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Introduction: Observations and Modeling of the Green Ocean Amazon (GoAmazon2014/5)

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Abstract. The Observations and Modeling of the Green Ocean Amazon (GoAmazon2014/5) Experiment was carried out in the environs of Manaus, Brazil, in the central region of the Amazon basin for 2 years from 1 January 2014 through 31 December 2015. The experiment focused on the complex interactions among vegetation, atmospheric chemistry, and aerosol production on the one hand and their connections to aerosols, clouds, and precipitation on the other. The objective was to understand and quantify these linked processes, first under natural conditions to obtain a baseline and second when altered by the effects of human activities. To this end, the pollution plume from the Manaus metropolis, superimposed on the background conditions of the central Amazon basin, served as a natural laboratory. The present paper, as the introduction to the special issue of GoAmazon2014/5, presents the context and motivation of the GoAmazon2014/5 Experiment. The nine research sites, including the characteristics and instrumentation of each site, are presented. The sites range from time point zero (T0) upwind of the pollution, to T1 in the midst of the pollution, to T2 just downwind of the pollution, to T3 furthest downwind of the pollution (70 km). In addition to the ground sites, a low-altitude G-159 Gulfstream I (G-1) observed the atmospheric boundary layer and low clouds, and a high-altitude Gulfstream G550 (HALO) operated in the free troposphere. During the 2-year experiment, two Intensive Operating Periods (IOP1 and IOP2) also took place that included additional specialized research instrumentation at the ground sites as well as flights of the two aircraft. GoAmazon2014/5 IOP1 was carried out from 1 February to 31 March 2014 in the wet season. GoAmazon2014/5 IOP2 was conducted from 15 August to 15 October 2014 in the dry season. The G-1 aircraft flew during both IOP1 and IOP2, and the HALO aircraft flew during IOP2. In the context of the Amazon basin, the two IOPs also correspond to the clean and biomass burning seasons, respectively. The Manaus plume is

present year-round, and it is transported by prevailing northeasterly and easterly winds in the wet and dry seasons, respectively. This introduction also organizes information relevant to many papers in the special issue. Information is provided on the vehicle fleet, power plants, and industrial activities of Manaus. The mesoscale and synoptic meteorologies relevant to the two IOPs are presented. Regional and long-range transport of emissions during the two IOPs is discussed based on satellite observations across South America and Africa. Fire locations throughout the airshed are detailed. In conjunction with the context and motivation of GoAmazon2014/5 as presented in this introduction, research articles including thematic overview articles are anticipated in this special issue to describe the detailed results and findings of the GoAmazon2014/5 Experiment.

1 Introduction

The Amazon basin functions as a giant biogeochemical reactor to influence regional climate, with both exports and imports of climate-relevant quantities to and from other regions of Earth (Keller et al., 2009). Biogenic emissions of gases and aerosol particles, in combination with high absolute humidity and strong solar radiation, maintain chemical and physical cycles that sustain the aerosol particle population, the cloud field, and the hydrological cycle of the basin (Salati and Vose, 1984; Lelieveld et al., 2008; Martin et al., 2010a). The biology of the forest has a critical role in regulating atmospheric composition and climate over the region (Pöschl et al., 2010; Artaxo et al., 2013).

Any accurate model of the Earth system must succeed in a good description of tropical regions and in particular the Amazon basin, both in its natural state as well as when perturbed by regional and global human activities. The hydrologic cycle of the basin is one of the primary heat engines of global circulation (Nobre et al., 2009). Models of future climate accounting for human activities have suggested a possible drying, especially in the eastern regions (Nobre et al., 1991; Boisier et al., 2015). Significant changes in the amounts and patterns of precipitation in the basin can have far-reaching consequences because of the nonlinear, multiscale interactions that affect clouds, precipitation, and atmospheric circulation, leading for example to possible modifications in the annual migration of the Intertropical Convergence Zone (ITCZ) (Wang and Fu, 2007). The hydrological cycle in the Amazon basin has changed over the past 2 decades, but the causes are not fully identified and understood (Davidson et al., 2012; Gloor et al., 2013).

At present, many aspects of continental tropical deep convection, such as the daily cycle, are poorly understood and inaccurately modeled (Betts, 2002; Dai, 2006). Cloud properties simulated in climate models have high sensitivity to changes in droplet concentration, droplet size distribution, and liquid water content (Dandin et al., 1997; Liu and Daum, 2002; Rotstayn and Liu, 2003). Cloud microphysical properties, cloud cover, precipitation, lightning, and regional climate over the Amazon basin can be significantly affected by aerosol particles (Andreae et al., 2004; Lin et al., 2006; Rosenfeld et al., 2008, 2014; Martins and Silva Dias, 2009; Altaratz et al., 2010; Koren et al., 2012; Gonçalves et al., 2015). For background conditions in the basin, aerosol particle concentrations at Earth's surface number several hundred per cubic centimeter in the wet season (Andreae, 2007; Martin et al., 2010a). By comparison, background concentrations increase by an order of magnitude in the dry season because of widespread biomass burning (Martin et al., 2010a; Artaxo et al., 2013). Shifts in the concentrations of cloud condensation nuclei (CCN) from a few hundred up to one thousand cm^{-3} can strongly affect cloud microphysics (McFiggans et al., 2006; Reutter et al., 2009; Koren et al., 2014). Future expansion of cities and population throughout the basin can be expected to alter particle concentrations, and changes in cloud properties can be expected.

