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Catherine Prigent, Carlos Jimenez, Lan Anh Dinh, Frédéric Frappart, Pierre Gentine, et al.. Diurnal and Seasonal Variations of Passive and Active Microwave Satellite Observations Over Tropical Forests. *Journal of Geophysical Research: Biogeosciences*, 2022, 127 (2), 10.1029/2021JG006677 . hal-03615921

HAL Id: hal-03615921

<https://hal.inrae.fr/hal-03615921>

Submitted on 17 Aug 2022

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JGR Biogeosciences

RESEARCH ARTICLE

10.1029/2021JG006677

Key Points:

- Strong diurnal cycles over tropical forests, for both microwave backscatter and emissivity, with amplitude similar to seasonal variations
- Seasonal and diurnal cycles of backscattering and emissivity temporally anti-correlated over most parts of the tropical forests
- Over Amazonia, seasonal cycle of backscatter and emissivity in phase in dry regions and diurnal cycle also in phase there during dry season

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Citation:

Prigent, C., Jimenez, C., Dinh, L. A., Frappart, F., Gentine, P., Wigneron, J.-P., & Munchak, J. (2022). Diurnal and seasonal variations of passive and active microwave satellite observations over tropical forests. *Journal of Geophysical Research: Biogeosciences*, 127, e2021JG006677. <https://doi.org/10.1029/2021JG006677>

Received 18 OCT 2021
Accepted 10 JAN 2022

Diurnal and Seasonal Variations of Passive and Active Microwave Satellite Observations Over Tropical Forests

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Abstract Documenting the large scale variability of tropical forest structure and function is needed for improved understanding of the carbon and water cycles. The seasonal and diurnal cycles of passive and active microwave satellite observations are jointly analyzed for the first time, using the Global Precipitation Mission (GPM). Collocated backscattering coefficients from the GPM Dual-frequency Precipitation Radar (DPR) and emissivities derived from the GPM Microwave Imager (GMI) are studied for 4 yr over the Tropics, at the available multiple frequencies, angles, and polarizations. Our analysis confirms the diurnal patterns already observed with radars, with a maximum backscatter in the early morning attributed to the water xylem refill at night. At the same time, early in the morning, we evidence a minimum emissivity over most of tropical forests: the backscatter and emissivity diurnal cycles tend to be in phase opposition, as well as their seasonal cycles. However, during the dry season in the south eastern Amazonian forest where precipitation can be low for several months, the emissivity diurnal cycle changes, implying a different behavior of the forest in this area, related to the state of the canopy.

Plain Language Summary The tropical forest plays an important role in the global water and carbon cycles, and it can be analyzed with satellite observations. The seasonal and diurnal cycles of passive and active microwave satellite observations are studied here simultaneously for the first time, thanks to the radar and radiometer on board the Global Precipitation Mission. Four years of observations are collected and analyzed over the Tropics. Our analysis shows that the passive and active observations vary both seasonally and diurnally in tropical forests, with similar amplitude within a day than over the year. The radar and radiometer signals tend to vary in phase opposition, seasonally and diurnally, over most of the tropical forests. However, during the dry season in the south eastern Amazonian forest where precipitation can be low for several months in a row, changes in the seasonal and diurnal cycles of the radiometer observations are evidenced, implying a different behavior of the forest in this area, related to the state of the canopy.

1. Introduction

Tropical forests represent ~25% of the global biomass and plays a key role in the global carbon cycle (Friedlingstein et al., 2020). However, droughts over the last two decades have severely impacted tropical forest dynamics (e.g., Brien et al., 2015; Brodrick et al., 2020; Lewis et al., 2011; Sullivan et al., 2020). With more frequent droughts expected in the Tropics under climate change (Stocker, 2014), documenting tropical forest variability in structure and function is needed, for an improved understanding of the carbon and water cycles.

Satellite microwave remote sensing offers opportunities to monitor vegetation phenology, biomass, and water content. Especially over tropical forest, optical-infrared remote sensing observations are hampered by persistent cloudiness, and the signal saturates over the dense canopy. Both passive and active microwave satellite observations provide an attractive alternative to optical-infrared observations for vegetation monitoring in these regions, because they penetrate through most clouds and saturates less in the presence of high biomass. So far, microwave remote sensing studies focused on the seasonal and inter-annual variability of the water content in the vegetation (Jones et al., 2014; Tian et al., 2018) or of its above ground biomass (Brandt et al., 2018; Fan et al., 2019; Liu et al., 2015). Disentangling the respective contribution from the vegetation biomass and water content to the microwave signal triggered some recent questioning (Konings et al., 2019; Liu et al., 2021; Momen et al., 2017;

Zhang et al., 2019). The analysis of the observations at different time scales was suggested to help separate the biomass and physiological water stress contributions to the microwave signal. In addition to the analyses of the seasonal and inter-annual variability of the vegetation parameters with microwaves, diurnal variations have also been noted, primarily in the active microwave observations.

From field observations, Ulaby and Batlivala (1976) and Brisco et al. (1990) evidenced the diurnal cycle of the backscattering observations over crops, and associated it with changes in the vegetation, not in the soil. From satellite observations, Satake and Hanado (2004) analyzed the backscattering seasonal and diurnal cycles over tropical forests, with the radar in Ku band on board the Tropical Rainfall Measuring Mission (TRMM). They did not observe a significant seasonal cycle, but a rather systematic diurnal cycle of 0.5 dB, with higher backscattering in the morning than in the evening: they attributed it to dew deposition on the leaves as modeled by radiative transfer. Similar backscattering differences were observed over tropical forests, with the SeaWinds Ku radar between 6 a.m. and 6 p.m. (Frolking et al., 2011), or with the ERS C band scatterometer between 10 a.m. and 10 p.m. (Friesen et al., 2012), and the possibility of higher vegetation water content in the early morning is suggested. The full diurnal cycle at Ku band was also observed with RapidScat on board the International Space Station (Paget et al., 2016; van Emmerik et al., 2017). With simultaneous dendrometer measurements of tree water status, van Emmerik et al. (2017) evidenced the changes in the radar signal from wet to dry periods over the Amazon, with a general backscattering drop and a reduction of its diurnal amplitude during the dry periods, emphasizing the sensitivity of the radar measurements to the forest water stress. Over Central Africa, Konings, Yu, et al. (2017) analyzed both the diurnal and seasonal cycles of the Ku backscatter, and concluded on its joint sensitivity to canopy biomass and physiological water stress.

The diurnal variations of the passive microwave observations over vegetated regions have not been examined extensively. This is mainly because the signal is strongly impacted by the surface temperature and that this daily modulation has to be first eliminated from the signal. Land surface emissivities have been calculated from satellite observations, by removing the atmospheric contribution and the surface temperature modulation for instance from SSM/I or AMSR observations (e.g., Moncet et al., 2011; Prigent et al., 2006). However, limited analysis of the emissivity diurnal changes over vegetation has been performed. Li and Min (2013) studied the emissivity variations at different time scales over two Amazon forest sites and noticed emissivity variations even at daily scale that they partly attributed to vegetation water content, including rain interception by the canopy. More recently, the vegetation optical depth (VOD) has been estimated from passive microwave observations, using a simplified radiative transfer model to isolate the vegetation effect from the soil contribution (see Frappart et al., 2020 for a review). Konings and Gentine (2016) and Konings, Williams, and Gentine (2017) analyzed changes in the VOD at X band between midday and midnight, to infer information about the vegetation physiological water regulation.

Here, we propose the first joint analysis of the diurnal and seasonal cycles from both active and passive microwave observations over the tropical forest, thanks to the Global Precipitation Mission (GPM). GPM includes an active instrument (the Dual-frequency Precipitation Radar [DPR] at Ku [13.5 GHz] and Ka [35.5 GHz] bands), as well as a passive microwave radiometer (the GPM Microwave Imager [GMI] from 10 to 190 GHz). GPM is not a Sun-synchronous mission: it provides observations of the full diurnal cycle, contrarily to most passive microwave imagers that observe a given location always at similar local times twice a day. We analyze 4 yr of GPM-derived colocated measured backscatter cross-section and retrieved land surface emissivity, under clear-sky conditions (Munchak et al., 2020). This is a unique multi-year data set, providing both multi-frequency active and passive microwave land surface parameters, with close-to-global coverage, and including the full diurnal cycle. The results are discussed, with respect to already published results or from the expected interactions between the forest and the microwave signals. The explored data set is very rich, with multiple frequencies and both active and passive observations, and this is a first attempt to exploit it for a better understanding of the tropical forest.

