Meteorological context of the onset and end of the rainy season in Central Amazonia during the 2014-15 GoAmazon Experiment

Jose A. Marengo[1], Gilberto F. Fisch[2], Lincoln M. Alves[3], Natanael V. Sousa[3], Rong Fu[4],
Yizhou Zhuang[4, 5]

[1]Centro Nacional de Monitoramento e Alerta de Desastres Naturais (CEMADEN), São Jose dos Campos, São Paulo, Brazil
[2] Instituto de Aeronáutica e Espaço/Centro Tecnológico Aeroespacial (IAE/CTA), São Jose dos Campos, São Paulo, Brazil
[3] Centro de Ciência do Sistema Terrestre/Instituto Nacional de Pesquisas Espaciais (CCST INPE), São Jose dos Campos, São Paulo, Brazil
[4] Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, California, USA
[5] Department of Atmospheric and Oceanic Sciences, School of Physics, Peking University, Beijing, China

Correspondence to: Jose A. Marengo (jose.marengo@cemaden.gov.br)

Abstract. The onset and demise of the rainy season in Amazonia are assessed in this study using meteorological data from the GoAmazon experiment, with focus is on the 2014-15 rainy season. In addition, global reanalyses are also used to identify changes in circulation leading to the establishment of the rainy season in the region. Our results show that the onset occurred in January 2015, 2-3 pentads later than normal, and the rainy season during austral summer of 2015 exhibited several periods with consecutive dry days in both Manacapuru and Manaus, which are not common for the wet season, and resulted in below normal precipitation. The onset of the rainy season has been strongly associated with changes in large-scale weather conditions in the region due to the effect of the Madden-Julian Oscillation (MJO). Regional thermodynamic indices and the height of the boundary layer did not present a significant difference between the onset and demise of the wet season of 2015. This suggests that local changes such the regional thermodynamic characteristics may not have influenced its onset. Thus, variability of the large-scale circulation was responsible for regional convection and rainfall changes in Amazonia during the austral summer of 2014-15.

1. Introduction

The Amazon region represents one of the main convective centers in the world tropics, together with equatorial Africa and the Indian monsoon regions. In this region, tropical convection is one of the key processes regulating the climate system, and plays an important role in the maintaining the water and energy balance, and also helping the development of the zonal and vertical components of the circulation. The interannual rainfall variability in the Amazon basin is linked to variations of sea surface temperatures (SST) in both tropical Pacific and Atlantic oceans (Marengo 1992; Ronchail et al. 2002; Yoon and Zeng 2010; Marengo and Espinoza 2015, and references quoted therein). Indeed, previous studies have documented that

warm conditions in the equatorial Pacific (e.g. El Niño events) produce a rainfall deficit in Amazonia, which can originate extreme drought periods, as observed in 1926, 1983, 1997-1998 and 2010 (Williams et al. 2005; Marengo et al. 2008, 2011; Espinoza et al. 2011; Marengo and Espinoza 2015).   In the early 21st century, large-scale extreme seasonal events, such as extreme droughts in 2005, 2010 and 2015 and floods (2009, 2012, 2014) have affected the Amazon region. Rainfall anomalies were the consequence of circulation changes forced by anomalous warming or cooling of the tropical Pacific and/or tropical north or south Atlantic Oceans as documented by Marengo and Espinoza 2015 and references quoted therein).

In sum, while we had several droughts in Amazonia linked to El Nino, as in 1925, 1983, 1987, 1998 and recently in 2015-16, some other drought events have been reported in 1963 and 2005, not related to El Nino but to a warmer topical North Atlantic. When the tropical North Atlantic is warmer than the tropical South Atlantic, the intertropical convergence zone is displaced northward leaving less rainfall in the region. This may happen with an El Nino (1983, 1998) or without an El Nino (2005). Every drought in Amazonia is different in terms of spatial coverage.

The occurrence of extreme weather and drought and floods events has changed people's perception of climate extremes — as happened after those extensive droughts and flooding. In Amazonia, the population perceives drought as anomalously low river levels during the peak season May-July, more than as low rainfall during the peak season in February-April. Drought is an impact while deficient rainfall is the climatic forcing of this impact.   However, in terms of some ecological impacts or for agriculture, drought may be more related to deficient rainfall during the peak of the rainy season, Drought and floods and their impacts in natural and human systems in the region show the vulnerability of residents and ecosystems to the occurrence of hydrometeorological extremes in the region.

Rainfall in the Amazon basin is mainly supported by the moisture flux from the equatorial Atlantic associated with the trade winds (Angelini et al. 2011). However, Amazon climate has to be seen as coupled interactive atmosphere-ocean-land phenomena (Runyan et al., 2012), and current research (Makaireva et al. 2013)) suggests that land surface processes may play a comparable part.equal in importance to that of the ocean; and have explored the role of the forest in the recycling of water, suggesting an active role of the vegetation in the regional water cycle. Previously, Salati and Vose (1984) calculated this influence to be 50% for inland Atlantic moisture and 50% for local recycling by evapotranspiration and precipitation, using isotope techniques. An intensification of the hydrological cycle in Amazonia over the last two decades has been identified by Gloor et al. (2013), who attributed it to an increase in atmospheric water vapour coming from a warmer tropical Atlantic. This is consistent with a positive trend in precipitation in the northwestern Amazon since 1990, and is also reflected water levels at Manaus and in the Amazon discharges at Óbidos (Marengo and Espinoza 2015).

Variability of wet and dry seasons suggests that the onset and demise of the wet and dry seasons and thus the length of the wet and dry season are changing with time (Marengo et al. 2012; Marengo and Espinoza 2015). Observational studies in southern Amazonia suggest that the dry season has increased in length by about one month since the 70's (Marengo et al. 2011; Fu et al. 2013). Furthermore, the length of the dry season also exhibits interannual and decadal-scale variations linked

either to natural climate variability, or as suggested by Wang *et al.* (2011), due to the results of the influence of changes in land use in the region. While it is important to know the future characteristics of the total rainy season rainfall, it is also important to highlight the urgency of improving our understanding and capability to detect and predict the rainy season onset and demise, as well as the variability of the wet and dry seasons, not just through model experiments but also through observational analysis. The droughts of 2005 and 2010 and their impacts on humans and on the tropical forest have been characterized by late onsets of the rainy season and/or longer dry seasons (Marengo et al. 2011; Marengo and Espinoza 2015). During the recent El Nino in 2015-16, rainfall over central-northern Amazonia has been below normal (by approximately 200-300 mm for the wet season), and this contributed to an extensive drought and subsequent problems in the hydrology of the region, as well as an increased number of fires there (CPTEC-www.cptec.inpe.br). The length of the dry season has a large temporal and spatial variability, and is strongly associated with dry conditions that may impact the occurrence of fires and their release of carbon and aerosols, and also affecting human systems (Aragao et al. 2016; Martin et al. 2016).

Various studies have discussed observational and modelled aspects of the onset and demise of the rainy season in Amazonia using a variety of climatic indicators, such as rainfall, outgoing long wave radiation or dynamic fields (e.g., Kousky 1988; Marengo et al. 2001, 2012; Fu et al. 1999; Liebmann and Marengo 2001; Gan et al. 2004; Wang and Fu 2004; Silva et al. 2007; Silva and Carvalho 2007; Raia and Cavalcanti 2008; Silva 2009; Marengo and Espinoza, 2015). However, modelling work still shows uncertainties in the representation of the onset of the rainy season. This may be due to the poor representation of clouds and land surface-atmosphere interactions or due to role of aerosols and other particles, which are still not well represented in models.

Moisture transport across the equator and its variations could influence convection and thus the wet season onset (Rao et al. 1996; Marengo et al. 2001; Wang and Fu 2002; Alves 2016). Li and Fu (2006) showed that weak and infrequent extratropical cold front penetrations during the transition season also contribute to a delay of the wet season onset. However, the complexity of the relationship between ENSO, Atlantic SSTs and the onset of the wet season over the southern and central Amazon remain unclear. Butt et al. (2011) identify significant differences in the onset of the rainy season in Rondonia between 1970 and 2000, due to land use changes in the region. However the uncertainties on the attribution of these extremes and their variations to natural and human influences are still great. This highlights the urgency of understanding the underlying causes of the onset and demise of the rainy season and our ability to predict them. Furthermore, evidence of the possible role of human influences (deforestation, increase of greenhouse gases and aerosol released due to biomass burning or urban pollution) on rainfall and river variability has started to appear in the literature recently (Cecchini et al. 2016; Alves 2016; Sparcklen and Garcia-Carreras 2015; Magrin et al. 2014; Zhang et al. 2008).

