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Large-Scale Vertical Velocity, Diabatic Heating and Drying Profiles Associated with Seasonal and Diurnal Variations of Convective Systems Observed in the GoAmazon2014/5 Experiment

Shuaiqi Tang[1], Shaocheng Xie[1], Yunyan Zhang[1], Minghua Zhang[2], Courtney Schumacher[3], Hannah Upton[3], Michael P. Jensen[4], Karen L. Johnson[4], Meng Wang[4], Maike Ahlgrimm[5], Zhe Feng[6], Patrick Minnis[7] and Mandana Thieman[8]

[1]Lawrence Livermore National Laboratory, Livermore, CA, 94550, USA
[2]School of Marine and Atmospheric Sciences, tony Brook University, Stony Brook, NY, 11794, USA
[3]Department of Atmospheric Sciences, Texas A&M University, College Station, TX, 77843, USA
[4]Brookhaven National Laboratory, Upton, NY, 11973, USA
[5]European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading RG2 9AX, United Kingdom
[6]Pacific Northwest National Laboratory, Richland,Washington, 99354, USA
[7]NASA Langley Research Center, Hampton, VA, 23681, USA
[8]Science Systems and Applications, Inc, Hampton, VA 23666, USA

Correspondence to: Shuaiqi Tang (tang32@llnl.gov)

Abstract. This study describes the characteristics of large-scale vertical velocity, apparent heating source (Q_1) and apparent moisture sink (Q_2) profiles associated with seasonal and diurnal variations of convective systems observed during the two intensive operational periods (IOPs) of the Green Ocean Amazon (GoAmazon2014/5) experiment, which was conducted near Manaus, Brazil in 2014 and 2015. The derived large-scale fields have large diurnal variations according to convective activity in the GoAmazon region and the morning profiles show distinct differences between the dry and wet seasons. In the wet season, propagating convective systems originating far from the GoAmazon region are often seen in the early morning, while in the dry season, they are rarely observed. Afternoon convective systems due to solar heating are frequently seen in both seasons. Accordingly, in the morning, there is strong upward motion and associated heating and drying throughout the entire troposphere in the wet season, which is limited to lower levels in the dry season. In the afternoon, both seasons exhibit weak heating and strong moistening in the boundary layer related to the vertical convergence of eddy fluxes. A set

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of case studies of three typical types of convective systems occurring in Amazonia - i.e., locally-occurring systems, coastal-occurring systems and basin-occurring systems - is also conducted to investigate the variability of the large-scale environment with different types of convective systems.

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1. Introduction

Amazonia is one of the major tropical convective regions in the global climate system. It provides moisture to the global hydrological cycle and energy to drive the global atmospheric circulation. Understanding convective systems over the Amazon region through observations is important for understanding and simulating global circulation and climate. However, most of Amazonia is covered by tropical forest with only a few observational sites. In order to collect the observations needed to improve our understanding of convective systems over Amazonia, several major field campaigns have been conducted in this area such as the Amazon Boundary Layer Experiments (Harriss et al., 1988; Harriss et al., 1990), the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) (Silva Dias et al., 2002b), and the CHUVA project (Machado et al., 2014).

Recently, an internationally collaborative experiment, the Observations and Modeling of the Green Ocean Amazon (GoAmazon2014/5) (Martin et al., 2016), was conducted in the region around Manaus, Brazil from January 2014 to December 2015 with a focus on the aerosol and cloud life cycles and aerosol-cloud-precipitation interactions over tropical rainforests. Two 40-day Intensive Operational Periods (IOPs) were conducted to investigate the seasonal variations of clouds and aerosols, as well as their interactions. IOP1 took place from 15 February to 26 March 2014 during the wet season, and IOP2 took place from 1 September to 10 October 2014 during the dry season. The goal of this study is to document and understand the seasonal variability and diurnal cycle of large-scale vertical velocity, heat and moisture budgets associated with the convective systems observed during the two IOPs in the GoAmazon2014/5 experiment.

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The Amazon region has a significant seasonal variation in precipitation amount. Rainfall is approximately 300 mm per month during the wet season while it is close to 100 mm per month during the dry season (Tanaka et al., 2014). Many studies have examined the seasonal variation of clouds and precipitation in Amazonia (e.g. Fu et al., 2001; Schumacher and Houze, 2003; Machado et al., 2004; Li et al., 2006; Marengo et al., 2012). Compared to the large variation in clouds and rainfall, the seasonal variation in CAPE is small (Machado et al., 2004; Martin et al., 2016), which implies that small perturbations in the large-scale circulation can drive dramatic changes in hydrological fields in this region. Few studies, however, have studied the seasonal variation of the diabatic heating and drying structures associated with the convective systems in the Amazon region.

The diurnal cycle of the atmosphere is an important feature that is poorly simulated in climate models. Many efforts have been made to observe and to understand the diurnal cycle over the Amazon basin using surface observations (e.g. Harriss et al., 1990; Cutrim et al., 2000; Machado et al., 2004; Tanaka et al., 2014) or satellite data (e.g. Minnis and Harrison, 1984; Greco et al., 1990; Janowiak et al., 2005; Burleyson et al., 2016). The diurnal cycle over the Amazon basin is complex because it is affected by three types of convective systems: locally-occurring systems (LOS) generated locally in the form of small convective cells (area less than 1000 km^2) with short life time (on the order of 1 hour), coastal-occurring systems (COS) initialized at the northeast coast of Brazil by the sea-breeze and propagating inland as squall lines, and basin-occurring systems (BOS) initialized in the Amazon basin in the form of mesoscale convective systems (MCS) with areas larger than 1000 km^2 (Greco et al., 1990). These systems reach Manaus, near the center of the Amazon basin, at different times of the day, causing a broad peak of precipitation from morning to early afternoon (e.g. Machado et al., 2004; Tanaka et al.,

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2014; Burleyson et al., 2016). Schumacher et al. (2007) examined the diurnal cycle of the large-scale Q_1 budget in the southwest Amazon during LBA, but used only two profiles per day, which do not capture the rapidly changing environment. In addition, the diurnal cycle over the highly deforested southwest Amazon is not necessarily representative of the more pristine central Amazonian rainforest.

In this study we use data collected from the comprehensive GoAmazon2014/5 field campaign to examine the seasonal and diurnal variations of the large-scale vertical velocity and heat and moisture budgets associated with the convective systems that occur in central Amazonia. Section 2 provides details of the data and method used to derive the large-scale profiles for the GoAmazon2014/5 experiment. Section 3 describes the synoptic conditions for the two IOPs. Sections 4 and 5 show the seasonal variation and diurnal cycle of the large-scale fields, respectively. Section 6 further investigates three selected cases representing different types of convective systems in the wet season. The summary and discussion are given in Section 7.

2. Data and Method

Due to the lack of an appropriate sounding array to capture the divergence and advection fields in the analysis domain, the large-scale vertical velocity and budgets analyzed in this study were derived by using, as a first guess, the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis data that are subsequently constrained with surface and top of atmosphere (TOA) observations. The upper-level fields from ECMWF analysis data are adjusted to conserve the vertical integration of mass, moisture and dry static energy through a constrained variational analysis technique described in Zhang and Lin (1997) and Zhang et al.

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(2001). As indicated in Xie et al. (2004), the use of the surface and TOA observations as constraints improves the quality of the large-scale vertical velocity and budgets in operational analysis data and makes the data suitable for budget analysis and cloud modeling studies. An important by-product of this study is the derived large-scale forcing data supporting modeling studies, which are available to the community at the Atmospheric Radiation Measurement (ARM) program Archive (http://iop.archive.arm.gov/arm-iop/0eval-data/xie/scm-forcing/iop_at_mao/).

