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Observations and Modeling of the Green Ocean Amazon: Year-to-Year Differences

S Martin

May 2013

ARM CLIMATE RESEARCH FACILITY

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Office of Science, Office of Biological and Environmental Research

Acronyms and Abbreviations

AAF	ARM Aerial Facility
AERI	atmospheric emitted radiance interferometer
AERONET	Aerosol Robotic Network
ALC	Aerosol Life Cycle
AMF	ARM Mobile Facility
AMS	aerosol mass spectrometer
AOD	aerosol optical depth
ARM	Atmospheric Radiation Measurement (Climate Research Facility)
ASR	Atmospheric System Research
BVOC	biogenic volatile organic compounds
CAPE	convective available potential energy
CAPI	Cloud-Aerosol-Precipitation Interactions
CCN	cloud condensation nuclei
CLC	Cloud Life Cycle
ENSO	El Niño-Southern Oscillation
ET	evapotranspiration
FIMS	fast integrated mobility spectrometer
FTS	Fourier Transform Spectrometer
GCM	global climate model
GNDRAD	ground radiometers on stand for upwelling radiation
GOAMAZON	Green Ocean Amazon
IN	ice nuclei
INPA	National Institute for Research in the Amazon
IOP	intensive operational period
ITCZ	intertropical convergence zone
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
MAOS	Mobile Aerosol Observing System
MFRSR	multifilter rotating shadowband radiometer
MPL	micropulse lidar
PASS	photo-acoustic soot and aerosol sensor
PI	principal investigator
PTR-MS	proton-transfer mass spectrometer
RH	relative humidity
SKYRAD	sky radiometers on stand for downwelling radiation
SOA	secondary organic aerosol

SP2	single-particle soot photometer
TCCON	Total Carbon Column Observing Network
UV	ultraviolet
VOC	volatile organic compounds

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Date and Location of Activities

Date: 1 January 2014 through 31 December 2015

Location: Central Amazon to the west of the city of Manaus. The main site, T3, is that of GOAMAZON (-3.21°S, -60.60°W), which is to the north of Manacapuru. The auxiliary site, T2, (-3.17°S, -60.0°W) is nearby Iranduba. Manaus, a city of two million people, is an isolated urban area within the Amazon Basin. Outside this industrial city there is natural forest for thousands of kilometers in every direction. The research sites intersect the heavily polluted plume of the growing Manaus metropolis on a regular basis. The airshed intersecting the main research site oscillates between (1) one of the most pristine and natural continental sites on Earth and (2) one heavily affected by tropical megacity pollution and its interactions with the forest natural emissions.

1.0 Campaign Abstract

The strong hydrologic cycle of the Amazon Basin is one of the primary heat engines of the Southern Hemisphere. Any accurate climate model must succeed in a good description of the Amazon Basin, both in its natural state and in states perturbed by regional and global human activities. At the present time, however, tropical deep convection in a natural state is poorly understood and modeled, with insufficient observational data sets for model constraint. An Atmospheric Radiation Measurement (ARM) Climate Research Facility planning document conferred a priority status to studies of deep tropical convection over land in the Amazon Basin (ARM 2007). Furthermore, future climate scenarios resulting from human activities globally show the possible drying and the eventual possible conversion of rain forest to savanna in response to global climate change. Based on our current state of knowledge, the governing conditions of this catastrophic change are not defined. Human activities locally, including the economic development activities that are growing the population and the industry within the Basin, also have the potential to shift regional climate, most immediately by an increment in aerosol number and mass concentrations, and the shift is across the range of values to which cloud properties are most sensitive (e.g., natural conditions of 300 particles cm^{-3} still prevail in much of the Amazon Basin during the pristine wet season and cloud properties are most sensitive to shifts from 300 to 1000 cm^{-3}).

The Green Ocean Amazon (GOAMAZON) campaign seeks to quantify and understand how aerosol and cloud life cycles in a particularly clean background in the tropics are influenced by pollutant outflow from a large tropical city. The GOAMAZON campaign addresses the susceptibility of cloud-aerosol-precipitation interactions to present-day and future pollution in the tropics. In particular, the second year of measurements will enable comparative year-to-year variability in the measurements and will be an important step forward in knowledge about interannual differences in the Amazon Basin and their effects of atmospheric and ecosystem functioning.

The interannual differences in the Amazon Basin are already known to be very significant. For instance, both 2005 and 2010 were very dry years. The year 2009 was exceptionally wet. Owing to dramatic changes from year to year, we can state, to a high likelihood, that the observations of 2014 and 2015 will be quite different in rainfall totals and associated impact in atmospheric composition, in particular for atmospheric cleansing downwind of the Manaus plume. Differences in rainfall initiate sequences of key differences in atmospheric and ecosystem functioning. The purpose of the second year of measurements is to increase the statistical population of cases and subcases, identifying those findings specific to one year or the other compared to those findings common to both years, thus validating the general representation in models of the effects of pollution on the natural atmosphere and ecosystem. The strategy to meet this objective is to employ a comparative analysis to a consecutive year’s data set. In the context of interannual variability, comparative differences and similarities between years 2014 and 2015 will quantitatively define the representativeness of many of the observations and place them within the context of longer historical and future time records.

This study is aligned with the ARM Climate Research Facility’s vision of obtaining a detailed, representative, and accurate description of Earth’s atmosphere in diverse climate regimes through the deployment of strategically located in situ and remote sensing observatories. In particular, the study will improve the understanding and representation in climate and earth system models of clouds and aerosols as well as their interactions and coupling with the Earth’s surface.

2.0 Campaign Summary and Scientific Objectives

The GOAMAZON campaign seeks to understand how aerosol and cloud life cycles are influenced by pollutant outflow from a large industrial city in the tropical rain forest, particularly the susceptibility to cloud-aerosol-precipitation interactions and the feedbacks among biosphere and atmosphere functioning and human activities. The scientific objectives are organized around the structure of the Atmospheric System Research (ASR) working groups—Aerosol Life Cycle (ALC), Cloud Life Cycle (CLC), and Cloud-Aerosol-Precipitation Interactions (CAPI). The data set of 2014 will respond to the objectives for one annual period. The measurements in 2015 will add the perspective of year-to-year differences. This perspective is especially important given the known variability in Amazonia. Better statistics are the basis for evaluating and improving formulations of aerosol-cloud interactions, as well as urban plume and forest interactions, in models.

Specific objectives within each of the broad ALC, CLC, and CAPI categories are as follows:

1. ALC: Interactions in the tropics of an urban pollution plume with biogenic volatile organic compounds, especially the impact on the production of secondary organic aerosol, the formation of new particles, and biogenic emissions of aerosols and their precursors.
2. ALC: Influence of anthropogenic activities in the tropics on aerosol microphysical, optical, cloud condensation nuclei, and ice nuclei properties.
3. CLC: Role of the daily transition of convection from shallow to deep on the evolution and dynamics of convective cloud systems, with comparison and understanding between tropical and other ARM environments.
4. CLC: Evolution of storms over tropical rain forest from (i) severe in the dry season to (ii) large but less intense in the wet season.
5. CAPI: Aerosol effects on convective clouds and precipitation, including the roles of aerosols in changing regional climate and atmospheric circulation and the effects of aerosols on tropical precipitation for clean and polluted situations.
6. CAPI: Data-driven improvement and evaluation of parameterizations of cloud-aerosol interactions, as used in the climate models.

The theme uniting the objectives is the development of a data-driven knowledge base for predicting how the present-day functioning of energy, carbon, and chemical flows in the tropical rain forest might change, both due to external forcing on Amazonia from global climate change and internal forcing from past and projected demographic changes in Amazonia. The ultimate goal is to estimate future changes in direct and indirect radiative forcing, energy distributions, regional climate, ecosystem functioning, and feedbacks to global climate. In this regard, the presented objectives are representative, and further definition and broadening can be expected as the science team spins up prior to deployment.

The campaign deployment includes (1) the G-1 aircraft of the ARM Aerial Facility (AAF), (2) the Mobile Aerosol Observing System (MAOS-A and MAOS-C), (3) the first ARM Mobile Facility (AMF1), and (4) several additional instruments. The deployment is from January 2014 through December 2015, downwind of the city of Manaus. The site is situated so that it experiences the extremes of (1) a pristine atmosphere when the Manaus pollution plume meanders and (2) heavy pollution and the interactions of that pollution with the natural environment when the plume regularly intersects the site. The deployment will enable the study of how aerosol and cloud life cycles, including cloud-aerosol-precipitation interactions, are influenced by urban pollutant outflow in the tropics for a wide range of synoptic and environmental conditions.