Increasing aerosol concentrations can have substantial impacts on spatial and temporal rainfall patterns in the Amazon (e.g., Martins et al. 2009a; Reutter et al. 2009; Pöhlker et al. 2016). The initial work by Andreae et al. (2004) suggest that aerosols from biomass burning in Amazonia may delay the onset of the rainy season in southern Amazonia, but not much is known on the possible roles of aerosols from urban areas upon rainfall and the water cycle in the Amazon region. Previous studies

have found that cloud microphysical properties, cloud cover, precipitation, lightning, and regional climate over the Amazon basin can be significantly affected by aerosol particles (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; Wang et al. 2016).

In this paper, we use data from the GoAmazon and CHUVA experiments during 2014-15 as well as global reanalyses to investigate regional and large-scale circulation and rainfall patterns during the onset and demise of the rainy season. Emphasis is on the identification of large-scale patterns leading to the onset and demise of the rainy season in the Manaus region in central Brazilian Amazonia in both years. We have taken advantage of the high resolution of surface meteorological data collected during these two field experiments as part of GoAmazon in 2014-15 and also the presence of El Nino during summer of 2015, to investigate daily and diurnal rainfall variability. We also investigated the large scale and regional circulation patterns linked to rainfall variability in those regions. With the GoAmazon data we have investigated the onset and demise of the rainy season of 2014-15, as well as convection and the planetary boundary layer (PBL) heights in some sites near Manaus, where thermodynamic indices were calculated to identify the transition regimes pre and post onset and demise of the rainy season.

2.   Methods

The data used for this study come from the GoAmazon Project (Martin et al. 2016), designed to study some of the characteristics on the rainy season in Amazonia, such as onset and demise of dry and wet seasons, and we have used some of the CHUVA and GoAmazon 2014/15 rainfall and surface and upper air meteorological data available from 2014 to 2015. The expression green ocean (Go) was introduced by Williams et al. (2002) due 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. Observations and data from modelling work from the GoAmazon Experiment (GoAmazon 2014/15- (http://campaign.arm.gov/goamazon2014/) were collected in the central region of Amazonia near Manaus from 1 January 2014 through 31 December 2015. More details on the nature and objectives of Go Amazon 2014/15 can be found in Martin et al. (2016).

As described by Machado et al. (2014), the CHUVA project—CHUVA, meaning "rain" in Portuguese, is the acronym for the Cloud Processes of the Main Precipitation Systems in Brazil: A Contribution to Cloud-Resolving Modelling and to Global Precipitation Measurement (GPM). It began in 2010 and has conducted five field campaigns while the last experiment was held in Manaus as part of the Go Amazon 2014/15 experiment. CHUVA's main scientific motivation is to contribute to the understanding of cloud processes, which represent one of the least understood components of the climate system. Field data from the CHUVA and GoAmazon 2014-15 campaigns are used to improve our understanding of the dynamics of the onset of the rainy season and the characteristics of the dry season during that year. The data came in handy since we now had the possibility of identifying the onset the rainy season over central Amazonia using high resolution meteorological data collected near Manaus since the end of 2013. In addition, we analyse ground-based remotely sensed data (ceilometer) to identify changes in the planetary boundary layer (PBL) during the onset and demise of 2014-2015 rainy

season. Wind, outgoing longwave radiation (OLR) and sea surface temperature data from National Centers for Environmental Prediction (NCEP)/Climate Prediction Center (CPC) are used to examine the influence of atmospheric and oceanic conditions on the onset and demise of the rainy seasons.

Rainfall data (at diurnal and daily levels) come from the Brazilian Meteorological Service (INMET) station at Manaus (Lat. 3.11^{o}S – Lon. 59.95^{o}W) and at Manacapuru from University of the State of Amazonas UEA (70 km upwind of Manaus Lat.: 03.05 ^{o}S – Lon. 60.00^{o}W). The pentad of the onset and end (or demise) of the rainy season in Amazonia was calculated using the criterion of rainfall accumulation data defined by Liebmann and Marengo (2001) and adapted by Bombardi and Carvalho (2009) using gridded rainfall data. This criterion was applied to data from the Manaus and Manacapuru (nearby Manaus) rainfall stations from the GoAmazon-CHUVA network during 2014-15, by averaging all available data for a given day from those two stations onto a 1.0^o grid. The availability of data from a large number of stations in a grid box as allows a more regional view as compared with single station data.

Additional data sets for regional rainfall analyses during those two rainy seasons come from the CPC/NCEP/NOAA (www.ncep.noaa.gov) and from the Global Precipitation Climatology Center (GPCC) gauge-based gridded precipitation dataset, available for the global land surface only (Rudolf et al. 1994). The GPCC datasets are available at spatial resolutions of 1.0° latitude/1.0° longitude as mean monthly precipitation totals and anomalies relative to the 1951-2000 mean.

Once the pentad of the onset was identified for Manaus and Manacapuru, various analyses are performed for the periods before and after the onset, in order to identify and understand possible shifts in atmospheric circulation and energy fluxes and characteristics of the PBL and thermodynamic indices convective available potential energy (CAPE) and convective inhibition energy (CIN) that would favour the establishment of the onset of the rainy season of 2014-15. CAPE and CIN values were computed using the original variables for the 500 m thick mixing layer parcel. The height of the PBL was derived from a ceilometer installed at the T3 site in Manacapuru and its hourly values were computed for pentads and post onset and demise of the rainy season in 2014-15. The latent (LE) andsensible (H) turbulent heat fluxes and the Bowen ratio were derived from these fluxes at the T3 site and the EMBRAPA Flux for 2014-15 in order to quantify their values before, during and after the onset and end (or demise) of the rainy season, so we could investigate the energy partition and convective processes that accompany the evolution of the rainy season during the days of the GoAmazon campaign. More details about the instrumentation used can be found in Machado et al. (2004), Martin et al. (2016) and Wang et al. (2016).

3.   Results

3.1   Characteristics of the 2014-15 rainy season in Amazonia

The mean climatic features of the Manaus region are described elsewhere (Greco et al. 1990; Cohen et al. 1995; Machado et al. 2004; Martin et al. 2016), where the peak of the rainy season occurs around March-May. The GPCC rainfall (Figure 1a-d) shows rainfall anomalies from December 2014-February 2015 (representing the wet season) to September-November 2015. Over entral and eastern Amazonia for the wet season, rainfall was about 80-90 mm/month below normal, while over western

Amazonia rainfall was about 50-90 mm/month above normal. For the SON period the rainfall was well below normal (by around 90 mm/month), in almost all of Amazonia. This is a signal of the impacts of El Nino 2015-16, whichwas under development in the tropical Pacific since the middle of 2015 (Figure 2). Warm surface waters (1.5-2.5 °C) were detected along the equatorial Pacific in the period from March to May 2015. This 2015-16 drought caused the longest fire season of the 21st century with five months exceeding 10,000 fire detections and the largest number of active fire occurrences per km^2 deforested (Aragão et al., 2016, CPTEC, 2015). This combination of a longer dry season, more frequent extreme droughts and an increased risk of fire could play a critical role in a future Amazon rainforest dieback in spite of the increased resilience of tropical forests in an elevated atmospheric CO_2 environment (Huntingford et al. 2013).

As to regional scale circulation features, the D2014-JF2015 season did not show signals of El Niño in the tropical Pacific but the warm surface waters were already present during MAM 2015 (Figure 2). This warming increased continuously until March 2016, indicating the intensification of El Niño in 2015-16, with warm surface water (3-4 ºC above normal) over the equatorial eastern Pacific by austral summer of 2016 (www.cptec.inpe.br). The low level circulation anomaly vectors show small southerly wind anomalies suggesting weakened northerly flow over the tropical North-Atlantic and Amazon sectors (Figure 2). Along the equator, Figure 2 shows that there are westerly anomalies, but these are away from the coast (looking at DJF). Along the Atlantic coast and north of the equator, however, the anomalies are near zero. There are huge positive transport anomalies from the equator into the southern Amazon, which are consistent with above-normal precipitation to the west (south of the equator), since there appears to be anomalous convergence of moisture there (Fig. 2a).An analysis of the near-surface and upper-air circulation discussed previously can provide a better idea of the regional east-west circulation of the region during December 2014 and January 2015. The east-west vertical cross-section along the equator (5N-5S) in Figure 3 shows upward motion anomalies over western Amazonia during both summer months while reduced convection and downward motion with subsidence is found over Central Amazonia, Eastern Amazonia and Northeast Brazil. The latter region has been experiencing a record drought since 2011 (Marengo et al. 2016). These circulation anomalies are consistent with negative rainfall anomalies over central Amazonia near the Manaus region. Therefore, interannual variations of the wet season onset in the Amazon appear to be influenced by changes in large scale and regional circulation over the tropical Atlantic and Pacific sectors.