First, the active-passive GPM microwave land surface data set is described (Section 2), as well as the method (Section 3). Section 4 presents the temporal analysis of the microwave land surface responses, seasonal and diurnal, at a few locations over the tropical forest, and it is extended to the tropical belt. The results are discussed in Section 5. Section 6 concludes this study.

2. Data

The GPM program is designed to monitor rainfall (Hou et al., 2014). The core satellite encompasses both a dual frequency radar (DPR) and a multi-channel passive microwave radiometer (GMI). It is in a 65° inclination non Sun-synchronous orbit, allowing a full sampling of all local Earth times approximately every 2 weeks. It is therefore particularly adapted for this study of the response of the vegetation over the diurnal cycle.

A database of co-located measured backscatter cross-section (σ_0) and retrieved land surface emissivity has been developed, derived from GPM DPR and GMI observations, under clear-sky conditions (Munchak et al., 2020). The data set covers more than 5 yr, with global land and sea ice coverage from −65°S to 65°N. Here, 4 yr of data are analyzed from 2015 to 2018, over the Tropics.

2.1. The Land Surface Microwave Backscattering Coefficients

DPR has a Ku band (13.6 GHz) and a Ka band (35.5 GHz) with a vertical resolution of 250 m and a horizontal resolution of ~5 km at nadir. It observes the Earth in a cross-track mode, with incidence angles up to 18° and 9°, respectively, on both sides of the nadir view to cover a swath of 250 and 125 km, respectively, at Ku and Ka bands. Under rain-free conditions, the backscattering signal corresponds to the Earth surface response. Given the scanning geometry of the DPR and its non Sun-synchronous orbit, each location is not often observed under the same incidence angle and the same local time. Time and space averaging is necessary to have enough observations of a given location, at a given local time, for a specific incidence angle. Note that the azimuth angle is not taken into account here, and the left and right sides of the scan are not separated. For a robust analysis of the variability of the land surface backscattering with local time, different tests have been conducted to select the optimum space, time, and angular averaging, for each given location and incidence angle. We chose to grid the data on a 1° × 1° regular grid, averaged per hour, per month over 4 yr (2015–2018), for six angular ranges of 3° at Ku band (between 0° and 18°) and for three angular ranges at Ka band (between 0° and 9°). As a consequence, for a given location (at a 1° × 1° resolution) and a given angular range, each hourly time step in the local diurnal cycle represents the average for the given month, over the 4 yr. For the diurnal analysis, the data are further averaged over seasons (JFM, AMJ, JAS, and OND). There is in average 220 samples available per hour, per season (3 months for the 4 yr), per 3° incidence angle ranges, and per 1° × 1° grid cell, over the Tropics. An analysis of the seasonal cycle is also conducted, for comparison with the diurnal variability of the signal: for this analysis, monthly mean averages over the 4 yr are calculated on the 1° × 1° regular grid, regardless of the local time, for each 3° angle range.

2.2. The Land Surface Microwave Emissivities

GMI is a microwave radiometer, with channels at 10.65, 18.7, 23.8, 36.5, 89.0, 166.0, and 183.3 ± 3 and ±7 GHz. All frequencies are observed in *V* and *H* polarizations, except the channels in the water vapor lines at 23 and 183 GHz (*V* polarization only). GMI is a conical scanner with a ~53° Earth incidence angle, and it provides wide-swath (885 km) brightness temperatures (T_b) data with resolutions ranging from 5 to 25 km depending on frequency.

The full 10–166 GHz emissivity vector is retrieved using optimal estimation (Rodgers, 2000). With GMI including water vapor sounding channels, retrievals of the atmospheric and surface state are performed simultaneously. The NASA Modern-Era Retrospective analysis for Research and Applications, 2 (MERRA-2, Gelaro et al., 2017) is adopted for the a priori atmospheric state and surface temperature information (T_s). The primary source of errors in the emissivity calculation is related to the surface temperature assumptions (Prigent et al., 1997). The calculations here assume that the emissivity is associated with the surface temperature, regardless of the observation wavelength. In desert environments, the radiation can come from below the surface (the longer the wavelength the deeper the penetration), with emission temperature different from T_s . However, the assumption holds here for the analysis of densely vegetated regions where the emissivities are effectively associated with T_s . The emissivities affected by cloud and precipitation are screened out. See Munchak et al. (2020) for more details about the emissivity calculations from GMI. The emissivity data set is averaged, using the same space and time averaging as for σ_0 , that is, on a 1° × 1° regular grid, averaged per hour, per month, over the 4 yr from 2015 to 2018.

The brightness temperatures are also systematically available in this database, along with the corresponding emissivities. The MicroWave Index (MWI) is calculated as $(T_bV - T_bH)/(T_bV + T_bH)$, where T_bV and T_bH are the brightness temperatures at vertical and horizontal polarizations, respectively. Neglecting the atmospheric contribution, the microwave brightness temperature T_b can be written as $T_b = \text{emissivity} \times T_s$, and MWI then corresponds to the ratio of the emissivity polarization difference normalized by its sum, thus eliminating the sensitivity to T_s . The diurnal cycle of MWI has been examined systematically during this study, and compared to the emissivity polarization difference calculated in the data set, in order to verify that the observed emissivity diurnal cycles were not related to spurious errors in the diurnal cycle of T_s used in the emissivity calculation.

2.3. A Few Maps

Figure 1 presents selected maps of active and passive microwave surface variables from GPM: the mean σ_0 over 4 yr at Ku band around 16° incidence angle, and the mean emissivity over 4 yr at 10 GHz, horizontal polarization (H), averaged over 1° in latitude and longitude. The Above Ground Biomass (AGB) from Saatchi et al. (2011) is also plotted for comparison. The map of the mean precipitation per day over the year is shown, along with the number of dry months (i.e., with precipitation <100 mm per month) per year, both derived from the Global Precipitation Climatology Project (GPCP; Pendergrass et al., 2020).

3. Method

The complex interaction between the vegetation and the microwave signal in active and passive modes depends upon the observing conditions (frequency, incidence angle, and polarization), as well as on the vegetation and soil properties (e.g., Konings et al., 2019; Ulaby et al., 2014; Wigneron et al., 2004, 2017; Zhang et al., 2019). Microwaves interact with the vegetation through absorption, emission, and scattering, in response to the structure and water content of the vegetation elements. With decreasing frequency, the microwave signal is expected to arise from lower in the vegetation canopy. The backscattering in Ku at 16° incidence angle increases with vegetation density, but also with topography. In general, the passive microwave emissivity tends to increase with vegetation density, and to decrease with the presence of surface water, leading to counteracting effects in inundated regions. On the maps in Figure 1, the very dense forest shows high emissivity, but the inundations around the Amazon or the Congo Rivers are characterized by low emissivity. Therefore, in the following analysis, the surface waters have been systematically filtered out, following the monthly mean surface water extent at 0.25° resolution, available from the Global Inundation Extent from Multi-Satellite version 2 (GIEMS 2; Prigent et al., 2020). With increasing frequency, the vegetation contribution is expected to increase, both for passive and active modes, with respect to the surface contribution. This study concentrates on the analysis of the satellite observations over tropical forests where the vegetation contribution is expected to dominate the microwave signals at 10 GHz and above, with limited effects from the underlying surface.

We first analyze the seasonal and diurnal patterns of the active microwave σ_0 and passive microwave emissivities, over many locations in the Tropics. Two regions that are representative of the general σ_0 and emissivity behaviors are selected and are delineated in Figure 1. The primary objective of this study is to analyze the diurnal cycle of the active and passive microwave signals, but it was found that the description of their seasonal cycle was also necessary to better understand the diurnal variations and put them in perspective.

In a second step, we extend the analysis from the selected regions to the tropical belt, to evaluate the regional representativity of the patterns observed locally.