3.0 Project Description

3.1 Introduction and Motivation

The convective activity and the atmospheric circulation of tropical South America are part of an American monsoon system (Zhou and Lau 1998), and any changes in tropical precipitation can have significant, potentially global consequences because of non-linear multiscale interactions of tropical waves with tropical precipitation in the Amazon, leading also to possible changes in the tropical Atlantic intertropical convergence zone (ITCZ) (Wang and Fu 2007). The effects of aerosol particles on cloud microphysical properties, cloud cover, precipitation, and regional climate over the Amazon are significant. The region is particularly susceptible to changes in aerosol particles because of the low background concentrations and high water vapor levels, indicating a regime of cloud properties that is highly sensitivity to aerosols. Aerosol concentrations undergo both rapid transient changes during biomass burning as well as secular trends related to economic development. The climatic implications for strong cloud-aerosol dynamic interaction are profound, (Williams et al. 2002; Andreae et al. 2004; Rosenfeld et al 2008; Khain and Lynn 2009) ranging from modulation of local precipitation intensity to modifying large-scale circulations and energy transport associated with deep convective regimes (e.g., Hadley or Walker circulation). Suppression of rainfall can potentially lead to a positive feedback through a drier land surface, stronger susceptibility to fires, and even greater aerosol-induced suppression of rainfall (Laurance and Williamson 2001). Preliminary studies indicate that higher concentrations of aerosol particles might increase the intensity of precipitation in the Amazon region (Lin et al. 2006, Martins and Dias 2009). Research progress requires data and observations, hence, the motivation for the ARM deployment.

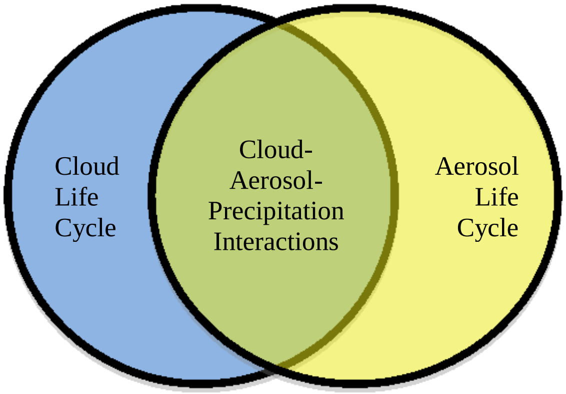

Figure 1. The relationship between ASR working groups.

The campaign will deploy the MAOS-A, MAOS-C, and AMF1 facilities for continuous operation from January 2014 through December 2015 as well as for the deployment of the AAF G-1 during intensive operating periods of four to six weeks each in the wet and dry seasons. The main research site, T3, and the auxiliary site, T2, are located downwind of the city of Manaus (Figure 2).

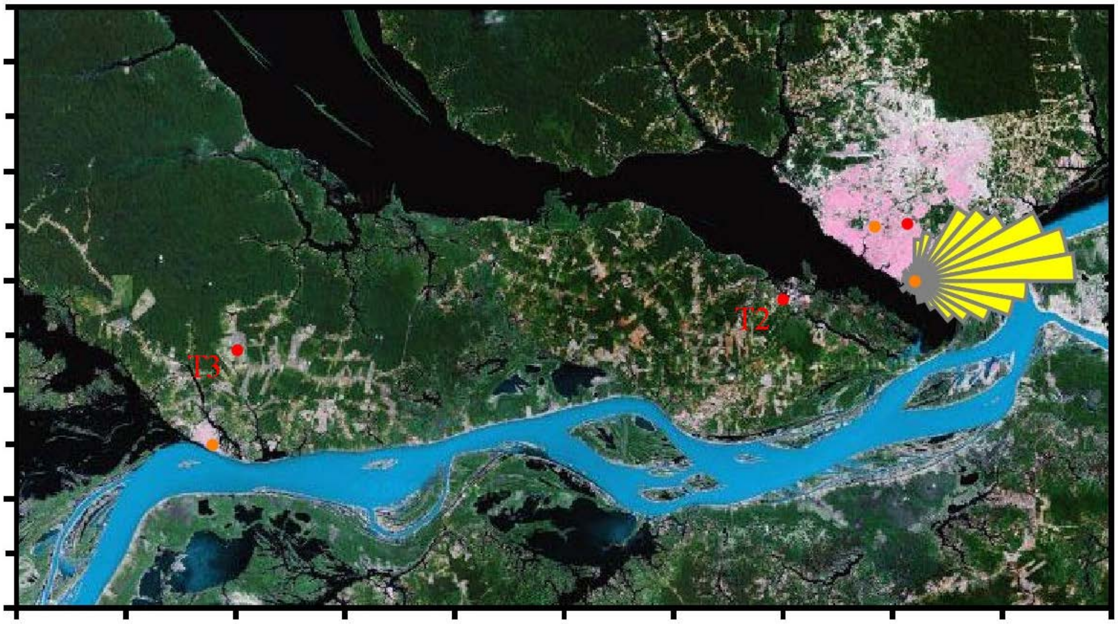

Figure 2. Map depicting the central Amazon to the west of the city of Manaus. The main research site, T3, (-3.21°S, -60.60°W) is to the north of Manacapuru. The auxiliary site, T2, (-3.17°S, -60.0°W) is near Iranduba. The yellow sectional chart shows the frequency of wind direction at 1 km for one year's data.

Manaus, a city of two million people and growing rapidly, is an isolated, highly polluted urban area (Figures 3 and 4) within the otherwise pristine Amazon Basin. The city has been a free trade zone since the 1960s, and this status was recently renewed for another 50 years by the Brazilian government. As a result, it is an industrial manufacturing city with one of the highest per capita incomes in Brazil. Most of the manufactured products are shipped approximately 3000 km by barge to the consumer market in the state of São Paulo.

As a consequence of this industrial and other economic activity (e.g., the city's electricity is produced in large part by burning high-sulfur fuel oil), there are high pollution levels in the plume. The width of the urban plume is about 20–25 km, resembling the dimension of the city itself, with little downwind spreading (i.e., there is distinct clean air on both sides of the pollution plume [Figure 4]). The atypically small edge mixing along the plume is a consequence of the persistent easterly winds throughout the year (Figure 2). The plume from the city has high concentrations of SO_2, NO_x, and soot, among other pollutants. Measurements in the plume show very strong formation of photochemical pollution, e.g., a threefold increase in ozone mixing ratios within the atmospheric boundary layer occur within a 100-km travel distance downwind of Manaus while peak NO concentrations of >10 ppb near Manaus drop precipitously with travel distance. Particle number and mass concentrations are 10 to 100 times greater in the pollution plume compared to the times when pristine conditions prevail.

Manaus is situated in an advantageous scientific location in the center of the Amazon Basin, meaning that it largely experiences the full range of Basin meteorology. Cold fronts, which typically occur in the southwest part of the Basin (Rondonia), also reach Manaus in June/July once or twice each year. Squall lines, which are frequent in the eastern portion of the Basin, also penetrate and propagate to Manaus, with the result of very common rain in Manaus in the late night. Local daily cycles of convection are common throughout the Basin, including in Manaus.

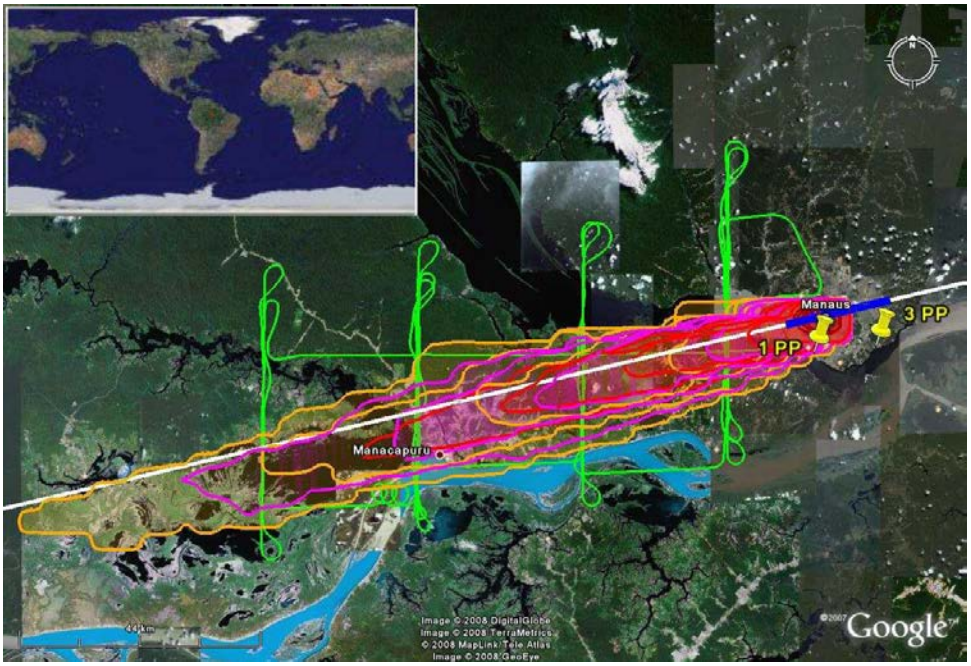

Figure 3. Land cover image with an overlay of a flight pattern on 19 July 2001 from 10:00–14:00 (local time) that samples the Manaus plume. Flight track global positioning system data are shown in green line. The output of a HYSPLIT dispersion model run from the Manaus plume is indicated by the red/orange contour lines. The two yellow pins indicate the locations of power plants (3 PP, 560 MW capacity; 1 PP, 125 MW). GOAMAZON site T3 is slightly north of Manacapuru. Figure is adapted from Kuhn et al. (2010).

