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1 **Coupling of clouds and tropospheric relative humidity**  
2 **in the tropical Western Atlantic: insights from**  
3 **multi-satellite observations**

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7 **Key Points:**

- 8 • The daytime drying of the mid-troposphere is associated with the large-scale subsi-  
9 dence and presumably with the diurnal pulses of ITCZ.
- 10 • The diurnal cycle of upper-level cloudiness is essential for tropospheric moistening by  
11 inducing local lifting.
- 12 • The upper level moisture feeds upper-level clouds and modulates their diurnal cycle.

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**Abstract**

We investigated the interactions between clouds and moisture at the diurnal scale in the Western Atlantic trade winds region. Profiles of tropospheric relative humidity from the SAPHIR/Megha-Tropiques sounder are combined with cloud categories obtained from geostationary satellites. In Winter, the mid-troposphere undergoes strong daytime drying due to air masses coming from the colder upper troposphere. The moistening near the surface triggered by solar radiation precludes the development of low-level clouds. At night rising moist air in the upper troposphere triggers the formation of high-altitude clouds and favors their presence. In Summer, daytime high-altitude clouds shield the solar forcing on the atmosphere and reduce drying from large-scale subsidence. After sunset, the development of upper tropospheric opaque clouds constitutes a local source of moisture. We argue that modulations of the diurnal cycle of clouds and relative humidity by season may be related to diurnal pulses of the ITCZ.

**Plain Language Summary**

The heat engine of the climate is the atmospheric water cycle. Understanding the relationships between clouds and the atmospheric relative humidity is crucial to improve our understanding of climate variability. Here we focus on the diurnal fluctuations of vertical profiles of tropospheric relative humidity and collocated clouds in the tropical Western Atlantic trade winds region. Profiles of water vapor and distribution of clouds, classified by altitudes, are obtained from space-borne instruments, and the other environmental characteristics such as sea surface and air temperatures are extracted from a weather model. Their joint diurnal variations are examined. Winter and Summer seasons are compared. The diurnal water vapor cycle of water vapor evolves from the bottom to the top of the atmosphere and is strongly associated with cloud types, with a seasonal modulation. During daytime a strong drying is associated with the downward dry air masses moving downward. The diurnal cycle of upper-level cloudiness plays a critical role in inhibiting daytime drying by shielding the mid-troposphere from this downward transport. The upper-level moisture feeds upper-level clouds and modulates their diurnal lifetime.

**1 Introduction**

There is no doubt that we need to improve our understanding of how clouds and cloud-related feedbacks impact on climate (Stephens et al., 2002; Bony et al., 2015). Critical

44 processes involving clouds and water vapor, such as detrainment and evaporation, typically  
45 occur at time scales of less than 6 hours. This calls for sub-daily analyses of observations.  
46 Regional variations in the diurnal cycle of clouds are caused by several parameters such  
47 as orography, land/sea circulation, air-sea fluxes and sea surface temperature (SST), their  
48 effect differing with the dominant cloud type (Yang & Slingo, 2001; Eastman & Warren,  
49 2014; Noel et al., 2018). The role of the free tropospheric water vapor in the evolution of  
50 clouds at the diurnal scale has not been extensively studied due to lack of observations. An  
51 improved understanding of how different cloud types and their diurnal cycles interact with  
52 the atmospheric water vapor is much needed in order to make the connections between the  
53 solar forcing, the surface and the atmospheric water cycle (cloud, vapor and rain).

54 For example, observations of rainfall rates associated with deep convection in the Indian  
55 Ocean warm pool region have revealed a predawn rainfall peak (Mapes & Houze, 1993;  
56 Sakaeda et al., 2018) triggered by solar absorption (Sakazaki et al., 2017) and invigorated  
57 by the oceanic warm layer in some regions (Bellenger et al., 2010). Ruppert and Johnson  
58 (2015) have highlighted the existence of a deepening of daytime convective clouds along  
59 with a parallel increase in moisture in the lower troposphere. In this region of the upward  
60 branch of the ITCZ characterized by active convection, these diurnal pulses are favored  
61 by a combination of increasing SST in the daytime and a reduced large-scale subsidence.  
62 These pulses are thought to further affect remote shallow convective areas through a strong  
63 feedback on daily precipitation and convective heating (Ruppert, 2016; Ciesielski et al.,  
64 2018).

65 The impact of clouds on solar radiation and related heating has also been addressed  
66 in numerous works. The direct absorption of shortwave radiation by optically opaque and  
67 elevated clouds (anvil-type clouds) is thought to cause a strong cloud-top heating (Hartmann  
68 et al., 1984; Ackerman et al., 1988; Mather et al., 2007; Powell et al., 2012) that increases  
69 buoyancy below, and a lifting towards the upper-levels, thereby causing a daytime peak in  
70 upper-level cloudiness to prevail (Ruppert & Klocke, 2019). Atmospheric tides, driven by  
71 solar heating and ozone absorption, have also an effect in the diurnal convection cycle and  
72 subsequent precipitation (Woolnough et al., 2004).

73 Studies focusing on oceanic shallow convective clouds, such as Stratocumulus and Cu-  
74 mulus, have shown that their diurnal cycle is linked to lower-tropospheric stability with a  
75 large-scale meteorological influence (Klein & Hartmann, 1993; Wood, 2012). The maximum

76 of occurrence of these low-level clouds has been observed in the early morning hours before  
77 sunrise and their diurnal cycle depend strongly on the region (Klein et al., 1995; Rozendaal  
78 et al., 1995; Eastman & Warren, 2014). The recent work of Vial et al. (2019) highlighted the  
79 challenge for high resolution models to represent the daily cycle of such shallow clouds. For  
80 example Chung et al. (2007) examined convectively active parts of Africa and the Atlantic  
81 ocean with the METEOSAT geostationary satellite. They revealed a peak on the Upper  
82 Tropospheric Humidity (UTH) at 3:00LT with a clear contrast between land and ocean,  
83 which remains a challenge to represent in several reanalyzes, thereby highlighting missing  
84 processes related to moisture (Chung et al., 2013).