Figure 1 shows the location of the GoAmazon2014/5 experiment and the analysis domain (the red octagon, referred to as the GoAmazon domain) used in this study. The observational research sites and major cities near the region are also shown on the map. The required surface and TOA fluxes as the constraints for the variational analysis are constructed as follows. The precipitation used in this study is derived from the System for the Protection of Amazonia (SIPAM) S-band (10 cm wavelength) radar operated at Ponta Pelada airport, the center of the GoAmazon domain. The SIPAM radar reflectivity constant altitude plan position indicator (CAPPI) at 2.5 km above ground was used to generate the rain rate products using a single Z-R relation of $Z = 174.8R^{1.56}$ derived from Joss-Waldvogel disdrometer data obtained by the CHUVA campaign near Manacapuru during the wet season of early 2014. Other surface constraint variables, such as surface radiative fluxes and latent and sensible heat fluxes, are obtained from the broadband radiometer (ARM Climate Research Facility, 1994) and eddy correlation flux measurement system (ARM Climate Research Facility, 2003) at the ARM Mobile Facility site near Manacapuru (3.213°S, 60.598°W; “ARM site” in Figure 1). Observations of latent and sensible heat fluxes at two other Brazilian research sites - K34 (“FLUXNET-BR Ma2” in Figure 1) and the Amazon Tall Tower Observatory (“ATTO Tower” in Figure 1) - are also used. Because of the limited number of surface sites, it is challenging to obtain domain mean fluxes that can well represent the analysis domain. In this study, we use the Cressman's objective analysis method (Cressman, 1959) to incorporate these limited observations into the analysis with the ECMWF analysis as the first guess. The TOA measurements of broadband radiative fluxes are estimated from the Thirteenth Geostationary Operational Environmental Satellite (GOES-13) 4-km visible (0.65 µm) and infrared window (10.8 µm) radiances using the narrowband-to-broadband (NB-BB) conversion method of Minnis and Smith (1998) that was updated similar to Khaiyer et al. (2010), with some modifications to more closely match those measured by the Clouds and Earth's Radiant Energy System (CERES) on the Aqua and Terra satellite. All data are interpolated into 3 h and 25 hPa (if applicable) temporal and vertical resolutions, respectively.

3. Background of Synoptic Conditions

The IOP-averaged sea-level pressure and 10-meter horizontal winds from ERA-Interim reanalysis (Dee et al., 2011) are plotted in Figure 2. During IOP1, the Atlantic Intertropical Convergence Zone (ITCZ) was located near the Equator; while during IOP2, it was located near 10°N. A fourteen-day trajectory study shows that the air masses over Manaus typically come from the Northern Hemisphere during IOP1 and from the Southern Hemisphere during IOP2 (Martin et al., 2016). The top three rows of Figure 3 show the domain-averaged zonal (u) wind, meridional (v) wind, and relative humidity relative to liquid water, from the adjusted ECMWF analysis. Consistent with those derived from radiosonde data in Martin et al. (2016), IOP1 was dominated by northeasterly winds in the lower troposphere, with moist air throughout the troposphere; IOP2 was dominated by easterly winds in the lower troposphere, with a dry free troposphere.

The cloud frequency and domain-mean precipitation observed during IOP1 and IOP2 are shown in the remaining two rows of Figure 3. The cloud frequency was derived from the Active Remote Sensing of Clouds (ARSCL) (Kollias et al., 2007) product, which uses a combination of the 95GHz W-band ARM cloud radar (WACR), micropulse lidar (MPL), and ceilometer located at the ARM site to determine a best-estimate cloud mask with 5-second temporal and 30-meter vertical resolution. The ARSCL product leverages each instrument's strengths: the WACR penetrates non-precipitating thick clouds, the MPL is sensitive to thin clouds, and the ceilometer reliably detects cloud base. The ARSCL-derived cloud mask data were then used to produce 3-hourly cloud frequencies following the method described in Xie et al. (2010b). The wet season has more cloud and precipitation events than the dry season. However, the convective systems in the dry season are typically more intense than those occurring in the wet season (Giangrande et al., 2016, accepted). Compared to 15-year climatology, the precipitation around Manaus during 2014 has a positive anomaly in IOP1 and negative anomaly in IOP2 (Burleyson et al., 2016; Martin et al., 2016). Nevertheless, the annual cycle in 2014 is still broadly representative of the climatology (Burleyson et al., 2016).

4. Seasonal Variation

In this section, we focus on the contrast between the dry and wet season large-scale vertical velocity and energy and moisture budgets. The upper row of Figure 4 shows the temporal evolution of large-scale vertical velocity in IOP1 (wet season, left) and IOP2 (dry

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season, right), and the IOP-mean profiles are shown as the black solid lines in the bottom row. We also define rainy (black dotted lines) and non-rain periods (gray lines) using a threshold of 0.2 mm hr^{-1}. A value of 0.2 mm hr^{-1} rather than 0 mm hr^{-1} is used because in some cases ground clutter in the SIPAM radar data may be misinterpreted as light precipitation. Changing the threshold affects the magnitude of the vertical profiles but does not change the seasonal contrast and the results of this study. Using this threshold, the percentage of the rainy period to the entire IOP is 36.9% for IOP1, but is 17.8% for IOP2, indicating that the rain frequency is an important factor impacting the seasonal mean contrast. The red and blue lines represent the mean profiles of morning (at 5 local time (LT)) precipitation systems and afternoon (at 14 LT) precipitation systems, respectively, which will be discussed in Section 5.

The non-rain vertical velocity profiles are relatively weak, with downward motion dominating in the upper troposphere during both dry and wet seasons. The rainy vertical velocity profiles show strong upward motion throughout the troposphere during both IOPs, but the level of maximum upward motion is different. The upward motion during the rainy period of IOP1 has a broad peak structure from ~700 to 300 hPa with the maximum at ~350 hPa. The 350-hPa upward motion peak is consistent with that shown in the Tropical Ocean and Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) (Lin and Johnson, 1996), but lower than the peak of ~265 hPa observed in the Tropical Warm Pool-International Cloud Experiment (TWP-ICE) (Xie et al., 2010a). The upward motion during the IOP2 rainy period also has a broad peak but the maximum is at a much lower level (~550 hPa) than in IOP1. Because the frequency of the rainy period is higher in IOP1 than in IOP2, the IOP-mean upward motion is stronger during IOP1 but weaker and limited to the lower troposphere during IOP2. As discussed in the next section, the difference in morning precipitation systems

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largely contributes to the seasonal contrast in the vertical velocity profiles between the wet and dry seasons.

Figures 5 and 6 show the temporal evolution and IOP-mean of apparent heating Q_1 and apparent drying Q_2 profiles, respectively. Q_1 and Q_2 were first introduced by Yanai et al. (1973) to estimate the diabatic processes:

$$\begin{aligned} Q_1 &= \frac{\partial \bar{s}}{\partial t} + \overline{\vec{V}} \cdot \nabla \bar{s} + \bar{\omega} \frac{\partial \bar{s}}{\partial p} \\ &= Q_{rad} + L_v\left(c-e\right) - \frac{\partial \overline{\omega' s'}}{\partial p} \end{aligned} , \qquad (1)$$

$$\begin{aligned} Q_2 &= -L_v\left(\frac{\partial \bar{q}}{\partial t} + \overline{\vec{V}} \cdot \nabla \bar{q} + \bar{\omega} \frac{\partial \bar{q}}{\partial p}\right) \\ &= L_v\left(c-e\right) + L_v \frac{\partial \overline{\omega' q'}}{\partial p} \end{aligned} , \qquad (2)$$

where $s = C_p T + gz$ is the dry static energy; q is water vapor mixing ratio; $\vec{V}$ is horizontal wind vector; ω is vertical velocity in pressure coordinate; Q_{rad} is radiative heating; $L_v\left(c-e\right)$ is the latent heat from water condensation and evaporation (in general it also includes the latent heat and water vapor change from ice phase change); the overbar refers to a horizontal average and the prime refers to a deviation from the average. Q_1 and Q_2 are calculated from the large-scale dynamics (the first lines of the equations) and represent the unresolved physical heat sources and moisture sinks (the second lines). The vertical distributions of heating and drying profiles are important to the large-scale circulation as discussed in many other studies (e.g. Hartmann et al., 1984; Lau and Peng, 1987; Puri, 1987; Hack and Schubert, 1990).

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Similar to the profiles of vertical velocity, non-rain Q_1 and Q_2 profile magnitudes in both IOPs are weak with small amounts of heating and moistening below 600 hPa indicative of non-precipitating or very weakly precipitating shallow cumulus and congestus clouds (Schumacher et al., 2008). Rainy period Q_1 and Q_2 profiles show strong heating and drying throughout the troposphere during both IOPs associated with deep convection, and both of them have double peak structures that vary between dry and wet seasons. Q_1 during IOP1 has a broad primary peak between 600 and 400 hPa, while the primary Q_1 peak during IOP2 maximizes more sharply at 550 hPa. The secondary peaks of Q_1 are at ~750 hPa in both IOPs. The peaks of Q_2 in IOP1 (at 500 and 750 hPa) are higher than those in IOP2 (at 650 and 800 hPa). The double peak features of Q_1 and Q_2 are likely due to different physical processes. For Q_1, the local minimum usually occurs near the melting level (~600 hPa), indicating latent cooling due to ice melting. Because the melting level is nearly constant in the tropics, the local minimums of Q_1 are more or less at the same level as seen in other tropical field campaigns (e.g. Schumacher et al., 2008; Xie et al., 2010a). For Q_2, the double-peak structure is the combined effect of convective (lower peak) and stratiform (higher peak) rain production (Lin and Johnson, 1996). The peak levels for stratiform and convective clouds may vary in different locations and times such as in the two IOPs in this study.