3.2   Daily rainfall variation and characterization of the onset and demise of the rainy season during 2014-15.

In order to verify the variability in rainy season characteristics, the onset and demise of the rainy season over Manaus has been defined following Liebmann and Marengo (2001) using daily precipitation data from Manaus station for the period 1961-2015. Using this methodology, the climatological onset is detected around pentad 64 (12-16/November) and the demise of the rainy season around pentad 29 (21-25/May). Figure 4 plots the pentad rainfall recorded during 2014/2015 for Manaus station. It also plots the annual precipitation climatology of the pentad cycle and the onset and demise of the rainy

season. The data showed anomalously late onset (around the pentad 69: 07-11/December) in 2014/15. The demise of the rainy season occurs around pentad 29 (21-25/May) agreeing with the climatological date, giving a shorter than-normal rainy season. In addition, the data showed that the Manaus station experienced reduced rainfall totals compared with climatology, with some dry spells.

5   As seen in the previous section, despite the oceanic and atmospheric conditions in the equatorial Pacific (Niño 1 + 2 and 3) which show ENSO-neutral conditions during the period before the onset, it is noted that the patterns of regional precipitation distribution over central and eastern Amazonia were consistent with a distinct phenomena that caused changes in weather conditions in the region, for example, the Madden-Julian Oscillation (MJO) (Madden and Julian 1994, Liebmann et al. 1999; De Souza and Ambrizzi 2006; Alvarez et al. 2015). This is shown in Figure 5 in the time diagram of OLR anomalies
10   between 5ºN-5ºS over the globe in 2014 and 2015.

It is observed that from July through late October 2014 the intraseasonal signal became less coherent, with a weaker anomaly field and is inconsistent with a canonical El Niño signal. The pattern became more organized during late November as the MJO strengthened as indicated by eastward propagation of alternating anomalies into January 2015. At this time, the MJO may have contributed to enhanced rainfall and the onset of rainy season for portions of Amazonia as indicated by negative
15   OLR anomalies (blue shading) favouring conditions for precipitation around 60ºW.

This fact was reflected in the temporal distribution of rainfall (Figure 4), which depicts the regional frequency of precipitation in this period. In summary, the phases of MJO associated OLR anomalies were evident throughout the equatorial region, and in particular over the central and eastern Amazon. This suggests that the negative MJO phase in mid-January may have contributed to favouring conditions to enable the convection and the onset of the rainy season from pentad
20   6. This is consistent with other atmospheric mechanisms on a local scale, for example, the near-surface local circulation and thermodynamic patterns.

Broadly speaking, the influence of the MJO on precipitation over the tropics occurs by eastward propagation of Rossby wave trains from the tropical Pacific Ocean (Muza et al. 2009). Previous observational and modeling studies generally indicated that the MJO and ENSO have a decadal variation and seasonal dependence (Tang and Yu, 2008; Hendon et al. 2007),
25   however, these have not been well identified due to their nonlinear nature. These studies also show significantly lagged correlations between MJO and ENSO indices. Despite this, recently Shimizu et al. (2016) examined the regional relationship between ENSO and MJO phases in climatological patterns of precipitation over South America. The results indicated that combined responses showed that precipitation is strongly influenced by the MJO phases rather than by ENSO conditions, especially during the austral summer. Thus, our results corroborate those of Shimizu et al. (2016) who observed highest
30   percentages of days with active MJO and increased rainfall occurring during El Niño and neutral year.

Figure 6 shows the daily variation of air temperature at 850 hPa, relative humidity and Bowen ratio at the T3 Manacapuru site. Wet conditions were consistent with higher relative humidity and lower temperatures, while dry spells occur with lower

relative humidity and higher air temperatures. Before the onset we noticed a reduction in temperature and humidity, while it is hard to see any tendency of the Bowen ratio before the onset or after the demise of the rainy season. The latent heat fluxes over the land surface are important sources of atmospheric humidity during the initial stages of the transition season between dry and wet periods (Fu and Li 2004). Together with changes in the onset of the rainy season, changes of dry season length may be key in favouring the present risk of fire. High land surface Bowen ratio during the preceding dry season would delay the subsequent wet season onset in the southern Amazon (Fu and Li, 2004), and this may have been the case in the onset rainfall in 2014-15.

3.3 Thermodynamic indicators and PBL behaviour during the onset and demise of the rainy season in 2014-15

Using the T3 radiosonde data, one-day averages of CAPE and CIN (Figure 7) were calculated for each profile and these in turn were averaged over pentads. One pentad was selected to encompass the onset of the rainy season and another, its demise. The figure shows that CAPE and CIN are very noisy; hence a two-sample t-test for daily average CAPE/CIN values during the rainy season (2015/1/26-2015/5/10) and before/after rainy season (2014/11/1-2015/1/25 and 2015/5/11-2015/12/1) was performed. Results suggest both CAPE and CIN values change between the two periods (during the rainy season and before/after the rainy season), indicating a difference significant t the 5% level in CAPE and CIN between the days with and without deep convection.

The diurnal cycle of the heights of the PBL was computed with the ceilometer installed at the T3 site. Figure 8a shows the composite PBL diurnal cycle for the wet season 2014-2015. The PBL height remained stationary at around 300-400 m during night-time (nocturnal boundary layer), then increased during daytime (convective boundary layer), and reached its maximum (1100 – 1200 m) in the early afternoon (14:00 LT). This pattern is consistent with the previous values obtained for Amazonia for the wet season (Fisch et al. 2004). There is no signal of the anomalous wet season in the PBL heights. Individual diurnal cycles for other months (Figures 8b,c) also did not present a significant difference between the onset and demise of the wet season of 2015.

A moistening of the planetary boundary layer and a lowering of the temperature at its top may reduce CIN and control the conditioning of the large-scale thermodynamics prior to onset (Fu et al. 1999). In addition, Li and Fu (2004) found that the main increase in CAPE and reduction in CIN occur prior to the rainy season onset, although in the tropical atmosphere a decrease CAPE often exists in the absence of deep convection (Williams and Renno 1993).

4.   Conclusions

The onset of the rainy season in Amazonia is assessed in this study based on changes in precipitation, large-scale synoptic flow fields and thermodynamic parameters during the GoAmazon experiment.

The focus was on the 2014-15 rainy seasons using the available climatic data from the GoAmazon field experiment as well as from other sources. From our results, based on the analysis of daily data from various sites of the experiment, it was observed that onset of the rainy season of 2014-2015 was delayed, occurring in January 2015, 2-3 pentads later than normal. On the other hand, during that rainy season there were several consecutive dry days between December 2014 and March 2015 in both Manacapuru and Manaus, which are not common in the wet season, and thus determining below normal precipitation. The onset of the rainy season has been strongly associated with changes in large-scale weather conditions in the region due to the effect of the MJO. Thus, the MJO may have contributed to enhancing rainfall in portions of Amazonia as indicated by increased convection favouring conditions for precipitation around 60ºW.

The CAPE and CIN \ show a significant change between the days with and without deep convection. However, while there is an increase in CAPE before the onset and decrease after the demise, no clear change of CIN during the onset period is detected. The diurnal cycle of the heights of the PBL also does not show any signal of the anomalous wet season and the individual PBL diurnal cycles did not present a significant difference between the onset and demise of the wet season 2015. While one of the main objectives of the GoAmazon Experiment was to assess the influence of the air pollution from the city of Manaus upon the rainy season in that region, the possibility that regional characteristics or pollution could have had an effect on the onset of the rainy season couldn't be ruled out. Our conclusion is that variability of the large-scale circulation was responsible for regional convection and rainfall changes in Amazonia during the austral summer of 2014-15.

Acknowledgements

Data were obtained from the Atmospheric Radiation Measurement (ARM) Program sponsored by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research, Climate and Environmental Sciences Division. This work was supported by FAPESP/DOE/FAPEAM GoAmazon grant 2013/50538-7.and FAPESP grant #2015/50122-0 and DFG-IRTG 1740/2.

References

Altaratz O, Koren I, Yair Y, Price C. (2010) Lightning response to smoke from Amazonian fires, Geophys. Res. Lett., 37, L07801, doi:10.1029/2010gl042679, 2010.

Alves LM (2016) Análise estatística da sazonalidade e tendências das estações chuvosas e seca na Amazônia: clima presente e projeções futuras. 2016. 166 p. (sid.inpe.br/mtc-m21b/2016/03.03.12.52-TDI). Tese (Doutorado em Meteorologia) - Instituto Nacional de Pesquisas Espaciais (INPE), São José dos Campos, 2016.

Andreae M O, Rosenfeld D, Artaxo P, Costa AA, Frank GP, Longo KM, Silva-Dias MAF (2004) Smoking rain clouds over the Amazon, Science, 303:1337-1342, 10.1126/science.1092779.

Angelini IM, Garstang M, Davis RE, Hayden B, Fitzjarrald DR, Legates DR, Greco S, Macko S, Connors V (2011) On the

coupling between vegetation and the atmosphere. Theor. Appl. Climatol. 105: 243–261, doi: 10.1007/s00704-010-0377- 5.

Aragao L, and coauthors (2016) Reducing Brazilian Amazon deforestation does not curb pervasive drought-related fire emissions, Submitted to Environ Res Letters.