85 To our knowledge, few studies have analyzed the diurnal cycle of atmospheric moisture.  
86 In addition, most studies have focused on UTH (a vertically-weighted integral of relative  
87 humidity zooming in the upper troposphere) rather than considering the vertical distribution  
88 of humidity. Moradi et al. (2016) showed that peak times for tropospheric relative humidity  
89 varied throughout the tropical belt using the Megha-Tropiques satellite. Chepfer et al.  
90 (2019) used the CATS spaceborne lidar to related this diurnal variability to the vertical  
91 properties of clouds.

92 In this study we analyze the relationships between clouds and atmospheric relative hu-  
93 midity (RH) and their joint diurnal variations by fully exploiting an ensemble of observation  
94 data from different space-borne instruments. We address the following question:

95 How are RH and clouds linked at the sub-daily scale ? Specifically is there a signature  
96 in RH before or after the cloud growth at the sub-daily scale ?

97 We focus on the tropical Western Atlantic region, ( $70^{\circ}\text{W}$ - $30^{\circ}\text{W}$  in latitude and  $10^{\circ}\text{N}$ -  
98  $30^{\circ}\text{N}$  in longitude) subjected to the large-scale forcing of the downward branch of the Hadley  
99 cells. This region is mostly characterized by shallow convection and most clouds are Stra-  
100 tocumulus and Cumulus. Vial et al. (2019) discussed the diurnal variability of cloud-base in  
101 this region through the prism of ground-based measurements and regional models. We aim  
102 to expand previous studies that investigated the diurnal variations of the ITCZ (Ruppert  
103 & Johnson, 2015; Ciesielski et al., 2018; Sakaeda et al., 2018) at its edges and offer new  
104 insights on the diurnal cycle of the subsiding branch of the overturning circulation.

## 2 Data and Methods

### 2.1 Datasets

Satellite estimates of cloud types and RH profiles are combined with other environmental parameters from the European Center for Medium-range Weather Forecast (ECMWF) ERA-5 reanalysis (Hoffmann et al., 2019).

The RH profiles are derived from the SAPHIR sounder on Megha-Tropiques. Since October 2011, this satellite provides 3 to 5 observations daily at any given point of the tropics. Its equatorial crossing time shifts backward by 100min due to the precession cycle of the platform (Roca et al., 2015). SAPHIR provides humidity profiles throughout the troposphere by sampling the atmospheric moisture in the 183.31 GHz line with six channels. The 1700km-swath of SAPHIR covers the  $\pm 30^\circ$  equatorial belt. Its nominal observations are performed at a horizontal resolution of 10km at nadir. Here we use the operational Level 2 RH profiles described in Sivira et al. (2015) and Brogniez et al. (2016). RH is preferred over absolute humidity to avoid dependency to temperature profiles.

Cloud types are taken from the Numerical Weather Prediction - Satellite Application Facility (NWP-SAF) algorithm developed for geostationary satellites (Derrien & Le Gléau, 2005; Sèze et al., 2015). A finer spatial scale is available for these cloud types than for RH profiles, which provides up to 20 geostationary pixels within each of the larger SAPHIR footprints. We consider five cloud types: "Very Low" with cloud top pressure  $P_{top} > 800\text{hPa}$ , "Low" with  $P_{top} \in [650\text{hPa}; 800\text{hPa}]$ , "Medium" with  $P_{top} \in [450\text{hPa}; 650\text{hPa}]$ , "High Opaque" and "High Semi-transparent" with  $P_{top} < 450\text{ hPa}$ . Among the cloud types in the trade winds, as defined by (Riehl, 1954), the Very Low category can be associated with shallow convective clouds with tops that do not exceed 4km, such as Cumulus Humilis and Chimney clouds. High Opaque and High Semi-transparent clouds are distinguished from each other by their concentration of water (ice/liquid) and their optical thickness.

The conditional evolution of RH for a given cloud type is nailed down by selecting SAPHIR footprints dominated by a given cloud type : if more than 90% of a SAPHIR footprint is filled with geostationary pixels of the same type, then the corresponding RH profile is attributed in its entirety to this particular type. This cautious selection retains only  $\sim 30\%$  of the total observations. It allows to extract clear co-variations between the clouds and the corresponding RH profiles.

136 Environmental conditions are described with ECMWF ERA-5 outputs at the 0.75°  
 137 latitude-longitude resolution grid:

- 138 1. skin temperature (SkT), used to relate to the solar heating;
- 139 2. air temperatures at 500hPa ( $T_{500}$ ) and 200hPa ( $T_{200}$ ), to deconstruct the moisture  
 140 and temperature signatures within the variability of RH;
- 141 3. lower tropospheric stability (LTS) that provides a measure of the inversion strength  
 142 between the surface ( $\theta_0$ ) and above the atmospheric boundary layer (ABL) at 700hPa  
 143 ( $\theta_{700}$ ) (Klein & Hartmann, 1993);
- 144 4. 10-m wind divergence ( $\nabla \vec{U}_{10m}$ ) and 500hPa-vertical atmospheric velocity ( $\omega_{500}$ ) as  
 145 indicative of the dynamical flows.