The Observations and Modeling of the Green Ocean Amazon (GoAmazon2014/5) Experiment was motivated by the need to gain a better understanding of aerosol–cloud–precipitation interactions and processes over the largest tropical rain forest on Earth. GoAmazon2014/5 sought to advance the goal of understanding how the chemical, hydrological, energy, and ecosystem cycles of the basin function today and how they might evolve under scenarios of future stress and pollution. The experiment assembled a network of observation sites to intercept both background air of the Amazon basin and pollution from the Manaus metropolis in the central region of Brazil (Fig. 1). Manaus, situated at the confluence of the Black River (Rio Negro) with the Solimões river, which together form the Amazon river, is an isolated urban region of over 2 million people (IBGE, 2015). The city has been a free trade zone since 1967 to encourage economic development, leading to the presence today of hundreds of local and global manufacturing companies. Most of the manufactured products are shipped thousands of kilometers by boat to the consumers in the southern states of Brazil. Outside of the city there is natural forest for over 1000 km in every direction. In this context, the airshed intersecting the GoAmazon2014/5 research sites downwind of Manaus oscillated between (i) one of the most natural continental sites on Earth and (ii) one characterized by the interactions of the pollution emissions of a tropical metropolis with the natural emissions of the rain forest. GoAmazon2014/5 was designed to explore cloud–aerosol–precipitation interactions over a tropical rain forest for which contrasting conditions of clean compared to polluted conditions were clearly and regularly delineated. The most heavily instrumented research site ("T3") of GoAmazon2014/5 was 70 km downwind of Manaus. Under the day-to-day variability in the meteorology, both clean and polluted air masses, mixed to variable degrees, arrived at T3. The pollution plume from Manaus

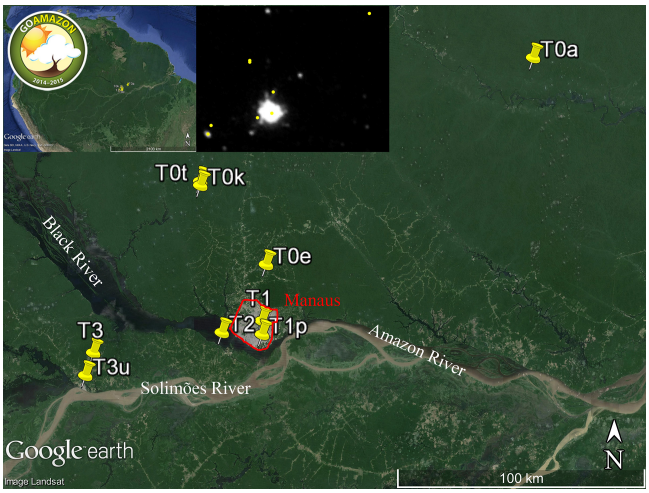

Figure 1. Locations of GoAmazon2014/5 research sites in the environs of the city of Manaus (−3.1°, −60.0°) in the state of Amazonas in the country of Brazil. Table 1 provides further information on the labeled sites. Manaus is located at the confluence of the Black River (Rio Negro) with the Solimões river, which together form the Amazon river. The map rectangle is drawn from (−3.66°, −60.92°) in the southwest to (−1.91°, −58.58°) in the northeast. The left inset shows the location of the experimental domain within South America. For prevailing winds, Manaus is on the order of 1200 (IOP1) to 1600 km (IOP2) from the South Atlantic. The right inset shows nighttime illumination in the environs of the city of Manaus for the year 2010. Figure S1 in the Supplement provides an expanded view of the regional nighttime illumination.

thus served as a laboratory for investigating perturbations to natural processes.

The regular synoptic changes between the wet and dry seasons offered an additional important scientific contrast. In the wet season, the Manaus plume aside, the Amazon basin is one of the cleanest continental regions on Earth (Andreae, 2007; Martin et al., 2010a). The particle population is in dynamic balance with the ecosystem (which produces them directly and indirectly) and the hydrologic cycle (which removes them). In the dry season, biomass burning is prevalent throughout the basin. The most intense burning and atmospheric perturbations take place at the southern and eastern edges of the vast forest. Local fire emissions as well as basin-wide background pollution also affect the Manaus region during this time period. Wet deposition also decreases during the dry season. As a result of these spatial and temporal differences, cloud–aerosol–precipitation interactions are significantly different between the two seasons (Andreae et al., 2004; Feingold et al., 2005; Artaxo et al., 2013).

The original use of the expression "green ocean" was related to the similarities in aerosol particle concentrations and cloud microphysics between the Amazon basin and remote oceanic regions during clean periods of the wet season (Williams et al., 2002). The expression, in reference to Green Ocean Amazon ("GoAmazon" for short) or "Observations and Modeling of the Green Ocean Amazon" (long version), has acquired a more general meaning to refer to the energy, water, and chemical cycles over the vast, mostly green-colored Amazon rain forest.

The anticipated publications for this special issue about GoAmazon2014/5 can be broadly categorized as related to (1) the aerosol life cycle, (2) the cloud life cycle, (3) cloud–aerosol–precipitation interactions, and (4) terrestrial ecosystems. The publications can be largely grouped as focusing on one or more of the following topics:

1. (a) perturbations of atmospheric composition and atmospheric oxidant cycle due to human activities in tropical continental regions, including interactions with biogenically produced volatile organic compounds; (b) associated influences on the number concentration, the mass concentration, the size distribution, and the optical, cloud-forming, and ice-nucleating properties of aerosol particles.

2. (a) the evolution of storms over tropical rain forests in the dry season (i.e., intense and relatively isolated storms) compared to the wet season (i.e., less intense but more widespread storms); (b) the daily transition in cloud development from shallow to deep convection, with comparison and understanding between tropical and other environments.

3. (a) effects of aerosol particles on clouds, precipitation, and lightning across a range of clean and polluted conditions; (b) the connections to aerosol direct, semi-direct, and indirect radiative effects.

4. (a) identities, amounts, and seasonal patterns of emissions of biogenic volatile organic compounds (BVOCs); (b) the controls on the fraction of assimilated carbon that is allocated to the production and emission of BVOCs.

This introduction to the special issue presents the objectives and motivation of the GoAmazon2014/5 experiment. It also provides a description of the field sites, the environmental conditions during the two Intensive Operating Periods (IOPs), and the context of the Manaus metropolis in the center of the largest rain forest on Earth.

2 Experimental design

The GoAmazon2014/5 Experiment took place in the environs of Manaus in the central region of the Amazon basin. Manaus, a city presently of over 2 million people and expanding rapidly, is an isolated urban region within the surrounding rain forest (Fig. 1). It is large enough to have an urban island heat effect of up to 3 °C relative to the surrounding forest (de Souza and dos Santos Alvalá, 2014).