4. Results

4.1. Temporal Analysis of the Microwave Land Surface Responses in Selected Locations

4.1.1. Seasonal Cycle

For two selected regions over the Amazon (72W65W 1S2N) and Congo (19E28E 2S3N; see Figure 1, middle panel), the 4-yr averaged seasonal cycles of σ_0 and emissivity are calculated, along with the mean precipitation seasonal cycles, as extracted from GPCP (Figure 2). The seasonal cycles have been systematically computed for σ_0 at Ku and Ka bands at all angle ranges, and for the emissivity at all frequencies below 89 GHz and both V and

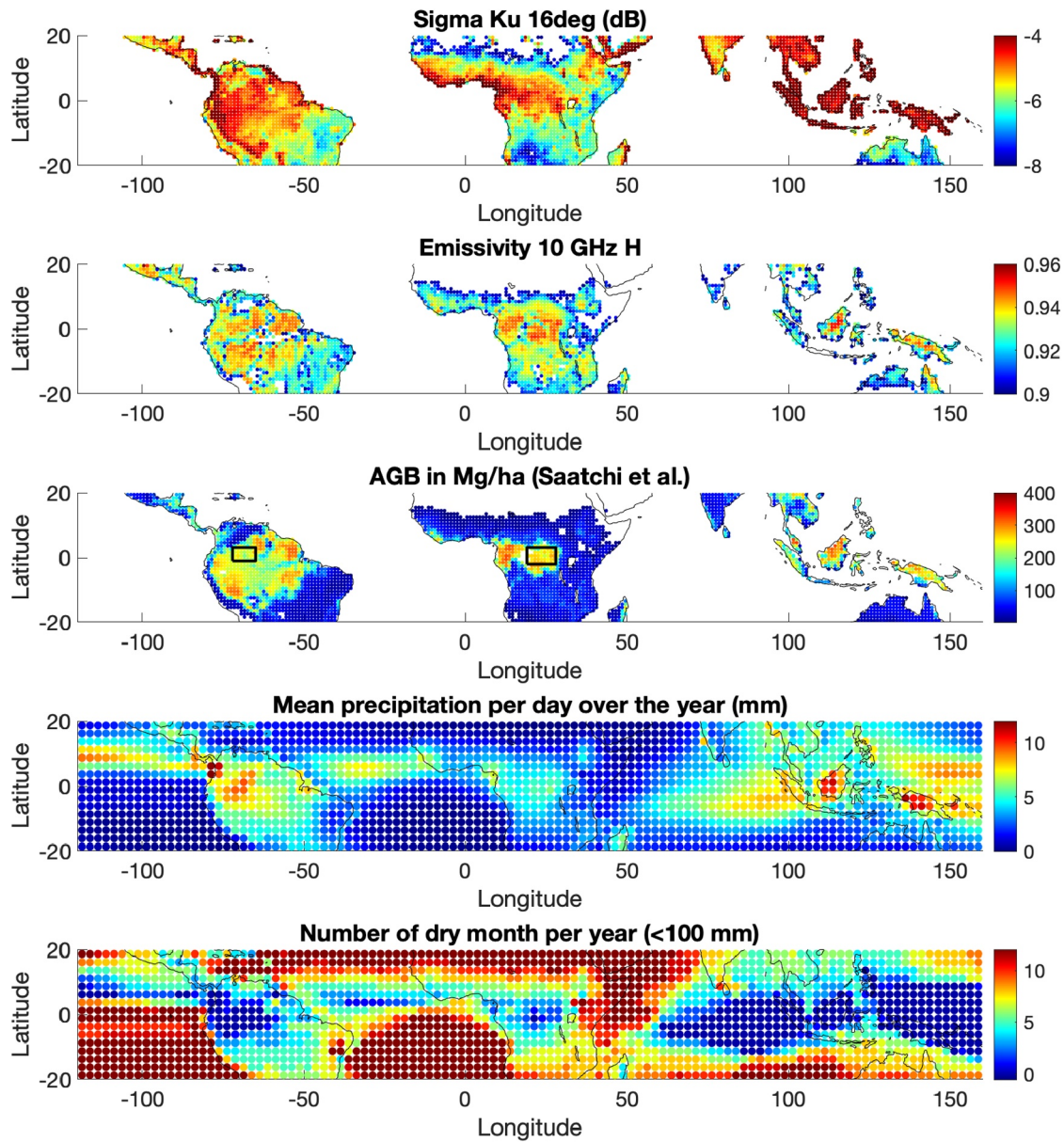


Figure 1. From top to bottom, maps over the Tropics of (1) the mean backscattering coefficient over 4 yr at Ku band around 16° incidence angle from GPM, (2) the mean emissivity over 4 yr at 10 GHz, horizontal polarization (H) from GPM, (3) the Above Ground Biomass (AGB) in Mg/ha from Saatchi et al. (2011), (4) the mean precipitation per day over the years in millimeter from GPCP, and (5) the number of dry months (with precipitation <100 mm per month) per year from GPCP. Two regions will be analyzed with more details and are indicated in black on the AGB map.

H polarizations. For clarity purposes, only two incidence angle ranges are presented here for σ_0 (at $\sim 8^\circ$ that is common to Ku and Ka bands), and for the emissivities, only the frequencies closest to the radar bands are shown (10 and 36 GHz). We checked that the emissivities were monotonically varying from the lower to the higher frequencies, for both polarizations.

As shown in Figure 2 over the Amazon location, the precipitation reaches a maximum in May. In contrast, the rainfall is more limited over the Congo, with two rainfall seasons peaking in April and October, with dryer periods around June and January. Despite rather different seasonal precipitation cycles, the seasonal cycle of σ_0 is limited (~ 0.5 dB) for both regions, emphasizing the limited biomass and water content change across the season in those evergreen tropical forests. σ_0 shows very similar seasonal variations for both Ku and Ka bands. The incidence angle dependence of σ_0 is also limited over very dense vegetation. Note that a slight decrease of

