floresta for about 15 years.

Figure 7.1b shows the time series of fine and coarse mode aerosol for Manaus, collected in a site called Balbina, about 150 Km North of Manaus during 6 years 91998-2004). It is important to notice that coarse mode aerosol dominates the $PM_{10}$ aerosol mass. From a $PM_{10}$ average of 10.9 µg/m³, coarse mass averages 6.8 µg/m³, and fine particles accounts for a very low 4.2 µg/m³. During the wet season, fine particles averages to low values of about 2 µg/m³. We can easily observe the input from Sahara dust in April-May each year.

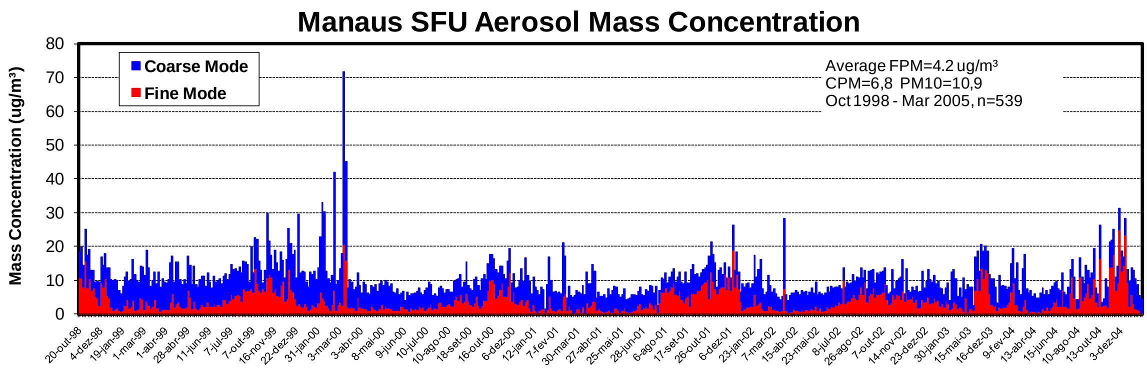



Figure 7.1b - Time series of fine and coarse mode aerosol for Manaus, collected in a site called Balbina, about 150 Km North of Manaus during 6 years.

The time series for Santarem shows a similar picture as for Manaus, but with a heavier impact from biomass burning in the state of Pará. In the wet season, concentration of fine particles averages bellow 2 µg/m³, an extremely low value and corresponds to background biogenic aerosol concentration in Amazonia.

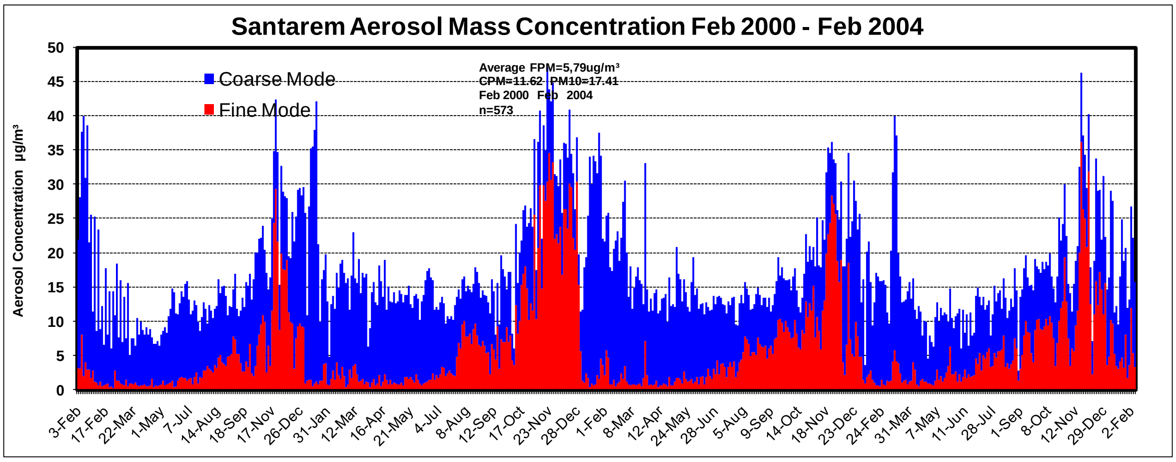



Figure 7.1c - Time series of fine and coarse mode aerosol for Santarem, Pará State. Collected during 4 years, from 2000 to 2004.