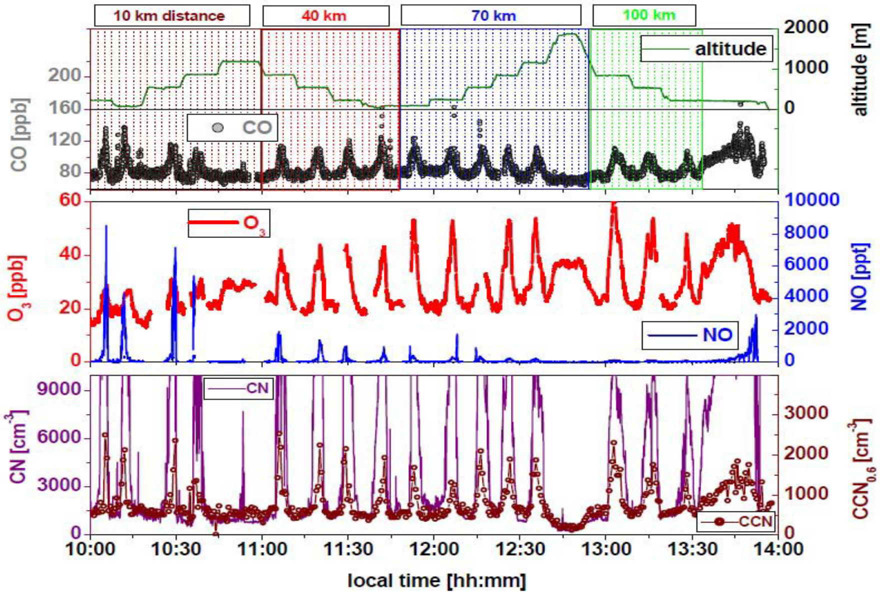

Figure 4. Time series of trace constituent measurements on plume transects on 19 July 10:00–14:00 local time. Vertical profiles of crosswind transects in the urban outflow are shown for successive distances (10, 40, 70, and 100 km) downwind of Manaus City. Figure is adapted from Kuhn et al. (2010).

As combined consequence of the meteorology, emissions, and chemistry, the main research site T3 experiences the extremes of (1) a pristine atmosphere when the Manaus pollution plume meanders somewhat north or south and (2) heavy pollution and the interactions of that pollution with the natural environment when the plume conforms to its mean flow. In the wet season, in regions outside of the Manaus plume, the Amazon Basin is one of the most pristine locations on Earth for continental aerosols (Andreae 2007; Martin et al. 2010). These aerosols are in dynamic balance with the ecosystem (which produces them directly and indirectly) and the hydrologic cycle (which removes them) (Pöschl et al. 2010).

In the dry season, there can be extensive biomass burning, often ranging from a dominating perturbation at the southern edge of the Amazon Basin to a more diffuse elevation of background pollution in the central part of the Basin where Manaus is located. There is also less removal by precipitation in the dry season. These spatial and temporal differences can dramatically affect the development of clouds and precipitation in different seasons (Andreae et al. 2004; Feingold et al. 2005). The urban plume of Manaus passes westward into the center of the Basin. Downwind, this plume greatly influences aerosol production and radiative balance. Therefore, in this unique scientific environment, sampling inside and outside of the plume can unambiguously demonstrate the influence of human activities on tropical atmospheric chemistry and drivers of climate.

GOAMAZON will enable the study of how aerosol and cloud life cycles, including cloud-aerosol-precipitation interactions, are influenced by pollutant outflow from a tropical megacity. At present, most knowledge of the influence of pollution outflow is based on studies carried out for cities at northern latitudes. The tropics represent a different regime of actinic flux, water vapor, temperature, and plant emissions, so there is significant uncertainty in the extrapolation of our present knowledge base. The city of Manaus in the center of the Amazon Basin represents an extraordinary scientific opportunity worldwide to study and understand how changes in human actions in the tropics influence the interactive physical, chemical, and biological processes that regulate atmospheric chemistry and climate.

In addition to understanding the present-day effects of a tropical megacity on a pristine environment, GOAMAZON will also provide important information for broader applications into thinking about possible future changes of climate planet-wide; human activities by the year 2050 are projected to greatly increase the megacity count worldwide, particularly in tropical regions. The large societal need is an understanding of how these perturbations of the inputs into the natural system result in changed clouds, radiative balance, climate, and feedbacks among them. The prevailing regime of cloud-aerosol interaction in the natural environment of the Amazon Basin is distinctly different from polluted continental regions, where particle concentrations are orders of magnitude higher. So far, however, the effects of urban outflow in modifying cloud condensation nuclei (CCN) properties of a pristine tropical rain forest have not been investigated. The existence of an isolated plume in an otherwise very pristine environment downwind of Manaus offers the possibility to investigate the evolution of the aerosols over several hours following emission. Future changes in CCN properties, both because of changes in chemical composition and changes in number-size distribution, can have important effects on the cloud life cycle, precipitation, and climate.

3.2 Variability

The scientific objectives of the GOAMAZON campaign respond to the question of, "What is the effect of pollution on natural atmosphere and ecosystem functioning and the couplings among them?" Measurements in 2015 will provide a second year's data set that begins to assess year-to-year differences associated with this question.

One prime example of both variability and scientific opportunity in the context of the two years of data is the El Niño-Southern Oscillation (ENSO), which has a cycle of about 3 to 6 years. The last warm phase of ENSO (El Niño) occurred in 2009–10, followed by a strong cold phase (La Niña) in 2010–11 and a weaker phase in 2011–12. Although prediction of the phase of ENSO is challenging, especially years in advance, the probability is high due to the quasi- periodic behavior of ENSO that parts of 2014 and 2015 may experience one or possibly even opposite phases of ENSO. During El Niño events, the central Amazon, where Manaus is located, typically experiences reduced rainfall in the wet season with the possibility of droughts in the dry season. Conversely, during La Niña events, central Amazon rainfall increases in the wet season, with the possibility of floods. These changes affect the vegetation cover and ecosystem functioning.

The variability of meteorological variables in the Amazon Basin has been remarkably high in the recent past (Liebmann and Marengo 2001; Zeng et al. 2008; Marengo et al. 2011, 2012) and might become more so in the future. Several global circulation models have projected an increase in the frequency and severity of drought events affecting the Amazon region as a consequence of anthropogenic greenhouse gas emissions (Lewis 2011). Such droughts may lead to a loss of some Amazon forests, which would accelerate climate change. In 2005, a major drought occurred, identified as a 1-in-100-year event, and it was associated with unusual Atlantic sea surface temperatures, more so than ENSO-related changes in the Pacific. During 2009, the Amazon Basin was hit by heavy flooding with a magnitude and duration that has only been observed a few times in several decades. By July 2009, water levels of the Rio Negro, a major Amazon tributary, reached a new record at Manaus harbor, the highest mark of the last 107 years.

The year 2010 featured a widespread drought in the Amazon rain forest, which was more severe than the "once- in-a-century" drought of 2005 (Marengo et al. 2011). Water levels of major Amazon tributaries fell drastically to unprecedented low values and isolated the human population in the floodplain whose transportation depends upon on local streams, which completely dried up. The 2005 and 2010 droughts appear to have transformed the forest from a net sink to a net source of global carbon over this time period (Davidson et al. 2012). Although interannual differences of the extent represented by 2005 and 2010 are believed rare, sampling intraday, interday, intraseasonal, and interseasonal variability from any random two years in the climatology of the Amazon Basin ensures a greatly increased statistical base for the general problem of inversion of a sampled population to a description of the population itself.