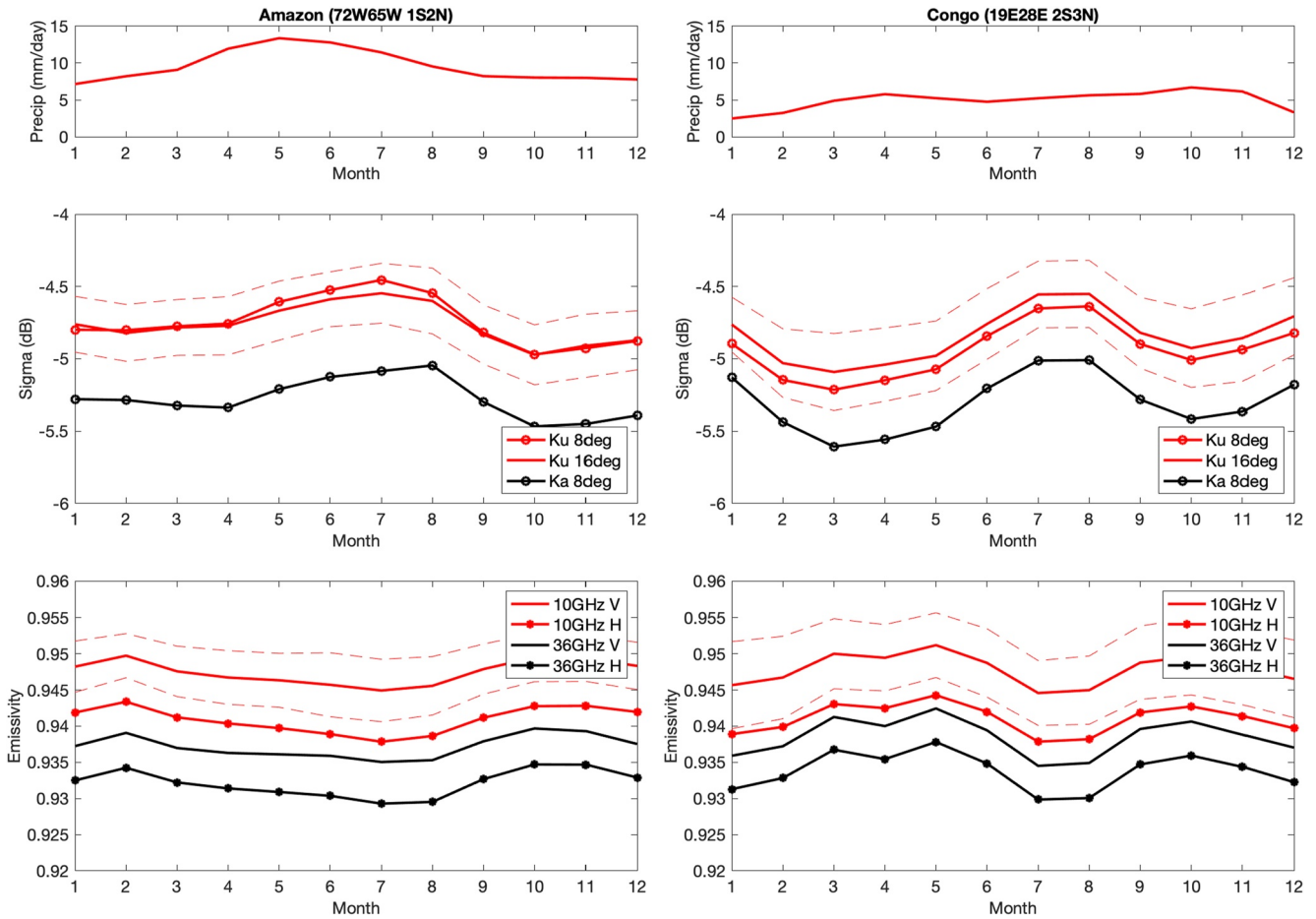


Figure 2. For two locations over the Tropics, the mean seasonal cycle over 4 yr (2015–2018), for precipitation (from GPCP; top panel), for σ_0 at Ku and Ka bands (two incidence angles for Ku and one for Ka; middle panel), and for emissivity at 10 and 36 GHz, V and H polarizations (bottom panel). Left panels: a region over the Amazon (72W65W 1S2N). Right panels: a region over the Congo (19E28E 2S3N). Plus and minus one standard deviation of the signals around the mean are also indicated by dashed line for one case of σ_0 (Ku, 16°) and emissivity (10 GHz, V). The regions are shown in Figure 1, middle panel.

σ_0 is expected with increasing angles (Prigent et al., 2014; Seto & Iguchi, 2007), as observed over the Amazon region. It is not the case over the Congo location, but the difference is small compared to the σ_0 standard deviation (dashed lines in Figure 2) and we checked that the expected angular dependence is observed for the lower incidence angles. σ_0 at Ka is systematically lower than at Ku, for the same incidence angles. The seasonal amplitudes of the emissivities are also small, and similar for both frequencies and polarizations. For a given polarization, the emissivities at 36 GHz are lower than at 10 GHz. For both regions, the seasonal cycles of σ_0 and emissivity are anti-correlated: the maxima in σ_0 tend to coincide with the minima in emissivity and vice-versa. Note that the precipitation seasonal cycle appears to be anti-correlated or lagged with the σ_0 and emissivity cycles.

4.1.2. Diurnal Cycle

For the same regions, same frequencies, angles, and polarizations, the diurnal cycles of σ_0 and emissivity are also computed, averaged over 4 yr for the four seasons (JFM, AMJ, JAS, and OND). The results for JFM are presented in Figure 3.

Comparing Figures 2 and 3 the amplitudes of the diurnal cycles for both σ_0 and emissivity are of the same order as the amplitude of the seasonal cycles. This behavior is observed for all frequencies and incidence angles.

The diurnal cycle of σ_0 shows a systematic maximum in the early morning (~6 a.m. local time), for both regions. Then, σ_0 tends to decrease up to the beginning of the afternoon, to slightly increase in the late afternoon (~4 p.m.), before decreasing again. The systematic σ_0 maximum in the early morning and systematic σ_0 minimum at night have been observed by several authors, especially over the tropical forest, for instance by Satake and

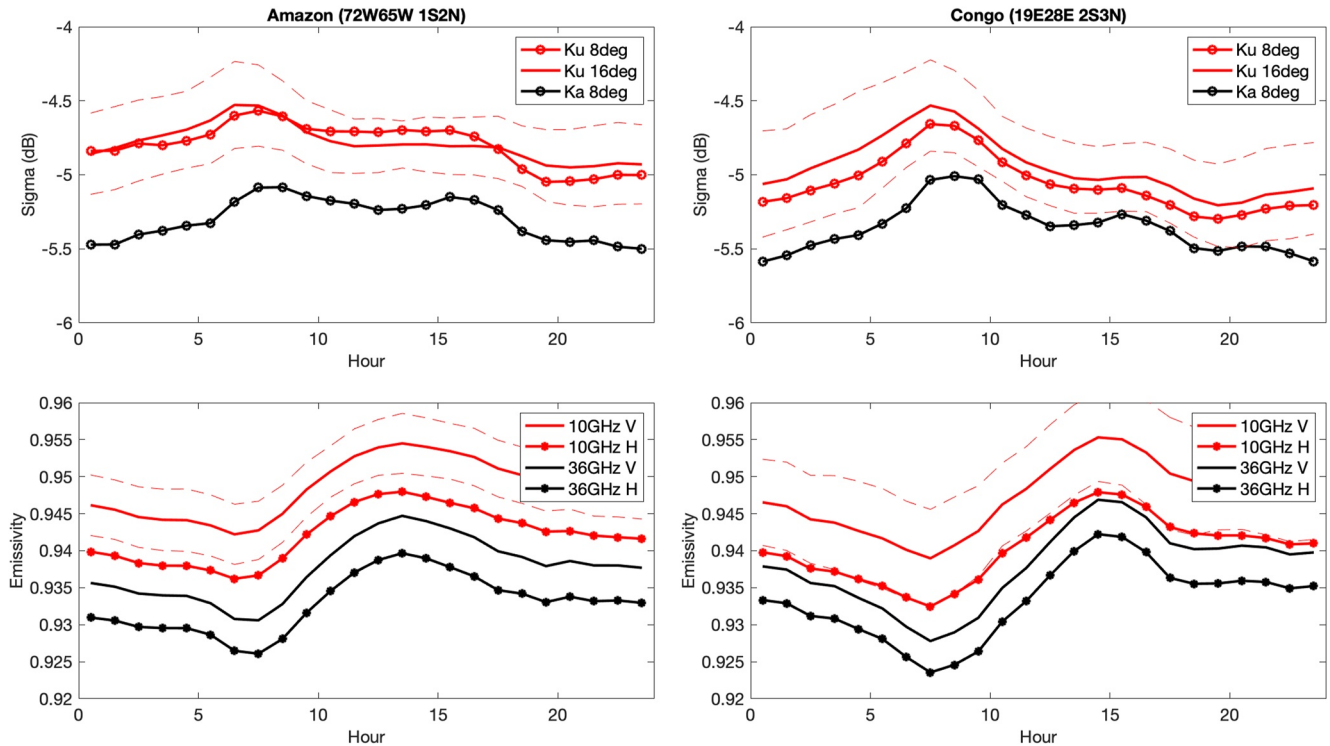


Figure 3. For two regions over the Tropics, the mean diurnal cycle averaged over January, February, and March (JFM), over 4 yr (2015–2018), for σ_0 at Ku and Ka bands (two incidence angles for Ku and one for Ka; top panel), and for emissivity at 10 and 36 GHz, V and H polarizations (bottom panel). Left panels: a region over the Amazon (72W65 W 1S2N). Right panels: a region over the Congo (19E28E 2S3N). The regions are shown in Figure 1, middle panel.

Hanado (2004) with TRMM at Ku band, or by Friesen et al. (2012) with ERS at C band. Note that we selected the same region over Congo as in Konings, Yu, et al. (2017) where QuickScat and RapidScat data at Ku band were used: similar σ_0 diurnal cycles are observed, but with a complete temporal sampling of the diurnal cycle in the present study. The diurnal variations in σ_0 have been attributed to changes in the amount of water content in the canopy (in and on the leaves mostly; Friesen et al., 2012; Konings, Yu, et al., 2017; Liu et al., 2021; Satake & Hanado, 2004; van Emmerik et al., 2017). Before sunrise, the photosynthetic activity is negligible, and the plant water content reaches maximum. In the early morning when the sun rises, the leaves start to lose water through transpiration, and possible dew starts to evaporate as well. Later in the day, stomatal closure limits the evapotranspiration and σ_0 reaches a plateau. During the night, the leaves rehydrate through water transport from the root and σ_0 increases, and possible dew forms on the leaves in the early morning, boosting the σ_0 increase. In the early morning, the respective contribution of leaf re-hydration and dew deposition has been discussed (Friesen et al., 2012; Satake & Hanado, 2004).