Alvarez M. S., C. S. Vera, G. N. Kiladis and B. Liebmann (2015) Influence of the Madden Julian Oscillation on precipitation and surface air temperature in South America. Clim. Dyn., 46 (1), 245-262. doi:10.1007/s00382-015-2581-6.

Bombardi RJ, Carvalho LMV (2009) IPCC global coupled model simulations of the South America monsoon system. Clim. Dyn., 33: 893–916, doi:10.1007/s00382-008-0488-1.

Butt N, de Oliveira PA, Costa MH (2011) Evidence that deforestation affects the onset of the rainy season in Rondonia, Brazil. J. Geophys. Res., 116 : D11120, doi:10.1029/2010JD015174. http://doi.wiley.com/10.1029/2010JD015174

Cohen JCP, da Silva Dias MAF, Nobre CA (1995) Environmental conditions associated with Amazonian squall lines: A case study. Mon. Wea. Rev., 123: 3163–3174, doi:10.1175/1520-0493(1995)1232.0.CO;2.

De Souza EB, Ambrizzi T (2006) Modulation of the intraseasonal rainfall over tropical Brazil by the Madden–Julian oscillation. Int J Clim 26(13):1759–1776

Espinoza JC, Ronchail J, Guyot JL, Junquas C, Vauchel P, Lavado WS, Drapeau G, Pombosa R (2011) Climate variability and extremes drought in the Upper Solimões River (Western Amazon Basin): Understanding the exceptional 2010 drought. Geophys Res Lett, 38:L13406

Fisch G, Tota J, Machado LAT, Silva Dias MAF, Lyra RF, Nobre CA, Dolman AJ, Gash JHC (2004) The convective boundary layer over pasture and forest in Amazonia. Theoretical and Applied Climatology, 78: 47-59 doi 10.1007/s00704-004-0043-x.

Foley, J. A. and coauthors (2007) Amazonia revealed: forest degradation and loss of ecosystem goods and services in the Amazon Basin. Front. Ecol. Environ. 5: 25–32.

Fu R, Zhu B, Dickinson RE (1999) How do atmosphere and land surface influence seasonal changes of convection in the tropical Amazon? J. Climate, 12: 1306–1321.

Fu R, Li, W (2004) The influence of the land surface on the transition from dry to wet season in Amazonia. Theor. Appl. Climatol., 78, doi:10.1007/s00704-004-0046-7. http://link.springer.com/10.1007/s00704-004-0046-7.

Fu R and coauthors (2013) Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection, online at www.pnas.org/lookup/suppl/doi:10. 1073/pnas.1302584110/-/DCSupplemental.

Gan MA, Kousky VE, Ropelewski CF (2004) The South America monsoon circulation and its relationship to rainfall over west-central Brazil. J. Climate, 17: 47-66.

Gloor MRJW, Brienen D, Galbraith TR, Feldpausch J, Schöngart W, Guyot JL, Espinoza JC, Lloyd J, Phillips OL (2013) Intensification of the Amazon ,hydrological cycle over the last two decades, Geophys. Res. Lett., 40, doi:10.1002/grl.50377.

Gonçalves WA, Machado LAT, Kirstetter PE (2015) Influence of biomass aerosol on precipitation over the central Amazon: an observational study, Atmos. Chem. Phys. 15: 6789–6800, doi:10.5194/acp-15-6789-2015,

Greco S, and Coauthors, (1990) Rainfall and surface kinematic conditions over central Amazonia during ABLE-2B. J. Geophys. Res. Atmos., 95: 17001-17014, doi:10.1029/JD095iD10p17001.

Huntingford C, Zelazowski P, Galbraith D, Mercado LM, Sitch S, Fisher R, Loma M, Walkenrn AP, Jones CD, Booth BBB, Malhi Y, Hemming D, Kay G, Good P, Lewis SL, Phillips OL, Atkin OK, Lloyd J, Gloor E, Zaragoza-Castells J, Meir, P, Betts R, Harris PP, Nobre CA, Marengo JA, Cox PM (2013) Simulated resilience of tropical rainforests to CO2-induced climate change. Nat. Geosci. 6: 268–273, doi: 10.1038/NGEO1741.

Hendon HH,Wheeler M, and Zhang C. (2007), Seasonal dependence of the MJO- ENSO Relationship, J. Clim., 20, 531 – 543.

IPCC (2013) Summary for policymakers. In Climate Change 2013: Impacts, Vulnerability and Adaptation. Part A: Global and Sectorial Aspects. Contribution of Working Group 2 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Field C, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjhee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds). Cambridge University Press: Cambridge, UK and New York, NY,1–32.

Koren I, Altaratz O, Remer LA, Feingold G, Martins JV, Heiblum RH (2012) Aerosol-induced intensification of rain from the tropics to the mid-latitudes, Nature Geoscience: 5, 118-122, 10.1038/ngeo1364.

Kousky VE, (1988) Pentad outgoing longwave radiation climatology for the South America sector. Revista Brasilera de Meteorología 3: 217-231.

Li W, Fu R. (2006) Influence of Cold Air Intrusions on the Wet Season Onset over Amazonia, J. Climate, 19:257-275.

Li W, Fu R, Dickinson RE (2006) Rainfall and its seasonality over the Amazon in the 21st century as assessed by the coupled models for the IPCC AR4, J. Geophys. Res: 111, D02111, doi:10.1029/2005JD006355.

Liebmann B, Marengo JA (2001) Interannual variability of the rainy season and rainfall in the Brazilian Amazon Basin. Journal of Climate 14: 4308–4318.

Liebmann, B., G. N. Kiladis, J. A. Marengo, T. Ambrizzi, and J. D. Glick, 1999: Submonthly convective variability over South America and the South Atlantic convergence zone. *J. Climate*, **12,** 1877–1891

Machado LAT, Silva Dias M.AF, Morales C, Fisch G, Vila D, Albrecht R, Goodman SJ, Calheiros AJP, Biscaro T, Kummerow C, Cohen J, Fitzjarrald D, Nascimento EL, Sakamoto MS, Cunningham C, Chaboureau JP, Petersen WA, Adams DK, Baldini L, Angelis CF, Sapucci LF, Salio P, Barbosa HMJ, Landulfo E, Souza RAF, Blakeslee RJ, Bailey J, Freitas S, Lima WFA, Tokay A (2014) The CHUVA Project. How Does Convection Vary across Brazil?, Bulletin of the American Meteorological Society, 95:1365-1380, 10.1175/bams-d-13-00084.1.

Madden, R. A.; P. R. Julian (1994) Observations of the 40–50-Day Tropical Oscillation—A Review. *Mon. Weather Rev.*, 122, 814–837.

Magrin GO, Marengo JA, Boulanger JP, Buckeridge MS, Castellanos E, Poveda G, Scarano FR, Vicuna S (2014) Central and South America. In Climate Change 2014: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge,

UK.

Makarieva AM, Gorshkov VG, Sheil D, Nobre AD, Li BL (2013) Where do winds come from? A new theory on how water vapor condensation influences atmospheric pressure and dynamics. Atmos. Chem. Phys. 13: 1039–1056, doi: 10.5194/ acp-13-1039-2013.

5   Marengo JA (1992) Interannual variability of surface climate in the Amazon basin. Int. J. Climatol. 12: 853–863.

Marengo JA, Espinoza JC (2015) Extreme seasonal droughts and floods in Amazonia: causes, trends and impacts. Int. J. Climatol., n/a – n/a, doi:10.1002/joc.4420. http://doi.wiley.com/10.1002/joc.4420

Marengo JA, Liebmann B, Kousky VE, Filizola NP, Wainer IC (2001) Onset and end of the rainy season in the Brazilian Amazon basin. J. Climate, 14: 833-852.

10   Marengo JA, Nobre CA, Tomasella J, Oyama MD, Oliveira GS, de Oliveira R, Camargo H, Alves LM, Brown IF (2008). The drought of Amazonia in 2005. J. Clim. 21: 495–516, doi: 10.1175/2007JCLI1600.1.

Marengo JA, Tomasella J, Alves LM, Soares W, Rodriguez DA (2011) The drought of 2010 in the context of historical droughts in the Amazon. region. Geophys. Res. Lett., 38: 1-5.

Marengo JA, Liebmann B, Grimm AM, Misra V, Silva Dias PL, Cavalcanti IFA, Carvalho LMV, Berbery H, Ambrizzi T,
15   Vera CS, Saulo AC, Nogues Paegle J, Zipser E, Seth A, Alves LM (2012) Recent developments on the South American monsoon system. Int. J. Climatol. 32: 1–21, doi: 10.1002/joc.2254.