Several important geographic features include the confluence of two large rivers, an urban landscape, and undulating land relief (50 to 200 m) that affects its daily meteorological cycles (dos Santos et al., 2014; Tanaka et al., 2014). GoAmazon2014/5 measurements were made from 1 January 2014 through 31 December 2015. Two Intensive Operating Periods, including aircraft and additional personnel and instrumentation at the ground sites, took place in the wet and dry seasons of 2014. GoAmazon2014/5 IOP1 took place from 1 February to 31 March 2014, and GoAmazon2014/5 IOP2 was active from 15 August to 15 October 2014. There were nine ground stations in and around Manaus as well as coordinated flights by research aircraft. The rationale for the use of the multiple platforms was to characterize the Amazonian atmosphere under varying degrees of urban influence and photochemical processing.

2.1 Site and aircraft descriptions

The locations of Manaus and the nine research sites are shown in Fig. 1. The latitude–longitude coordinates of each site are listed in Table 1. The sites range from time points zero (T0) upwind of the pollution, through time points one (T1) and two (T2) closer to the pollution sources, to time points three (T3) furthest downwind of the pollution. Instrumentation at each site, including the aircraft, is catalogued in Tables S1 to S13 in the Supplement. The scope and duration of the data sets that were collected by this combined set of instrumentation represents a new milestone for the study of climate and air quality in the Amazon basin.

Site T0a was the Amazonian Tall Tower Observatory (ATTO) (Andreae et al., 2015). Although the site has been active since 2012, the 325 m tall tower (inaugurated in August 2015) had not yet been completed during the IOPs of GoAmazon2014/5. Measurements were instead made from two 80 m towers at the site. Site T0e was located at a branch of the Brazilian Agricultural Research Corporation (EMBRAPA) about 10 km beyond the northern limits of the Manaus metropolitan area (Barbosa et al., 2014). Sites T0k and T0t were situated in the Cuieiras Biological Reserve ("ZF2") that has been a central part of Amazonian ecology and climate studies for over 20 years. In particular, T0k was the tower "K34" that has been the centerpiece of the Large-Scale Biosphere–Atmosphere (LBA) experiment since its construction in 1999 (Araújo et al., 2002). Site T0t was tower "TT34" established for the Amazonian Aerosol Characterization Experiment (AMAZE-08) in 2008 (Martin et al., 2010b). The T0 sites were typically upwind of Manaus so that the pollution plume was not present most of the time. In all cases, however, except possibly for T0a, the local winds did occasionally transport some pollution to these sites (Chen et al., 2015).

Within Manaus, site T1 was a tower in a forested section of the campus of the National Institute of Amazonian Research. Site T1p was located at the military airport at Ponta Pelada in Manaus. Site T2 consisted of a research container placed at a hotel on the western edge of the Black River and just across the river from Manaus (J. Brito, personal communication, 2015). It sampled the fresh Manaus pollution plume across approximately 8 to 11 km of river width depending on the prevailing wind direction. Site T3u was located on the regional campus of Amazonas State University in Manacapuru.

The most comprehensively instrumented site of GoAmazon2014/5 was T3. For 24 months, a suite of containers representing the Atmospheric Radiation Measurement (ARM) Climate Research Facility of the United States Department of Energy operated at T3. This facility included the ARM Mobile Facility One (AMF-1) and the ARM Mobile Aerosol Observing System (MAOS) (Mather and Voyles, 2013). There were four additional containers of instrumentation deployed by university investigators and other scientists during the two IOPs. The T3 site was located 70 km downwind of Manaus, representing several hours of air travel time depending on the daily wind speeds. It was a pasture site of 2.5 km by 2 km situated 2 km to the north of a lightly traveled two-lane road (AM-070) that connects Manaus to Manacapuru. Manacapuru was 10 km downwind of T3 to the southwest.

Two aircraft, a low-flying G-159 Gulfstream I (G-1) (Schmid et al., 2014) that mostly sampled the atmospheric boundary layer and low clouds and a high-flying Gulfstream G550 (HALO) (Wendisch et al., 2016) that mostly observed the free troposphere, collected data during the two IOPs. The flight tracks of HALO appear in Wendisch et al. (2016), constituting 14 research flights, mostly in the mid- and upper troposphere, during IOP2. The domain of flights was across a large part of the Amazon basin. There were two dedicated flights coordinated with the G-1 aircraft, including for instrument comparison. The G-1 carried out 16 flights in IOP1 and 19 flights in IOP2, mostly in the late morning and early afternoon (local time). Figure 2 shows all flight tracks of the G-1. Figures S2 and S3 segregate the tracks by altitude. Other than a few flight missions set up to sample background conditions, the flight tracks shown in Fig. 2 represent a synopsis of the actual location of the Manaus pollution plume on specific days. The flight tracks show that easterly winds carried the plume westward over the rain forest. On a given day, flight plans were filed in the early morning based on boundary layer winds sampled by radiosondes as well as on the forecasted location of the pollution plume. A plume forecast was prepared using the CATT-BRAMS model (Coupled Aerosol and Tracer Transport model to the Brazilian developments on the Regional Atmospheric Modelling System) (Freitas et al., 2009). In some cases, adjustments to the flight plans were made during flight once the instrumentation had identified the actual location of the daily plume.

Table 1. Names and locations of research sites and platforms deployed in GoAmazon2014/5. Other common names, as well as the relative distances and angles from T1 (National Institute of Amazonian Research, INPA), are also listed.

		Location		Position relative to T1			
GoAmazon2014/5 reference	Other reference	Latitude	Longitude	Distance (km)	Direction (0° N)	Description	Reference
T0a	ATTO	−2.1466°	−59.0050°	151.4	45.8°	Forested site upwind of Manaus, 325 m tall tower (inaugurated Aug 2015)	Andreae et al. (2015)
T0e	EMBRAPA	−2.8942°	−59.9718°	22.5	4.3°	Pasture site north of Manaus	Barbosa et al. (2014)
T0k	K34, ZF2	−2.6091°	−60.2093°	59.4	335.5°	Closed canopy, forested site north of Manaus	Araújo et al. (2002)
T0t	TT34, ZF2	−2.5946°	−60.2093°	60.9	336.1°	Broken canopy, forested site north of Manaus	Martin et al. (2010b)
T1	INPA	−3.0972°	−59.9867°	n/a	n/a	On INPA campus in Manaus	
T1p	Ponta Pelada	−3.1461°	−59.9864°	5.4	179.6°	Ponta Pelada Airport (PLL)	
T2	Tiwa Hotel	−3.1392°	−60.1315°	16.8	253.9°	Adjacent to river, just downwind of Manaus; river width of 7.5 to 11.7 km depending on direction of prevailing winds	
T3	MAOS, AMF-1, Fazenda Agropecuária Exata	−3.2133°	−60.5987°	69.4	259.2°	Pasture site downwind of Manaus	Mather et al. (2014)
T3u	UEA	−3.2953°	−60.6282°	74.6	252.9°	On campus of Amazonas State University (UEA) in Manacapuru	
G-1	AAF, G-159 Gulfstream I	n/a	n/a	n/a	n/a		Schmid et al. (2014)
HALO	Gulfstream G550	n/a	n/a	n/a	n/a		Wendisch et al. (2016)