5. Diurnal Cycle

The diurnal cycles of domain mean radar-derived precipitation and surface CAPE and convective inhibition (CIN) for both IOPs are plotted in Figure 7. Precipitation in IOP1 extends from early morning to afternoon, consistent with Tanaka et al. (2014). In IOP2, most of the

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precipitation occurs in the afternoon. The magnitude of afternoon precipitation in IOP2 is just slightly smaller than that in IOP1, but the magnitude of morning precipitation in IOP2 is significantly lower than that in IOP1, indicating that the differences between dry and wet seasons are mainly due to the morning precipitation events. The surface CAPE has similar magnitudes in the daytime during IOP1 and IOP2, but in the early morning it rises later and slower during IOP1 than during IOP2, probably because early morning precipitation during IOP1 has released atmospheric instability. The surface CIN is typically small, especially during IOP1, which is due to the high surface relative humidity over the Amazon rainforest.

The diurnal cycles of cloud frequency, large-scale vertical velocity, Q_1, Q_2 and $Q_1 - Q_2$ for IOP1 (left) and IOP2 (right) are shown in Figure 8. Derived from Eq. (1) and (2),

$$Q_1 - Q_2 = Q_{rad} - \frac{\partial \overline{\omega' h'}}{\partial p} \quad (3)$$

where $h = s + L_v q$ is the moist static energy. With the phase change of water vapor cancelled, $Q_1 - Q_2$ represents the radiative effect and the vertical convergence of eddy fluxes.

Consistent with the diurnal cycles of precipitation, the observed clouds and large-scale vertical velocity differ primarily in the morning between IOP1 and IOP2. In IOP1, the early morning upward motion peaks at 700 hPa and extends to the upper troposphere around 200 hPa. The early afternoon upward motion peaks at the upper troposphere and extends above 100 hPa. Accordingly, clouds are mainly seen between 800 and 500 hPa in the early morning but throughout the entire troposphere in the afternoon. In IOP2, morning convective systems are generally limited to the lower levels, as shown by weak upward motion below 600 hPa and downward motion above. Thus, few clouds are observed in the lower and middle troposphere

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while some high clouds remain from the previous day's convective activities. The afternoon convective systems are strong and deep in both IOPs, with upward motion in the upper troposphere associated with convective cloud growth and downward motion in the lower troposphere associated with convective downdrafts.

Consistent with the clouds and vertical velocity, Figure 8 also shows significant seasonal differences of Q_1 and Q_2 profiles in the morning, with heating and drying extending to the upper troposphere in IOP1 but cooling and moistening above 600-650 hPa in IOP2. In the afternoon, both IOPs show strong heating and drying in the middle and upper troposphere with weak heating and strong moistening occurring below 700 hPa. The low-level heating and moistening feature has been observed in trade wind regimes during westerly wind bursts and monsoon break periods (Nitta and Esbensen, 1974; Lin and Johnson, 1996; Johnson and Lin, 1997; Xie et al., 2010a), in which the vertical convergence of eddy fluxes and detrainment of shallow cumulus were considered as the causes. In this study it is also seen in the afternoon precipitating periods (red lines in Figure 5 and 6). The last row in Figure 8 shows $Q_1 - Q_2$ where two positive centers are seen during daytime at ~750 to 950 hPa and ~250 to 550 hPa, respectively. Considering the two terms in the right-hand-side of Eq. (3), the troposphere usually has a radiative cooling effect and therefore Q_{rad} is usually negative. The positive $Q_1 - Q_2$ has to be due to the vertical convergence of eddy fluxes of moist static energy associated with convective process, where positive Q_1 comes from vertical convergence of dry static energy flux, and negative Q_2 comes from vertical convergence of moisture flux.

6. Case Studies

A set of case studies is conducted to further understand the large-scale vertical velocity and heat and moisture budgets for the three typical types of convective systems that often occur in the wet season in Amazonia: locally-occurring systems (LOS), coastal-occurring systems (COS), and basin-occurring systems (BOS). Previous studies have found that LOS often occur in the afternoon characterized as scattered convections generated through solar heating at the surface, while most COS and BOS are propagating systems associated with mid-level easterlies and westerlies, respectively (e.g. Cifelli et al., 2002; Silva Dias et al., 2002a; Williams et al., 2002), and affect Manaus in the early morning. COS occurring in easterlies are often westward propagating squall-lines with intense leading lines that are more vertically developed. BOS generated in the westerlies are generally less vertically developed MCSs with a broad horizontal area and relatively homogeneous precipitation extending over a long time (Cifelli et al., 2002). Table 1 gives the number of each type of precipitation system observed during the two IOPs, identified from the radar loop (available at https://www.youtube.com/playlist?list=PLVqbwaasmlvtcu2kl_U5RaaNF0kYqW6ua) and the satellite infrared images (available at http://www-pm.larc.nasa.gov/). The two BOS cases identified in IOP2 both occurred in the Amazon basin, but their structures are more like COS as squall lines propagating westward. There are more COS and BOS in IOP1 than in IOP2, but the number of afternoon LOS in IOP1 is just slightly higher than that in IOP2. This again indicates that the frequency of morning propagating convective systems contributes to the variation of the diurnal cycle between the wet and dry seasons.

The three selected cases are a LOS starting from 11 LT, 13 March 2014, a COS starting from 2 LT, 20 March 2014 and a BOS starting from 17 LT, 1 March 2014. The times of these events are marked by the black lines in Figure 3. Mid-level wind was dominated by westerlies

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on 1 March (day 60) and easterlies on 20 March (day 79). Figure 9 shows representative scans of the radar reflectivity at elevation angle of 0.9° for these three cases, as well as the time series of the domain mean precipitation. The LOS case has many small-scale scattered convective cells that last for very short times (typically a couple of hours). Because of the small horizontal coverage of the convective cells, the domain mean precipitation is less than that in the other two cases. The COS case has a clear bow-shape echo indicating a squall line front. The horizontal size of the precipitating system is about 100 km and it moves quickly westward. The BOS case has a much larger horizontal area of moderate precipitation with some embedded convective cells. It moves southeastward and lasts more than 10 hours over the GoAmazon domain.

The point-observed cloud frequency and domain-averaged surface CAPE and CIN, u- and v-winds, relative humidity, large-scale vertical velocity, Q_1, and Q_2 for the three cases are shown in Figures 10-12, respectively. For the LOS case, the cloud frequency is much smaller than in the other two cases, since the convective cells have small horizontal extent and only occupy a small portion of the region. A shallow-to-deep transition of convective clouds can be seen. The surface CAPE is large, with weak mid-level winds and moist air at the surface before the convection occurred. Upward motion corresponds to the deep convection, and the magnitude is smaller than in the other two cases, consistent with weaker precipitation. Starting around 9 LT, Q_1 shows diabatic heating throughout the troposphere during the deep convection, while Q_2 shows strong moistening between 750 and 950 hPa and weak drying above that layer. The daytime moistening between 750 and 950 hPa due to the vertical convergence of eddy moisture fluxes can also be seen on many other days during the two IOPs and was discussed in Section 5. Note that there is a time lag between observed cloud frequency and the domain-averaged large-scale fields, which might be partially due to the fact that the cloud frequency observations were taken from vertically pointing instruments at the ARM site 67.8 km downwind of the center of the GoAmazon domain.