Martin ST, Artaxo P, Machado LAT, Manzi AO, Souza RAF, Schumacher C, Wang J, Andreae M O, Barbosa HMJ, Fan J, Fisch G, Goldstein AH, Guenther A, Jimenez JL, Pöschl U, Silva Dias MA, Smith JN,, Wendisch M (2016) Introduction: Observations and modeling of the Green Ocean Amazon (GoAmazon2014/5), Atmospheric Chemistry and Physics, 16:
20   4785-4797, 10.5194/acp-16-4785-2016,

Martins JA, Dias MAF, Goncalves, FLT (2009a) Impact of biomass burning aerosols on precipitation in the Amazon: A modeling case study, Journal of Geophysical Research-Atmosperes, 114: 19, 10.1029/2007jd009587, 2009a.

Martins JA, Goncalves FLT, Morales CA, Fisch GF, Pinheiro FGM, Leal JBV, Oliveira CJ, Silva EM, Oliveira JCP, Costa AA, Silva Dias MAF. (2009b) Cloud condensation nuclei from biomass burning during the Amazonian dry-to-wet transition
25   season, Meteorology and Atmospheric Physics, 104: 83-93, 10.1007/s00703-009-0019-6.

Muza MN, Carvalho LMV, Jones C, Liebmann B (2009) Intraseasonal and interanual variability of extreme dry and wet events over Southeastern South America and Sub- tropical Atlantic during the Austral Summer. J Clim 22:1682–1699.

Pöhlker ML, Pöhlker C, Klimach T, Hrabe de Angelis I, Barbosa HMJ, Brito J, Carbone S, Cheng Y, Chi X, Ditas F, Ditz R, Gunther SS, Kesselmeier J, Könemann T, Lavrič JV, Martin ST, Moran-Zuloaga D, Rose D, Saturno J, Su H, Thalman R,
30   Walter D, Wang J, Wolff S, Artaxo P, Andreae MO, Pöschl U (2016) Long-term observations of atmospheric aerosol, cloud condensation nuclei concentration and hygroscopicity in the Amazon rain forest – Part 1: Size-resolved characterization and new model parameterizations for CCN prediction Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-51.

Raia A, Cavalcanti IFA (2008) The Life Cycle of the South American Monsoon System. Journal of Climate 21: 6227–6246.

Rao VB, Cavalcanti IFA, Hada, K. (1996) Annual variation of rainfall over Brazil and water vapor characteristics over

South America. *J. Geophys. Res.*, 101: 835 26539-26551, doi:10.1029/96JD01936.

Reutter P, Su H, Trentmann J, Simmel M, Rose D, Gunther SS, Wernli H, Andreae MO, Pöschl U (2009) Aerosol and updraft-limited regimes of cloud droplet formation: influence of particle number, size and hygroscopicity on the activation of cloud condensation nuclei (CCN), Atmos. Chem. Phys., 9:7067– 7080, doi:10.5194/acp-9-7067-2009.

Ronchail J, Bourrel L, Cochonneau G, Vauchel P, Phillips L, Castro A, Guyot JL, de Oliveira E (2005) Climate and inundations in the Mamoré basin (South-Western Amazon – Bolivia). J. Hydrol. 302: 223–238.

Rudolf B, Beck C, Grieser J, Schneider U (2005) Global precipitation analysis products, Global Precipitation Climatology Centre (GPCC), DWD, 1–8.

Runyan CW, D'Odorico P, Lawrence D (2012) Physical and biological feedbacks of deforestation. Rev. Geophys., 50, RG4006,doi:10.1029/2012RG000394. http://doi.wiley.com/10.1029/2012RG000394

Salati E, Vose PB (1984) Amazon basin: a system in equilibrium. Science, 225: 129–138.

Shimizu MH, Ambrizzi T, Liebmann B. (2016) Extreme precipitation events and their relationship with ENSO and MJO phases over northern South America, Int. J. Climatol., Published online in Wiley Online Library, wileyonlinelibrary.com) DOI: 10.1002/joc.4893

Silva AE, Carvalho LMV. (2007) Large-scale index for South America Monsoon (LISAM). Atmospheric Science Letters, 8: 51-57.

Spracklen DV, Garcia-Carreras L (2015) The impact of Amazonian deforestation on Amazon basin rainfall. Geophys. Res. Lett., 42, 9546–9552, doi:10.1002/2015GL066063. http://doi.wiley.com/10.1002/2015GL066063.

Wang H, Fu R (2002) Cross-Equatorial Flow and Seasonal Cycle of Precipitation over South America. Journal of Climate, 15: 1591-1608.

Wang G, Sun S, Mei R (2011) Vegetation dynamics contributes to the multi-decadal variability of precipitation in the Amazon region. Geophys. Res. Lett., 38: L19703.

Wang H, Fu R (2002) Cross-equatorial flow and seasonal cycle of precipitation over South America. J. Climate, 15: 1591-1608.

Wang J, and coauthors (2016) Amazon boundary layer aerosol concentration sustained by vertical transport during rainfall, Nature-Letters, doi:10.1038/nature19819.

Williams E, Renno N (1993) An Analysis of the Conditional Instability of the Tropical Atmosphere, Mon Wea Rev. 121: 21-36.

Williams E, Dall'Antonia A, Dall'Antonia V, de Almeida J, Suarez F, Liebmann B, Malhado ACM. (2005) The drought of the century in the Amazon basin: an analysis of the regional variation of rainfall in South America in 1926. Acta Amazonia 35(2): 231–238, doi: 10.1590/S0044-59672005000200013.

Zhang Y, Fu R, Yu J, Qian Y, Dickinson R, Silva Dias MAF, da Silva Dias PL , Fernandes K (2009) Impact of biomass burning aerosol on the monsoon circulation transition over Amazonia, Geophys. Res. Lett., 36, L10814, doi:10.1029/2009GL037180.

Yoon JH, Zeng N. (2010) An Atlantic influence on Amazon rainfall. Clim. Dyn. 34: 249–264, doi: 10.1007/s00382-009-0551-6.