Figure 5 presents the climatology of some meteorological quantities for the Manaus region (1968–1991) (Machado 2004). July and August have the lowest cloud cover and rainfall (i.e., heart of dry season) while February and March have the highest (i.e., heart of wet season) (Figures 5A and 5B). In the dry season, there is a significant difference between cloud cover and high cloud cover (Figure 5A), reflecting the decrease in convective intensity compared. The transition season from dry to wet and the beginning of the wet season is generally the period of strongest intensity of convection. The annual climatology of the convective available potential energy (CAPE) is presented in Figure 5C. There is only a weak seasonal variation in CAPE, which is typical of the rain forest vegetation sites that are close to the equator. The small variation in CAPE (Figure 5C) yet large variation in cloud cover and rainfall (Figures 5A and 5B) has an important implication: relatively small changes in large-scale circulation can modulate relatively large changes in rainfall in this region. The two-year data set of 2014 and 2015 will begin a knowledge base to further the understanding and quantification of these connections for the tropical rain forest, both for natural variation and for changes instigated by human economic activities.

The seasonal variation in the number of thunderstorms (lightning, thunder, and hail reported by ground observers) is represented in Figure 5D. Although the frequency of thunderstorms is approximately constant throughout the year, the intensity and duration vary greatly (data not shown). The wet season tends to rain more continuously but less intensely, compared to the invigorated storms that take place in the dry season. Figure 5E presents the number of synoptic organized convective systems apparent in satellite images. The frequency of organized synoptic convective events is highest during the end of the wet season, with a secondary peak during the start of the wet season. These events arise mainly from the monsoon circulation that increases the ITCZ activity over Amazonia and from the squall lines that originate near the coast and propagate into central Amazonia. Compared to other regions of Amazonia, Manaus has an exceptionally large number of events per month—around six during March and three during October—presumably because this region is influenced by both types of synoptic perturbations (Fisch and Nobre 1998).

Even so, the total number of events is still small with respect to probabilistic treatment. Scientific analysis separates and classifies thunderstorm cases by life cycle duration, aerosol concentration, cloud size, and precipitation intensity (e.g., Figure 5), yet the small number of samples is often insufficient to deeply explore major features. The two-year data set of 2014 and 2015 is important for approximately doubling the number of relatively rare events to improve greatly the quality of the statistics of the observations and findings. The thunderstorms are chosen as one type of example for presentation, but this general statement of improved statistics for rare events by a second year of measurements generalizes to many other annual but nevertheless rare events (i.e., small in number) in the meteorology and atmospheric chemistry of the Basin (e.g., detectable new particle formation at the surface is rare in Amazonia).

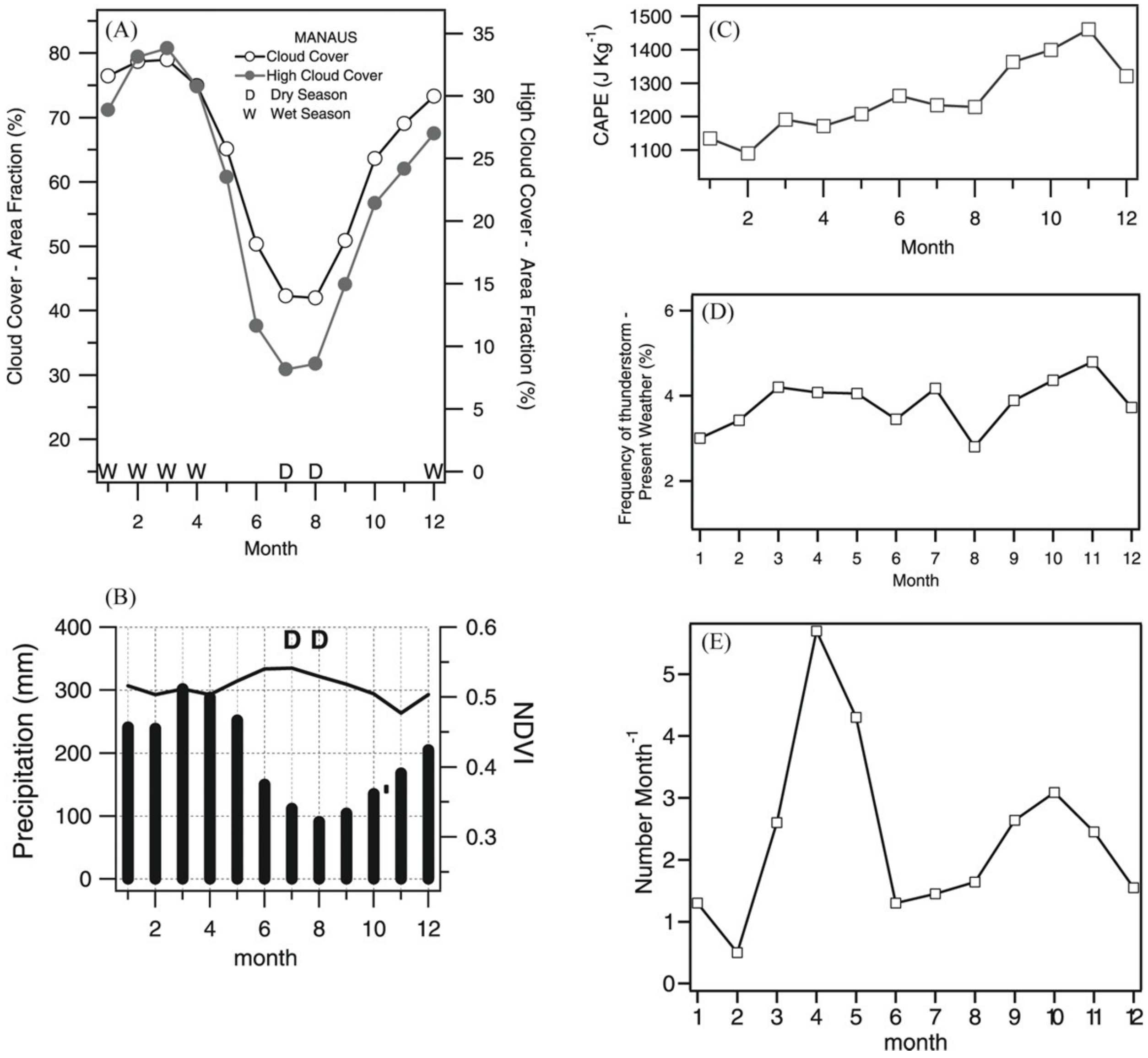

Figure 5. Annual climatological cycle of meteorological quantities for the Manaus region (1968–1991). (A) Seasonal variation of the cloud cover and high cloud cover fraction for a region of 2.5° × 2.5° centered on Manaus. “W” indicates wet season and “D” indicates dry season, as defined using high cloud cover (i.e., convective systems). (B) Seasonal variation of the Normalized Difference Vegetation Index and rainfall. (C) Seasonal variation of CAPE. Measurements of temperature and humidity at the surface were used to estimate CAPE, although the radiosoundings were at 08:00 (local standard time) and therefore the moment of maximum CAPE value was not captured. (D) Seasonal variation of thunderstorm events observed by surface observer. (E) Number of synoptic convective perturbations from satellite data for a region of 10° × 10° centered on Manaus. Ref: Machado et al. (2004).

Year-to-year differences in rainfall initiate sequences of key differences in atmospheric and ecosystem functioning that affect the aerosol life cycle. Rainfall directly impacts atmospheric composition and is indicative of the amount of convective transport in the region. There is considerable variability in rainfall from year to year (Satyamurty et al. 2010). At stations throughout the Amazon Basin, changes in total rainfall from year to year of about 1000 mm are quite common and may be as high as 2000 mm. Drier than normal or wetter than normal years may be linked to different emissions from ecosystem and different lifetimes of airborne species. Three examples relevant to the aerosol life cycle:

1. A dry year initiates an increase in fire spots in the Amazon Basin and hence general background pollution, coupled to a lower rate of atmospheric cleansing because of reduced wet deposition. Although the “arc of fire” that represents the largest number of fire spots is far from Manaus, Manaus is episodically affected by local fires as well as regional meteorological patterns that can transport biomass-burning plumes across long distances. With respect to Manaus, in 2009 large local biomass burning led to heavy and dense plumes over the city, which was quite unusual (i.e., not noted previously in the two-decade record).
2. Aerosol Robotic Network (AERONET) aerosol optical depth (AOD) measurements for the last 12 years show variability in particle mass concentrations (Figure 6), which can at times be explained by fire spots. However, there are additional features apparent in the detailed semi-daily time series that appear tied in ways yet to be fully defined to rainfall patterns and shifts in ecosystem functioning (Martin et al. 2010).
3. A key hypothesis, emerging from preliminary data sets at two locations in the Amazon Basin, is that water stress tied to variation in rainfall and soil moisture influences the emission of biogenic volatile organic compounds (BVOCs) and therefore the formation of secondary organic aerosols that serve as the dominant source of CCN in the Basin (Martin et al. 2010; Pöschl et al. 2010). Unknown at this time is the susceptibility to anthropogenic influences and the variability of this susceptibility to year-to-year changes in rainfall and soil moisture. The collection of year-to-year data sets can be used to study the influence of various types of environmental stress on the full range of ecosystem fluxes (CO_2, BVOCs, CO, CH_4, NO_x, transpiration, etc.) and to develop an understanding of the linkages (including lags) between ecosystem function and the environment (e.g., CCN formation) as well as the feedbacks between them.