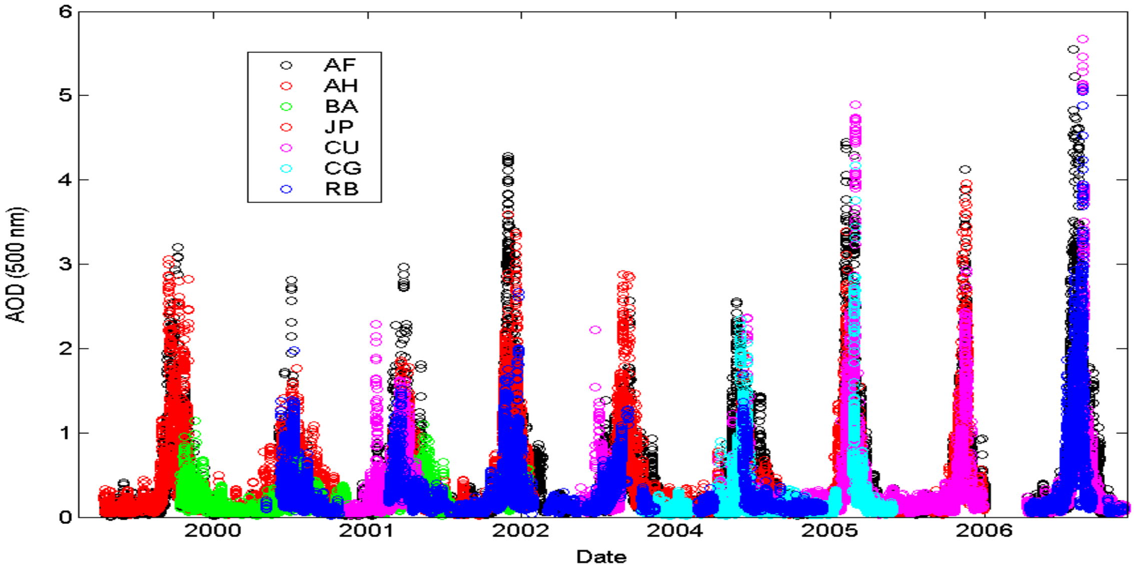



Figure 7.2 – Aerosol optical thickness measured at 7 sites in Amazonia from 2000 to 2007.

Figure 7.2 shows results from the AERONET network in operation in Amazonia for the last 7 years, for 7 sites. A large number of papers reports results from these measurements (Eck, 2003, Procópio et al., 2003, 2004, 2008, Schafer et al., 2002, 2008).

Previous solar radiation measurement studies (Schafer et al., 2002, Procópio et al., 2004, Yamasoe et al., 2006) showed that biomass burning aerosol particles reduce significantly the amount of PAR and solar radiation reaching the surface. AERONET retrieved aerosol optical properties indicate that biomass burning aerosol particles has moderate single scattering albedo and from this database a dynamical biomass burning aerosol optical model was proposed by Procópio et al. (2003). Results from one ongoing project financed by FAPESP (2006/56550-5) show that those particles can also increase the diffuse fraction of solar radiation reaching the surface and modify the radiation spectrally, reducing significantly blue light compared to red light.

Previous studies have modeled aerosol forcing but just for one single site (Rondônia), and were published by Procópio et al., 2003, 2004. Figure 7.3 shows the direct radiative forcing measured at Rondônia with AOT coupled with flux sensor and an aerosol model for biomass burning aerosol. It is clear the very high values (up to -300 watts/m²) instantaneous forcing in Rondônia. (Procópio et al., 2003, 2004). We want to extend this analysis to other sites and to the whole Amazon basin.

