Opposite eco-hydrological processes in flood and drought years caused comparable anomaly in dry-season canopy growth over southern Amazon

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Abstract
While the influences of droughts on Amazon rainforest have been extensively examined, little attention was paid to the extremely wet years characterized by low radiation which may limit the rainforest growth. Here, based on a series of satellite-observed vegetation and hydro-meteorological products, we found a two-stage canopy growth anomaly in the record-breaking wet year 2009, i.e. negative anomalies during April–July followed by positive ones during August–November. Our analysis suggests that, in April–July, low radiation associated with above-average rainfall and cloud cover was the most likely cause for negative anomalies in the canopy growth. In August–November, the rainfall and cloud cover were close to the average, but the solar radiation reaching the land surface was considerably above the average. This was because the atmospheric aerosols were extremely low, resulting from reduced biomass burning activities under the wet conditions. Large-scale positive anomalies in the canopy growth were observed during this 4 month period, mainly driven by the above-average radiation. During the severe drought year 2005, the forest canopy growth also experienced a two-stage process, but in the opposite order from the one in 2009. In April–July, enhanced canopy growth was observed in response to the above-average radiation. With the drought progress and soil water depletion, the canopy senescence was observed during the drought peak in August–November. Interestingly, if we examined the regional canopy growth anomaly during the typical dry season (i.e. July–September), both years showed similarly negative anomalies, but resulting from opposite eco-hydrological processes. This study identifies the explanation for the negative anomalies in the dry-season canopy growth over southern Amazon rainforest in both flood and drought years, and also underscores the necessity to separate different hydro-meteorological stages to better understand vegetation responses to extreme events.

1. Introduction
Amazon rainforest is the largest rainforest on the earth. It functions as a large dynamic reservoir of carbon, and plays an important role in the global climate changes and carbon cycles (Cox et al 2004, Malhi et al 2006, Pan et al 2011).

During the last two decades, several extreme climatic events hit the Amazon, e.g. 2005, 2010, 2015/2016 droughts and 2009, 2012, 2014 floods. The negative impacts of droughts on Amazon rainforest were extensively studied from a range of perspectives, including increased mortality (Phillips et al 2009, Doughty et al 2015, Feldpausch et al 2016), the reduction of carbon stocks (Brando et al 2008, Fan et al 2019, Wigner et al 2020), increased forest fires (Aragão et al 2007, 2018), negative anomalies in canopy greenness (Samanta et al 2010, Atkinson et al 2011, Xu et al 2011, Bi et al 2016, Yan et al 2019). With the development of remote sensing technology, the sun-induced chlorophyll fluorescence (Lee et al 2013, Liu et al 2017, Koren et al 2018, Yang et al 2018),
and the canopy water content retrieved from radar observations (Frolking et al 2011, 2017, Saatchi et al 2013, van Emmerik et al 2017) and passive microwave observations (Liu et al 2018) were also used to investigate the impacts of Amazon droughts. However, the responses of Amazon rainforest under the condition of rainfall excesses received little attention, which narrows the understanding of the responses of Amazon rainforest to extreme events and climate change.

A number of studies have discussed whether water or light limits photosynthesis in the Amazon forest. The results of in-situ studies and satellite data both support a view that solar radiation plays a crucial role in forest growth over Amazon region when water storage is sufficient (Graham et al 2003, Huete et al 2006, Bi et al 2015, Saleska et al 2016). Even in the water limited dry season, water in deep roots would be reallocated to support forest growth (Oliveira et al 2005). Nevertheless, when sustained drought occurs, soil moisture deficits intensify and land surface temperature (LST) is above average (Fisher et al 2007, Toomey et al 2011). Water and heat stress would reduce the canopy photosynthesis in forest (Brando et al 2008, Doughty et al 2015, Guan et al 2015, Wagner et al 2016). Furthermore, heat stress may reduce the surface biomass even in the absence of water stress, when canopy temperature is close to or higher than the physiological threshold (Toomey et al 2011). However, under the condition of rainfall excesses, the amount of cloud is very likely above average as well, which may reduce the available sunlight and consequently limit the rainforest growth (Graham et al 2003).