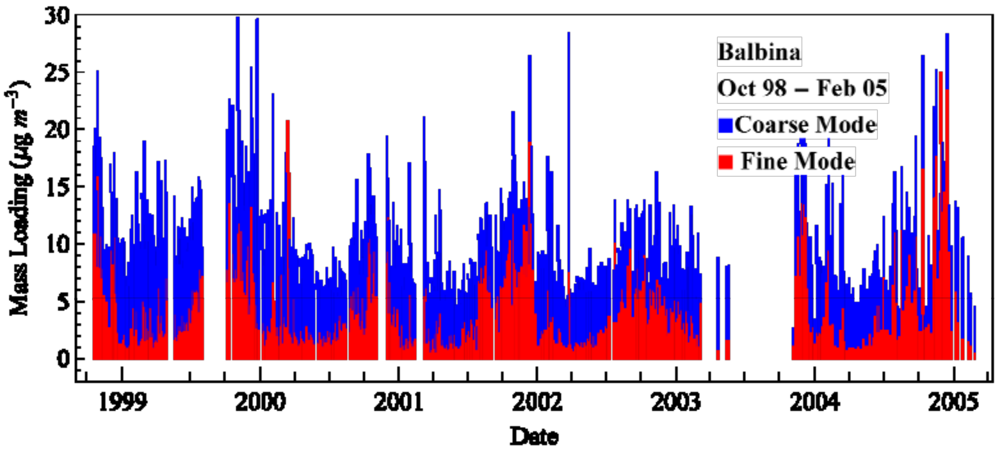

Figure 6. Time series of particle mass concentrations in pristine rain forest north of Manaus (Balbina). Data are shown as stack bar plots of fine (red; < 2 µm) and coarse (blue; 2 to 10 µm) size fractions. Adapted and updated from Artaxo et al. (2002).

More accurate quantification and more confident mechanistic understanding of these and other year-to-year differences necessitates staying in the same area and measuring the same parameters for a minimum of at least two years so that a comparative study is possible. The study is aligned with the ARM vision of obtaining a detailed, representative, and accurate description of Earth’s atmosphere in diverse climate regimes through the deployment of strategically located in situ and remote sensing observatories. In particular, with respect to representativeness, GOAMAZON will be a definitive first step forward in the need to understand interannual variability. In light of an ARM goal of a permanent site in Amazonia, the combined detailed data sets of 2014 and 2015 will provide an important year-to-year baseline for the contextual interpretation of data from a possible less-instrumented future permanent site.

3.3 Instrumentation

3.3.1 AMF1 and MAOS Surface Measurements

Aerosol properties

MAOS-A, MAOS-C, and AMF1 will be used for ground-site characterization of aerosols, clouds, radiation, and meteorology. A scanning mobility particle sizer and an ultra-high sensitivity aerosol spectrometer provide size distributions, ranging from 15 nm to 1 µm. Size-resolved aerosol mixing state and hygroscopicity are measured using a humidified tandem differential mobility analyzer. A particle-into-liquid sampler coupled to chromatographic analysis and an aerosol chemical speciation monitor provide aerosol chemical composition.

A CCN counter, coupled to a differential mobility analyzer, measures the size-resolved CCN activation of aerosols. A suite of instruments, including a nephelometer, aethelometer, humidgraph, and multifilter rotating shadowband radiometer (MFRSR), characterize aerosol optical properties. Scattering and absorption coefficients, single-scattering albedo, hygroscopic response (i.e., f(RH)), and AOD are measured. An ice nuclei (IN) counter is requested given the importance of IN in deep convection. The micropulse lidar (MPL) maps the vertical distribution of aerosol, and under non-cloudy sky conditions, these data, when combined with surface radiation data, permit direct calculations of radiative heating; under cloudy sky conditions, the MPL data provide estimates of particle number being entrained into cloud base. Gases including carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), sulfur dioxide (SO_2), ozone (O_3), oxides of nitrogen (NO_x), and volatile organic compounds (VOCs) are measured by trace gas analyzers (including a Los Alamos National Laboratory [LANL] PICARRO cavity-ring down spectrophotometer) and a high-resolution proton-transfer mass spectrometer (PTR-MS). Accurate CO measurements are essential for distinguishing natural air masses (60 to 90 ppb CO in the Amazon Basin) from those influenced by anthropogenic activities. Likewise, capability for NO_x measurement to 20 ppt is required. For ozone, values as low as 5 ppb must be accurately measured. These requirements are within the performance capabilities of the ARM instruments. During the intensive measurement periods, OH and H_2SO_4 measurements from guest investigators are highly warranted, as are measurements with high-resolution aerosol mass spectrometers. These instruments can be included by guest investigators during the intensive operational periods. These measurements allow examination of the controlling processes for the production and aging of aerosols and identification of air masses.

Cloud properties

AMF1 includes a suite of active and passive remote sensing instrumentation for the observation of clouds. The dual-wavelength Ka-/W-band scanning cloud radar with Doppler and polarimetric capability provides simultaneous observations of clouds and light precipitation over a 15–20 km range. The three-channel microwave radiometer (MWR3C; 20, 30, and 89 GHz) is a vertically pointing system that provides improved retrievals of integrated water vapor content and cloud liquid water path. The flexible, adaptive capabilities of these radars allow for dynamic operational scanning strategies to approach the cloud-scanning challenges in the Amazon Basin. Measurements will include base radar and polarimetric moments (e.g., radar reflectivity at an estimated sensitivity of -30 dBZ at 10 km as well as radial velocity) and detailed Doppler spectra. AMF1 also includes a vertically pointing W-band cloud radar that provides base radar moments and Doppler spectra, an MPL providing information on clouds in the vertical column, a ceilometer providing measurements of cloud base height (below approximately 7.5 km), and a Doppler lidar providing sub-cloud vertical velocities.

Radiation, energy, and water budget

Surface downwelling and upwelling broadband radiative fluxes at solar, infrared, and ultraviolet wavelengths are measured by the sky radiation (SKYRAD) and ground radiation (GNDRAD) collection of radiometer systems. These systems provide redundant observations of the diffuse, direct, and total radiative fluxes at the surface. Additional terms in the surface energy budget are measured by the eddy correlation flux system, including measurements of the surface turbulent fluxes of momentum, sensible heat, latent heat, and carbon dioxide. Spectrally resolved observations of downwelling radiation are provided by the atmospheric emitted radiance interferometer (AERI) and MFRSR. The AERI measures the spectral radiance of the sky in the range from 3 to 19.2 µm, with a spectral resolution of 1.0 cm^{-1} every 20 seconds. These data can be used for cloud property retrievals and the determination of vertical profiles of temperature and relative humidity (RH). The MFRSR provides measurements of the direct normal, diffuse, and total solar irradiance in six different wavelength bands (415, 500, 615, 673, 870, and 940 nm) at 20-second intervals. These observations are used to derive atmospheric column-integrated measures of O_3, H_2O vapor, and AOD (Michalsky et al. 1995), as well as aerosol size distributions and single-scatter albedo (Kassianov et al. 2005).