146 All these parameters are considered at the hourly time scale, except  $\omega_{500}$  that is used at the  
 147 monthly time scale to define climatologically stable conditions. All outputs are translated  
 148 into the local time of observation (LT).

## 149 2.2 Method: composite diurnal cycle

150 All instantaneous observations from the Western Atlantic sub-region taken during the  
 151 periods January-February-March (JFM) and July-August-September (JAS) 2012-2017 are  
 152 gathered to create a composite diurnal cycle for all variables.

153 In order to link with large-scale dynamics, the data is categorized into ascending ( $\omega_{500} < 0$ )  
 154 and subsiding ( $\omega_{500} > 0$ ) categories. Relative anomalies of each variable with respect to  
 155 their daily averages are computed as follows:

$$156 \quad Y'(t) = 100 \times \frac{Y(t) - \bar{Y}}{\bar{Y}} \quad (1)$$

157 where  $Y(t)$  is either the number of situations of a given cloud type or the RH value at a  
 158 given pressure level at time  $t$  (hours), and  $\bar{Y}$  is the corresponding daily mean.

159 Harmonic functions are fitted on the composite hourly time series using a least-squared error  
 160 method, with a diurnal harmonic (24h cycle) and a semidiurnal harmonic (12h cycle; see  
 161 example on Fig. 3). From these fits, lagged-correlations are computed between anomalies  
 162 of RH with respect to time  $t$  and  $X$  (cloud prevalence or environmental parameters) with  
 163 respect to time  $t + i$ . They are noted  $R(i)$  for a time lag  $i$ , with  $\sigma_{RH}$  and  $\sigma_X$  the variances  
 164 of  $RH$  and  $X$ :

$$165 \quad R(i) = \frac{E[(X_t - \bar{X})(RH_{t+i} - \bar{RH})]}{\sigma_X \sigma_{RH}} \quad (2)$$

166 The correlation significance is tested with a Student t-test (95% confidence interval).

### 167 **3 Results**

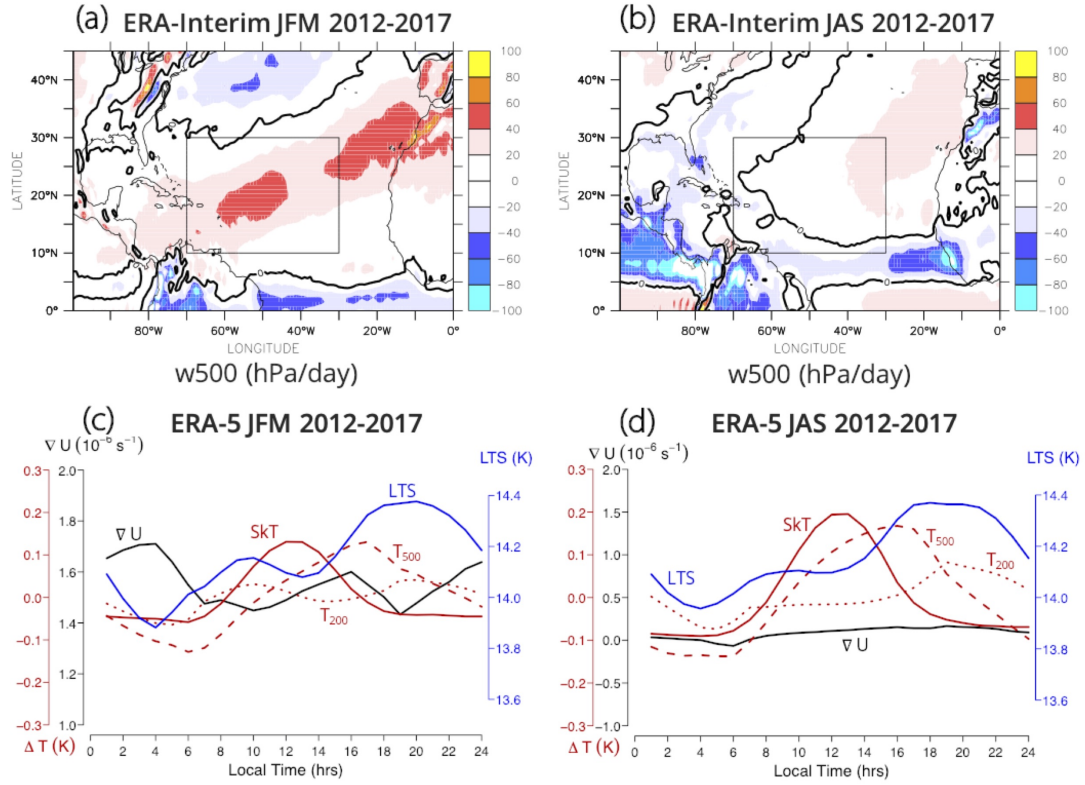
#### 168 **3.1 Regional temporal variability**

169 Figure 1 displays the seasonal differences in large-scale circulation in the tropical West-  
 170 ern Atlantic area with a climatology of  $\omega_{500}$  (Fig.1 a-b) and the diurnal fluctuations of SkT,  
 171  $\nabla U_{10m}$  and LTS (Fig.1 c-d). During JFM, this region is subjected to strong subsidence  
 172 aloft (Fig.1 a). During JAS, the region is on the edge of the ITCZ and is generally charac-  
 173 terized by weaker vertical motions (Fig.1 (b)). In terms of cloudiness, the two seasons are  
 174 populated by different cloud types: during the JFM period, low-altitude clouds associated  
 175 with the trade winds are dominant, while the JAS period is characterized by both high and  
 176 low-altitude clouds associated with the ITCZ ((Konsta et al., 2012); see also Fig. 2). We  
 177 focus on the large-scale subsiding category ( $\omega_{500} > 0$ ) to minimize the sampling of deep  
 178 convective systems by the SAPHIR microwave sounder (Burns et al., 1997; Brogniez et al.,  
 179 2013).