The COS (Figure 11) and BOS (Figure 12) cases both show a shallow-to-deep convective cloud transition from the previous evening to late afternoon, with a moist lower-level atmosphere. Both cases have smaller surface CAPE than the LOS case, possibly because the convective systems have released the atmospheric instability in the morning. The COS case passed through the GoAmazon domain between 6 and 12 LT in strong mid-level easterlies, with deep clouds and strong upward motion associated with the squall line. Stratiform clouds, associated with weak upward motion, remained in the upper levels until ~16 LT. Condensation from the deep convection contributes to strong diabatic heating and drying throughout the troposphere, while after the passage of the squall line, a few isolated convective cells moved in and the large-scale structure becomes similar to that in the LOS case, with upper-level heating and drying, low-level heating and moistening. The BOS case entered the GoAmazon domain earlier than the COS case. In weak mid-level westerlies and descending mid-to-low-level northerlies, the system moved slowly southeastward and remained in the domain for a longer time. Strong upward motion related to the MCS is seen from 18 to 6 LT. Large diabatic heating and drying related to the strong condensation is also seen. The remnant high clouds were maintained until ~18 LT with precipitation weakening over time. The upper-level heating and drying, lower-level cooling and moistening indicate that there are precipitating stratiform clouds in the upper level and evaporation of precipitation underneath.

7. Summary and Discussion

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This study presented the characteristics of the seasonal variation and diurnal cycle of the large-scale vertical velocity and diabatic heating (Q_1) and drying (Q_2) profiles for the two IOPs conducted during the GoAmazon2014/5 experiment. A constrained variational analysis method was used to derive the large-scale vertical velocity and Q_1 and Q_2 profiles based on surface and TOA observations and ECMWF analysis. The derived profiles correspond well with observed clouds and precipitation describing convective systems over Amazonia.

The large-scale environment over the region near Manaus has distinct seasonal variations and diurnal cycles. The wet season (IOP1) has more frequent precipitation events than the dry season (IOP2), especially in the morning. The large-scale upward motions during rainy periods have similar strength in both IOPs, however, the peak level in IOP1 is much higher than that exhibited in IOP2 (350 hPa vs. 550 hPa). Q_1 and Q_2 both have a double-peak feature during rainy period, but the physical mechanism may be different: the double peak of Q_1 may be due to the cooling near the melting level while the double peak of Q_2 may be due to the different height of convective and stratiform systems. The seasonal contrast is mainly due to the higher occurrence of morning mesoscale convective systems observed during IOP1. In the morning, upward motion peaks at ~700 hPa and extends to the upper troposphere during IOP1, while it is limited to the lower levels with downward motion at the upper levels during IOP2. Afternoon convective systems have a higher vertical motion peak than their morning counterparts, and both IOPs show similar vertical structures for the afternoon systems. The large-scale vertical velocity shows upward motion above 700 hPa and downward motion below. Accordingly, Q_1 and Q_2 also exhibit middle and upper level heating and drying related to the deep convection. Below 750 hPa, the profiles show relatively weak heating and strong moistening. This heating and moistening feature is due to the vertical convergence of eddy fluxes of heat and moisture in the boundary layer.

Three cases from IOP1 representing different types of convective systems that often occur in the region were chosen and analyzed in this study: locally-occurring systems (LOS), coastal-occurring systems (COS) and basin-occurring systems (BOS). The LOS case was characterized by many scattered and short-lived convective cells. It had relatively weak upward motion, heating and drying in the free troposphere, and heating and moistening in the boundary layer. The COS case occurred in strong mid-level easterlies. It was characterized as a squall line with deep strong profiles of upward motion, heating and drying. The BOS case mainly happened in weak mid-level westerlies and descending mid-to-low-level northerlies. It was characterized as widespread, moderate precipitation with embedded convective cells, and lasted much longer than the other two systems. The precipitating stratiform clouds remained at upper levels for several hours evident by upper-level condensational heating and lower-level evaporative cooling. The frequency of LOS cases is similar in both IOPs while the COS and BOS events occur much more often during the wet season than the dry season. The seasonal variation of the diurnal cycle of precipitation, clouds, and environmental variables is mainly due to the COS and BOS events observed in the morning.

Previous studies have also shown that the river breeze has an important influence on the diurnal cycle near the Amazon River (e.g. dos Santos et al., 2014; Tanaka et al., 2014; Burleyson et al., 2016) and that the impact of the local circulation can extend as far as 50 km away from the river. This local circulation and the horizontal inhomogeneity of large-scale vertical velocity, heating, and moistening could be better studied using high-resolution 3-D gridded large-scale forcing data from the three-dimensional constrained variational analysis recently developed by Tang and Zhang (2015) and Tang et al. (2016). This will be the subject of a future study.

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Figure and Table Captions:

Table 1: number of convective systems identified in the morning and afternoon during IOP1 and IOP2.

Figure 1: The location of GoAmazon site (top) and the analysis domain for this study (bottom). The SIPAM radar is located at Ponta Pelada (indicated by red pentagram). Locations of other cities and measurement sites are also indicated.

Figure 2: The sea-level pressure (shaded) and 10-meter horizontal wind (vector) averaged for IOP1 (left) and IOP2 (right). The pentagram indicates the location of GoAmazon site.

Figure 3: Domain averaged time series of (from top to bottom) horizontal (u) wind, meridional (v) wind, relative humidity, cloud frequency (point observation at the ARM site) and precipitation for IOP1 (left) and IOP2 (right). The blank areas in cloud frequency indicate missing data. The three straight black lines in IOP1 show the three cases chosen in section 6.

Figure 4: The time series (top) and temporal mean profiles (bottom) of large-scale vertical velocity for IOP1 (left) and IOP2 (right).

Figure 5: The time series (top) and temporal mean profiles (bottom) of apparent heating source Q_1 for IOP1 (left) and IOP2 (right).

Figure 6: The time series (top) and temporal mean profiles (bottom) of apparent moisture sink Q_2 for IOP1 (left) and IOP2 (right).

Figure 7: The diurnal cycle of precipitation (up) and CAPE and CIN (bottom) for both IOPs.

Figure 8: The diurnal cycle of (from top to bottom) cloud frequency, large-scale vertical velocity, Q_1, Q_2 and $Q_1 - Q_2$ for IOP1 and IOP2. The black lines are zero-lines.

Figure 9: SIPAM radar reflectivity snapshots (left) and time series of domain-mean precipitation (right) for three cases of precipitating systems. From top to bottom: LOS, COS and BOS. The black octagons indicate the GoAmazon domain, and the red arrows indicate the propagating direction of the system.

Figure 10: The time series of (a) cloud frequency, (b) surface CAPE and CIN, (c) u wind, (d) v wind, (e) relative humidity, (f) vertical velocity, (g) Q_1 and (h) Q_2 for the LOS case. The black lines are zero-lines. The shaded and white areas in (b) indicate nightime and daytime.

Figure 11: The time series of (a) cloud frequency, (b) surface CAPE and CIN, (c) u wind, (d) v wind, (e) relative humidity, (f) vertical velocity, (g) Q_1 and (h) Q_2 for the COS case. The black lines are zero-lines. The shaded and white areas in (b) indicate nightime and daytime.

Figure 12: The time series of (a) cloud frequency, (b) surface CAPE and CIN, (c) u wind, (d) v wind, (e) relative humidity, (f) vertical velocity, (g) Q_1 and (h) Q_2 for the BOS case. The black lines are zero-lines. The shaded and white areas in (b) indicate nightime and daytime.

	IOP1		IOP2	
	Morning	Afternoon	Morning	Afternoon
Locally Occurring Systems (LOS)	0	19	0	14
Coastal Occurring Systems (COS)	7	6	0	3
Basin Occurring Systems (BOS)	3	3*	2**	0

* the afternoon BOS are continued from the morning time.
** the two BOS in IOP2 are initialized in the Amazon basin but propagating westward as squall lines.

Table 1: number of convective systems identified in the morning and afternoon during IOP1 and IOP2.