In 2009, a rare heavy flood hit Amazonia leading to the high-water levels in recent decades (Marengo and Espinoza 2016). The longer rainy season and extreme rainfall resulted in excessive cloud coverage over Amazon region for a longer time relative to the normal years (Marengo et al 2012). Atkinson et al (2011) examined the anomalies in Amazon rainforest canopy greenness in the dry season (July–September) during the period 2000–2010 based on the optical vegetation indices from moderate-resolution imaging spectroradiometer (MODIS), and found large-scale negative anomalies in canopy greenness (i.e. browning) in both wet year 2009 and drought year 2010. On top of that, the drought year 2005 showed an overall positive anomaly (i.e. greening). There have been arguments regarding Amazon rainforest canopy greening or browning in the dry season of 2005 (Saleska et al 2007, Samanta et al 2010); one major cause for these uncertainties is the high-level cloud cover and aerosol concentration present over the Amazon region (Asner and Alencar 2010, Hilker et al 2012, Ten Hoeve et al 2012), which limits the capacity of optical based vegetation observation (Huete et al 2002, Levy et al 2010, Zelazowski et al 2011).

The passive microwave-based vegetation observation, referred to as vegetation optical depth (VOD), is minimally affected by clouds and atmospheric aerosols due to the longer microwave wavelength and its stronger penetration capacity (Wigneron et al 2017, Brandt et al 2018, Li et al 2021). VOD is a radiometric parameter characterizing the attenuation degree of microwave radiation from the Earth surface by the vegetation layer (Konings et al 2019, Moesinger et al 2020), which is not a well-defined ‘easily validated’ geophysical parameter (Liu et al 2011). Field experiments showed that VOD is linearly related to the water content in the aboveground vegetation layer (Jackson et al 1982, Jackson and Schmugge 1991, Wigneron et al 1993), including both photosynthetic (leaf) (Momot et al 2017) and non-photosynthetic (branches) components (Tian et al 2016, 2017). In addition, a number of studies found that VOD is positively correlated with the above-ground biomass (Liu et al 2015, Fan et al 2019) and plant productivity (Teubner et al 2018, 2019), and provides complementary vegetation information to optical remote sensing, especially in forest, where VOD is less susceptible to saturation at high biomass level (Jones et al 2011, 2013, Liu et al 2013, Fan et al 2018, Tian et al 2018, Tong et al 2019, Frappart et al 2020, Wigneron et al 2021).

The objective of this study is two-fold. First is to examine the Amazon rainforest canopy dynamics during the wet year 2009 based on the passive microwave-based vegetation observation, and identify the most likely factors limiting the rainforest growth: reduced radiation only or the combined effect of several hydro-meteorological variables. Second is to reconcile the seemingly contrasting anomalies in dry-season (July–September) canopy dynamics in wet year 2009 and drought year 2005. Better understanding the influences of hydro-meteorological conditions on canopy dynamics during wet and drought years will improve our prediction capacity of rainforest responses to future extreme climatic events which are predicted to be more frequent.

2. Materials and methods

2.1. Satellite-based datasets

In this study, we focused on the intact rainforest in southern Amazon (2.5° S–12.5° S, 75° W–50° W, see figure 1(a)) where dry-season canopy browning was found in both 2009 (Atkinson et al 2011), and also where was hit by 2005 drought (Saleska et al 2007, Samanta et al 2010, Lewis et al 2011, Bi et al 2016). We characterized the rainforest canopy dynamics using the passive microwave-based VOD with 0.1° resolution, which was derived from the Advanced Microwave Scanning Radiometer—Earth Observing System (AMSR-E) onboard Aqua satellite and retrieved by the Land Parameter Retrieval Model (LPRM) algorithm (Owe et al 2001, 2008).
Night-time observations (1:30 am, equator crossing time) were used here. VOD is a dimensionless variable that can represent water content dynamics in above-ground vegetation (Jones et al. 2011, Liu et al. 2011, 2013), and over the closed canopy Amazon rainforest, the AMSR-E VOD mainly represents the canopy dynamics (Zhou et al. 2014, Zhang et al. 2021a). More details of the AMSR-E VOD were provided in the supplementary material.

A number of satellite-based variables were also used here to characterize hydro-meteorological conditions, including: precipitation (Pre) (Huffman et al. 2007), photosynthetically active radiation (PAR) (Wielicki et al. 1996), aerosol optical depth (AOD), cloud optical thickness (COT), terrestrial water storage (TWS) (Swenson and Wahr 2006, Landerer and Swenson 2012), surface air temperature (Ta), and surface relative humidity (RH) and LST (Teixeira 2013, Olsen et al. 2017). Ta and RH were used to calculate vapor pressure deficit (VPD). Details about these datasets can be found in table 1.