2.2 Climatology

In the middle of the Amazon basin, Manaus is situated in an attractive scientific location because the full range of basin meteorology can be encountered. Cold fronts, which typically occur in the southwest part of the basin (Rondônia), can reach further north and affect the meteorology of the central part of the basin, most often in June and July. Squall lines, which are frequent in the eastern portion of the basin, also penetrate and propagate from the South Atlantic to the middle of the basin (Greco et al., 1990; Cohen et al., 1995; Alcântara et al., 2011), often leading to late night or early morning precipitation in Manaus (Machado et al., 2004). Organized synoptic convective events are most common at the start and the end of the wet season. These events are caused in large part by a monsoon circulation that shifts the ITCZ southward over Manaus and by squall lines that originate near the coast and propagate to the central region of the basin. A consequence of these dual synoptic perturbations is that the number of organized synoptic convective events per month is high in Manaus: around six during March and three during October (Machado et al., 2004).

The cloud cover and rainfall around Manaus is lowest in July and August during the central period of the dry season and highest in February and March in the midst of the wet season. Although seasonal variation in convective available potential energy (CAPE) is small, as is typical for rain forest close to the equator, rainfall in the wet season is more continuous but less intense compared to the dry season. The transition period between dry and wet seasons and the onset of the wet season are the time periods of maximum intensity for convection. Little seasonal variation in CAPE yet large variation in cloud cover and rainfall taken together imply that small perturbations in large-scale circulation in this region can possibly drive dramatic changes in rainfall.

2.3 Air pollution sources in metropolitan Manaus

Major sources of air pollution from Manaus include the vehicle fleet, power plants, and industrial activities, all of which are increasing annually. The population of Manaus grew from 1.5 million in 2004 to 2.0 million in 2014. Measured by percent growth, Manaus was the fastest growing major Brazilian city during this time period (IBGE, 2015). Manaus accounts for 80 % of the economic activity of the state of Amazonas.

In regard to the vehicle fleet, in December 2014 there were 622 675 vehicles registered in Manaus (DENATRAN, 2015). Outside of Manaus, there were an additional 133 088 vehicles in the state of Amazonas. For comparison, 10 years earlier (December 2004), there were 242 893 registered vehicles in Manaus, meaning a 250 % increase in the fleet from 2004 to 2014. In 2014, 255 758 registered vehicles used alcohol or gasoline, 281 811 consumed gasoline only, 54 158 were powered by diesel, and 30 948 employed another fuel or were unclassified. There were 326 806 passenger vehicles,

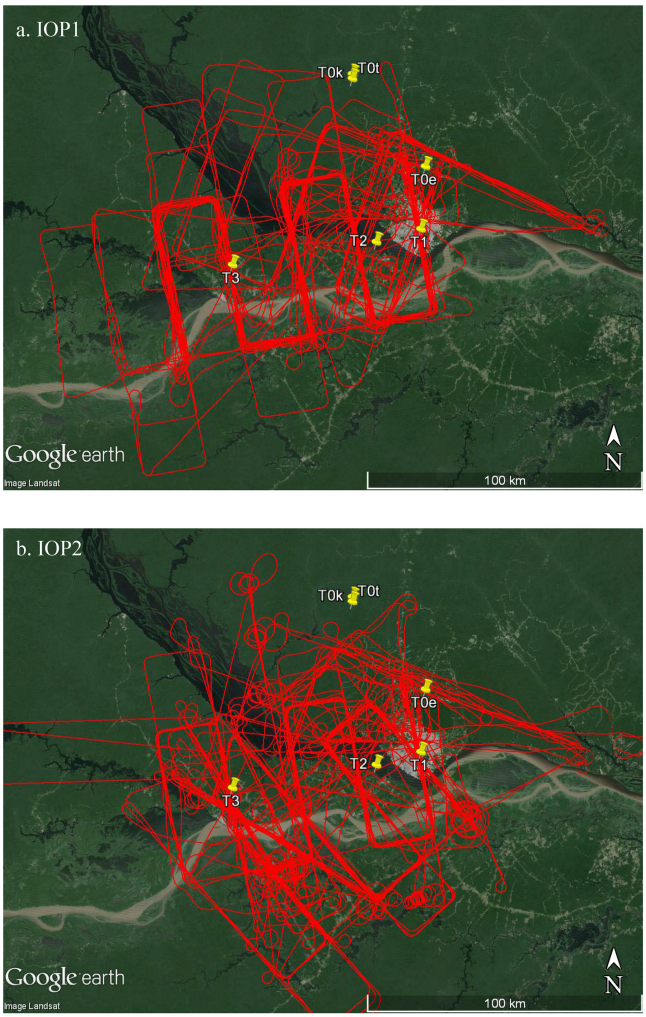

Figure 2. Flight tracks of the G-1 aircraft during **(a)** IOP1 and **(b)** IOP2 for all altitudes. The flight periods were from 22 February to 23 March 2014 in IOP1 and 6 September to 4 October 2014 in IOP2. The flight tracks grouped by altitude appear in Figs. S2 and S3.

150 127 motorcycles, 91 099 pickups, 28 285 trucks, 10 688 buses, and 15 690 vehicles of other types.