The solar-tracking LANL Fourier Transform Spectrometer (FTS) measures photon intensity in the visible-ultraviolet region of the solar spectrum at ultra-high resolution. It will measure columnar concentrations of CO_2, CH_4, N_2O, CO, NO_2, and H_2O, as well as AOD. Of particular interest is the measurement of pollutant concentrations such as NO_2 and CO that are present in the Manaus pollution plume as well as of several organic species that are possible precursors to aerosol formation. Furthermore, the LANL FTS is part of the global Total Carbon Column Observing Network (TCCON) network being used to validate Greenhouse Gases Observing Satellite and will be used as tropical validation site for the OCO-2 satellite. Because the Amazon region is grossly undersampled, there are large uncertainties, and validation of the Amazon area is a critical gap in the TCCON network. The FTS deployment therefore represents a value-added product regarding the carbon cycle. The FTS will open a new observational window into the couplings between the cloud-aerosol-water and carbon cycles, potentially leading to discovery of new couplings that may be missing in current models.

Surface and remote sensing meteorological measurements

The ARM surface meteorological instrumentation provides 1-minute statistics of surface wind speed, wind direction, air temperature, RH, barometric pressure, and rain-rate. These data are employed to understand the basic atmospheric conditions near the surface and are crucial for modeling studies. Four times per day, radiosondes acquire profiles of temperature, humidity, and horizontal winds providing the basic data to understand atmospheric conditions. These profiles are also required for studies that make use of cloud-resolving models. The frequency of the soundings will increase to six times per day during the intensive operating periods to fully track daily cycles of the local atmosphere.

3.3.2 AAF G-1 Measurements

The AAF G-1 platform will be deployed for in situ measurements of trace gas and aerosol properties. A fast integrated mobility spectrometer (FIMS) (Kulkarni and Wang 2006a, 2006b) and ultra-high sensitivity aerosol spectrometer measure the aerosol size distribution at a time resolution of 1 Hz. A particle-into-liquid sampler system and an aerosol mass spectrometer (AMS) provide particle chemical composition. CCN activity is measured at multiple supersaturations. A suite of instruments, including nephelometer, aethalometer, photo- acoustic soot and aerosol sensor (PASS-3; 400, 532, 780 nm), single-particle soot photometer (SP2) humidgraph, and MFRSR characterize aerosol optical properties, including scattering and absorption coefficients, single-scattering albedo, f(RH), and AOD. The counter-flow virtual- impact inlet (e.g., CHAPS and CALWATER campaigns) will be deployed to allow analysis of the composition of droplet residuals, thus helping to understand chemistry and aerosol processing inside of the clouds. Trace gas measurements include CO, CO_2, SO_2, NO, NO_2, NO_y, and O_3; VOCs are quantified by PTR-MS. CO, SO_2, and the ratio CH_3CN/CO are tracers of urban, power plant, and biomass burning, respectively. Ratios of compounds that react at different rates such as NO_x/NO_y and benzene/toluene serve as photochemical clocks providing the exposure of emissions to OH radical. Information on atmospheric processing of isoprene is obtained by the product/parent ratio (methyl vinyl ketone + methacrolein)/isoprene.

The G-1 will be used in vertical profiles to an altitude of 5 to 6 km to determine changes to gases and particles within the detrainment levels of shallow cumulus clouds, to investigate properties of polluted layers, and to characterize cloud dynamics, thermodynamics, and microphysics. Two types of flight patterns out of the Manaus airport will be used. In the first, the plume will be crisscrossed at multiple downwind distances so that evolution of properties along the plume can be determined. The Manaus plume is well-defined because of persistent easterly winds. An upwind transect as well as continuations of transects beyond plume boundaries will yield a direct comparison between pristine and polluted air masses. In the second type of flight pattern, the aircraft will fly along a gradient downwind of Manaus to capture the spatial extent of the plume.

3.4 Science

ALC Objective—The interactions in the tropics of an urban pollution plume with BVOCs, especially the impact on the production of secondary organic aerosol (SOA), the formation of new particles, and biogenic emissions of aerosols and their precursors.

Detailed characterization of the aerosols during both wet and dry seasons will be carried out to understand the governing processes of the aerosol life cycle in Amazonia. The concept of an aerosol life cycle begins with direct emissions of primary particles or alternatively of gaseous precursors that undergo secondary chemical reactions in the atmosphere to form low-volatility particle-phase products. Particles change size and composition during their lifetimes by coagulation, condensation of additional material, cycling through condensation-evaporation processes in clouds, and heterogeneous chemical reactions. Particles are removed by dry and wet deposition processes or advection or convection out of a region of interest. In the atmosphere, particles scatter and absorb solar radiation influencing the energy budget, particles take up water to serve as CCN influencing the cloud life cycle, and particles serve as surfaces and containers for heterogeneous chemistry that can influence the atmospheric oxidant cycle and hence the production of pollution such as ozone as well as the formation of additional particle-phase material. Understanding these complex interactions, including their unique features in the Amazon Basin, (Martin et al. 2010) requires combining observations and models on a variety of scales. The ARM deployment in the Amazon Basin, along with aircraft measurements and existing measurements, will provide a rich data set for use in analyses and models.

Within the plume core, aerosol concentrations are strongly enhanced, with number concentrations reaching 30,000 cm^{-3} compared to background conditions of 300 cm^{-3} (Figures 3 and 4). The particle light-scattering coefficients increased with plume age, suggesting particle growth by condensation of soluble organic or inorganic species. A large part of this additional, aged material is believed to be tied to the production of SOA. Chen et al. (2009) making measurements in February–March 2008 north of Manaus (as part of the Amazonian Aerosol Characterization Experiment [AMAZE-08] [Martin et al. 2010]) established the dominance of secondary organic material to the submicron particle mass concentration for pristine conditions of the wet season. SOA production in the Amazon Basin is facilitated by a high burden of biogenic isoprene from the background rain forest atmosphere and high concentrations of OH radical in the humid, irradiated tropics. How the natural mechanisms are affected by the outflow from a tropical megacity is an outstanding scientific challenge that we intend to address with the data set resulting from the ARM deployment.

Kleinman et al. (2008, 2009) demonstrated successful approaches for quantifying SOA production in a region dominated by an urban center (Mexico City). Manaus presents an interesting contrast to Mexico City because of the importance of biogenic aerosol precursors downwind of the urban area. Several pieces of information will be brought together to quantify urban-biogenic interactions. Aerosol yield normalized to CO will be compared with other urban locations (de Gouw, et al. 2005; Kleinman et al. 2008) at a similar photochemical age to see if organic aerosol production is appreciably enhanced. AMS mass spectra taken aboard the G-1 will be compared with those measured at the surface site (in and out of the Manaus plume), at other urban locations, and under controlled laboratory conditions, looking for similarities and differences using multivariate statistical methods that can be used to apportion the organic aerosol measured on the G-1 to urban and forest sources. The high-resolution PTR-MS at the surface site, capable of distinguishing isobaric compounds, will provide insights into oxidized aerosol precursors, in and out of the Manaus plume.

A secondary site (T2 in Figure 2) in the proximity of Iranduba, Amazonas, is being developed as part of GOAMAZON. This site is located just across the river downwind of Manaus. The purpose of this site is to provide initial measurements of trace gas species and aerosol particle physics and chemistry at a time zero point. These species arrive 2 to 6 hours later at the principal site, T3, near Manacapuru. In this way, transformations, such as the loss of NO_x and the corresponding build-up of O_3 and SOA particles, can be quantified and subsequently understood. The Iranduba site will house one AMF container throughout the deployment as well as instruments of 6 to 8 additional investigators during the intensive operating periods.

ALC Objective—Influence of anthropogenic activities in the tropics on aerosol microphysical, optical, CCN, and IN properties.

Background concentrations of aerosol particles and CCN over the Amazon are more than 10 times lower than background conditions of polluted continental regions (Martin et al. 2010). The Amazonian concentrations are increased, however, by two orders of magnitude when influenced by episodic biomass burning and by an order of magnitude in the plume of chronic pollution outflow from Manaus. The large changes in aerosol concentrations and properties have important consequences on boundary-layer stability, cloud microphysical properties, and precipitation dynamics. In addition, biogenic particles can be good CCN and IN (Pöschl et al. 2010), and these biogenic particles can interact with the abundant convective clouds and can possibly lead to very different cloud properties, cloud radiative forcing, precipitation, and possibly even regional circulation.

Many aerosol measurements have been carried out during short periods of intensive campaigns in the Amazon Basin over the past 20 years. There have been many more recent advances, however, in instrumentation, as included in the ARM Facility. These improvements include capabilities for characterizing aerosol microphysics, chemistry, optical properties, and CCN activity (e.g., FIMS, HR-ToF-AMS, SP2, PASS-3, PASS-UV, and size-resolved CCN counters). In particular, aerosol light scattering and absorption measurements are now available at ultraviolet (UV) wavelengths and are especially important for the investigation of potential photochemical reactions. The optical properties of aged carbonaceous particles can be altered significantly by both chemical and microphysical transformation (e.g., coating) upon aging, and there is emerging evidence that aged organic aerosols can have large absorption in the UV and can modify the photochemistry and radiation budget (Flowers et al. 2010). The ARM deployment of these instruments will provide a comprehensive data set to examine the impact of anthropogenic activities on aerosol properties, including an evaluation of variability on daily, seasonal, and annual cycles as well as a series of closure studies on aerosol optical and CCN properties. The results from these studies will improve the simulation in global models of aerosol radiative properties, photochemical transformation, and cloud microphysics.