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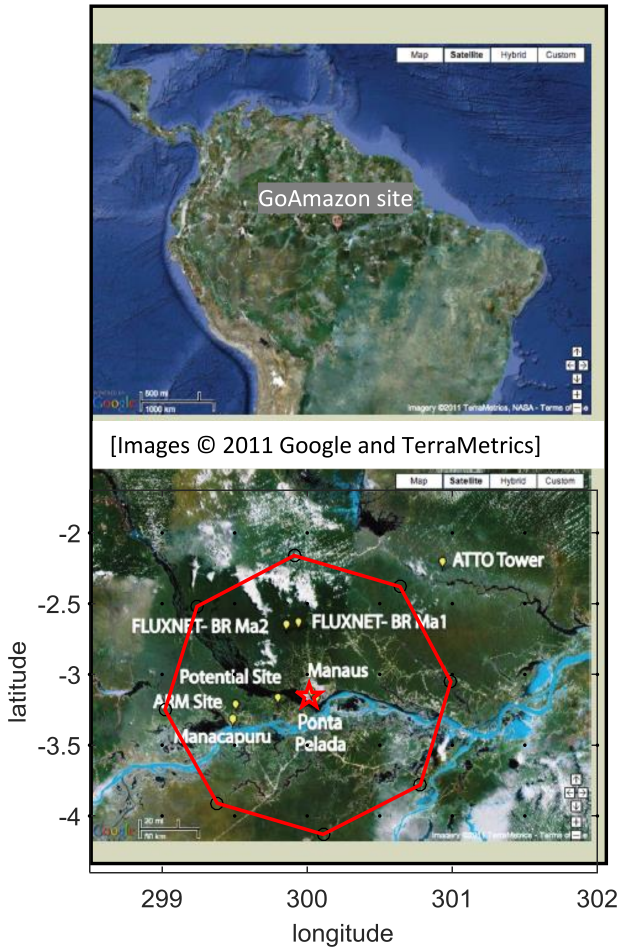

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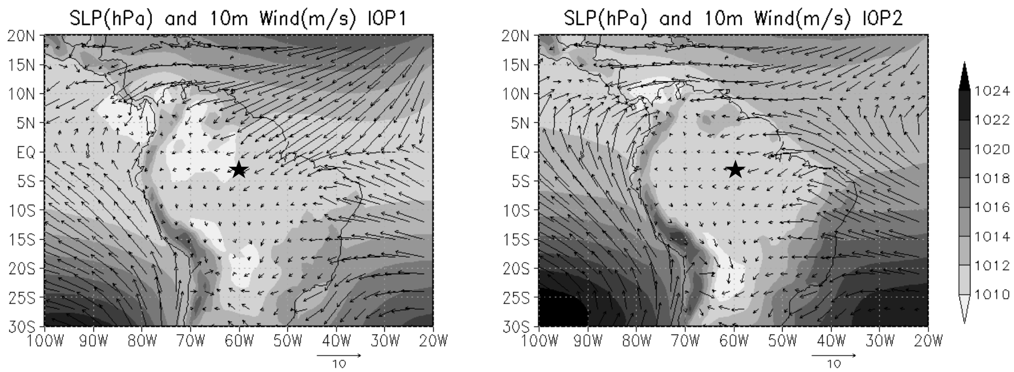

Figure 2: The sea-level pressure (shaded) and 10-meter horizontal wind (vector) averaged for IOP1 (left) and IOP2 (right). The pentagram indicates the location of GoAmazon site.

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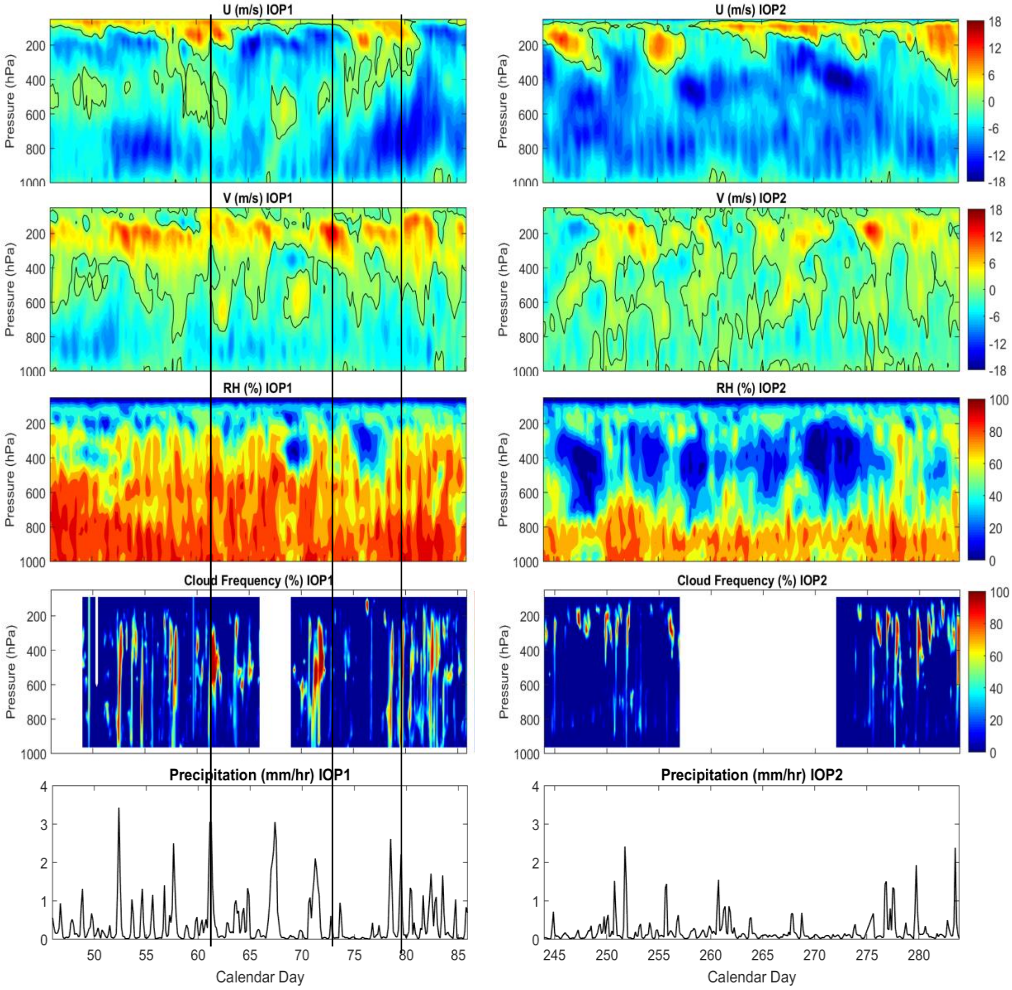

Figure 3: Domain averaged time series of (from top to bottom) horizontal (u) wind, meridional (v) wind, relative humidity, cloud frequency (point observation at the ARM site) and precipitation for IOP1 (left) and IOP2 (right). The blank areas in cloud frequency indicate missing data. The three straight black lines in IOP1 show the three cases chosen in section 6.

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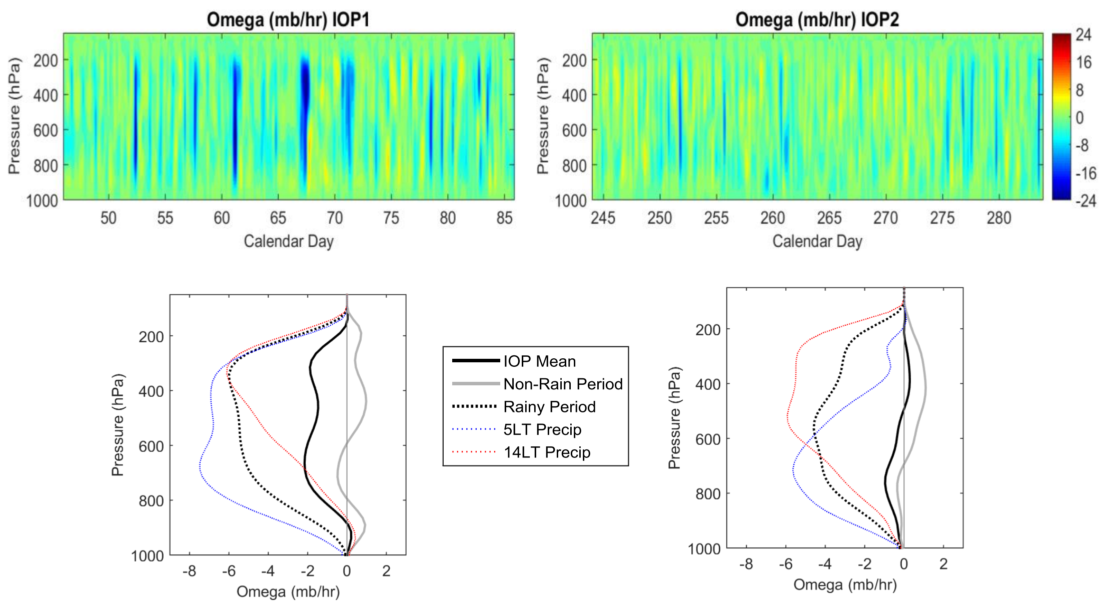

Figure 4: The time series (top) and temporal mean profiles (bottom) of large-scale vertical velocity for IOP1 (left) and IOP2 (right).