Yoon JH, Zeng N. (2010) An Atlantic influence on Amazon rainfall. Clim. Dyn. 34: 249–264, doi: 10.1007/s00382-009-0551-6.
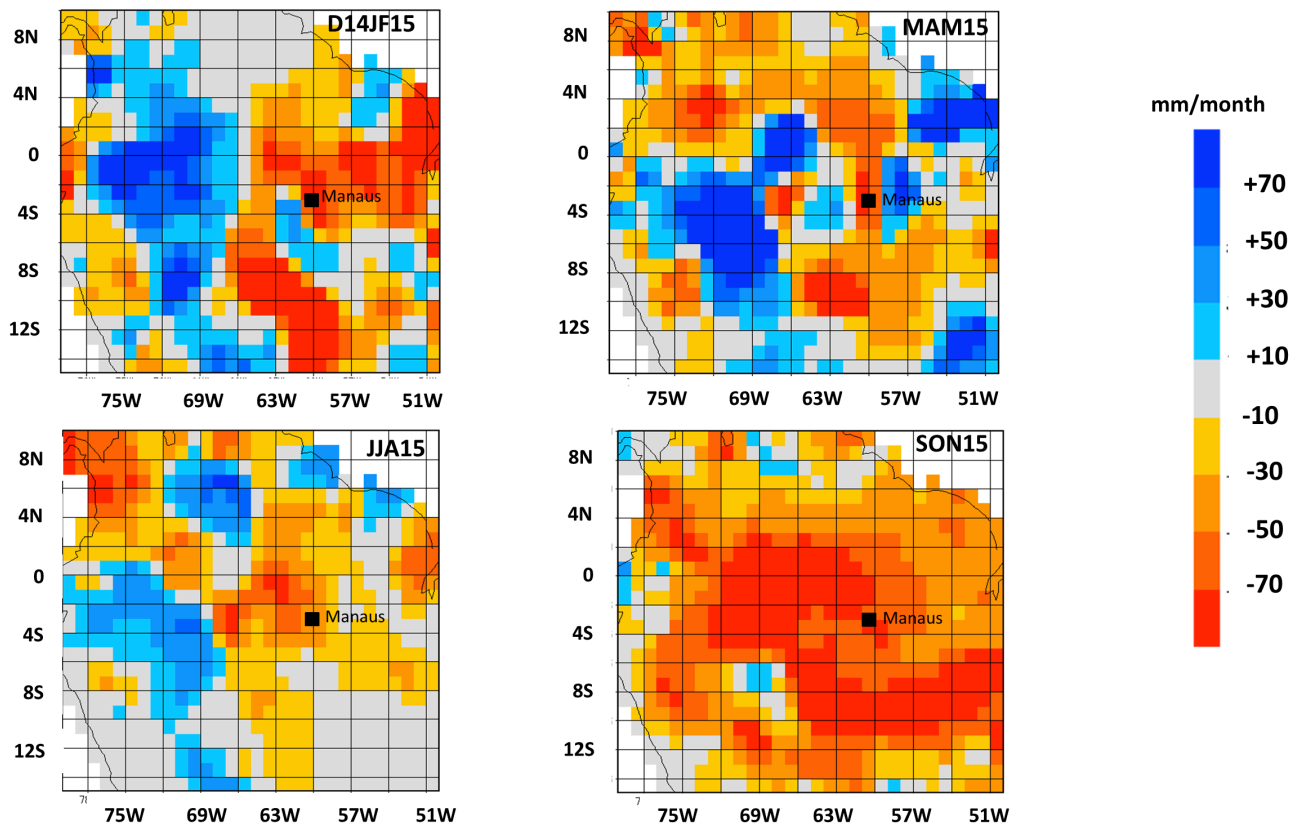
Figure 1. Rainfall anomaly (mm month^{-1}) for 3-month periods from December 2014-May 2015 to September-November 2015. Data comes from GPCC and anomalies are relative to the 1951-2001 climatology. Black square indicates the location of Manaus.
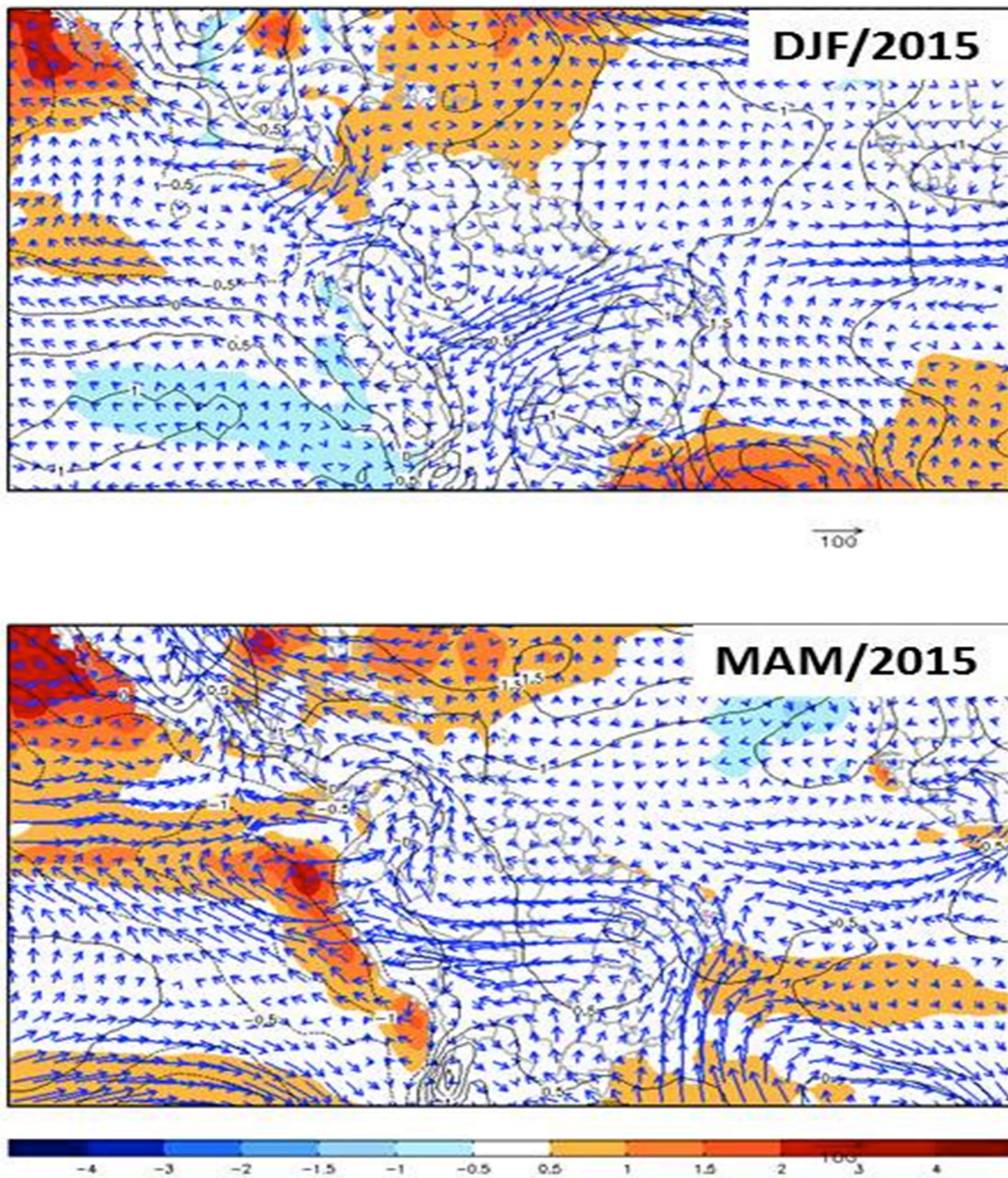
Figure 2. Seasonal SST anomalies (ºC), SLP anomalies (hPa), and anomalies of vertically integrated moisture transport (vectors) from the surface to 500 hPa in South America from December 2014 to May 2015. SST and circulation anomalies correspond to the 1961–2012 long-term mean. The bar at the bottom of the panel shows the scale of the SST anomalies. The vector at the bottom of the panel shows the scale of the moisture transport ($kg^{-1}ms^{-1}$). Black full lines show SLP anomalies (hPa)