The diurnal cycle of the emissivity shows a systematic minimum in the early morning (~ 6 a.m. local time), for both regions. The emissivities increase from early morning to the beginning of the afternoon, then decrease for 2–4 hr and finally reach a plateau for the rest of the day. As noted in Section 2.2, the diurnal cycles of the MWI and the emissivity polarization differences have been systematically compared. They show very similar diurnal cycles, ruling out the possible errors in the diurnal cycle of T_s to explain the emissivity diurnal cycle. In addition, the diurnal cycles of the 10 and 36 GHz emissivities show very similar patterns. This excludes obvious atmospheric effects on the emissivities, with much more sensitivity expected at 36 than at 10 GHz to the atmospheric water vapor and cloud contributions that tend to increase in the afternoon in these tropical regions. As for the seasonal cycle, the diurnal cycle of σ_0 and emissivity appears anti-correlated, at least until mid-day, with less marked variations after ~ 1 p.m. For a high level of water content in the canopy resulting in a strong crown attenuation, a decrease of the emissivity with increasing water content in the vegetation has been modeled by Wigneron et al. (1993), and observed and modeled by Min and Lin (2006) and Li and Min (2013). In that case, the emissivity and backscattering tend to vary in opposite directions, as also theorized by Peake (1959) and Ulaby et al. (1982), following Kirchhoff's law.

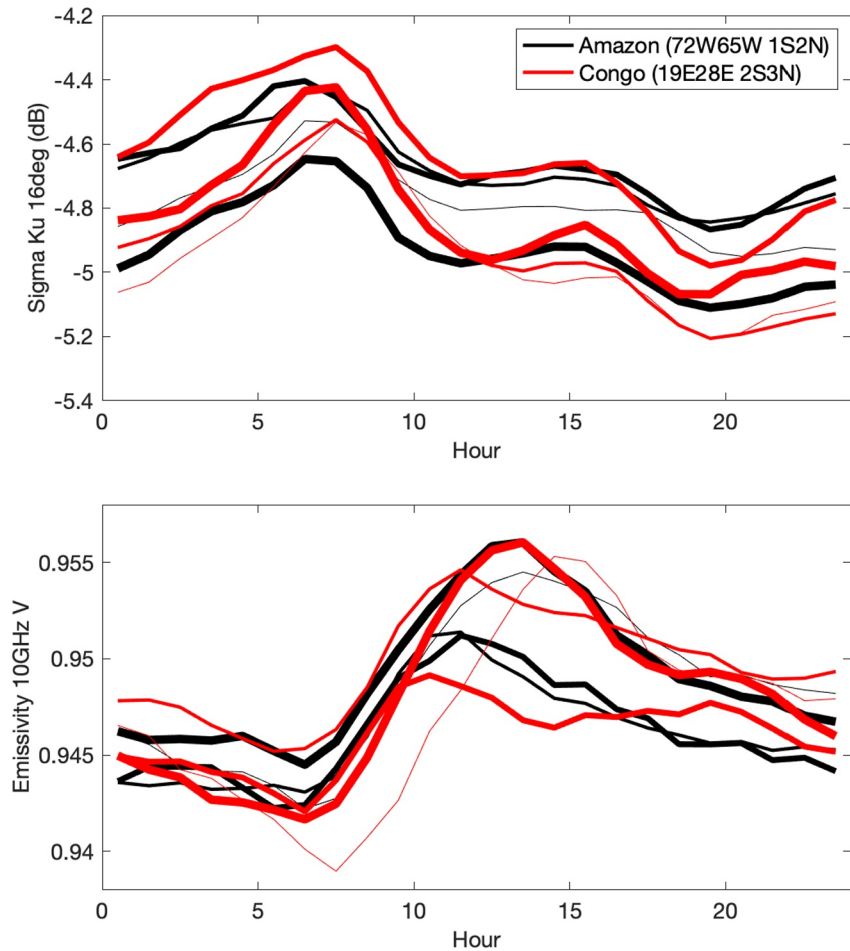


Figure 4. For two selected regions over the Tropics, the mean diurnal cycle averaged for the four seasons, over 4 yr (2015–2018), for σ_0 at Ku, 16° (top panel), and for emissivity at 10 GHz, V (bottom panel). The thickness of the lines indicate the season, from JFM for the thinner lines to OND for the thicker ones. The regions are shown in Figure 1, middle panel.

Figure 4 shows the evolution of the diurnal cycle of σ_0 (at Ku band at 16° angle) and emissivity (at 10 GHz V polarization), for the four seasons. For both σ_0 and emissivity, similar diurnal patterns have been observed for all seasons, over these two regions.

4.2. Large Scale Analysis of the Microwave Land Surface Responses

In the previous section, we analyzed very similar behaviors of the seasonal and diurnal variations of the microwave signals over two locations in the Amazon and the Congo basins. Is this behavior observable all over the tropical forest?

4.2.1. Seasonal Cycle

The seasonal cycles of σ_0 and emissivity appeared rather anti-correlated in the two tested regions. Figure 5 shows the temporal linear correlation between the seasonal cycles of σ_0 (Ku, 16°) and emissivity (10 GHz, V), over the tropical forest (pixels with AGC < 50 Mg/ha have been suppressed). It shows that over Africa and Asia, the two seasonal cycles are dominantly anti-correlated. In South America, the north western part of the tropical forest shows the same anti-correlation, but in the south eastern part of the Amazonian forest, a clear correlation between the seasonal cycle of σ_0 and emissivity is observed.

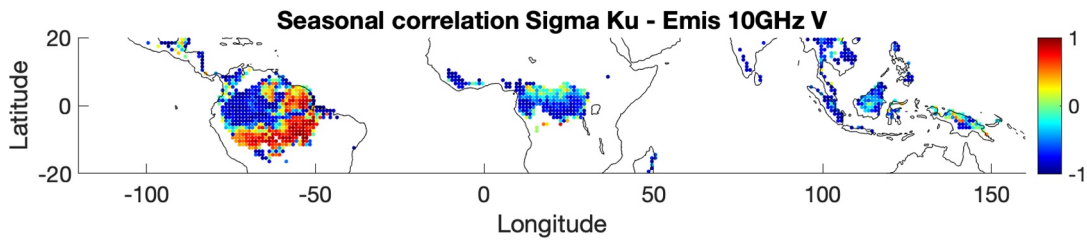


Figure 5. Temporal linear correlation over the tropical forest (pixels with AGC < 50 Mg/ha have been suppressed) between the seasonal cycles of σ_0 (Ku, 16°) and emissivity (10 GHz, V).

4.2.2. Diurnal Cycle

A maximum σ_0 early in the morning has been systematically observed by several authors with different instruments over the tropical forest as already discussed, and it has also been seen for two locations with the GPM radar in Section 4.1. With the GPM radiometer for the same two locations, we observed a minimum microwave emissivities in the early morning at approximately the same time. Figure 6 presents the time of the maximum σ_0 (Ku, 16°) during the day, along with the time of the minimum emissivity (10 GHz, V), for two seasons (JFM and