Electricity in Manaus is largely produced by the combustion of fossil fuels. In 2013, the power plants consumed 2.5×10^8 kg of fuel oil (providing 14 % of electricity produced), $1.3 \times 10^9\,m^3$ of natural gas (55 %), and 6.1×10^8 L of diesel (31 %) (A. Medeiros, personal communication, 2015). The nominal installed capacity was 1.5 GW for fossil fuel power plants (Eletrobras, 2013). The locations of the plants in the urban region are shown in Fig. S4. The consumption of fossil fuels was complemented by a hydroelectric power plant (250 MW), which has operated in Balbina to the north of the city since 1989. Following the opening in November 2009 of a gas pipeline (661 km) from Urucu to Manaus and passing through Manacapuru, the fuel matrix for electricity production has been shifting from a historical reliance on sulfur-laden fuel oil and diesel to one having an increasing fraction of natural gas.

In addition to Manaus, important but less consequential sources of air pollution include multiple small municipalities along the Amazon river extending hundreds of kilometers to the east all the way to the South Atlantic. Between Manaus and T3, there are dozens of small brick factories (Fig. S5). These factories nearly exclusively use wood to fire the kilns (B. Portela, personal communication, 2015). Site T2 was impacted by these factories when well-known daily patterns of local river breezes transported air masses from the west (direction opposite to Manaus) (G. Cirino, personal communication, 2015) (Silva Dias et al., 2004; Trebs et al., 2012; dos Santos et al., 2014). With respect to T3, although the simulated wind trajectories at times passed near and through the locations of these factories, elevated concentrations of biomass burning tracers such as acetonitrile or levoglucosan were rare for the data sets of IOP1, suggesting that brick factory emissions did not have a significant influence on measurements at T3 most of the time (S. de Sá, personal communication, 2015). With respect to background air entering the Manaus region, the pollution from the small municipalities along the Amazon river as well as eastern coastal cities can become important in the dry season because of prevailing easterly winds during that season. Biomass burning also takes place throughout the basin, especially along the eastern and southern edges of the forest during the dry season, and can be an important source of regional pollution.

In 2001, the pollution plume from Manaus was characterized in transect flights by Kuhn et al. (2010). At that time, the plume consisted of high concentrations of oxides of sulfur, oxides of nitrogen, submicron aerosol particles, and soot, among other pollutants. Ozone was produced by photochemical reactions in the plume (Trebs et al., 2012). The width of the urban plume was 20 to 25 km, on the order of the size of the city itself.

3 Mesoscale and synoptic meteorology during the Intensive Operating Periods

3.1 IOP1

The account of mesoscale and synoptic meteorology is based on soundings as well as satellite observations. The trade winds carried equatorial air from the South Atlantic into the Amazon basin. Fourteen-day back trajectories, originating 100 m above Manaus, are grouped together and shown in Fig. 3a. Manaus (−3.1°) was typically under air masses coming from the Northern Hemisphere during IOP1 because of the southern positioning of the ITCZ during this time period.

Time series of altitude profiles of winds and relative humidity based on soundings launched at the T3 site, as well as a time series of regional rainfall based on retrievals from a radar at T3p, are presented in Fig. 4. Northeasterly winds

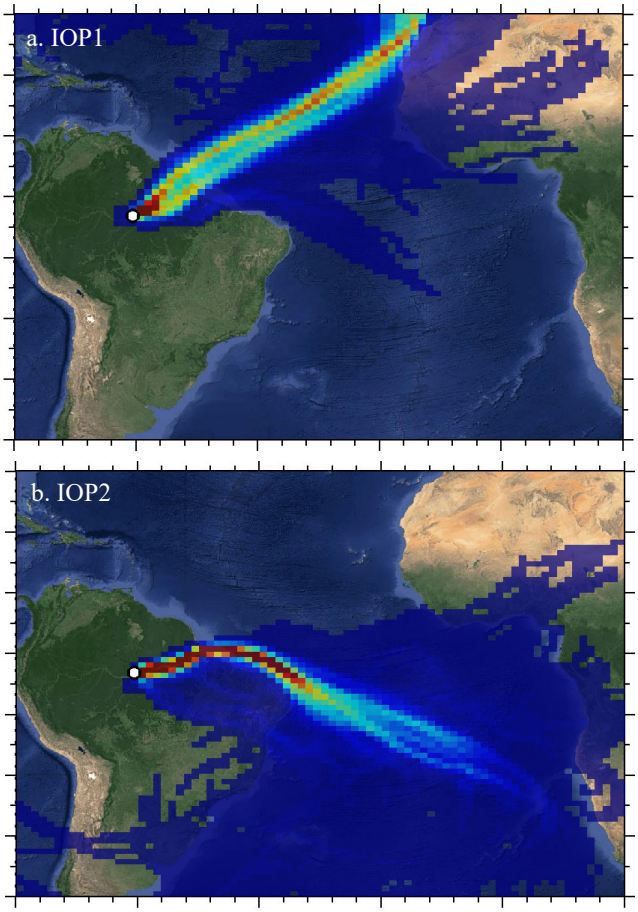

Figure 3. Fourteen-day back trajectories initialized at 100 m above T3 during **(a)** IOP1 and **(b)** IOP2. Meteorological fields were from the $1^\circ \times 1^\circ$ Global Data Assimilation System (GDAS). Source: http://www.arl.noaa.gov/HYSPLIT_info.php; last access: 15 August 2015.

prevailed in the atmospheric boundary layer of the Manaus region (Fig. 4a1 and a2). Regular and strong precipitation events are apparent in the time series of daily rainfall amounts (Fig. 4a3). Deep tropospheric moistening because of regular large rain events is apparent (Fig. 4a4).

The precipitation climatology for 2000–2014 and the associated weather anomalies are shown in Fig. 5a across a broad region of the Amazon basin in the wet season. A band of high precipitation from the South Atlantic to the central region of the basin accompanied squall lines that originated at the coast and propagated into the basin (Fig. 5a1). The maximum runs along the ITCZ. The precipitation anomalies, meaning the precipitation during the IOP compared to that of the 15-year climatology during that same period, were positive along the general trajectory of winds from the ocean coast to Manaus (Fig. 5a2). Positive anomalies were consistent with the discharges of the Madeira river, the main southern tributary to the Amazon river, which were 74 % higher than normal. The maximum level (June) of the Black River at Manaus in 2014 corresponded to the fifth highest during 113 years of records (Espinoza et al., 2014). Figure 5a2 also suggests that regions of strong positive anomalies in rainfall were associated with nearby regions of negative anomalies, suggesting an importance of mesoscale circulations of various types (e.g., forest–pasture, river breeze, and topography). On the synoptic scale, there was an intense warm anomaly in sea surface temperature (SST) in the southern South Atlantic and a weaker cold anomaly in the northern and equatorial South Atlantic (Fig. S6a). This anomaly in the SST gradient drove moisture transport from the South Atlantic toward the southwestern region of the Amazon basin. As a result, there was increased precipitation in the western part of the basin.