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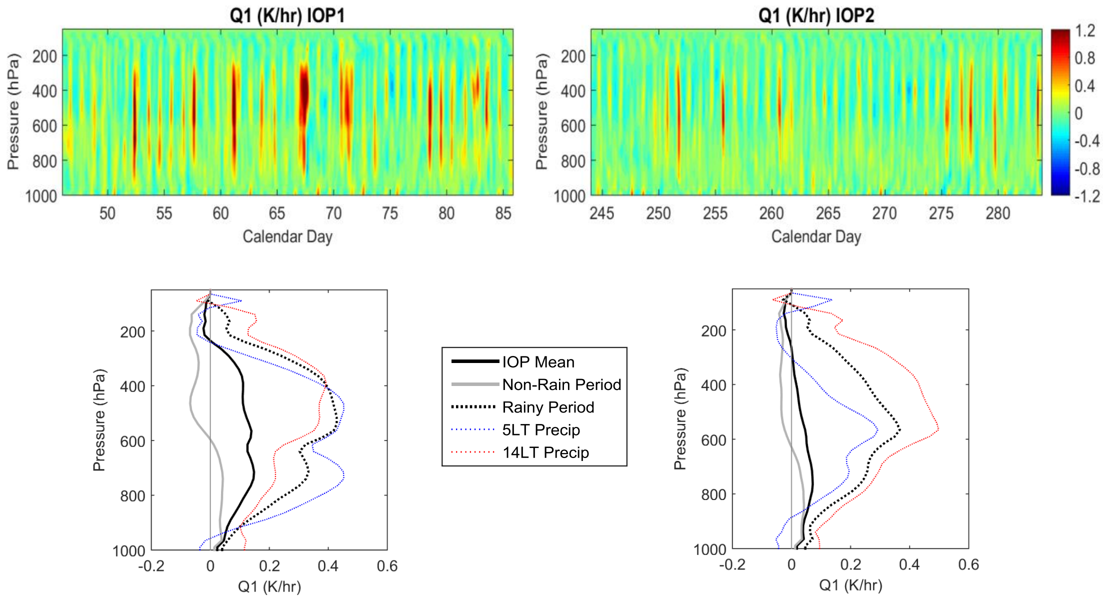

Figure 5: The time series (top) and temporal mean profiles (bottom) of apparent heating source Q_1 for IOP1 (left) and IOP2 (right).

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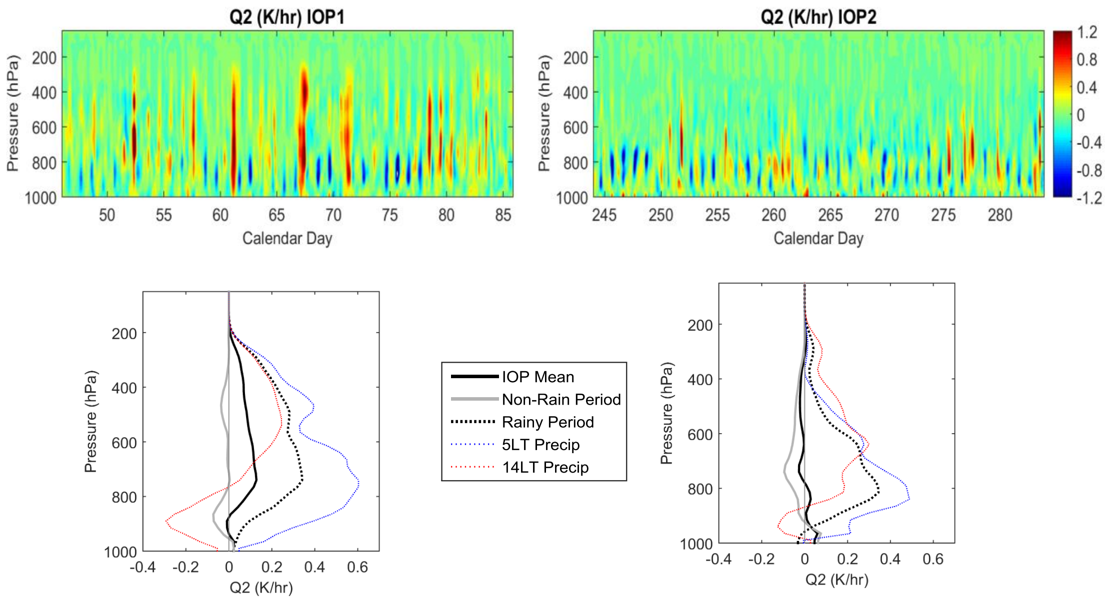

Figure 6: The time series (top) and temporal mean profiles (bottom) of apparent moisture sink Q_2 for IOP1 (left) and IOP2 (right).

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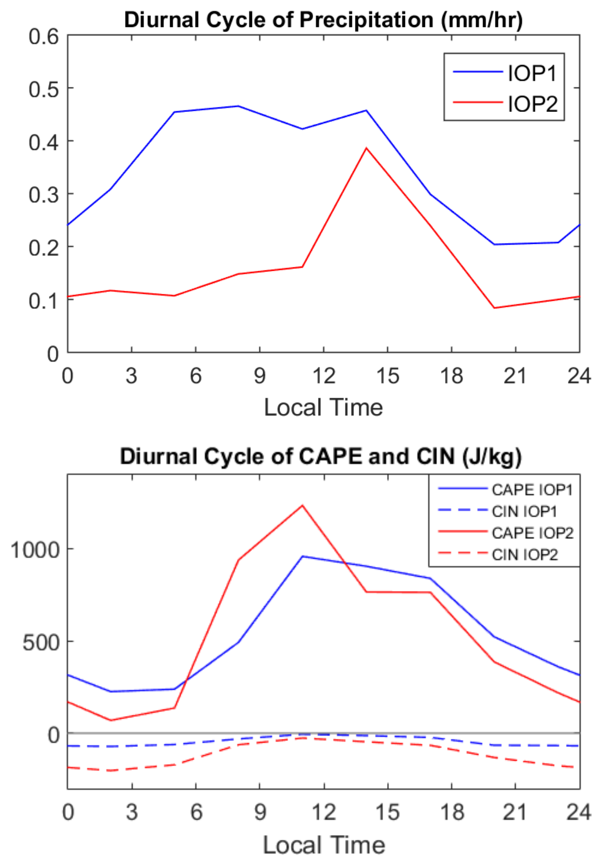

Figure 7: The diurnal cycle of precipitation (up) and CAPE and CIN (bottom) for both IOPs.

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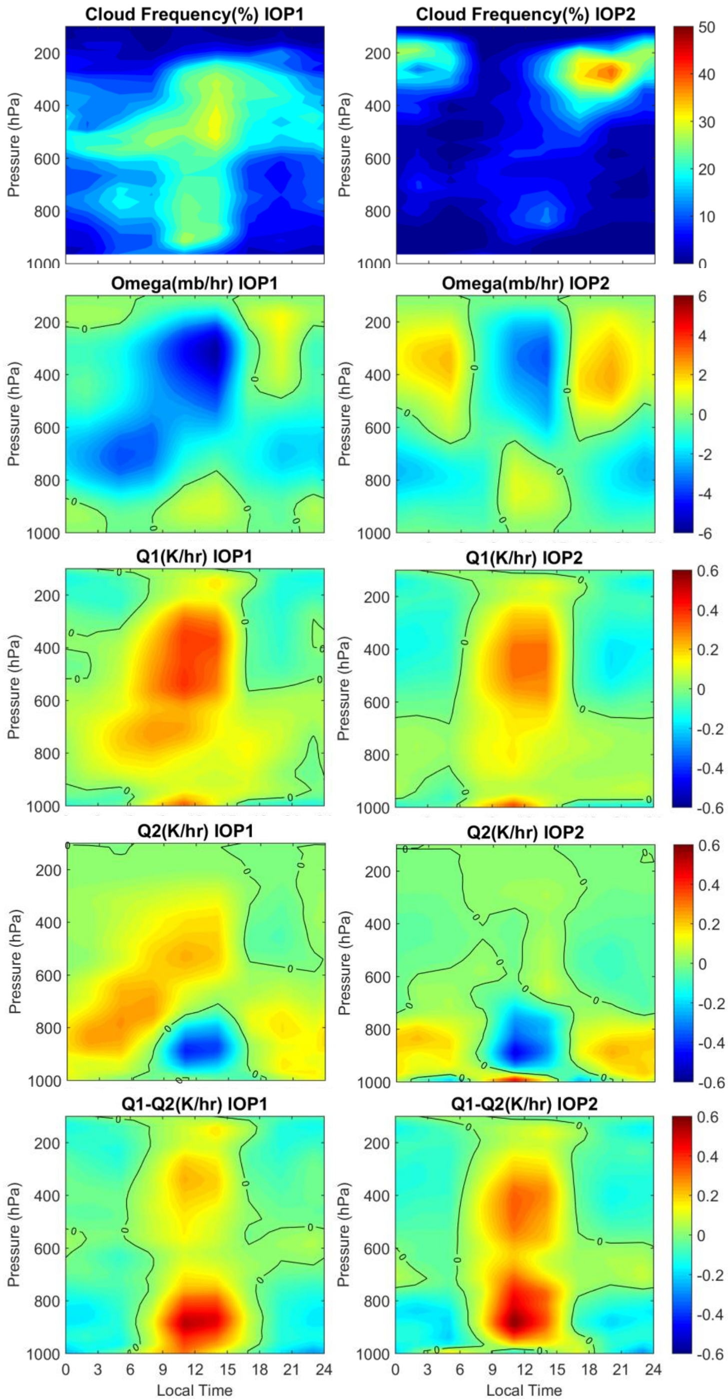