All these datasets cover the period January 2003 through December 2010. For a direct comparison, they were re-sampled to 0.10° resolution by bilinear interpolation with monthly interval. The 0.05° MODIS land cover product (MCD12C1) of 2010 was used to delineate the intact forest in southern Amazon. When the land cover type of all four 0.05° grid cells is forest, the corresponding 0.10° grid cell is classified as forest (figure 1(a)). Grid cells with VOD < 0.9 were eliminated to remove the influences of large open water on VOD estimates (Bousquet et al. 2021).

2.2. Analysis methods
To understand vegetation responses in wet 2009 and drought 2005, we first examined the hydro-meteorological conditions over southern Amazon rainforest by comparing with the average values during the period 2003–2010. Next, we identified the minimum value of monthly average TWS of the multi-year average (referred to as TWSmin), the
maximum value of LST and VPD of monthly average LST and VPD of the multi-year average (referred to as LSTmax and VPDmax) as the thresholds for available water and heat stress for the entire study area (figures 1(f)–(h)) as well as for each grid cell (Fisher et al 2006, 2007, Guan et al 2015, Liu et al 2018). When TWS > TWSmin, LST < LSTmax, and VPD < VPDmax, we assume that the hydro-meteorological conditions are within the tolerance limits of the rainforest. When TWS < TWSmin, LST > LSTmax, VPD > VPDmax and satellite-based vegetation indicators are below the average, the vegetation is very likely under water and heat stress conditions. Accordingly, we examined whether Amazon rainforest suffered from water or heat stress in 2009 and 2005. The rationale for choosing these thresholds as the basis for judgment was provided in the supplementary material.

Furthermore, to reconcile the seemingly contrasting dry-season (July–September) vegetation dynamics in 2005 and 2009 (Saleska et al 2007, Samanta et al 2010, Atkinson et al 2011, Bi et al 2016), we compared the anomalies in canopy water content represented by VOD for three periods: wet-to-dry season (April–July), late dry season (August–November) and the typical dry season (July–September), respectively. The method used to define the typical dry season was described in detail in the supplementary material. During each of the three periods mentioned above, the standard anomalies of hydro-meteorological variables and VOD on each grid cell were calculated to examine their spatiotemporal consistency to identify the most likely factor driving VOD dynamics. The method for standard anomalies calculation was described in the supplementary material. The Pearson correlation coefficient and regression analysis were performed on the regional anomalies in Pre, PAR and VOD, to further identify the main factor for canopy growth. All datasets were processed in Matlab.

### Table 1. Detail information about datasets that use in this study.

| Dataset name                     | Product name                                                                 | Spatial and temporal resolution | Reference                  |
|----------------------------------|------------------------------------------------------------------------------|---------------------------------|-----------------------------|
| Land cover type                  | MCD12C1,V051                                                                 | 0.05°, year                     | Friedl et al (2010)         |
| VOD                              | Retrieved by Land Parameter Retrieval Model (LPRM) based on AMSR-E          | 0.10°, monthly                  | Liu et al (2018)            |
| Precipitation (Pre)              | TRMM 3B43 V7                                                                 | 0.25°, monthly                  | Huffman et al (2007)        |
| Photosynthetically active radiation (PAR) | CERES_SYN1deg_Ed3A(PAR Surface Flux Direct and PAR Surface Flux Diffuse) | 1°, monthly                     | Wielicki et al (1996)       |
| Aerosol optical depth (AOD)      | MOD08_M3('Aerosol_Optical_Depth_Land_Ocean_Mean_Mean')                       | 1°, monthly                     | Platnick et al (2015)       |
| Cloud optical thickness (COT)    | MOD08_M3('Cloud_Optical_Thickness_Combined_Mean_Mean')                       | 1°, monthly                     | Platnick et al (2015)       |
| Terrestrial water storage (TWS)  | RL05.DSTvSCS1401                                                             | 1°, monthly                     | Landerer and Swenson (2012)  |
| LST                              | Aqua_AIRS_Level3('SurfSkinTemp_A') and 'SurfSkinTemp_D'                      | 1°, monthly                     | Teixeira (2013)             |
| Surface air temperature (Ta)     | Aqua_AIRS_Level3('SurfAirTemp_A') and 'SurfAirTemp_D'                       | 1°, monthly                     | Teixeira (2013)             |
| Surface relative humidity (RH)   | Aqua_AIRS_Level3('RelHumSurf_A') and 'RelHumSurf_D'                         | 1°, monthly                     | Teixeira (2013)             |

3. Results and discussion

#### 3.1. Hydro-meteorological anomalies in wet year

Although 2009 was a wet year, there were strong variations in rainfall anomalies in each month (figure 1(b)). While the highest positive anomaly was observed in April (~80 mm above the average), November witnessed a negative anomaly of 21 mm. Overall, rainfall was above average during the wet-to-dry season (April–July) (figures 2(a) and (i)), but slightly below average during the late dry season (August–November) (figures 3(a) and (i)).