CLC Objective— Role of the daily transition of convection from shallow to deep, including the effects of landscape heterogeneity (i.e., the Manaus urban area as well as the 10-km scale of the nearby river widths) on the evolution and dynamics of convective cloud systems, with comparison and understanding between tropical and other ARM environments.

The concept of cloud life cycle encompasses a complex and interlocking set of physical processes. Cloud growth and organization are linked tightly to surface fluxes of radiation, moisture, and heat and to atmospheric profiles of temperature, humidity, and wind. In the Amazon Basin, these factors generally interact to lead to shallow cumulus clouds early in the day (Koren et al. 2004) and strongly precipitating convective clouds that reach well into the upper troposphere later in the day (Hartmann 1994). Changes in land cover can impact convective precipitation as a consequence of changes in the sensible and latent heat fluxes on the availability of moisture and on the CAPE (Pielke et al. 2001, 2007). In addition, surface heterogeneity, such as complex topography, rivers, and urban areas, induces local circulations at several scales and can trigger the formation of convective clouds as well as alter their spatial patterns (Shephard 2005; Zhang et al. 2010). The intrinsic non-linearity of these processes and their complex feedbacks are challenging intellectual problems in any region, and more so in the global climatically important region of the Amazon Basin. These processes (i.e., the daily cycle of convection and sub-grid scale land surface forcings) are also poorly captured in global climate models.

Data from the ARM deployment in the Basin will be used to explore the daily cycle of continental tropical convection (particularly the growth from non-precipitating shallow to deep precipitating convection), the role of landscape heterogeneity (such as the urban area of Manaus or km-scale river widths of Rio Negro and Rio Soliemões), the relationship of mesoscale dynamics to cloud life cycle, and the influence of CCN microphysical properties and aerosol radiative heating profiles on cloud development and growth. The scanning, dual-wavelength capabilities of the new AMF radar systems enhance the ability to retrieve cloud microphysical properties (e.g., liquid water content, droplet size, cloud fraction, and cloud base [Huang et al. 2009]) and to observe in-cloud dynamics and cloud (Kollias et al. 2007). The observations can be statistically related to large-scale dynamics and the background thermodynamic atmospheric state observed by AMF soundings and other profiling instruments. Doppler spectra of the cloud radar will allow for additional microphysical and dynamical insights and to advance the development of new retrieval methods. There is significant benefit in using spectral-based techniques to address data quality and insect identification (Luke et al. 2008), cloud-to-drizzle transitions in mixed-phase regions (Luke et al. 2010), and joint dynamic/microphysical retrievals of droplet size distributions and vertical air motions (Giangrande et al. 2010).

Another primary motivation for the ARM deployment in the Amazon Basin is to collect an observational data set that can be compared with data sets collected at other ARM sites, with the goal of synthesizing a unified understanding of cloud life cycle processes based on a multi-site data set. The present collection of ARM data sets has no information from any tropical rain forest site such as the Amazon Basin, which is a critical absence from the perspective of observational and model comparisons. Due to its longitudinal extent, the Amazon Basin presents distinct regions of convective development (Kousky and Kayano 1981; Monlion 1987; Cohen 1989). Cloud development in the eastern sector is linked to sea-breeze circulations and the influence of the ITCZ. Cloud development in the western region tends to produce mesoscale convective systems and is influenced by the South Atlantic convergence zone. Modulation by the annual cycle of water vapor poses another constraint on the development of convection (Petersen and Rutledge 2001; Laurent et al. 2002). Shallow convection is observed more frequently during the wet compared to the dry season (Rickenbach et al. 2002; Williams et al. 2002; Rickenback 2004) and, correspondingly, deep convection occurs more frequently in the dry season. Surface coverage, such as represented between forested and deforested areas, as well as topography, also affects the development of deep convection (Fu et al. 1999; Durieux et al. 2003). The relative importance of each influence and the interactions among them vary in importance depending on prevailing regimes of cloud development. The region around Manaus provides an excellent laboratory to study many of these convective types and environmental forcings due to its central location in the Basin.

CLC Objective—Evolution of storms over tropical rain forest from (1) severe in the dry season to (2) large but less intense in the wet season.

The timing of the wet season onset dictates, in part, how much rain the Amazon will receive each year, impacting agriculture, hydroelectric power generation, and local ecosystems. Wet season onset is highly variable, and the exact mechanisms of onset are not agreed upon. Furthermore, tropical heat sources associated with convective cloud systems can trigger circulation anomalies far away from the source region through atmospheric teleconnections. In particular, convective heating associated with Amazonian rainfall acts as a major driver of the atmospheric circulation in the tropical Atlantic region. A global climate model dry bias in Amazonian rainfall can result in weaker trade winds over the equatorial Atlantic that in turn impact the zonal sea surface temperature gradient across the basin. Thus, a realistic representation of Amazonian convection and its associated heating and rainfall is an essential requirement for global climate models to be able to simulate the tropical climate accurately.

Changes in convection features from the dry to the wet season in the Amazon Basin have been investigated by several approaches. Satellite observations show differences in intensity and vertical development of convection and the effects of deforestation on rainfall in the different seasons of Amazonia (Marchand et al. 2009; Evans et al. 2010). Seasonal variations in ground-based radar and lightning observations can also be linked to variations in biomass-burning emissions and aerosols (Williams et al. 2002). In addition, interactions between the atmosphere and land surface undergo seasonal changes that influence convection in the Amazon Basin (Fu et al. 1999). The interactions among all of these processes, however, remain poorly understood.

In this regard, one of our primary goals is to understand how large-scale atmospheric properties in the two seasons drive cloud life cycle and, given similar large-scale drivers, how changes in aerosol and surface properties affect the cycle. A methodology has been developed for an atmospheric state classification of ARM locations (Fu et al. 1999; Evans et al. 2010). Members of each state have similar large-scale meteorological fields and cloud occurrence profiles. The large-scale fields, upon which the classification is built, are derived from numerical weather prediction. The cloud occurrence profiles, which determine state robustness and uniqueness, are measured by radar. Compositing observations within each state results in probability distributions of cloud properties such as liquid water path and cloud radiative forcing at the surface. Retrieved cloud microphysical properties are then composited by state to link variations in cloud properties with the variations in large-scale forcing. The combination of large-scale states and associated statistical distributions of cloud properties provides a unique framework for modeling studies of cloud life cycle using cloud-resolving models. These data are critical for the evaluation and further improvement of the turbulence and convection parameterizations that are presently implemented in large-scale models.

CAPI Objective—Aerosol effects on convective clouds and precipitation under different aerosol and synoptic regimes, including the roles of aerosols in changing regional climate and atmospheric circulation and the effects of aerosols on tropical precipitation under clean and polluted situations.

Comparison among modeling results reveals that global climate models (GCM) simulations are highly sensitive to changes in cloud properties such as droplet concentration, droplet effective radius, the shape of the distribution, and liquid water content (Dandin et al. 1997; Liu and Daum 2002; Rotstayn and Liu 2003). Cloud microphysical regimes are typically most sensitive to shifts of increasing CCN concentration from a few hundred up to 1000 cm^{-3}, above which there is often saturation with respect to the effects of increasing particle concentration. For pristine conditions in the wet season, total particle concentrations average around 300 cm^{-3} in the Basin, which can be compared to contemporary background continental concentrations in the Northern Hemisphere of 2,000 to 3,000 cm^{-3}. Economic development in the Amazon Basin can therefore be anticipated to shift background particle concentrations to values much higher than 300 cm^{-3}. Within the Basin, both numerical simulations (Martins et al. 2009) and empirical studies (Lin et al. 2006) show that the sensitivity of precipitation to cloud microphysical properties is highly complex. Depending on environmental conditions, higher CCN concentrations can either increase or decrease total precipitation, as well as affecting the timing of precipitation in cloud systems. For instance, during the dry-to-wet season transition in the Amazon Basin, an increase in CCN concentration from biomass-burning aerosols leads to a decrease in the cloud droplet spectral dispersion, with direct consequences on the cloud reflectivity. In contrast, this behavior is not observed for data sets from previous ARM field campaigns. We expect that the ARM deployment in the Amazon will provide new insights and an unprecedented data set that can be used to improve cloud-aerosol-precipitation parameterizations for that region. More generally, the ARM deployment in the Amazon Basin presents a unique opportunity for exploration of cloud-aerosol-precipitation interactions due to the expected wide range of aerosol concentrations and chemistry and the strong coupling between the vegetative surface, boundary layer, and convective initiation. This knowledge can be critically important for understanding of tropical precipitation.