3.2 IOP2

During the dry season, the ITCZ shifted northward and the Manaus region was under air masses coming from the Southern Hemisphere (Fig. 3b). The trade winds carried air and moisture from the South Atlantic to the middle of the Amazon basin. Importantly (cf. Sect. 4), at times there was a recirculating pattern from the southern part into the middle section of South America. In the central region of the Amazon basin, strong easterlies prevailed in the surface boundary layer (Fig. 4b1 and b2). Compared to the wet season, rainfall was lower and the free troposphere was drier (Fig. 4b3 and b4). Moistening and higher levels of rain occurred in the final 10 days. Unlike IOP1, temperature anomalies over the South Atlantic during IOP2 were no longer significant (Fig. S6b). A strong warm anomaly was, however, present over the equatorial Pacific Ocean, corresponding to an El Niño development. The climatology of precipitation in the basin differs between the wet and dry seasons in both magnitude and geographical distribution (Fig. 5a1 compared to Fig. 5b1). There is in general little rainfall in the eastern part of the basin in the dry season, and, in particular for 2014, the precipitation anomaly was overall negative (Fig. 5b2), especially in September (not shown).

4 Regional and long-range transport of emissions during the Intensive Operating Periods

The wet season is viewed as a clean time period for background air, except for the episodic intrusions from Africa (Martin et al., 2010a). The dry season is sometimes alternatively referred to as the biomass burning season. During times of continental recirculation (cf. Sect. 3), biomass burning emissions from the southern edge of the forest transported south and southeast across the Atlantic coast of Brazil could in part return to the central Amazon. The backtrajectories in the dry season also passed reliably along the Amazon river, carrying the pollution of riparian communities and at

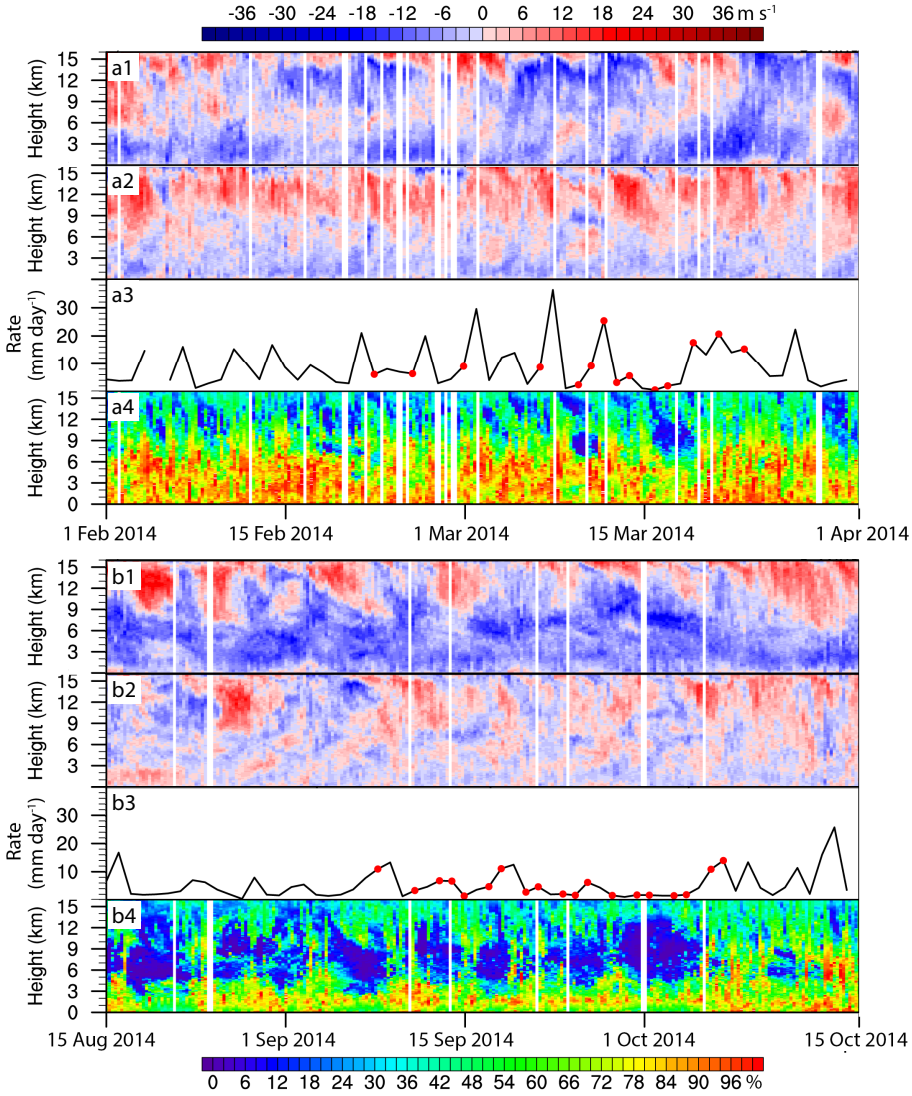

Figure 4. Time series of meteorological quantities during **(a)** IOP1 and **(b)** IOP2. (1) Altitude profile over T3 of wind velocities from the east (negative values; "*U*" winds). (2) Same as panel (1) but for wind velocities from the north (negative values; "*V*" winds). (3) Area-averaged rain rate in the Manaus region. Red circles indicate when the G-1 research aircraft flew a mission. (4) Altitude profile of relative humidity over T3. Scale bar of panels (1) and (2) is at the top of the figure. Scale bar for panel (4) is at the bottom of the figure. Data for wind and relative humidity were collected by four daily radiosondes launched at T3, and rows 1, 2, and 4 were prepared by interpolation of these data sets. Precipitation rates were based on measurements by an S-band radar operated by the Amazon Protection System (SIPAM) at T1p for returns at a height of 2.5 km and within a range of 110 km. Other data sources: https://www.arm.gov/campaigns/amf2014goamazon; last access: 12 September 2015.

times of large cities in the coastal northeast of Brazil into the Manaus region.