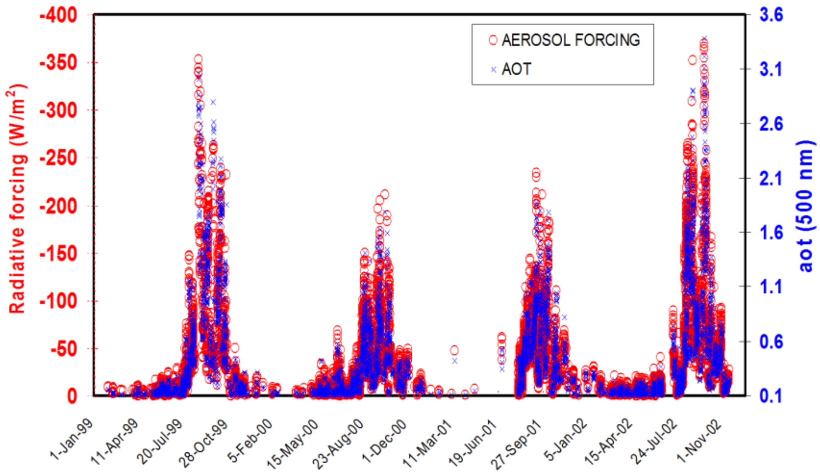



Figure 7.3 - Direct radiative forcing measured at Rondônia with sunphotometer measured AOT coupled with radiation flux sensors and an aerosol model for biomass burning aerosol. Calculations using SBDART radiative transfer model.

Regional distribution of aerosols over South America using a simple aerosol model in BRAMS shows strong forcing over large areas in South America (Figure 7.4). A reduction in radiation field for about 500 watts/m² can be modeled using this simple coupling. We need to improve these estimative with better optical properties, higher resolution models and better overall parameterization of critical parameters.

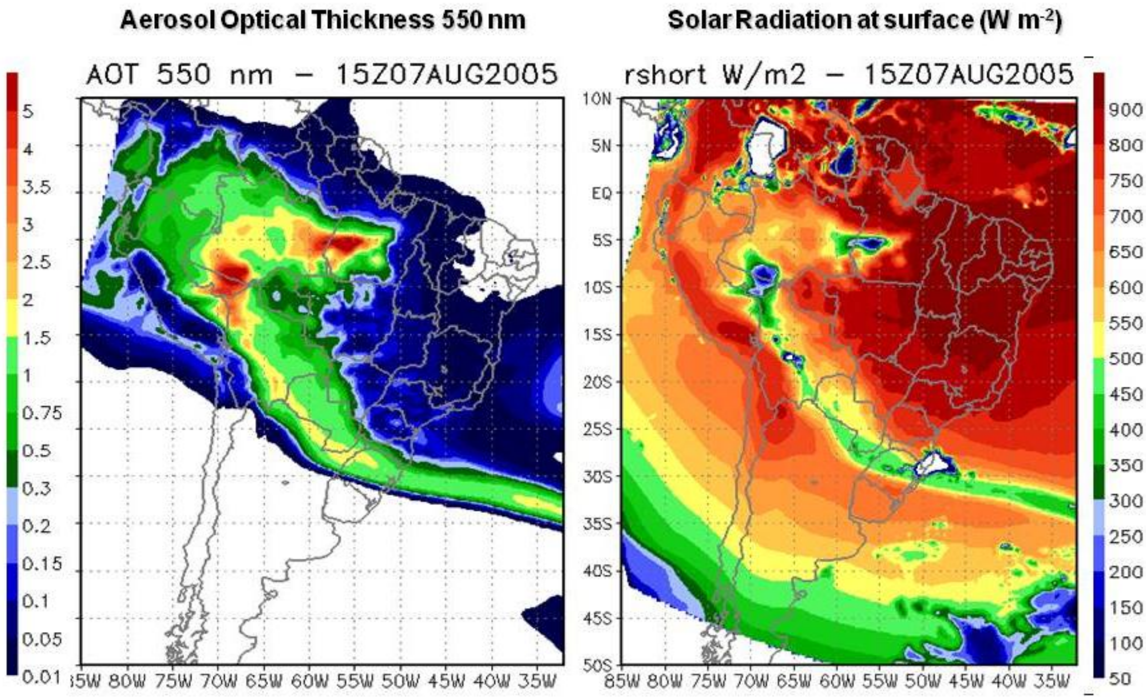



Figure 7.4 – Simulations of AOT and solar flux at surface using the BRAMS model with preliminary aerosol model shows strong forcing over large areas in South America.