Convective clouds play crucial roles in circulation and the hydrological cycle. Many factors such as RH and wind shear (Fan et al. 2009, Khain and Lynn 2009) could explain the effects of aerosols on convection and precipitation (Martins et al. 2009, Khain and Lynn 2009). Aerosol effects on clouds and precipitation under different aerosol and atmospheric conditions can be systematically examined using model simulations combined with ARM observations. Process-oriented simulations using cloud-resolving models with size-resolved aerosol and cloud microphysics will improve our understanding of cloud-aerosol interactions (Khain and Lynn 2009). Expected aerosol regimes include pristine continental aerosols (biogenic sources), biomass-burning aerosols (high BC/soot), African dust (favored when the ITCZ is south of the equator), and urban plumes (high sulfate content) from Manaus. Synoptic regimes, such as monsoon active and break periods, can be identified using statistical and clustering approaches.

A longstanding challenge in convection is to explain the contrast in intensity between tropical land and ocean. Convective regions over the oceans tend to have greater cumulative precipitation. There is greater cloud-to-ground lightning activity, however, for continental convection, and this greater activity is often taken as a proxy for convective intensity (Christian et al. 2003). Correlations between aerosol concentration and lightning activity lead to a hypothesis of a causative effect of aerosols on lightning and, by extension, convection (Naccarato et al. 2003; Steiger and Orvile 2003; Farias et al. 2009; Kar et al. 2009). Tropical Rainfall Measuring Mission radar reflectivity at high altitude is an indicator of cloud ice abundance at these altitudes and also exhibits a land-ocean contrast (Zipser et al. 2006). Albrecht et al. (2011) show that during the wet season there is a clear sensitivity of cloud electrification to aerosol content. By comparison, in the dry season there is no response relationship between cloud intensity and electrification features, suggesting an aerosol overload during these periods. The detailed observations of aerosols and CCN from the ARM measurements, collocated with remotely sensed 3D structure of clouds (i.e., radars and satellites), will allow development of new and more accurate understanding. The ultimate intended result is to understand and better quantify aerosol influences on convection.

CAPI Objective—Data-driven improvement and evaluation of parameterizations of cloud- aerosol interactions, as used in the climate models.

At present, global and regional models with parameterized convective schemes either simplify or entirely neglect cloud microphysics and associated aerosol effects. This approach can be an important source of bias when comparing to satellite observations, and it also neglects important feedbacks when predicting future climate change. Preliminary development and tests of convective parameterization including microphysics show that one difficulty in evaluating schemes is the lack of observational data in active convection regions. In this regard, the ARM deployment will lead to a crucial and new data set. These data, in conjunction with those of aerosol properties and effects, will provide new possibilities for advancing our understanding and quantification of convection and thereby better represent it in models. For example, parameterizations of shallow cumulus clouds in the large-scale models do not include aerosol effects. Barahona and Nenes (Barahona 2007) developed an extension of an aerosol activation scheme that accounts for the dependence on entrainment. This scheme can be validated and modified with the measurements of entrainment in the boundary layer and shallow cumulus clouds to improve the representation of shallow cumulus clouds in the large-scale models. The data set will be used to evaluate the performance of existing parameterizations and subsequently to improve them with respect to capturing the variability of convection and precipitation.

4.0 Relevancy to Long-Term Goals of the U.S. Department of Energy Office of Biological and Environmental Research

BER Climate Change Research Long-Term Measure: *Deliver improved scientific data and models about the potential response of the Earth's climate and terrestrial biosphere to increased greenhouse gas levels for policy makers to determine safe levels of greenhouse gases in the atmosphere*

The research to be conducted during this campaign squarely fits the mission of Climate and Environmental Sciences Division of the Office of Biological and Environmental Research (sidebar). The hydrologic cycle of the Amazon Basin is one of the primary heat engines of the tropics. GCMs, however, do not accurately simulate convective clouds and their associated precipitation and radiative effects over tropical land regions. The simulations can only be improved by observational studies that provide the necessary data for model formulation and validation. For these reasons, the 2007 ARM planning document conferred a priority status to a deployment in the Amazon Basin (ARM 2007); the relevant portion of that document is reproduced below. Moreover, the ASR Science and Program Plan of January 2010 states that: "The primary objective of climate research... is to develop understanding of the processes that control climate change and to represent this understanding in models (GCMs)... to represent the full range of climatically relevant physical processes... The ASR program will use the new ARM Facility observational tools to characterize and quantify these processes so that they can be better represented in numerical models..." Our approach to the scientific challenge is to deploy the ARM Facility and to divide the complex research into components that span the entire set of important processes: the Aerosol Life Cycle, the Cloud Life Cycle, and Cloud-Aerosol-Precipitation Interactions. These observations will lead to model formulations of the interactive physical, chemical, and biological processes that regulate the total earth system as well as the changes that are occurring in the earth system and the environment and how these changes are influenced by human actions.

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BER hosted a workshop on October 31-November 1, 2007, to assess how the ACRF might expand and enhance its observational network to best advance the science of cloud radiative forcing processes relevant to improving global climate models. A group of 34 scientific experts were invited to participate in the workshop, and all have provided their input to this final report. Expertise at the workshop encompassed all research elements of the Climate Change Science Program, including remote sensing, process studies, cloud system modeling, general circulation modeling, and decision support. During the workshop, breakout groups focused on the following areas: fixed sites, mobile facilities, aerial vehicles, and data products. The panel was asked to consider each area and identify priorities for an ACRF expansion that would enable observations of key atmospheric processes influencing radiative transfer in the atmosphere: clouds, aerosols, and water vapor properties. Because of the importance of carbon dioxide on radiative forcing and the broader importance of carbon to U.S. Department of Energy's mission, carbon cycle measurements also were considered. The ACRF has an opportunity to play a critical role in measuring carbon dioxide and other gases important both to the climate and energy policy. Enhancement of ACRF's capability would enhance U.S. Department of Energy's ability to play an important role in this country's energy decisions.

> The Amazon rain forest, the world's largest, is an ideal site to study deep tropical convective clouds over land, which have profound effects on global circulation yet are poorly simulated in climate models. The Amazon rain forest experiences tropical deep convective clouds, which are important for driving large-scale circulation of the atmosphere and exert a large control on the radiation budget. Climate models have great difficulty in simulating deep convective clouds and their radiative effects. The ACRF has recognized this as a serious problem and invested heavily in observations of ocean convection. However, the deep convection over land behaves differently than over the ocean. With the exception of the 2006 mobile facility campaign to Niger, the ACRF has not had the ability to observe deep convection over land. An Amazon rain forest site would provide an unprecedented opportunity to study a large, perennially cloudy climatic region for which there is little in situ data.
>
> Tropical deep convective clouds are important for driving the large-scale circulation of the atmosphere and exert a large control on the radiation budget. Climate models have great difficulty in simulating deep convective clouds and their radiative effects. The ACRF has invested heavily in observations of ocean convection; however, with the exception of the 2006 Niamey Niger campaign, it has failed to observe deep convection over land. Deep convection over land behaves differently than over ocean. For example, a strong diurnal cycle to deep convection with shallow convection clouds occurs early in the morning that grows into deeper clouds and precipitates by early evening. The role of downdraft driven cold pools in triggering new convection is more important over land and could be studied by horizontal scanning or sampling. The triggering of new convection by cold pools is not represented in current climate models, which, in part, explains the difficulties of the models in simulating convective precipitation over tropical continents. This diurnal cycle of convective clouds is simulated extremely poorly by climate models, and the models, in general, do a poor job of simulating the deep convection in the Amazon. A study of convective clouds in the Amazon would have other benefits. Cumulus clouds have 3-D structures that cause significant 3-D radiative transfer effects. These effects could be studied by a scanning cloud and precipitation radar. Also, the large amount of biomass burning in the Amazon provides an opportunity to study the influence of biomass-burning aerosol on convective clouds and the precipitation that results.

The details of the GOAMAZON campaign carry the ideas introduced in the 2007 ARM Planning Document into a plan of action for the Amazon Basin.

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