Fire locations in the near field of the Manaus region as well as in the far field of South America are plotted in the upper and lower rows of Fig. 6, respectively, for each IOP. A breakdown by week is shown in Figs. S7 and S8. Near-field fires represent upwind locations requiring on the order of 1 day for transport to the Manaus region. Pollution from these fires can be expected to have the physical and chemical signatures of fresh emissions. Far-field fires represent upwind locations requiring several days or more for transport to the Manaus region. The signatures become significantly aged during transport to the Manaus region. Figure 6 generally shows a low incidence of fires during the wet season (IOP1) compared to a high incidence during the dry season (IOP2).

Concentrations and emissions of aerosol particles on a hemispheric scale can be visualized by satellite by maps of aerosol optical depth (AOD). Weekly maps are shown in Fig. S9 for the two IOPs. Dust and biomass burning emissions from equatorial Africa were transported episodically

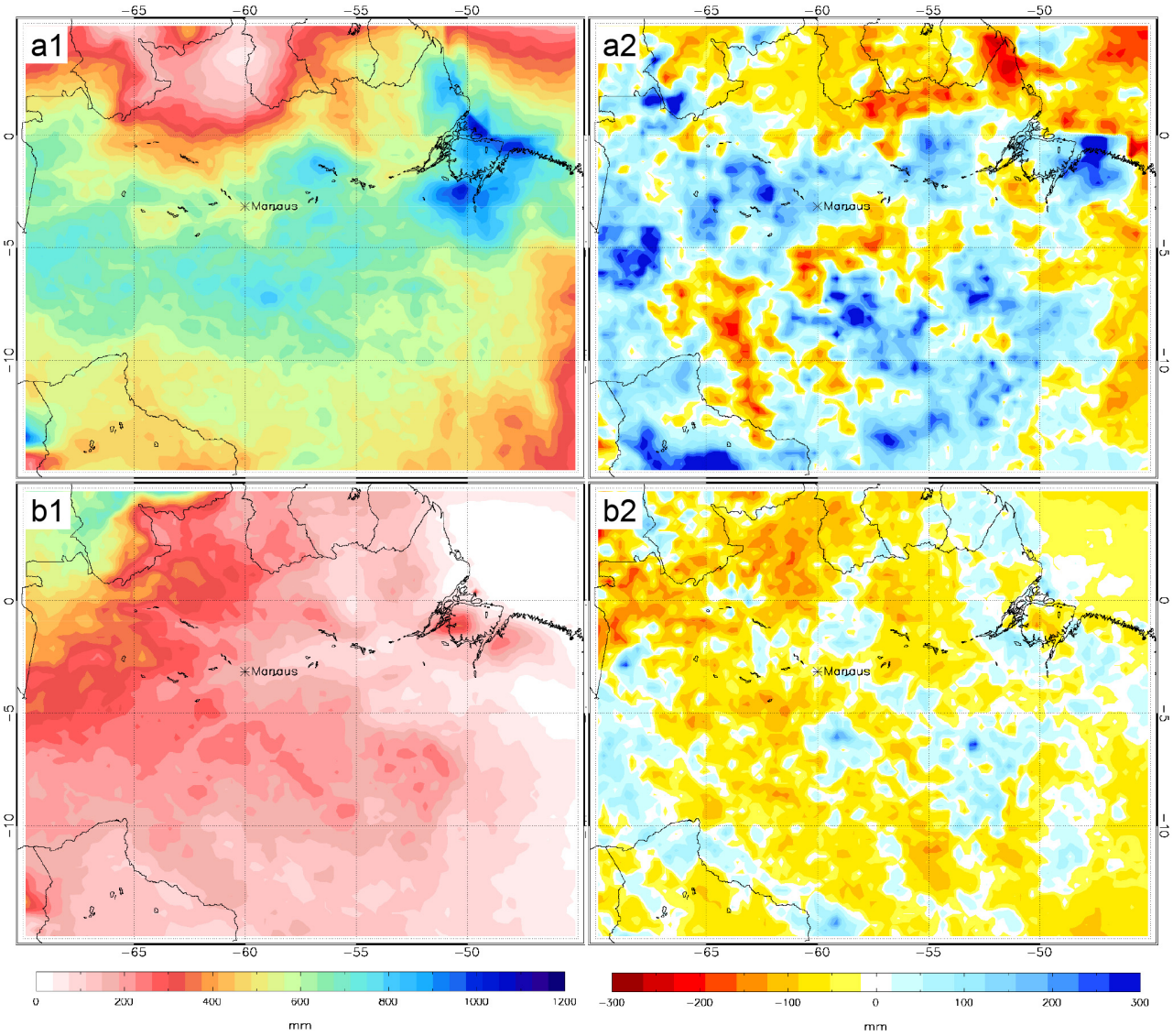

Figure 5. Mean accumulated precipitation (left column) from 2000 to 2014 throughout the Amazon basin based on the Tropical Rainfall Measuring Mission (TRMM) satellite and the Multi-Satellite Precipitation Analysis (TMPA) product (version 7 of the 3B42 algorithm). Anomaly of 2014 (right column) compared to the mean of 2000 to 2014. Results are shown for time periods of (top row) IOP1 and (bottom row) IOP2. Source: ftp://meso-a.gsfc.nasa.gov/pub/trmmdocs/3B42_3B43_doc.pdf; last access: 12 September 2015.

into the central Amazon, as explained by the southern positioning of the ITCZ during this time period. By comparison, during IOP2 these emissions passed northward to the Caribbean, as explained by the northward shift of the ITCZ during this time period. During IOP2, there were two regions of intense biomass burning. The first was the central region of South America, representing the burning edge of the Amazon rain forest and called the "arc of deforestation". Recirculation patterns for the dry season can transport a portion of these emissions to the central part of the Amazon basin where Manaus is located. The second region of biomass burning was the central part of Africa. Emissions from both of these regions arrived into the central region of the Amazon basin during IOP2, as can be inferred by an overlay of the backtrajectories apparent in Fig. 3 and the emissions and transport implied by the aerosol optical depth in Fig. S9. Although mass concentrations were greatly reduced during transport, the central Amazon represents quite clean baseline conditions so that even relatively small amounts of imported emissions (compared to the source regions) can have a regionally dominant effect compared to the otherwise clean receptor region.