WAM- Western Amazonia
CAM-Central Amazonia (nearby Manaus)
EAM-Eastern Amazonia
NEB- Northe4ast Brazil
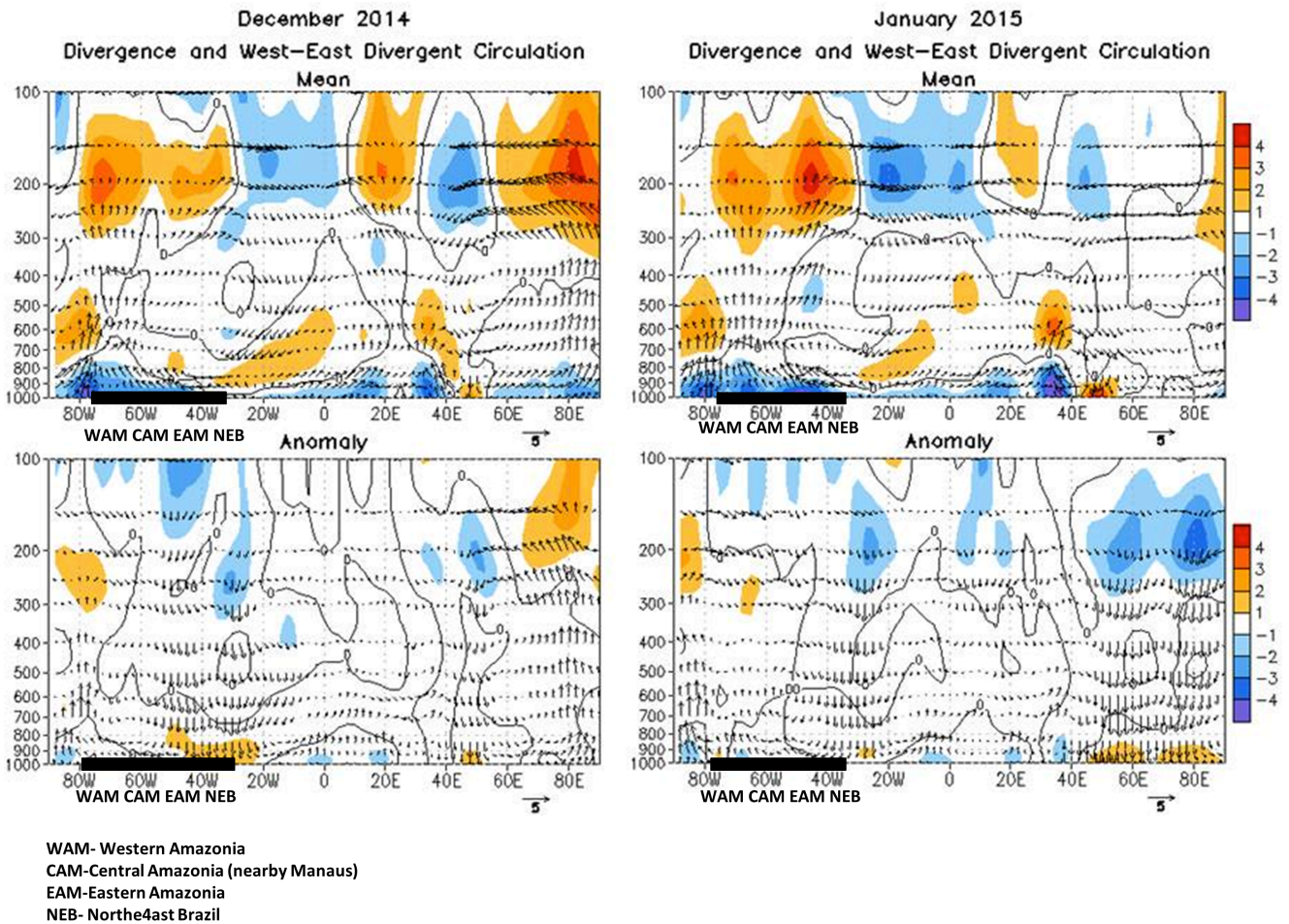
Figure 3. Pressure-longitude section (80°W-100°E) of the mean (top) and anomalies (bottom) of divergence (contour interval is 1 x 10⁻⁶ s⁻¹) and divergent circulation between 5°N-5°S. The divergent circulation is represented by vectors of combined vertical velocity and the divergent component of the zonal wind. Red shading and solid contours denote divergence (top) and anomalous divergence (bottom). Blue shading denotes convergence (top) and anomalous convergence (bottom). Anomalies are departures from the 1981-2010 long term mean.
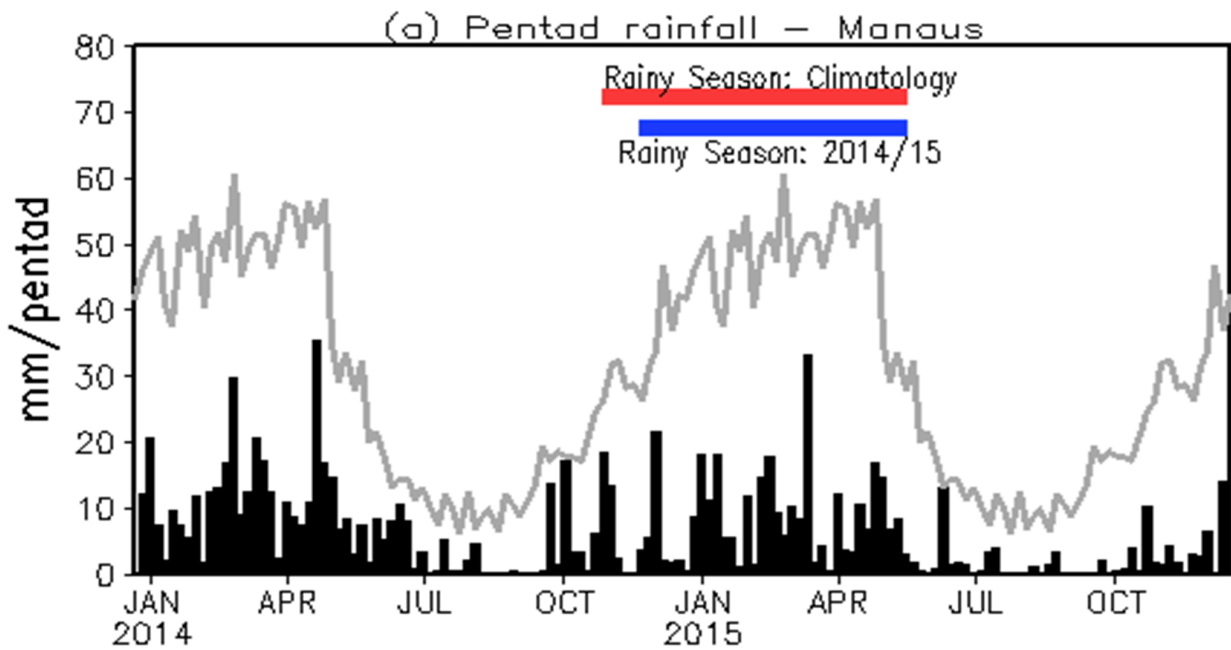
Figure 4. Pentad rainfall (mm/pentad) at Manaus (INMET site) from January 2014 to December 2015. Red bar
5   **shows the climatological occurrence of the onset and end of the rainy season, while blue bar indicates the onset and**
end for 2014-15. Grey line is the climatological annual cycle of pentad mean precipitation.