705

706 Figure 8: The diurnal cycle of (from top to bottom) cloud frequency, large-scale vertical velocity, Q_1, Q_2
707 and $Q_1 - Q_2$ for IOP1 and IOP2. The black lines are zero-lines.

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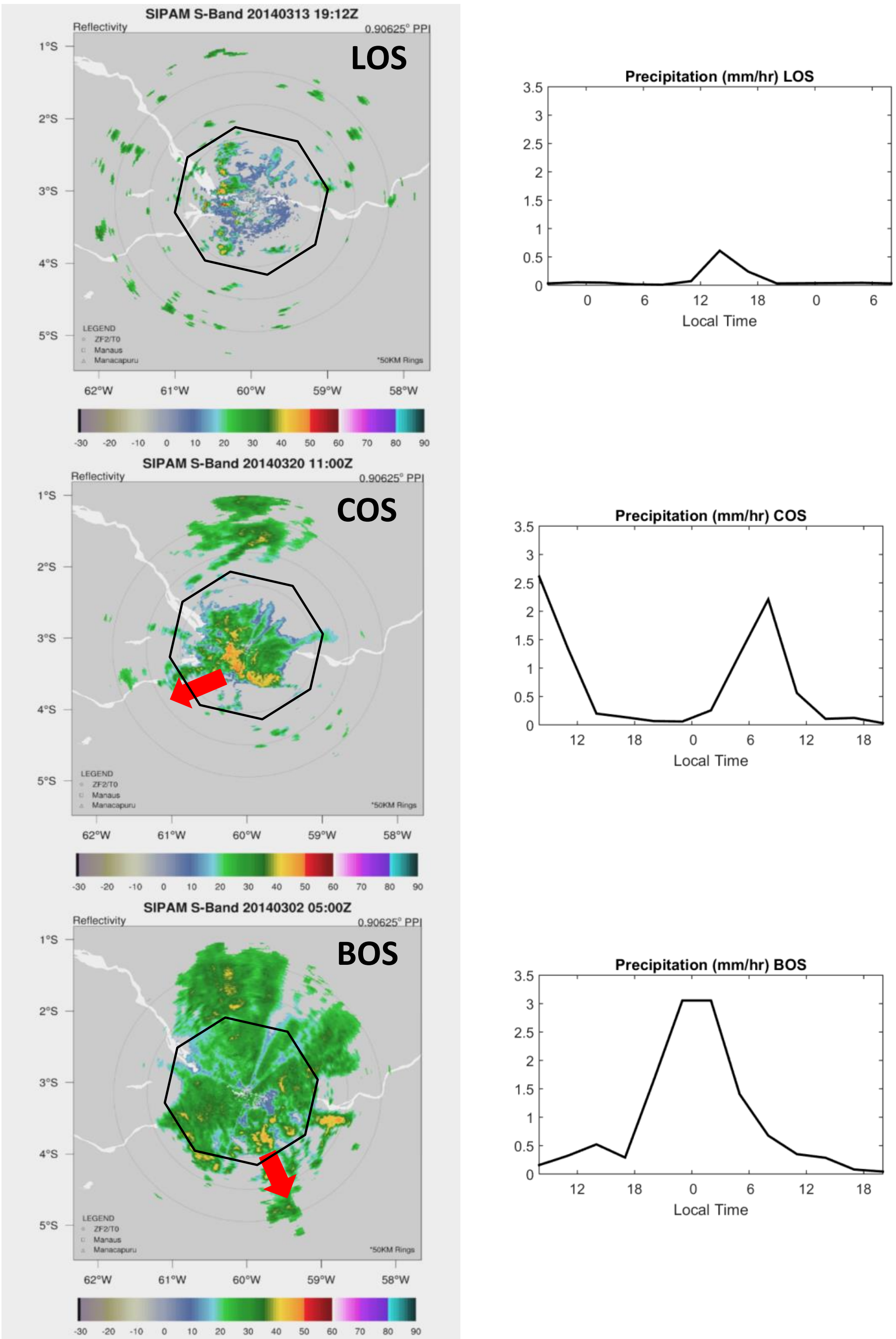

Figure 9: SIPAM radar reflectivity snapshots (left) and time series of domain-mean precipitation (right) for three cases of precipitating systems. From top to bottom: LOS, COS and BOS. The black octagons indicate the GoAmazon domain, and the red arrows indicate the propagating direction of the system.

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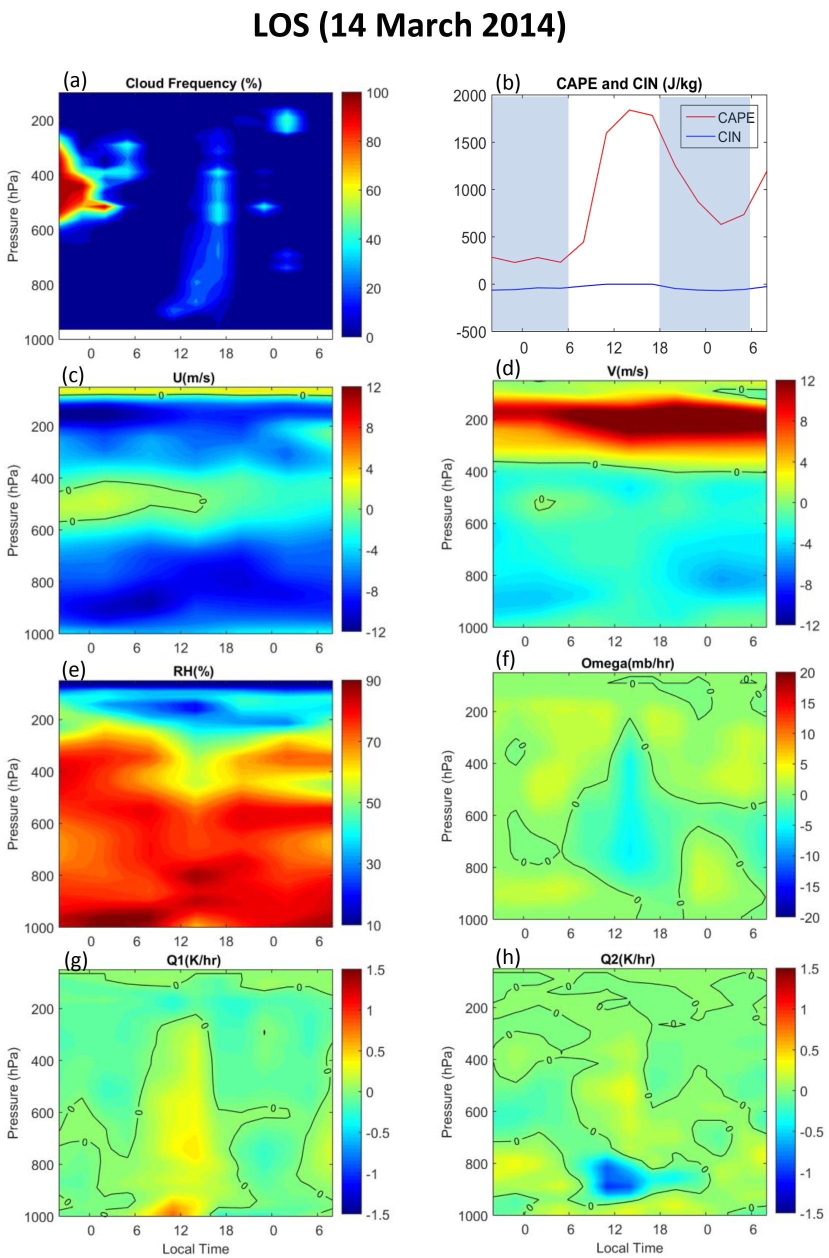

713

714 Figure 10: The time series of (a) cloud frequency, (b) surface CAPE and CIN, (c) u wind, (d) v wind, (e)
715 relative humidity, (f) vertical velocity, (g) Q_1 and (h) Q_2 for the LOS case. The black lines are zero-lines.
716 The shaded and white areas in (b) indicate nighttime and daytime.