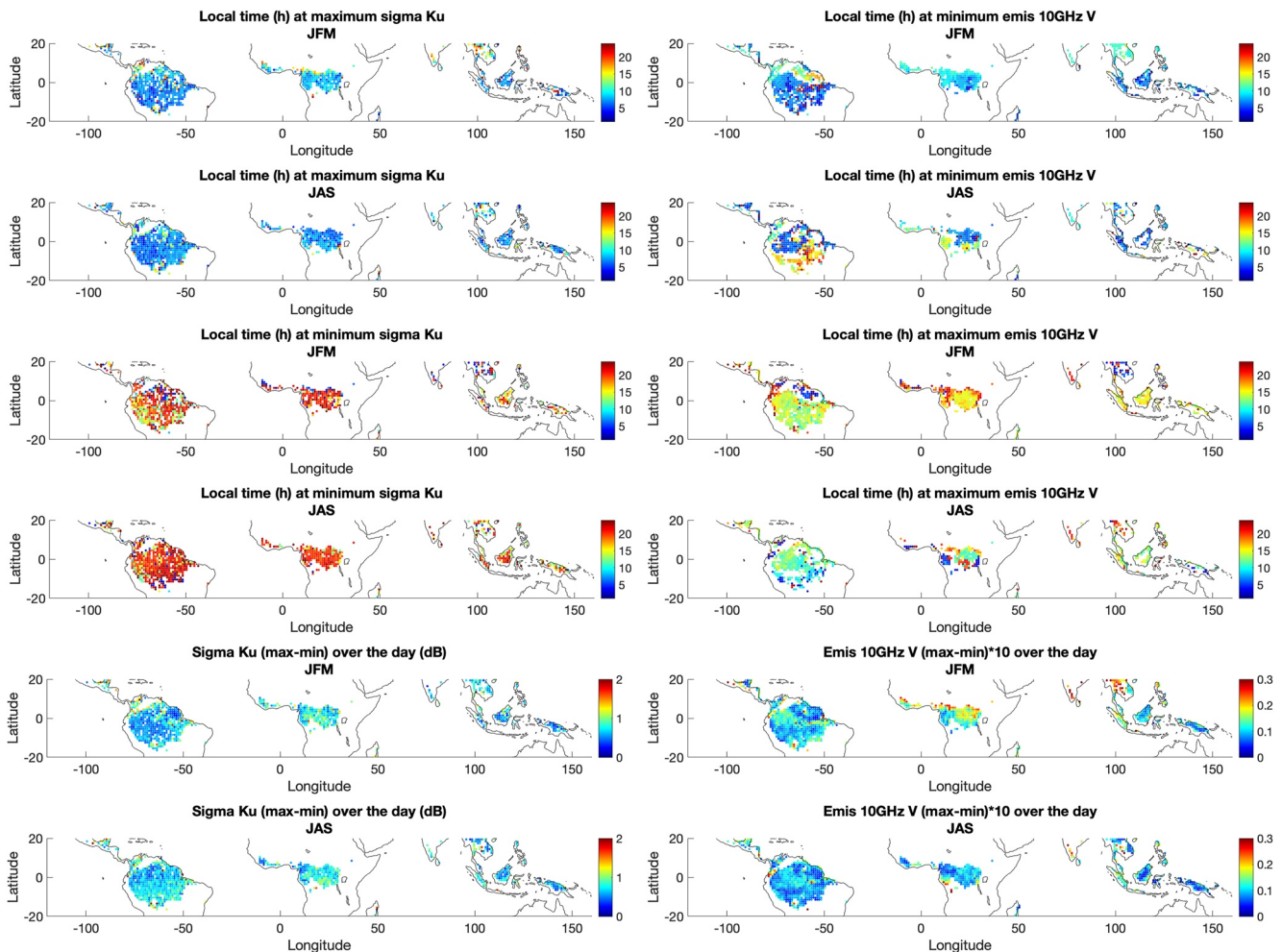


Figure 6. From top to bottom: (1) Time of the maximum σ_0 (Ku, 16°) during the day (left) and time of the minimum emissivity (10 GHz, V) during the day (right) for two seasons (JFM first row and JAS second row); (2) Time of the minimum σ_0 (Ku, 16°) during the day (left) and time of the maximum emissivity (10 GHz, V) during the day (right) for two seasons (JFM third row and JAS fourth row); (3) Amplitude of the diurnal cycle in σ_0 (Ku, 16°) (left) and in emissivity (10 GHz, V) (right) for two seasons (JFM fifth row and JAS sixth row).

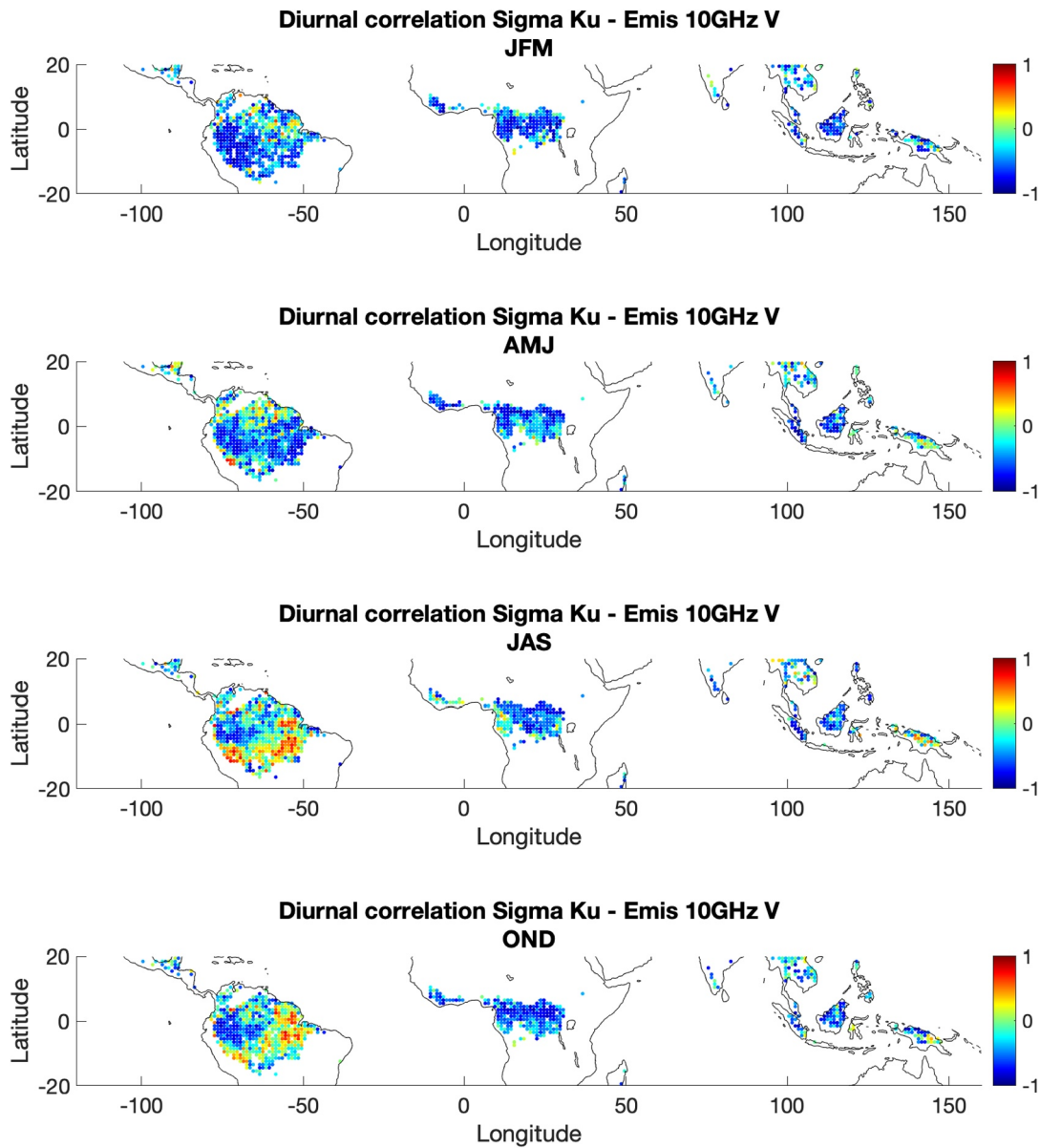


Figure 7. Temporal linear correlation between the diurnal cycle of σ_0 (Ku, 16°) and emissivity (10 GHz, V) for the four seasons.

JAS), for the tropical band. In JFM, the maximum σ_0 coincides in time with the minimum emissivity, over the tropical forest. In JAS, it does as well, except in the south of the Amazonian forest. The time of the minimum σ_0 during the day is also evaluated in Figure 6: it is around 8 p.m. regardless of seasons (all seasons have been tested). The maximum of emissivity is reached earlier in the afternoon, and it changes slightly with seasons. Finally, Figure 6 shows the differences in σ_0 and emissivity between their maximum and minimum values during the day. The amplitudes of the diurnal cycles are relatively stable in σ_0 across the Tropics, for the different seasons (only two shown). Over the African equatorial forest, the amplitude of the diurnal cycle changes slightly more than elsewhere, from a season to the next.