In summary, the GoAmazon2014/5 Experiment focused on the complex interactions among vegetation, atmospheric

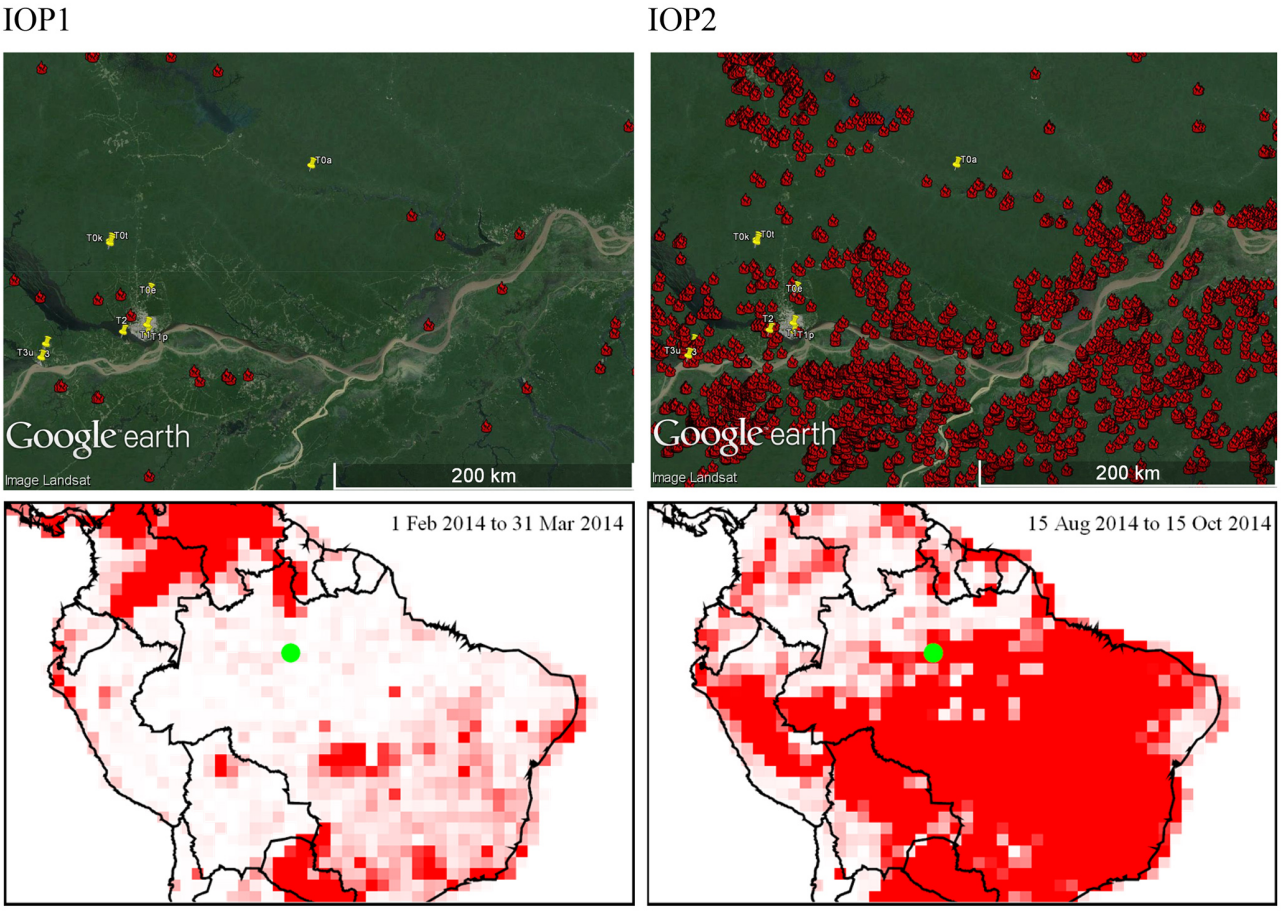

Figure 6. Satellite-based detection of fires (top) on the regional scale and (bottom) on the scale of South America. Left and right columns represent periods of IOP1 and IOP2, respectively. On the regional scale, each fire icon indicates the detection of one fire event during the 2-month observation period of each IOP. The yellow markers indicate the locations of GoAmazon2014/5 research sites (cf. Fig. 1). On the scale of South America, the color scaling in red runs from 0 to 100 fire events detected in a $1° \times 1°$ grid box during the 2-month observation period of each IOP. Some grid boxes have more than 100 events. The green point represents the location of Manaus. Source: http://www.dpi.inpe.br/proarco/bdqueimadas/; last access: 7 August 2015.

chemistry, and aerosol production and their connections to aerosols, clouds, and precipitation. It sought to understand how aerosol and cloud life cycles were influenced by pollutant outflow from a large city in the tropical rain forest, particularly the susceptibility of the biosphere and atmosphere to human activities, for a wide range of synoptic and environmental conditions. It was driven by the need to develop a knowledge base of data, processes, and mechanisms for inclusion in models of different types and scales. The intended future legacy of GoAmazon2014/5 is that more accurate predictions (embedded in models) should be developed of how the present-day functioning of energy, carbon, and chemical flows in the Amazon basin might change, both due to external forcing on the basin from global climate change and internal forcing from past and projected economic development in the basin. There can be future changes in direct, semi-direct, and indirect radiative forcing, energy distributions, regional climate, ecosystem functioning, and feedbacks to global climate.

In conjunction with the introduction presented herein, research results and findings of GoAmazon2014/5 appear in the articles of this special issue. The special issue is open for new submissions for 3 years. Overview articles are planned for summarizing and synthesizing the findings of the papers of the special issue. These planned overviews encompass the several objectives of GoAmazon2014/5.

The Supplement related to this article is available online at doi:10.5194/acp-16-4785-2016-supplement.

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