180  
 181 The environmental conditions displayed on Figures 1c-d provide insight into the pro-  
 182 cesses governing the formation of clouds. Surface warming by solar heating reaches a maxi-  
 183 mum at 12:00 LT, and is associated with a known weak cycle in  $\nabla \vec{U}_{10m}$  (Nitta & Esbensen,  
 184 1974), that is almost inexistent during JAS, and with a steadily increasing LTS. The diurnal  
 185 variations in LTS indicate lower instability in the morning hours (minimum of LTS at 4:00  
 186 LT) at the same time as the peak of cloud occurrences (Fig. 2 a-e). In both seasons, in-  
 187 creased stability is observed as the day progresses until a peak is reached around 18:00-20:00  
 188 LT which inhibits vertical cloud extension. In JFM, a second peak of LTS is observed at 9:00  
 189 LT coinciding with the start of solar heating, and, to a lesser extent, with the daily maxi-  
 190 mum of wind convergence. Vertical heating of the atmosphere shifts progressively over time  
 191 from the bottom (SkT, maximum at 12:00 LT) to the middle ( $T_{500}$ , maximum at 16:00 LT)  
 192 and then to the top ( $T_{200}$ , maximum at 20:00 LT, with a second maximum near 8:00-10:00  
 193 LT).

194 Figure 2 shows the hourly evolution of the prevalence of the five cloud types within  
 195 the Western Atlantic area along with the daily fluctuations in the average RH profile for  
 196 JFM (a-d) and JAS (e-h). In order to highlight the amplitude of the diurnal cycle, relative





**Figure 1.** (top panel) Interannual averages of the 500hPa atmospheric vertical velocity (hPa/day) computed over the period 2012-2017 for (a) JFM and (b) JAS. The isoline indicates  $\omega_{500} = 0$  hPa/day. The box delineates the area of interest. (bottom panel) Composite diurnal cycles for (c) JFM and (d) JAS defined for the area of interest indicating: the average divergence for the 10-m wind ( $\nabla U$  in  $10^{-6} \text{ s}^{-1}$ ; black curve), anomalies of SkT (in K; red curve),  $T_{500}$  (in K; red-dashed curve) and  $T_{200}$  (in K; red-dotted curve), and the average LTS (in K; blue curve).

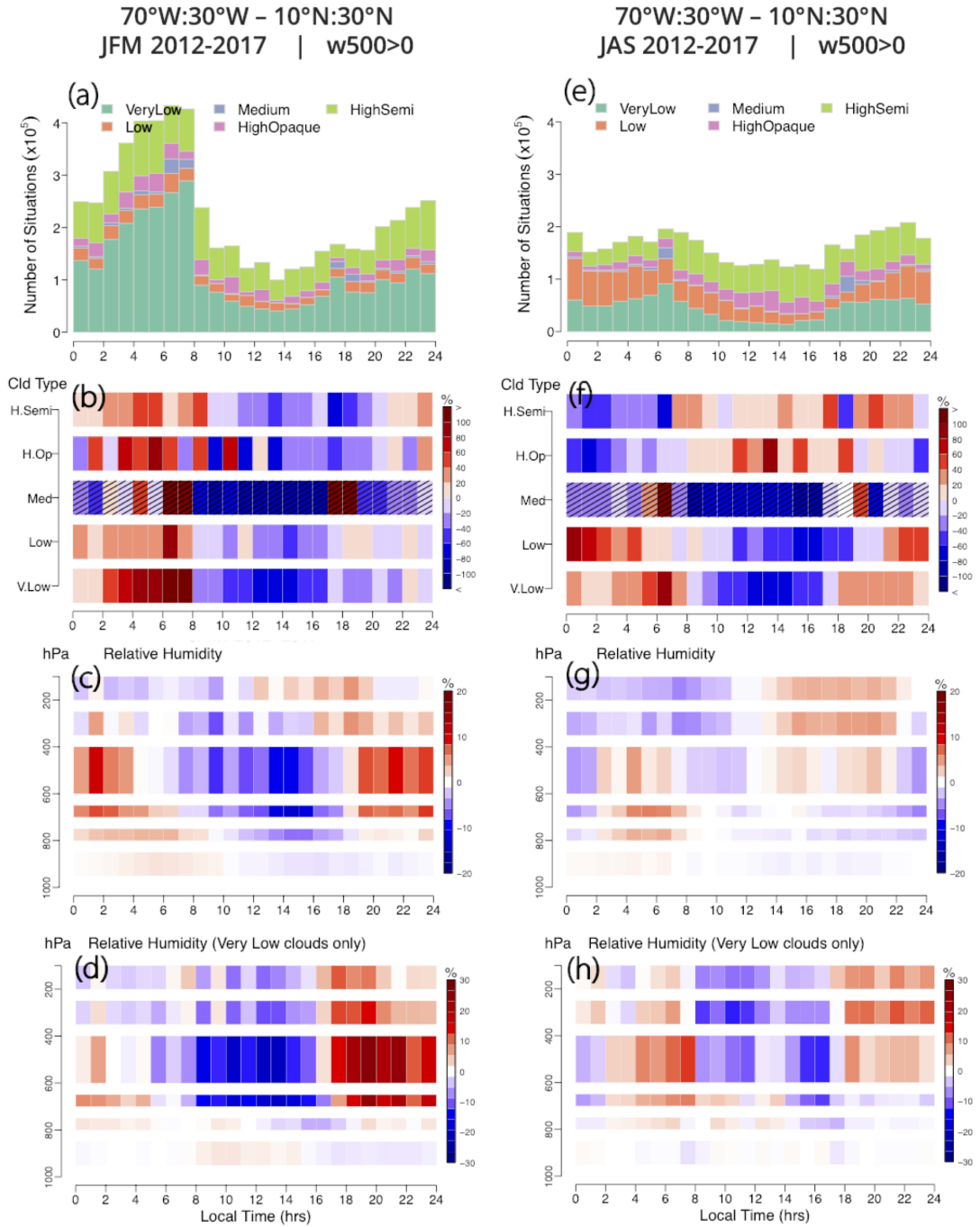
197 anomalies with respect to the mean daily states are shown by cloud types (Fig. 2 b and f)  
198 and for RH (Fig. 2 c and g). Figures 2 (d) and (h) present the daily variations of RH in  
199 situations filled with "Very Low" clouds exclusively.