Meanwhile, the radiation was below average in April–July and above average in August–November. The radiation anomalies during these two periods seemed in agreement with rainfall anomalies, but actually were caused by different drivers. In April–July, while the atmospheric aerosols were below average, the high-level cloud cover associated with rainfall excesses (figure 2(c)) was the main reason for the low radiation (figure 2(b)). In August–November, though the regional cloud cover was slightly below average which could increase the amount of radiation reaching the land surface (figure 3(c)), the spatiotemporal consistency of anomalies in radiation and atmospheric aerosols suggested the extremely low aerosol concentration was the main driver for above-average radiation (figures 3(b) and (d)). The regional aerosol value in August–November 2009 was only 62%
The primary reason was that biomass burning activities declined considerably (figure S1) when the regional wetness level was extremely high (Chen et al. 2013, Reddington et al. 2015).

According to terrestrial water storage, water supply for rainforest was sufficient throughout the year 2009 (figure 1(f)), which is not surprising in a record-breaking wet year. TWS was consistently above average and higher than the TWSmin (figures S2(a) and S3(a)). Although regional VPD was slightly above average in October and November 2009, VPD values were mostly below the VPDmax in our study area (figures 1(g), S2(b) and S3(b)). As for LST, the maximum value of the multi-year average (LSTmax) was observed in October. LST was slightly exceeded...
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3.2. Hydro-meteorological anomalies in drought year

Contrary to the hydro-meteorological pattern of wet year, rainfall in 2005 was generally below average from the wet-to-dry season (April–July) through the late dry season (August–November) (figures 1(b), 2(i) and 3(i)). Radiation was above average in April–July (figures 1(c) and 2(f)), which was mainly associated with the below-average rainfall and cloudiness (figures 2(i) and (k)). In August–November, the above-average atmospheric aerosols associated with increased burning activities (figures 3(l) and S1) were the main reason for the below-average radiation (figure 3(j)).

Although rainfall and TWS were below average in April–July of drought year (figures 1(b) and (f)), TWS, VPD and LST were within the ranges of TWSmin, VPDmax and LSTmax, respectively (figures 1(f)–(h) and S2(d)–(f)). This suggested sufficient water supply and no heat stress during this period. In the late dry season (August–November), VPD and LST were above average and TWS was below average (figures 1(f)–(h)). In the meantime, there were 3 months with TWS lower than TWSmin and 2 months with LST higher than LSTmax (figures 1(f) and (h)) which indicated water and heat stress occurred, especially in southwest (figures S3(d) and (f)).

3.3. VOD anomalies in wet and drought years

3.3.1. VOD anomalies in the wet-to-dry season and the late dry season

The regional standardized anomalies in VOD over southern Amazon rainforest from April through November of 2005 and 2009 are shown in figure 4. A striking temporal pattern is clearly seen between 2009 and 2005, i.e. reduced-preceding-enhanced canopy growth in 2009 versus the opposite in 2005. When it comes to the average of standardized anomaly of April–November, a positive value is obtained in 2005 versus a negative value in 2009. Spatially, widespread negative anomalies in VOD were observed in April–July 2009 (figure 5(a)), while large-scale positive anomalies were detected in August–November (figure 5(d)). The opposite spatiotemporal patterns of VOD anomalies were observed in 2005 (figures 5(b) and (e)). The temporal pattern of canopy growth during April–November of 2010, another once-in-a-century drought, was similar to that of 2005 (figure S4). The fact that the extreme wet 2009 preceded the drought 2010 might influence the vegetation physiology, resulting in a slightly different pattern of canopy growth in 2010 (Zhang et al. 2021b).

The negative anomalies in August–November 2005 were primarily concentrated over southwestern Amazon rainforest (figure 5(e)), while more grid cells with negative anomalies were observed over the southwest, south and east in 2010 (figure S4(f)). This spatial distribution agreed well with the distribution of water deficit (figure S6) and the increased tree mortality and reduced rainforest growth in 2005 and 2010 according to ground observations (Phillips et al. 2009, Feldpausch et al. 2016), which gave us reasonable confidence in the anomalies captured by the microwave-based VOD dataset. For August–November 2009, the negative anomalies were mainly distributed along the major river (figure 5(d)). The VOD values over these grid cells might be influenced by the flood (Marengo et al. 2012, Liu et al. 2013, Marengo and Espinoza 2016, Bousquet et al. 2021). However, removing these grid cells did not essentially change the results of this study.