These changes in the radiation field as shown in Figures 7.3 and 7.4 have profound impacts on the carbon uptake for the intact part of the Amazonian forest. When AOT varies from a background value of 0.1 to about 1 at 500 nm, Net Ecosystem Exchange (NEE) actually increases because of the larger fraction of diffuse radiation. This increase can be as high as 40%, having very strong effects on carbon balance (Oliveira et al., 2007). After that, NEE decreases sharply to zero for AOT around 4 at 500 nm due to the strong decrease of the overall radiation flux. This impact affects the dry and wet seasons, and have important implications for the Amazonian carbon cycle.

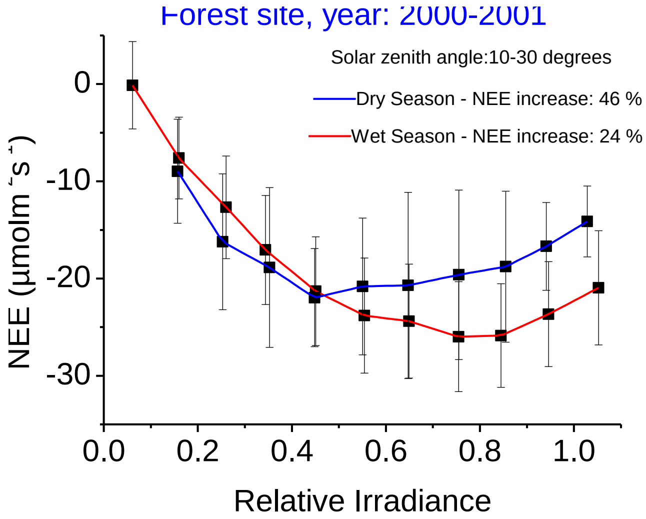



Figure 7.5 – Carbon uptake (expressed as Net Ecosystem Exchange) varies significantly with aerosol loading in Amazonia, as show for the site of Rondônia. When AOT varies from a background value of 0.1 to about 1 at 500 nm, NEE increases because of the larger fraction of diffuse radiation. This increase can be as high as 40%. After that, NEE decreases sharply to zero for AOT around 4 at 500 nm (Oliveira et al., 2007).

## 8) Scientific challenges and the means and methods to overcome them

Several challenges have to be overcome in this proposal. On the measurement field, it is not easy to continually operate 3 sampling stations in remote areas in difficult conditions, measuring with state-of-the-art instrumentation. To overcome this challenge, we will use the LBA infrastructure and the Max Planck tower infrastructure to help guarantee the continuous data collection that is necessary to characterize the large seasonal variability in Amazonia. These detailed long term measurements are critically important to build an aerosol model that shows seasonality and is accurate enough and based on detailed field measurements. The continuous operation of the AERONET sun photometers is also not easy because of the difficulties with importation and exportation of scientific equipment from Brazil. We plan to have spare instruments to allow continuous operations for the whole duration of this FAPESP project.

The calculation of closure along the vertical column in Amazonia were never performed, and we believe that with the combination of detailed ground measurements and vertical profile with Raman Lidar coupled with 1D models, it will be possible to do a good closure of optical properties.

In terms of instrumentation development, the construction of the polar nephelometer, were we can measured directly the phase function will be done at NASA in partnership with IFUSP, and we will validate these measurements by simultaneously measuring light scattering trough the 3 lambda TSI Nephelometer with integrated and backscattered radiation coupled with simultaneous size distribution and model calculations. Additionally the Cloud Scanner Instrument to be developed by NASA and IFUSP will be critical to measure cloud properties in-situ.