200 Figures 2 (a) and (e) confirm that the VeryLow clouds are the dominant cloud type dur-  
201 ing JFM, followed by HighSemi clouds. The contributions of VeryLow, Low and HighSemi  
202 are more evenly prevalent during JAS. During both periods the frequency of occurrence of  
203 these cloud types indicate a strong diurnal cycle with a peak around 7:00 LT, and a dip  
204 early afternoon around 13:00 LT, as the solar heating inhibits the vertical development of  
205 clouds by stabilizing the column (Randall et al., 1991).

206 During both seasons, total cloud distribution for the VeryLow and Low classes (and to a  
207 lesser extent Medium) reaches a peak in the morning, between 0:00 LT and 8:00 LT caused  
208 by shallow convection (Fig. 2b-f). While VeryLow clouds display similar diurnal variations  
209 across both seasons, there are seasonal variations in the diurnal cycles of the other cloud  
210 types. The peak of the diurnal cycle for Low clouds shifts from 6:00-8:00 LT in JFM to  
211 0:00-2:00 LT in JAS, and for HighOpaque and HighSemi clouds it shifts from the morning  
212 (4:00-11:00 LT) in JFM to the afternoon (12:00-20:00 LT) in JAS. The higher the clouds,  
213 the greater the shift in peak occurrence between JFM and JAS.

214 During the JAS period, HighOpaque cloudiness is maximal in the late afternoon and  
215 early night (16:00-24:00 LT). It coincides with a moistening of the upper troposphere (Fig.  
216 2 b). This moistening may be induced by their detrainment of moisture (Soden & Fu, 1995;  
217 Sassi et al., 2001; Garot et al., 2017) and by local lifting of moisture in regions of high cloud  
218 cover.

219 The diurnal variations of the tropospheric RH are shown in Fig 2 (c) and (g). The  
220 vertical profile displays diurnal vertical heterogeneity. The relative variations of RH within  
221 the ABL ( $\sim 850$ - $950$  hPa) are of lower amplitude than in other layers. This is normal because  
222 the ocean surface maintains moist conditions in the ABL all day-long ( $\sim 80\%$ ) and lessens  
223 moisture variations. In this layer, RH peaks around 6:00-8:00 LT when the cloud cover is  
224 maximal. Just above ( $\sim 800$ - $600$  hPa), RH diurnal variations are maximal around 4:00 LT.  
225 A weak secondary moistening is visible around 20:00 LT in JFM. In the free troposphere  
226 ( $\sim 600$ - $300$  hPa) this maximum point shifts to an earlier time (2:00-4:00 LT), and in both  
227 JFM and JAS, the maximum point is reached in the evening around 20:00 LT. Finally, in  
228 the upper layers (above 300 hPa) the first maximum point disappears and is replaced by a



**Figure 2.** Composite diurnal cycles defined over the tropical Western Atlantic region during JFM (left column) and JAS (right column) over the period 2012-2017. Panels (a) and (e): prevalence of each cloud type accumulated for the area. Panels (b) and (f) : relative anomaly of cloud prevalence compared to their respective daily averages (in %). The hatched part indicates that the computation is performed with less than 1% of the total population. Panels (c) and (g) : relative anomaly of the vertical profiles of RH relative to the daily average of the considered atmospheric layer (in %). (d) and (h) same as (c-g) but using only the RH profiles associated with VeryLow clouds.

229 strong drying while afternoon moistening is strengthened. These patterns are similar overall  
 230 between the two seasons, but the diurnal gradients are weaker during JAS, when the region  
 231 is on the edge of the ITCZ, compared to JFM, when the region is located within a strong  
 232 large-scale subsidence. Fig 2 (c) and (g) reveal a vertical consistency across layers, with  
 233 the moistening and drying shifting over time from the top layers to the bottom layers. It  
 234 suggests that both the large-scale subsidence and diurnal pulses in the fluxes of atmospheric  
 235 moisture have an influence.