The temporal correlation between the diurnal cycle of σ_0 (Ku, 16°) and emissivity (10 GHz, V) is then investigated for the four seasons (Figure 7). It shows a significant anti-correlation between σ_0 and emissivity, for tropical forests in Africa and Asia. In South America, the western part of the tropical forest also shows this anti-correlation. However, for the rest of the Amazonian forest, the correlation changes with seasons, and tends to be rather positive and high during the second half of the year (JAS and OND) that corresponds to the dryer season.

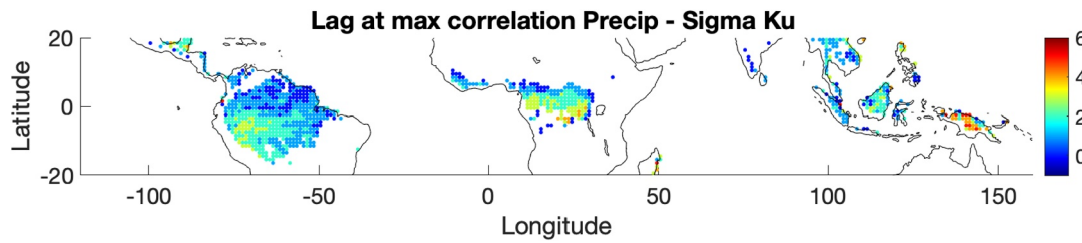


Figure 8. Time lag (in months) to reach maximum temporal correlation between the seasonal cycles of precipitation and σ_0 (Ku, 16°), over the tropical forest (pixels with AGC < 50 Mg/ha have been suppressed).

5. Discussion

5.1. σ_0 Seasonal and Diurnal Cycles, as Compared to Previous Studies

σ_0 variations have rather similar behaviors across tropical forests, seasonally and diurnally. In terms of seasonal variations, maximum σ_0 is observed 2–3 months after the precipitation maximum. Figure 8 shows the time lag (in months) to reach the maximum linear correlation between σ_0 and precipitation seasonal cycles. Over Congo with QuickScat and RapidScat, Konings, Yu, et al. (2017) observed a maximum σ_0 during the dry seasons: the Congo region having two precipitation peaks per year, this is equivalent, and not contradictory, to a high correlation between the maximum σ_0 and the precipitation, with a 3-month lag, as we observe here all over the tropical forest. With RapidScat and in situ water deficit measurements over the Amazon, van Emmerik et al. (2017) also observed a delay between the σ_0 increase (attributed to the vegetation recovery from stress) and the end of the water stress. The greening of tropical forest during the dryer and higher sunlight season has already been documented, with visible satellite observations (Saleska et al., 2016), as well as with modeling (Manoli et al., 2018). Canopy biomass growth and new leaves following old leaf flush have been mentioned as potential contributors to the σ_0 increase, several months after the maximum precipitation, and even during the dry season (Jones et al., 2014; Konings, Yu, et al., 2017; van Emmerik et al., 2017).

Frolking et al. (2011) observed a reduced diurnal amplitude of σ_0 during acute and persistent droughts over the Amazon. Steele-Dunne et al. (2012) suggested the σ_0 diurnal amplitude as an indicator of physiological water stress, with the canopy being unable to recover to the full leaf water content during the night under water stress conditions. Here, there is no clear sign that the amplitude of the σ_0 diurnal cycle changes with season, in relation to changes in precipitation and possible water stress (Figure 6). The signal being averaged here over 4 yr to provide a detailed description of the diurnal cycle, this effect might be smoothed out in our analysis.

5.2. σ_0 and Emissivity Anomalous Relationships in the Dryer Amazonian Forest

For the emissivity, the seasonal and diurnal cycles tend to be in phase opposition with σ_0 cycles, except over the south eastern part of the Amazonian forest. To further explore the different behaviors in the Amazonian forest, Figure 9 presents the seasonal cycles of precipitation, σ_0 (Ku, 16°), and emissivity (10 GHz, V; similar to Figure 2), in the south east of Brazil (58W52W 9S6S) where a contrasting microwave signature is observed. For the same region, the diurnal cycles of σ_0 (Ku, 16°) and emissivity (10 GHz, V) are also presented in Figure 10 (similar to Figure 3), along with the comparison of the diurnal cycles for the four seasons (same as Figure 4). Contrarily to the previously explored locations, there is a clear dry season in this region (Figure 9 top panel), with very limited precipitation from June to August. This also appears in Figure 1 (bottom panel), with a larger number of dry months per year, compared to the western part of the Amazonian forest.

The seasonal cycle of σ_0 shows a stronger amplitude in this region than previously observed in the two other locations (see Section 4.1.1). σ_0 appears to lag behind the precipitation cycle by roughly 2 months (similar to what was observed for the other locations). Contrary to the previous locations, the emissivity seasonal cycle (which has a rather small amplitude) is in phase with the σ_0 seasonal cycle. The σ_0 diurnal cycle in this region has the same behavior as in the other regions, with a maximum value reached in the early morning. For the emissivity diurnal cycle, during the wet months (see JFM), the behavior is the same as in the two previously selected regions. However, changes are observed after the start of the dry period (see JAS), with a slight increase of the emissivity in the morning up to a maximum at ~10 a.m.

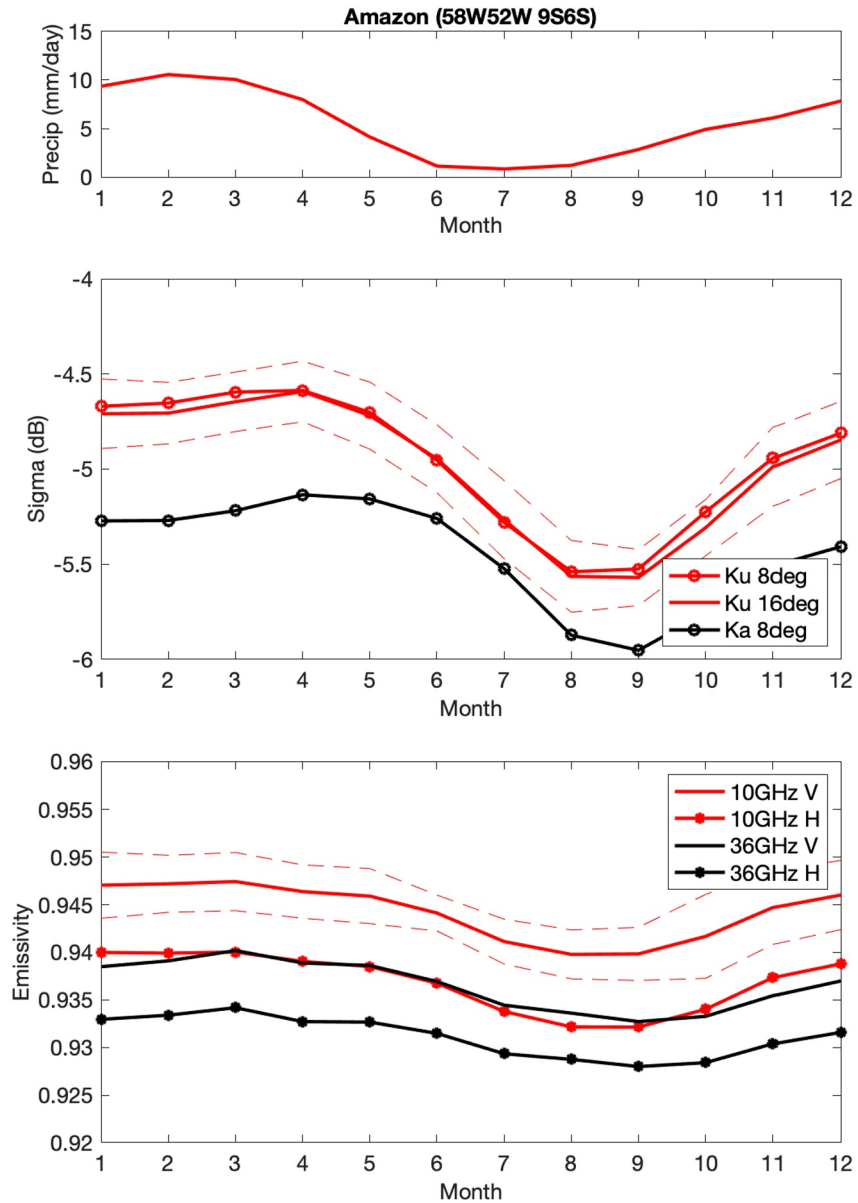


Figure 9. Seasonal cycles, similar to Figure 2, for a region south east of the Amazon forest (58W52W 9S6S).