In the modeling arena, the challenge is to reproduce the vertical profile and the boundary layer concentration continuously along the seasons for several sites in Amazonia. Parameterizations for aerosol removal will have to be improved, as well as the convective transport. The use of two different regional models will help to choose and implement the best possible aerosol model for the studied regions.

A deeper understanding on the effects of aerosols on Amazonian clouds requires sufficiently large statistics with detailed information about the cloud vertical structure on a cloud-by-cloud basis. The ideal methodology for this study requires two simultaneous goals:

a) Deliver detailed information of the instantaneous vertical structure of cloud microphysics (droplet size) and thermodynamic phase (ice, water, or mixed);

b) Provide large statistics to allow for confident conclusions about the physical processes inside the cloud.

As described in Marshak et al., 2006, Martins et al. 2007, and Zinner et al. 2008, these goals can be met by measuring radiances from clouds using two aircraft instruments: the Cloud Scanner and the Rainbow Polarimeter, both developed in collaboration between the Joint Center for Earth Systems Technology (JCET) at UMBC and NASA GSFC. The Cloud Scanner is an imaging radiometer composed of five wavelengths in the near infrared (0.87, 0.91, 1.65, 2.10 and 2.25 µm) that allow the identification of the thermodynamic phase in clouds, together with visible and thermal infrared wavelengths (0.47, 0.55, 0.66 and 11 µm) that allow for the remote sensing retrieval of droplet size profiles in clouds. The Rainbow Polarimeter is a multi-angle system with six wavelengths (0.47, 0.55, 0.66, 0.76, 0.87, and 0.91 µm) used to retrieve water droplet effective radii and droplet distribution width in clouds using the cloudbow technique (Breon et al., 2005). Both instruments have been previously integrated and tested onto the Brazilian INPE/Bandeirante research aircraft.

As part of this project, we propose the INPE Bandeirante to fly in several occasions for the next years over the Amazon Basin, under varying conditions of aerosols (type, loading), clouds (type, development stages, cover area) and local meteorology (convective, frontal). The Brazilian INPE/Bandeirante aircraft will be equipped with state-of-the-art in situ aerosol and CCN instrumentation from the Institute of Physics, University of São Paulo, which will complement the instrumentation described above for the study of aerosol-cloud interactions.

Cloud side observations such as the ones proposed for the Cloud Scanner can be performed from the ground, from mountain tops, aircraft or from satellites with specific advantages and disadvantages on each case. Observations from mountain tops and low altitude aircraft like the Bandeirante eliminate problems with water vapor absorption, ground temperature and its infrared emissivity that occur in ground measurements. The disadvantages of the low aircraft geometry are cloud shadows in the upper views and the interpretation of the multiangle distribution in the analysis of a single cloud. Both issues can be tackled in a successful manner, although they increase the amount of data processing necessary for retrieving the vertical profiles of effective cloud droplet size. The polarization measurements to be performed by the Rainbow Camera require high polarimetric accuracy in order to be useful for retrievals of droplet size and its distribution width. This issue can be overcome by maintaining a frequent calibration protocol before and after each measurement campaign in the field. Validation of retrieved droplet size profiles is another important issue, and it will be tackled by specific experimental campaigns. One such effort is currently under way at the VOCALS experiment in Chile and the preliminary data shows good agreement between expected and retrieved results.

## Description of the study sites

Amazonia and Pantanal are large regions and very different from several points of view. They were chosen because of their relevance in terms of South America and tropical regions, and they allow different aspects of the aerosol-cloud-climate interactions to be studied. Three sites are planned to be used in this FAPESP proposal. The first one is the INPA ZF2 tower, North of Manaus, where natural biogenic aerosol can be analyzed. The site is show in Figure 8.1 bellow. The tower already exists and is part of the EUCAARI European Union project. The Max Planck Institute plans to install a new 65m tower further North, but close to this site, in additional to a proposed 300 meters high tall tower. We will use this cluster of towers to better suit the measurement needs to fulfill the objectives of this project.


**Figure 8.1.** Image of Northern Brazil. The locations of the tower and of Manaus are marked. The flow pattern is very constant and it is important to measured properties of natural biogenic aerosol in Amazonia. The site occasionally receives the plume of Manaus, what makes it interesting to analyzed urban emissions loaded with NOx interacting with the vegetation VOCs producing aerosol particles.