To quantify the contrasts between April–July and August–November, we plotted the distribution of the magnitudes of standardized anomalies of these 2 years by roughly 0.2–0.3 K in September and October 2009 (figure 1(h)), mainly due to extremely high-level radiation rather than water shortage. LST decreased to the level below LSTmax with the decline in radiation since November 2009.

Figure 4. Time series of monthly standardized anomaly in VOD over southern Amazon rainforest during April–November of 2005 and 2009 (solid lines). The orange and blue dashed lines represent the average of standardized anomaly during April–November in 2005 and 2009, respectively.
Table 2. Correlations of the regional anomalies between VOD and Pre, PAR in southern Amazon with sufficient water.

|                      | VOD-Pre | VOD-PAR |
|----------------------|---------|---------|
| April–November       | −0.77** | 0.77**  |
| in 2009              |         |         |
| April–July in 2009   | −0.85***| 0.74**  |
| and 2005             |         |         |
| Wet season and       | −0.76***| 0.66*** |
| wet-to-dry season in  |         |         |
| 2009 and 2005        |         |         |

Notes: *, ** and *** stand for $p < 0.1$, $p < 0.05$ and $p < 0.01$ (statistically significant values of Pearson correlation), respectively.

When it came to 2005, the water storage was still adequate in the wet-to-dry season (April–July) of drought year (figure S2(d)), so the enhanced canopy growth was mainly driven by the above-average radiation (figure 2(j)) (Hilker et al 2014, Bi et al 2015, Guan et al 2015). With further rainfall deficit into August–November, water and heat stress became severe (figures S3(d) and (f)) and adversely affected the rainforest growth (figures 5(e) and S7(b)) (Phillips et al 2009, Toomey et al 2011). The temporal pattern of hydro-meteorological conditions and canopy growth in 2010 were similar to that of 2005 (figures S4 and S5). Hence, radiation was the main factor for canopy growth when water was adequate in both wet and drought years. Regional anomalies in radiation were positively correlated with VOD anomalies during April–July in 2009 and 2005 ($r = 0.74$, $p < 0.05$), while Pre showed a significant negative correlation with VOD ($r = 0.85$, $p < 0.01$) (table 2). Moreover, the correlation between anomalies in VOD, Pre and radiation were consistent with that in wet season (December–March). Through the comparison of regional anomalies between VOD, Pre and radiation in different extreme events, we found VOD responded to the changes of Pre quickly in the wet and wet-to-dry season (figure 6(a)). VOD anomalies increased with the decreased Pre anomalies in wet and wet-to-dry season, while VOD anomalies decreased as soon as rainfall anomalies increased. During this period, VOD anomalies were statistically correlated with the anomalies of Pre and radiation with coefficients of $−0.76$ and $0.66$ ($p < 0.01$), respectively (figures 6(b) and (c), table 2).
3.3.2. VOD anomalies in the typical dry season

In the typical dry season (i.e. July–September), the overall VOD anomalies of southern Amazon rainforest were below average for both wet and drought years (figure 5(i)), but apparently caused by different processes (figure 4). In 2009, the stronger negative anomalies in July and August dominated the average of July–September, whereas in 2005 the negative anomalies in September overweighted the positive in July. In July–September of 2009 and 2005, more than half of the study area showed negative anomalies in VOD (figures 5(g) and (h)).

Several studies suggested that the limited ability of optical remote sensing techniques in tropical forests was considered responsible for the blurry and debate in canopy changes during the typical dry season (July–September) between drought and wet years (Samanta et al 2010, Atkinson et al 2011, Hilker et al 2012, Morton et al 2014). Here, we also found no considerable difference in canopy growth anomalies during the typical dry season between drought and wet years using passive microwave observations that is minimally influenced by clouds and aerosols. However, according to the canopy growth patterns from the wet-to-dry season to the late dry season, we found the response of Amazon forest during wet and drought events was distinct. We demonstrated that the seemingly identical VOD changes during the typical dry season of wet and drought years were caused by different processes.