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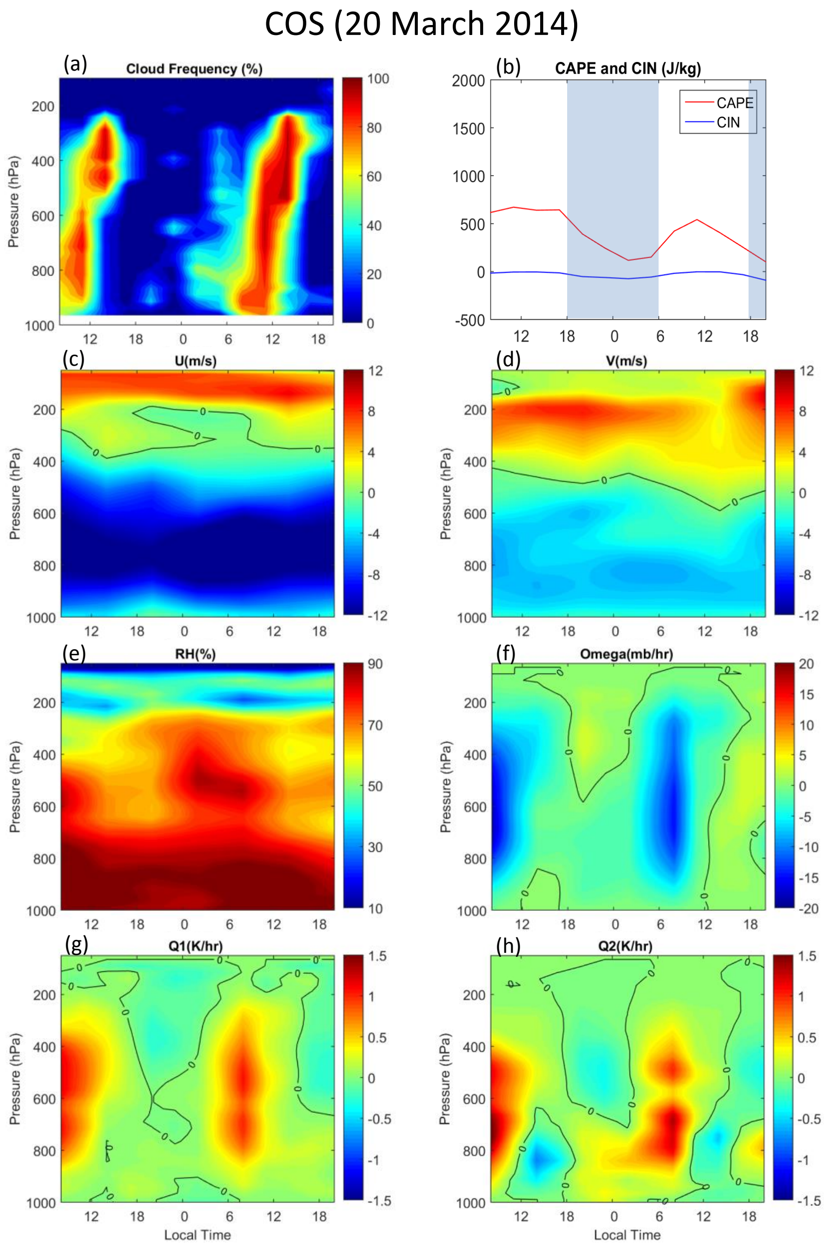

Figure 11: The time series of (a) cloud frequency, (b) surface CAPE and CIN, (c) u wind, (d) v wind, (e) relative humidity, (f) vertical velocity, (g) Q_1 and (h) Q_2 for the COS case. The black lines are zero-lines. The shaded and white areas in (b) indicate nightime and daytime.

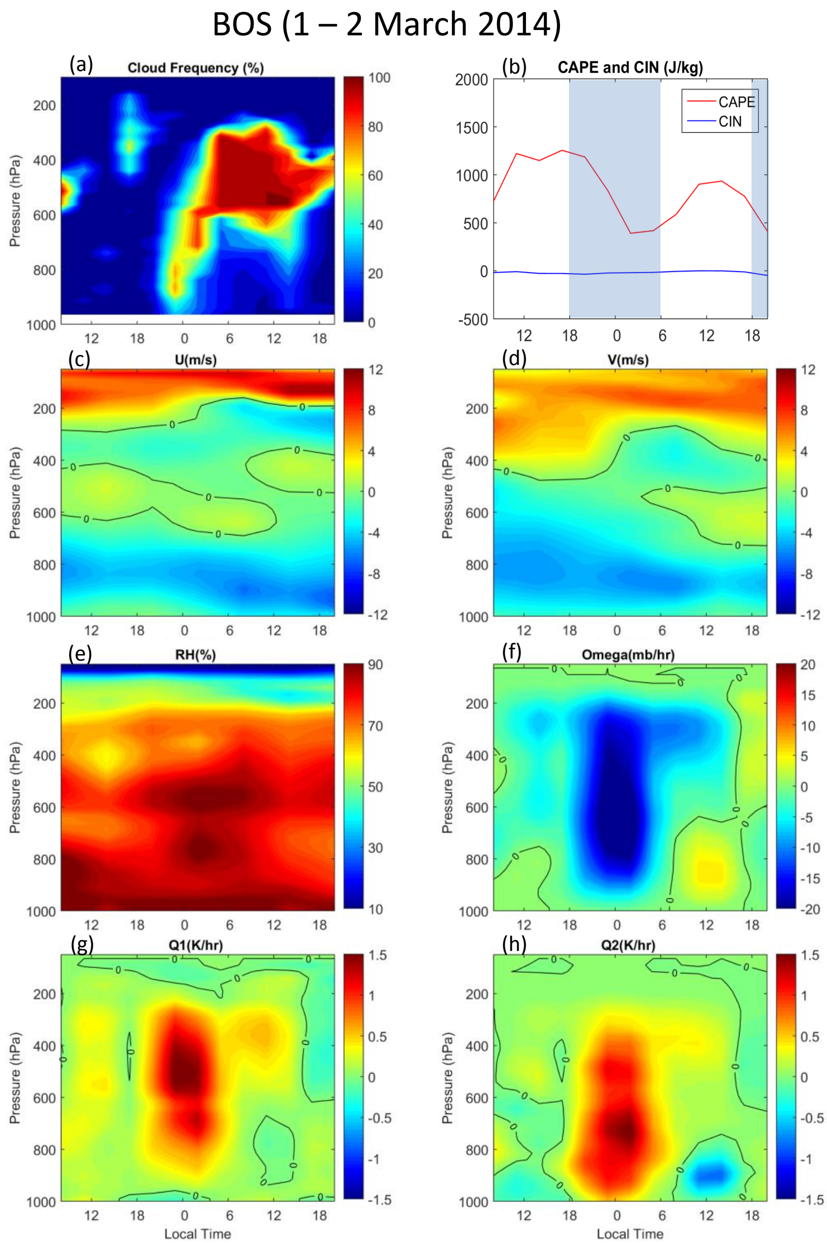

Figure 12: The time series of (a) cloud frequency, (b) surface CAPE and CIN, (c) u wind, (d) v wind, (e) relative humidity, (f) vertical velocity, (g) Q_1 and (h) Q_2 for the BOS case. The black lines are zero-lines. The shaded and white areas in (b) indicate nightime and daytime.