The second sampling site is planned to be located in Alta Floresta, North of Mato Grosso state, a site heavily loaded with biomass burning aerosols during the dry season. A third site at the Pantanal regional was chosen to analyze the impact of the outflow of aerosols from Amazonia into the Southern part of South America, and also because there was no atmospheric study done do far in this large region. This region is also important because of the impacts on the hydrological cycle. Figure 8.2 bellow shows the location of these 3 sites. These aerosol monitoring stations will be operated at least for 1 full year for each site.

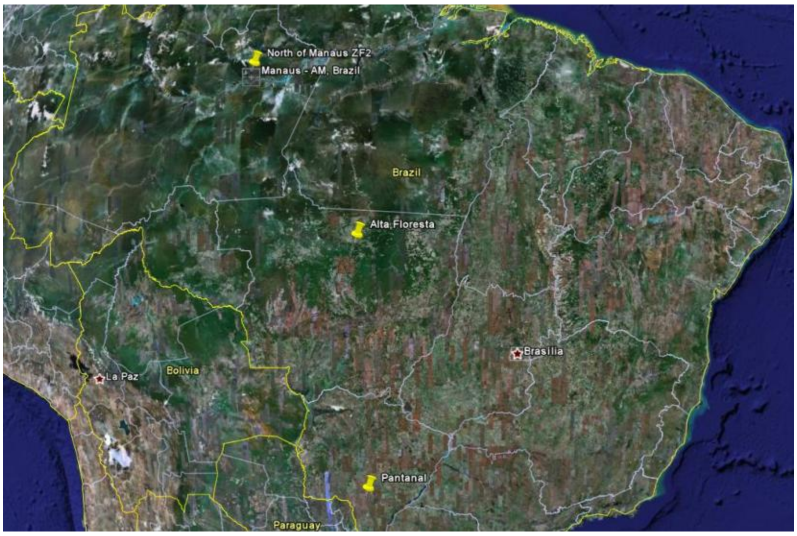



Figure 8.2 - Map of South America with the location of the three proposed sampling sites: Manaus, Alta Floresta and Pantanal. These aerosol monitoring stations will be operated at least for 1 full year for each site, providing critical data for the project.

# 9) Timetable

This proposal is planned to be run for 4 years, starting in April 2009. The timetable of activities can be structured in semesters, with the following activities:

**Semester 1** – Importation of equipments (Raman Lidar, nephelometers, MAAP, SMPS, sun-photometers, radiometers, etc.). Implementation of preliminary measurements in Manaus with the instruments already in Brazil (CCN, SFU, etc); implementation of the basic modules in the regional models (WRF-Chem and CATT-BRAMS). Implementation of infrastructure for remote sensing analysis. Analysis of data collected previously in the AMAZE and other campaigns that could contribute to build a better aerosol optical model for Amazonia.

**Semester 2** – Implementation of the full sampling station in Manaus, that will be operated for one year (Oct. 2009 - Oct. 2010). Implementation of algorithms to obtain aerosol optical thickness by MODIS in high resolution over Amazonia. Continuation of the work with model development, with the implementation of aerosol codes in the regional models. Implementation of Bill Cotton cloud parcel models at IAG/USP. Interactions with the FAPESP group on building the Brazilian Global Climate Model (BGCM). Publication of papers with the first year results.

**Semester 3** – In the Manaus site, implementation of the LBA/BAIRE 2010 intensive sampling campaign in partnership with MPIC, Harvard, Helsinki and Lund Universities. Continuation of Manaus measurements, and preparation of the Alta Floresta sampling site.

Finishing development of the polar nephelometer and cloud scanner instruments. Calculation of the regional aerosol distribution using MODIS and CALIPSO. Specifications to be done for the radiation code of the BGCM.

**Semester 4** – Data analysis for the one year continuous sampling at Manaus and for the LBA/CLAIRE experiment. Implementation of the Alta Floresta detailed sampling site. Implementation of the cloud resolving model with parameters measured in previous aircraft missions. Publication of papers with results for the second year.