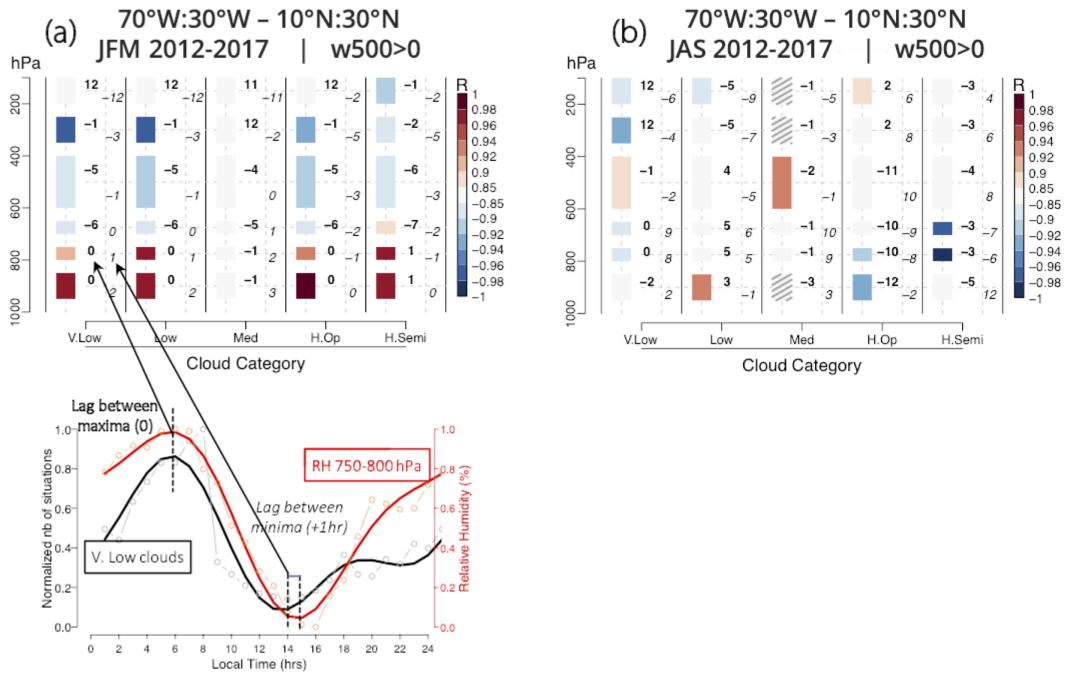
236 The variability of RH in situations where only VeryLow clouds are detected in the  
 237 SAPHIR pixels is presented in Fig 2 (d) and (h). Under these conditions, the vertical  
 238 diurnal cycles of RH are more similar during JFM and JAS, with a strong daytime drying  
 239 of the mid-troposphere (700 to 300 hPa) surrounded by moister atmospheric layers, and an  
 240 early night moistening which becomes remarkably stronger after sunset (18:00-22:00 LT)  
 241 during JFM. The JAS cycle is more pronounced in this case when compared to the cycle  
 242 including all cloud types (Fig. 2 (g)). This confirms that the vertical structure and diurnal  
 243 variations of atmospheric moisture is strongly related with the diurnal cycle of clouds. The  
 244 RH vertical diurnal cycle remains less pronounced during JAS than during JFM, which may  
 245 be due to the lower frequency of prevalence of VeryLow clouds during JFM.

## 246 **3.2 Analysis of correlations**

247 To quantify the relationships between the moisture field and the clouds, Figure 3 dis-  
 248 plays lagged correlations between the harmonic fits on the RH profiles and the number of  
 249 each cloud type. We also show the lag between the maxima as well as the lag between  
 250 the minima defined from the fitted hourly evolutions. While the temperature is the first-  
 251 order driver of RH, the other environmental parameters are also closely linked to RH at  
 252 the diurnal scale. These statistics reveal that the co-variations between the different cloud  
 253 categories and RH the low troposphere on one hand, and RH in the free troposphere on the  
 254 other hand, have notable opposite variations during JFM. This is less obvious for JAS.

### 256 **3.2.1 Winter patterns**

257 During JFM, RH diurnal variations display similar departures with respect to the Very-  
 258 Low and Low diurnal variations. Below 750hPa, the diurnal variations of RH are highly



**Figure 3.** Lagged correlation (intensity in color scale) computed for the subsiding regime category between RH at a given pressure level and the cloud prevalence sorted by category. (a) January-February-March (JFM) and (b) July-August-September (JAS). As described by the inset below, the bold number is the lag between the maximum of the two times series and the italic number is the lag between their minimum. If the lag is  $<0$  then the maximum/minimum of the chosen cloud prevalence precedes the maximum/minimum of RH. Dashed boxes are non-significant correlations with  $p$ .values  $> 0.05$ .

259 correlated with those of the VeryLow ( $R_{V.Low}=0.90-0.96$ ) and Low ( $R_{Low}=0.97$ ) cloud cat-  
 260 egories. Such correlations suggest that common processes link both diurnal cycles in the  
 261 PBL. The clouds and RH maxima coincide (lag=0) while the RH diurnal minima are slightly  
 262 shifted with respect to the cloud minima (1 to 2 hours). This delay is consistent with Fig.  
 263 2 (b) and (c) and indicates that the moistening of the layer may result from the dilution of  
 264 low-level clouds as suggested by (Eastman & Warren, 2014). Note that it coincides with the  
 265 daytime increase of  $T_{500}$  (Fig. 1c), so the drying processes of this part of the atmosphere are  
 266 in phase with the warming of the free troposphere. This suggests that the daytime warming  
 267 of the mid-troposphere, through shortwave (near-infrared) absorption by clouds and water  
 268 vapor, as well as by the surface heating, is strongly linked to the dilution of low-level clouds  
 269 and the subsequent moistening of the near-surface troposphere.

270 In the mid-troposphere ( $\sim 700-400\text{hPa}$ ) correlation magnitudes remain high but become neg-  
 271 ative ( $R_{V.Low}=-0.88$ ,  $R_{Low}=-0.90$ ), with little to no lag between minima, while RH peaks  
 272 5-6hrs earlier than the clouds. It suggests that processes different than those in the PBL  
 273 jointly affect the diurnal cycles of RH and clouds. Moving to the upper troposphere, the  
 274 RH diurnal minima increasing lead the cloud diurnal minima (e.g. -3 hrs at 250-350hPa),  
 275 while the lead of RH diurnal maxima gradually decreases (e.g. from -5 hrs at 400-600hPa  
 276 to -1 hr at 250-350hPa), indicating that the processes at play are vertically connected.