Over the Amazon, the higher positive correlation between σ_0 and emissivity (both in seasonal and diurnal variations) tends to correspond to the region with a longer and more acute dry season (Figure 1). It also coincides with regions where Leaf Area Index is lower (Myster, 2016) and where forest basal area is smaller (Malhi et al., 2006). Note that in these regions in the south and south eastern part of the Amazon Basin, the local time at minimum emission at 10 GHz at V polarization shifts from early morning in JFM to evening in JAS (Figure 6). These regions are subject to a large decrease in rainfall between JFM and JAS, and, also, a rise in the surface sensible heat flux during dry years (Harper et al., 2014). In the recent years, this part of the Amazon Basin was strongly affected by extreme droughts (Frappart et al., 2012, 2013; Marengo et al., 2012; Panisset et al., 2018), with strong impact on the forest (Feldpausch et al., 2016; Jiménez-Muñoz et al., 2016; da Silva et al., 2018).

Jones et al. (2014) analyzed multiple satellite-derived data sets over the Amazon. They showed that the southern equatorial Amazon forest has a distinctive seasonal cycle from west to east below 0°S, in relation with seasonal changes in water and solar radiation availability. Although these two quantities are generally abundant in the region, they suggest that the forest adapts itself to local conditions in terms of biomass growth and leaf flush to

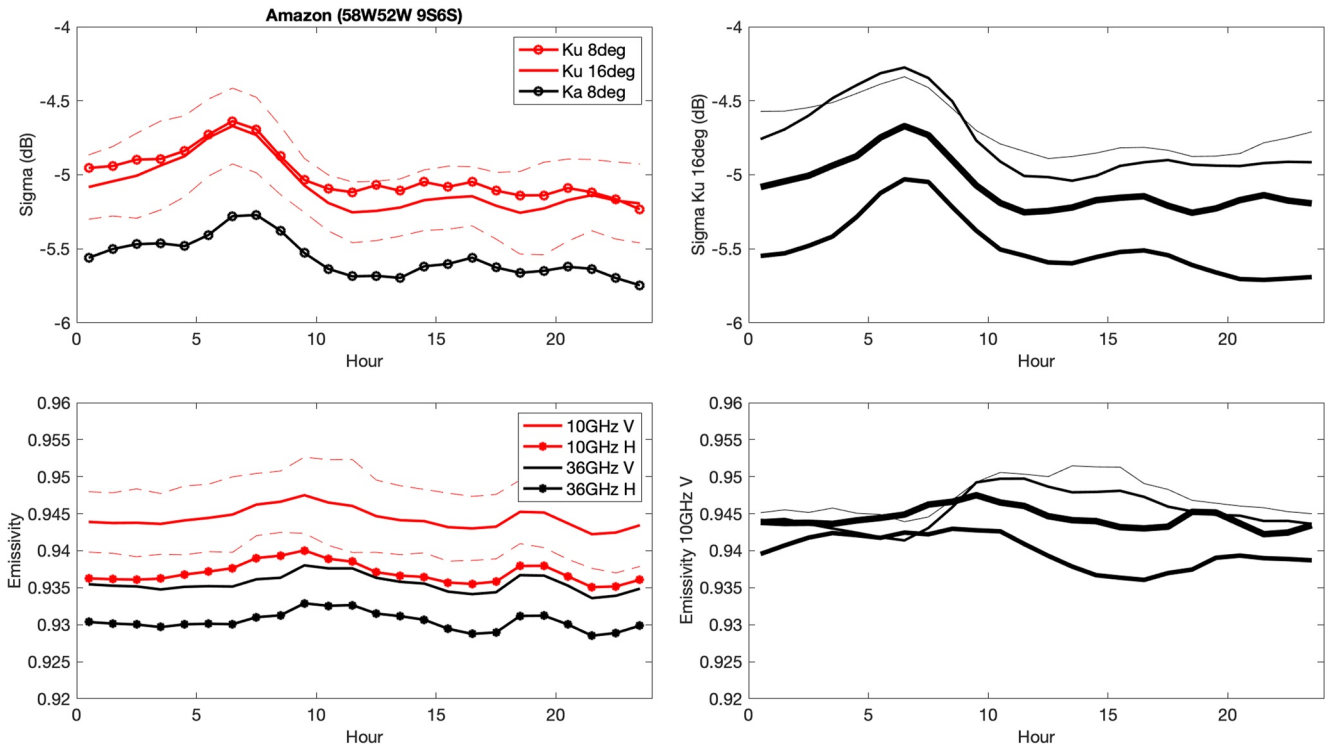


Figure 10. For a region south east of the Amazon forest: (1) Left: Diurnal cycles, similar to Figure 3, in OND. (2) Right: Comparisons of the diurnal cycles over the four seasons, similar to Figure 4, with the thickness of the lines indicating the season from thin lines in JFM to thick lines in OND.

reduce its drought susceptibility. Here, the phase shift in the seasonal cycle and in the diurnal cycle during dry months between σ_0 and emissivity from west to east is also likely related to the sensitivity of these two satellite observations to different vegetation quantities, linked to water content and biomass. As already observed and modeled (Li & Min, 2013; Min & Lin, 2006; Wigneron et al., 1993), the relationship between emissivity and vegetation water content is not monotonic. Under moderate water content in the canopy, as during the dry season in the south eastern Amazonian forest, σ_0 increases with increasing water content in the canopy, and the emissivity also increases with water content in the canopy. Under very high water content in the canopy, both passive and active signals are dominated by high scattering, σ_0 still increases with increasing water content, but the emissivity decreases, as observed in most parts of the tropical forest.

6. Conclusion

The seasonal and diurnal cycles of passive and active microwave satellite observations have been jointly analyzed for the first time, using GPM DPR and GMI measurements. The analysis focuses on the tropical forest. The data set prepared by Munchak et al. (2020) is adopted, and 4 yr of σ_0 and emissivity are systematically studied, at the available multiple frequencies, angles, and polarizations. For a given mode (passive or active), rather similar seasonal and diurnal patterns are observed for frequencies in the 10–36 GHz range (Ku to Ka bands).

Our analysis confirms the diurnal patterns already observed with radars, with a maximum σ_0 in the early morning attributed to the water refill in the plants at night. At the same time (i.e., early in the morning), we evidenced a minimum emissivity over most of the tropical forest: σ_0 and emissivity diurnal cycles tend to be in phase opposition, as well as their seasonal cycles. However, during the dryer seasons in the south eastern Amazonian forest, when precipitation can be low for several months in a row, the emissivity diurnal cycle changes, reflecting lack of full xylem refilling in this region and physiological stress.

Satellite observations in the microwaves, passive or active, over the tropical forest, are sensitive to the vegetation biomass and water content at different time scales. However, understanding and quantifying the respective contributions of biomass and water in the vegetation to the microwave signal, as a function of observing frequency

for the two modes (passive or active), is still very challenging, despite the recent efforts of the remote sensing community in that direction. With a joint analysis of passive and active modes, this study is a step forward in understanding the complex interaction between the microwave signals and the vegetation. Additional observation analysis and radiative transfer modeling, combining passive and active microwaves in a physically consistent scheme, will have to be conducted to improve our understanding of the intricate emission, absorption, and scattering processes of the radiation in the complex forest structure, at the spatial scales of the individual tree to the satellite pixel, and at diurnal, seasonal, and inter-annual temporal scales. This is necessary to decipher global forest ecological and physiological behaviors with promising multiple microwave satellite observations.

Data Availability Statement

The GPM σ_0 and emissivity data set is available at <https://iee-dataport.org/open-access/active-passive-microwave-land-surface-classification-gpm>.

Acknowledgments

We are grateful to Andrew Friend for fruitful discussions during the development of this work. We thank the editor and two reviewers for their careful reading of the article and for their suggestions to improve it.

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