**Semester 5** – Continuation of measurements at Alta Floresta. Airborne campaign with the INPE Bandeirante plane. Implementation of the radiation code for the BGCM. Measurements of cloud droplet distribution using the cloud scanner. Implementation of the parameters measured in the airborne campaign in the cloud resolving model.

**Semester 6** – Installation and operation of the aerosol sampling station in the Pantanal. Compilation and data analysis for the Alta Floresta site. Integration of remote sensing measurements with simulations from the regional models. Publication of papers with results for the third year.

**Semester 7** –Continuation of the operation of the aerosol sampling station in the Pantanal. Integration of remote sensing measurements with the regional models.

**Semester 8** – Implementation of the developed aerosol forcing parameters in the global model. Comparison between simulations with the global model and the upgraded regional models. Compilation of data collected in the three sampling stations. Construction of aerosol model for biogenic and biomass burning aerosol. Publication of papers with the integrated results.

## 11) Other financial support

The main project that is associated with this proposal is the Minister of Science and Technology National Institute for Global Change Research. It is coordinated by Dr. Carlos Nobre, and most o f the researchers in this proposal are strong players in the NIGC proposal. There is no budget at the NIGC to carry out the research per si, but the Institute will serve as a focal point in climate change research in Brazil. The proposal was approved for the period 2008-2013.

We will have strong super computer support/time. The important modeling component of this proposal will demand a substantial amount of supercomputer processing time as well as storage space. These will be provided by the new supercomputer currently being bought by the Brazilian government, and which will be used mainly for climate change research. Before the new supercomputer arrives, we will rely on the resources available to our research team at both INPE and USP. These include a NEC SX6 supercomputer and three SUN cluster with 1100, 512 and 200 processors, respectively. No computing time is being budgeted in this proposal.

# 12) Broader impacts

It will be difficult to implement coherent reductions in deforestation rate in Amazonia, greenhouse gas emissions for mitigation of global change without reducing uncertainties in key issues of climate change, including the impact of aerosols on climate and in the hydrological cycle. Also detailed studies on the changes in the radiation balance and its ecological impacts in the Amazonian and Pantanal ecosystem functioning is important for Brazil. This proposal will work on a comprehensive characterization of atmospheric properties in two key ecosystems in Brazil that are suffering important changes and are key in the mitigation strategy for Brazil. The work in this proposal on properties of biomass burning particles can also be applied to smoke plumes from other regions such as Africa and Southeast Asia.

The effect of aerosols on clouds represents one of the strongest anthropogenic effects on climate and weather with potentially important effects on the water cycle. Accurate measurements of the vertical profile of effective radius and thermodynamic phases are essential for our understanding of the effect of aerosol on cloud development, evolution, and life time. This study has even stronger impact as performed in a region with such global importance as the Amazon. As part of the LBA team, we will also integrate our results in the larger LBA framework. The integration of this proposal with the new National Institute for Global Change (NIGC) from MCT will allow the use of science produced in this project in public policies regarding strategies to reduce emissions from deforestation and land use change in Amazonia that the NIGC will do as one of their task. Most of the participants in this proposal are also members of the NIGC. The results of this project will help researchers and society in general to be aware of the changes in our atmospheric environment, and jointly help to find strategies to mitigate impacts.

The work we are planning to do in terms of new and more realistic aerosol-radiation-clouds parameterizations for regional and global climate models are key in improving the proposed Brazilian Global Climate Model. Improving global climate models are critically important to define better and more realistic strategies to mitigate greenhouse gases and aerosol emissions, both globally and regionally. In terms of education we have a strong commitment as part of the LBA community in working with local scientists, providing Master and PhD guidance for students from Amazonia and Pantanal. This is done because some members of the science team are formal advisors for PhD courses at INPA and University of Mato Grosso. Additionally, the local people will operate sophisticated instrumentation such as Raman Lidar and optical properties equipment that will help to train local people and transfer knowledge to researchers from INPA and University of Mato Grosso.

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