277 The correlations and lags profiles of the RH diurnal variations display similar features with  
 278 HighOpaque and HighSemi clouds. As for VeryLow and Low clouds, in the PBL the corre-  
 279 lations are high and positive while somewhat lower and negative in the mid-troposphere.

280 The RH diurnal minima increasing lead the cloud diurnal minima from the surface (lag=0hr)  
 281 to 250-350hPa (lag=-5hrs) except at the highest altitude range (lag=-2hrs). The RH max-  
 282 ima display slight or no delay in the PBL, and significant leading time just above the PBL  
 283 (lag  $\sim -6\text{hrs}$ ) that decreases with altitude. As noted in Fig 2 (c) and (g), the moistening  
 284 and drying shifts over time from the top layers to the bottom layers suggest the influence  
 285 of large-scale subsidence and diurnal pulses in the fluxes of atmospheric moisture.

286 It is hypothesized that the warming of the mid-troposphere by shortwave absorption  
 287 triggers air masses to lift a few hours later from increased buoyancy produced by heating  
 288 (Ackerman et al., 1988; Mather et al., 2007; Powell et al., 2012). This lifting causes the mid-  
 289 troposphere to dry while supplying the upper tropospheric layer with additional moisture.  
 290 This moisture is later pumped to maintain HighSemi clouds that could develop from the  
 291 debris of dissipating HighOpaque clouds (i.e. anvils) (Luo & Rossow, 2004). Such physical

292 links could be evaluated in hourly reanalyses such as ERA5, by looking at the similarities in  
293 the diurnal cycles of clouds and RH and at the evolution of the 3-D wind field and heating  
294 profiles. The use of field campaigns data (e.g. the recent EUREC4A campaign; Bony et al.  
295 (2017)) would also be greatly beneficial.

### 297 *3.2.2 Summer patterns*

298 During JAS, large-scale ascent associated with the ITCZ influences the cloud processes  
299 in the region. The observed diurnal moisture and clouds variabilities are more strongly  
300 associated with the diurnal pulses of the ITCZ than during JFM. The higher diversity of  
301 cloud types in JFM (Fig. 2e) makes it more difficult to analyze how a specific cloud type  
302 affects the RH diurnal cycle. It is reflected by the lower correlations between RH diurnal  
303 variations and those of clouds than during JFM. For example, the correlations with the  
304 Medium cloud category is weak or non-significant.

305 The profiles of correlation and lags display less structure than during JFM, but one can  
306 note specific patterns. First, the lags between the maxima of RH and clouds prevalence  
307 change their sign near 400hPa for all clouds categories but HighSemi. This suggests that  
308 different moistening processes occur below and above 400hPa. In situations of HighSemi  
309 cloud cover the entire troposphere moistens 3 to 5 hrs after the cloud maximum growth.  
310 Second, the lags between the minima change their sign near 700hPa for all cloud categories  
311 without exception. Hence, a drying below 700hPa precedes the minimum of formation for  
312 the VeryLow and Low clouds while above this is the opposite (minimum of clouds before  
313 minimum of RH). For the HighOpaque and HighSemi clouds, the processes at play turn  
314 the diurnal cycles: below 700hPa the minimum of RH follows the minimum of prevalence  
315 of these clouds (6 to 9 hrs after) while above the drying precede their dissipation by 4 to  
316 10hrs.

317 We believe that these results corroborate studies on the diurnal variabilities of convection  
318 and precipitation that highlight radiative-dynamics-convective interplays (Randall et al.,  
319 1991). These studies suggest that large anvil clouds dampen the heating of the atmospheric  
320 column (via their shade). It feedbacks on precipitation via locally-enhanced upward motion  
321 within the cloudy column as compared to neighboring cloud-free columns (Chen & Houze,  
322 1997; Ruppert & Klocke, 2019).

323 The moistening patterns of the upper troposphere observed during the JFM period  
 324 point towards different mechanisms. Overall the presence of upper level cloudiness is sig-  
 325 nificantly reduced. Peak occurrence (albeit small) is observed near sunrise while there is  
 326 an upper level moistening between 14:00 and 22:00 LT. This local moistening is more pro-  
 327 nounced when no elevated clouds are present in the column (Fig. 2 (d)). It could be induced  
 328 by horizontal advection of moisture from remote areas (Pierrehumbert & Roca, 1998; Sher-  
 329 wood et al., 2010), and could be associated to the diurnal pulses of the ITCZ (Ciesielski et  
 330 al., 2018) as well as by variations in the upward motion forced by solar heating.