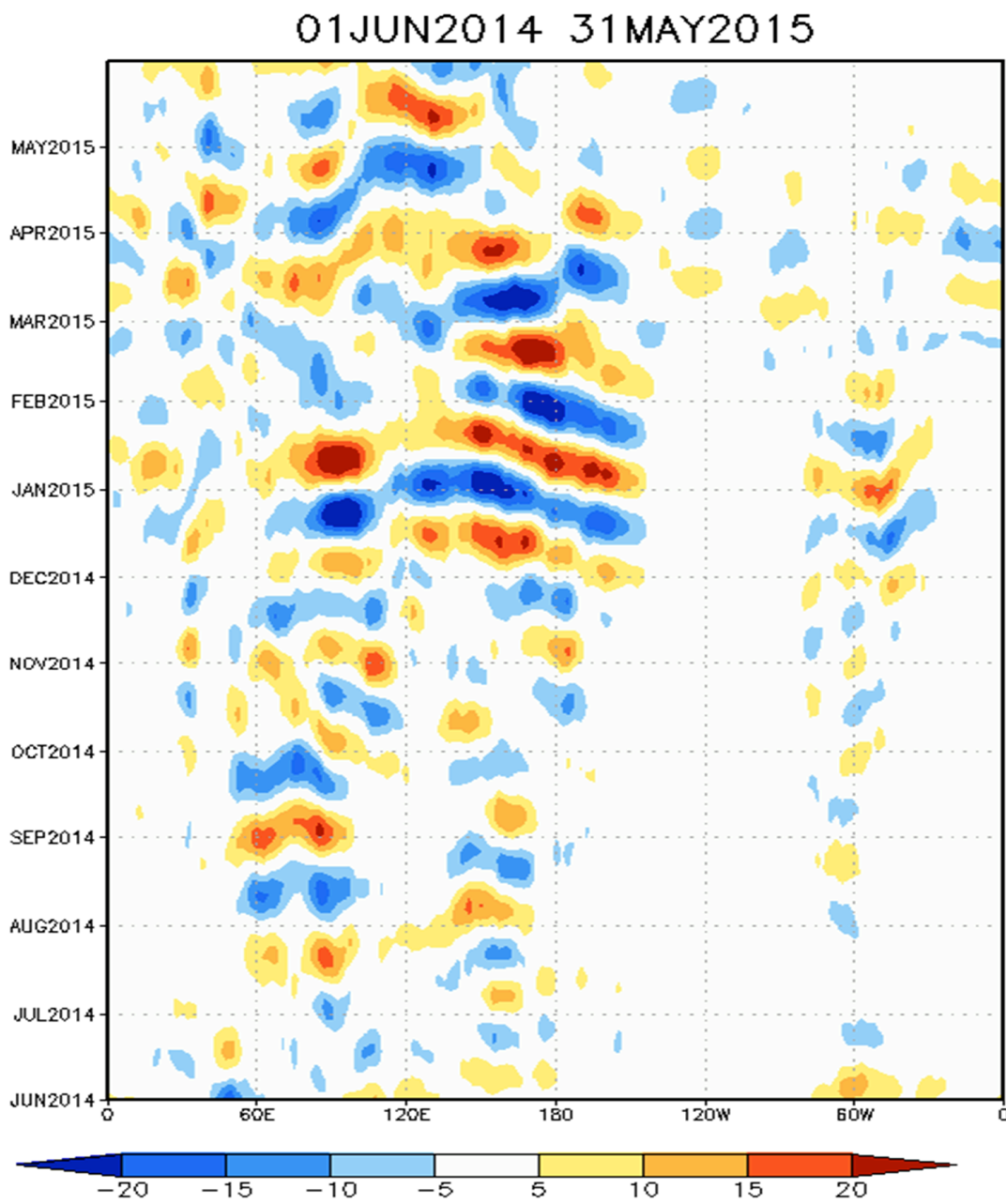
Figure 5. Hovmoller diagram of 30-60-day filtered OLR anomalies (W m^{-2}) along the Equator (5ºN-5ºS) during the period of June 2014 to May 2015.
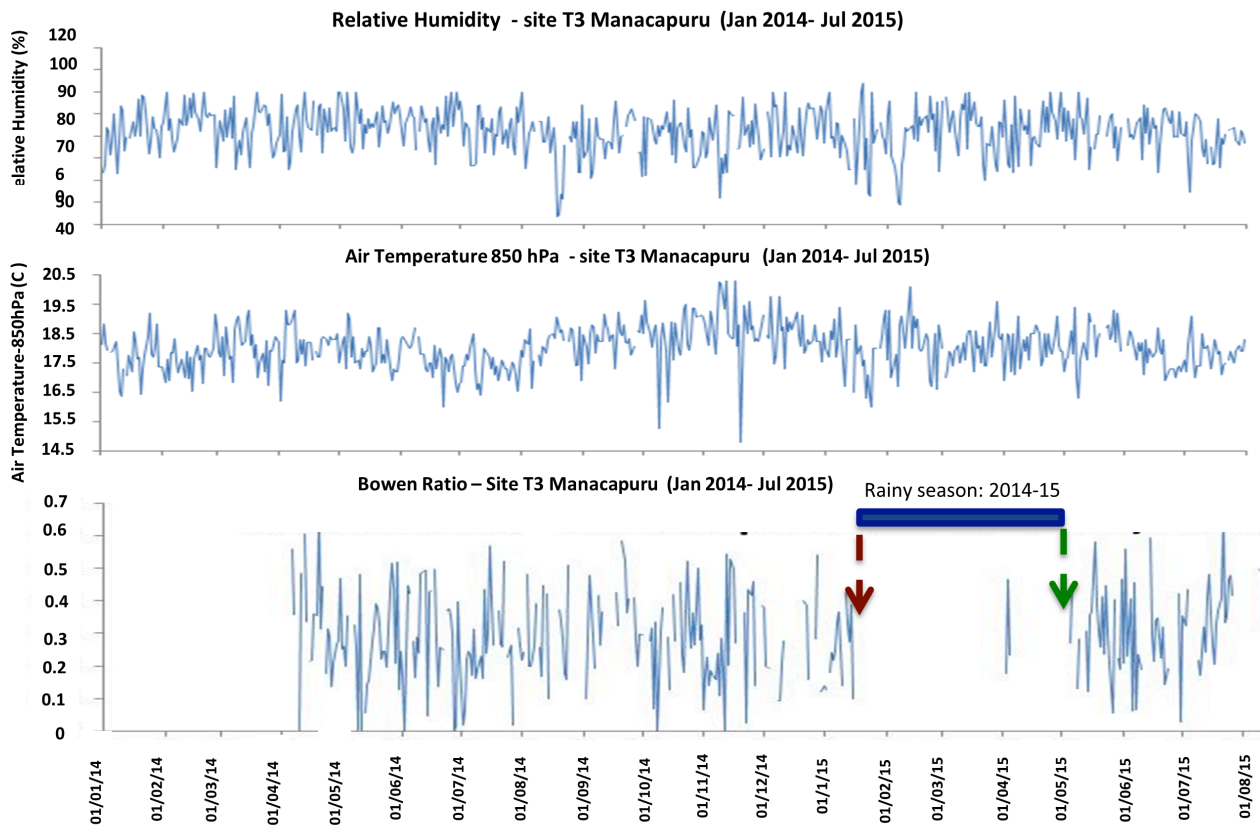
Figure 6. Daily variation of relative humidity (%), 850 hPa air temperature (°C) and Bowen ratio at the T3 Manacapuru site, from January 2014 to July 2015. Blue bar indicates the onset and end of the rainy season for 2014-15. No Bowen ratio data were available during some days between January 2014 and July 2015.
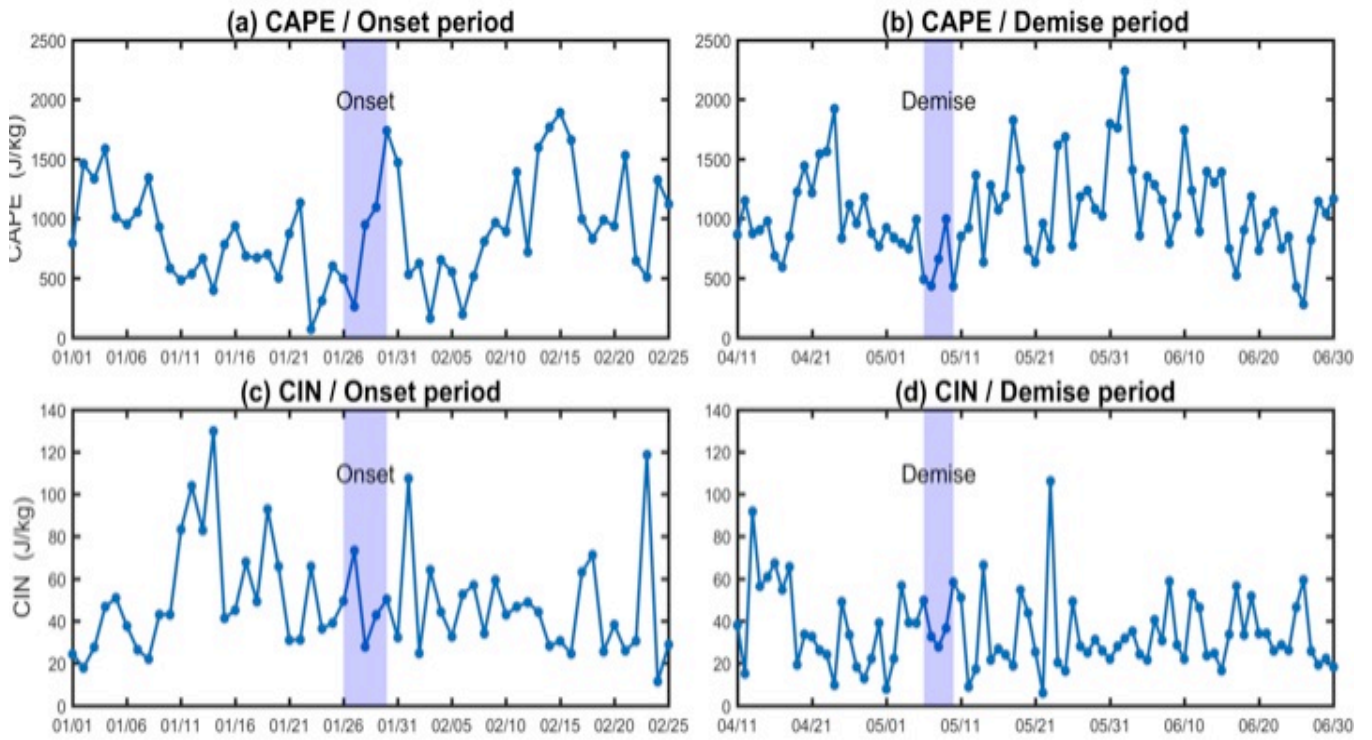
Figure 7. Daily variation of CAPE and CIN (J kg⁻¹) from January 1 to February 25, 2015 (around the onset of the rainy season) and from April 11 to June 30 (around the demise of the rainy season) at Manaus. Pentads of the onset and demise are identified with blue vertical bars.
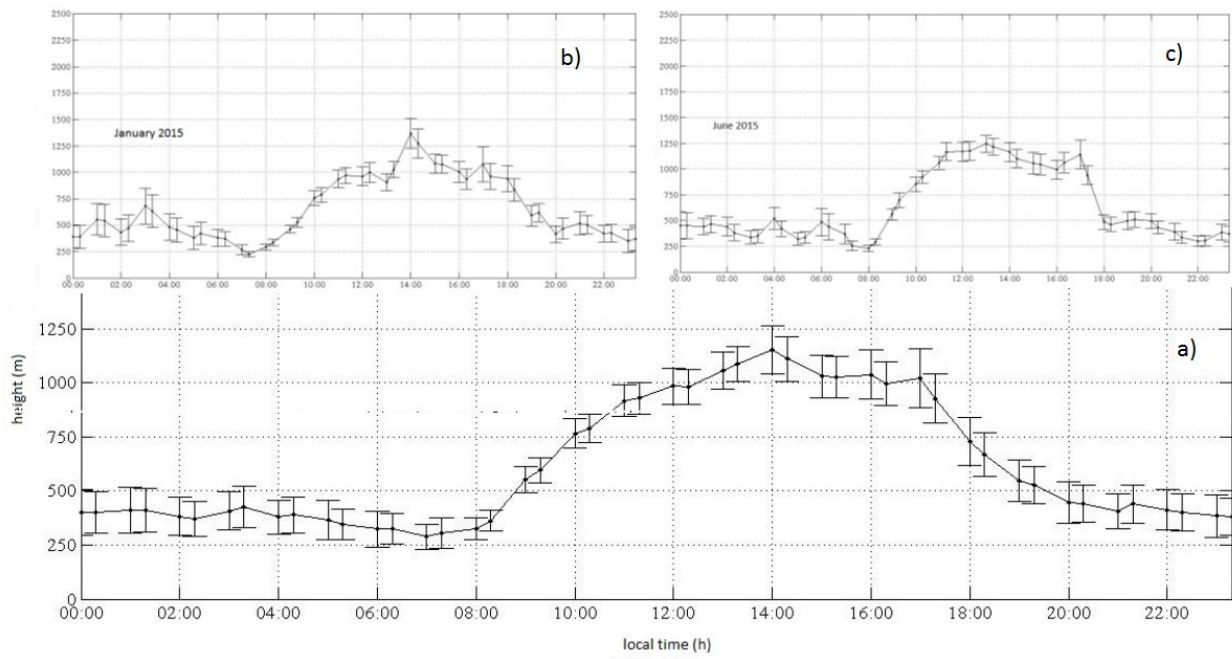
Figure 8. Diurnal cycle of the height of boundary (m) layer (average from January 1 up to June 30, 2015) (a); from January 2015 (b) and June 2015 (c).