In drought years, the positive VOD anomalies during the wet-to-dry season and negative VOD anomalies during the late dry season are consistent with previous studies which found that canopy growth increased in the onset of dry season (Huete et al 2006, Myneni et al 2007, Brando et al 2010, de Moura et al 2015) and canopy senescence was observed in the sustained drought (Brando et al 2008, Phillips et al 2009, Doughty et al 2015). The hydro-meteorological conditions in the wet-to-dry season of drought are consistent to the onset of dry season in the normal years (Liu et al 2018). The increased productivity of forest in the wet-to-dry season is the result of the response to increased radiation with the adequate water (Graham et al 2003, Bi et al 2015, Saleska et al 2016, Tang et al 2017, Liu et al 2018). Resource allocation is prioritized to leaves growth followed by wood in the dry season of the normal years (Restrepo-Coupe et al 2013, Wu et al 2016). Therefore, forest green-up was found by enhanced vegetation index (EVI) in dry season (Saleska et al 2016). However, photosynthesis and sap flow are reduced due to water deficit in the subsequent drought (Fisher et al 2006, 2007). In contrast, canopy leaves growth and sap flow of canopy branches were limited by the light availability in the wet-to-dry season of wet 2009 when negative VOD anomalies were observed (Graham et al 2003), while canopy leaf growth was enhanced with the increased radiation in the late dry season when water supply was abundant (Wagner et al 2016, 2017) with positive VOD anomalies. Furthermore, given the original spatial resolution of hydro-meteorological variables were 1°, we resampled VOD to 1° and performed the same analysis. The results

![Figure 6. Comparison of (a) monthly anomaly in VOD, Pre and PAR in wet season (December–March) and wet-to-dry season (April–July) of 2009 and 2005. The linear regression of (b) monthly anomaly of Pre and (c) PAR against monthly anomaly of VOD during the wet and wet-to-dry season in 2005 and 2009.](image-url)
were similar to that based on the resampling datasets with 0.1° resolution (figures S8–S11). For preserving the detailed spatial information of VOD, we showed the results for the 0.1° datasets here.

Our analysis demonstrates that, to better understand the vegetation responses to extreme events over southern Amazon rainforest, it is necessary to examine the hydro-meteorological and vegetation conditions since the months when rainfall apparently started to deviate from the average (e.g. April in 2005 and 2009). For a direct comparison between wet and dry years, here we compared the hydro-meteorological and vegetation anomalies during the same period (i.e. April–July, August–November, July–September) for different years. Several studies show that the onset and duration of the dry season over Amazon rainforest can vary in different years and regions (Marengo et al 2012, Silva et al. 2013, de Moura et al. 2015), which suggests that identifying the exclusive dry season for each year according the actual situation and then comparing the hydro-meteorological and vegetation conditions in the dry season of different years may explain the inter-annual vegetation dynamics as well. The assessment of Amazon forest response to extreme hydro-meteorological events using VOD can better capture the vegetation anomalies, particularly under thick clouds and smoke, and improve our understanding of vegetation dynamics in extreme events.

4. Conclusions

In this study, we first investigated the evolution of hydro-meteorological conditions and vegetation canopy responses over southern Amazon rainforest during the wet year 2009 and compared with drought year 2005. In wet 2009, the low solar radiation associated with above-average rainfall limited the canopy growth in April–July. In August–November, the atmospheric aerosols were considerably lower than the multi-year average as the high-level wetness of Amazon Basin was unfavorable for biomass burning. This led to extremely high-level radiation reaching the ground and enhanced the rainfall canopy growth.

A two-stage dynamic pattern was also observed in 2005 drought, but in the opposite phase of 2009. In April–July of 2005, canopy growth was enhanced in response to above-average radiation, below-average rainfall and sufficient water supply from the soil. This was followed by canopy senescence in August–November when water and heat stress became severe with further progress of droughts. Nevertheless, if only focusing on the typical dry season (July–September), the overall regional anomaly in canopy water content was slightly negative for both years, as the magnitudes of negative signals dominated the 3 month average. Our results help better understanding the rainforest responses during wet and drought years over southern Amazon, and highlight the importance of identifying the stages of different hydro-meteorological conditions in eco-hydrological studies.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

In this study, multi-source data were obtained from different data centers. The authors thank NASA and the Clouds and the Earth’s Radiant Energy System for making their data freely available. The authors are grateful to the anonymous reviewers and editors for their constructive comments.

Conflict of interest

The authors declare no conflict of interest.

Funding

This work was funded by a Nanjing University of Information Science and Technology (NUIST) startup Grant (2243141701020) and the Postgraduate Research and Practice Innovation Program of Jiangsu Province (KYCX21_0956).

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