#### 331 **4 Summary and conclusions**

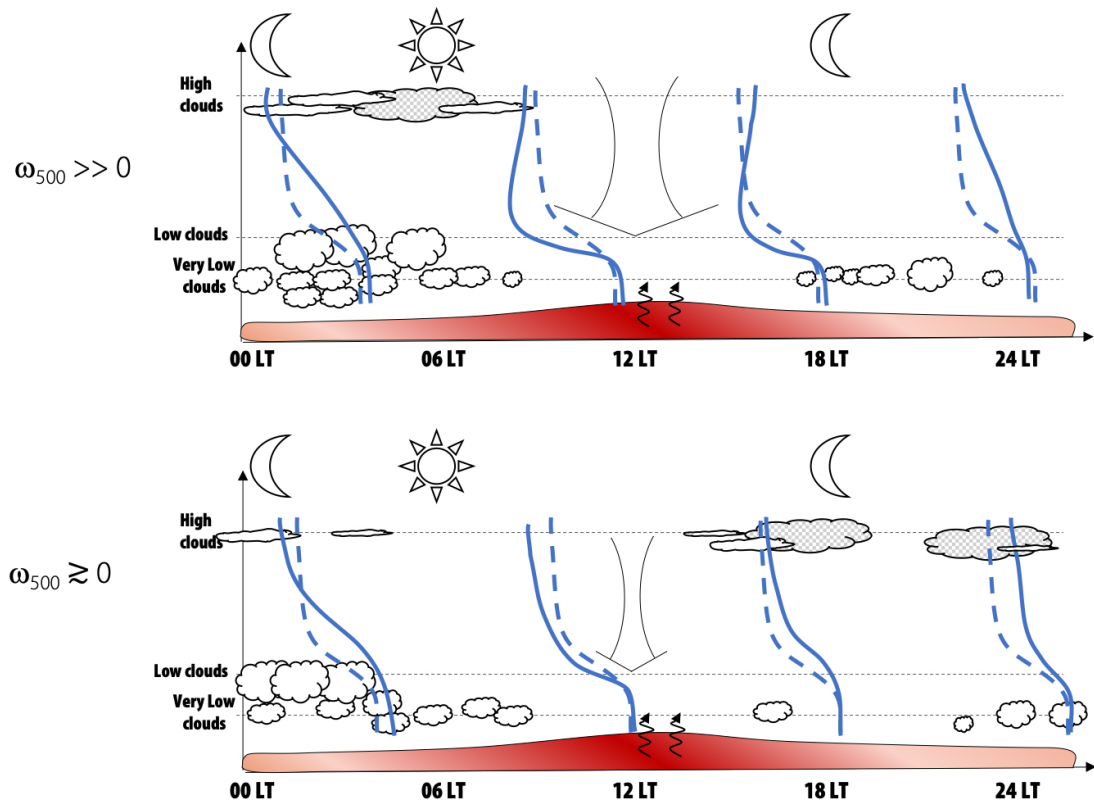
332 In this study, we show how the Megha-Tropiques satellite adds value to the study of  
 333 the diurnal cycle of atmospheric moisture. By collocating SAPHIR observations with those  
 334 of cloud types and environmental conditions over the Western Atlantic Trades during JFM  
 335 and JAS 2012-2017, a robust depiction of the diurnal co-evolution of clouds and moisture  
 336 in areas remotely connected to the rainy ITCZ is provided.

337 Here, we target the diurnal variation of RH in areas less affected by strong convective  
 338 motions and dominated by a mean downward flow. Fig. 4 provides a sketch that summarizes  
 339 the observed patterns.

340 In the strongly subsiding situation ( $\omega_{500} \gg 0$ , corresponding to JFM) :

- 341 (i) After sunrise (06:00-12:00 LT), the mid-troposphere is mostly free of clouds and under-  
 342 goes a strong drying linked to the mean downward motion that brings dry air masses from  
 343 the colder upper troposphere.
- 344 (ii) The daytime warming (12:00-18:00 LT) of the mid-troposphere is linked to the dilution  
 345 of low-level clouds and triggers moistening of the low troposphere a few hours later.
- 346 (iii) At sunset (18:00-24:00 LT), the longwave radiative cooling starts to dominate, thereby  
 347 increasing the vertical cooling rate. The increased temperature gradient yields mixing mois-  
 348 ture vertically. We hypothesize that this behavior is remotely connected to the ITCZ diurnal  
 349 pulses and its afternoon peak, as suggested by (Ruppert & Klocke, 2019).
- 350 (iv) The lifting of moist air in the upper troposphere triggers the formation of high-altitude  
 351 cirriform clouds at night (18:00-24:00 LT). Moisture is pumped from below to maintain  
 352 them.





**Figure 4.** Diagram that shows the evolution of the RH profile (solid line) around its daily average (dashed line). The top panel is for the period of strong subsidence (i.e. JFM,  $\omega_{500} \gg 0$ ) and the bottom panel is for the period of moderate subsidence (i.e. JAS,  $\omega_{500} \approx 0$ ). HighOpaque clouds are in gray while HighSemi clouds are in white, and the large vertical arrows represent the mean downward motions.

353 In the moderate subsiding situation ( $\omega_{500} \simeq 0$ , corresponding to JAS) :

354 (i) The presence of high-altitude clouds during daytime (12:00-18:00 LT) shields the atmo-  
 355 spheric column from solar forcing and reduces the drying due to large-scale subsidence.

356 (ii) The development of upper tropospheric opaque clouds after sunset (18:00-06:00 LT),  
 357 associated with the ITCZ convective systems, constitutes a local source of moisture via  
 358 detrainment.

359 It is hypothesized that the development of VeryLow and Low clouds is driven by con-  
 360 ditions independent of the season, whilst the other categories of clouds are driven by large  
 361 scale dynamics conditioned by the seasonal variations of the ITCZ.

362 These findings help to refine an atmospheric moisture budget for a quiescent area of the  
 363 tropics, and emphasize the important role of relative humidity constrained by clouds and  
 364 dynamics. In future works the impact of the seasonal and diurnal variability of the ITCZ  
 365 will be considered thanks to this observational dataset. The impact of these connections  
 366 will be explored by taking the entire tropical belt into consideration, and by looking at  
 367 moisture profiles dependent on cloud types. This undertaking will contribute to improve  
 368 the assessment of the cloud-water vapor feedback.

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