Response of African humid tropical forests to recent rainfall anomalies

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During the last decade, strong negative rainfall anomalies resulting from increased sea surface temperature in the tropical Atlantic have caused extensive droughts in rainforests of western Amazonia, exerting persistent effects on the forest canopy. In contrast, there have been no significant impacts on rainforests of West and Central Africa during the same period, despite large-scale droughts and rainfall anomalies during the same period. Using a combination of rainfall observations from meteorological stations from the Climate Research Unit (CRU; 1950–2009) and satellite observations of the Tropical Rainfall Measuring Mission (TRMM; 1998–2010), we show that West and Central Africa experienced strong negative water deficit (WD) anomalies over the last decade, particularly in 2005, 2006 and 2007. These anomalies were a continuation of an increasing drying trend in the region that started in the 1970s. We monitored the response of forests to extreme rainfall anomalies of the past decade by analysing the microwave scatterometer data from QuickSCAT (1999–2009) sensitive to variations in canopy water content and structure. Unlike in Amazonia, we found no significant impacts of extreme WD events on forests of Central Africa, suggesting potential adaptability of these forests to short-term severe droughts. Only forests near the savanna boundary in West Africa and in fragmented landscapes of the northern Congo Basin responded to extreme droughts with widespread canopy disturbance that lasted only during the period of WD. Time-series analyses of CRU and TRMM data show most regions in Central and West Africa experience seasonal or decadal extreme WDs (less than $2600 \text{ mm}$). We hypothesize that the long-term historical extreme WDs with gradual drying trends in the 1970s have increased the adaptability of humid tropical forests in Africa to droughts.

1. Introduction

In the second half of the twentieth century, a drying trend has been observed by the instrumental records in West Africa and the northern edge of the tropical African rainforest zone [1]. This drying trend has been primarily associated with changing of a natural low-frequency mode (65–80 years) of the sea surface temperature, known as the Atlantic Multidecadal Oscillation [2]. Recent studies also show that the West African drought is part of historical phases of alternating wet and dry periods of the West African monsoon that has been a natural pattern over the past 3000 years [3,4]. Other studies focusing on palaeoclimate data have broadly indicated that forests in the Atlantic Equatorial region and south and central Congo Basin have experienced dramatic changes (forest loss) over the last 4000 years related to variations in rainfall patterns caused by sea surface temperature anomalies and human impacts [5,6]. Given this history, a key unresolved question is related to the resilience of African rainforest and its response to future changes of climate [7].

Extensive research in Amazonia has shown a relatively rapid response of forests to extreme climate anomaly [8–10]. In the past decade, Amazonian forests experienced two major droughts within the span of only 5 years, both associated with the warming of tropical Atlantic Ocean [11]. The droughts occurred during the 2005 and 2010 dry seasons, causing the water level of the Amazon River drop
to its lowest in the last century [11–13]. Ground observations in Amazonia showed large-scale tree mortality and leaf fall of canopy trees after the 2005 drought [10]. The response of the Amazon forest to these droughts was also examined by time-series satellite observations. Data from conventional optical sensors suggested inconclusive results. One study showed the greening of the forest (increase in vegetation index) due to higher active radiation (less clouds) during the early stages of drought [14], while others proposed either browning of the forest from water stress [15], or greening in later stages of drought from opening of the canopy from potential tree mortality [16]. Satellite optical observations over tropical forests are impacted by clouds and atmospheric aerosol, causing noise in surface reflectance data [15]. The first cloud and smoke-free observation of the impacts of recent droughts on the forests of Amazonia was captured by time-series measurements of the satellite microwave scatterometer (QuickSCAT, QSCAT) [17]. With the advantage of penetrating through clouds and aerosols, the radar backscatter data from QSCAT showed large-scale changes of canopy structure and moisture in western Amazonia from the 2005 drought. Remarkably, despite the gradual recovery of total rainfall in subsequent years, the decrease in canopy backscatter persisted until the next major drought, in 2010. The decline in backscatter is attributed to changes in structure and water content associated with the forest upper canopy, most probably associated with large tree mortalities [18].

In Central Africa, unlike Amazonia, the lowland rainforests exist under significantly drier conditions, with an average precipitation of 1500–2000 mm yr⁻¹ in the central Congo Basin. Only along the Atlantic coastal region of Central and West Africa can rainfall reach 2500–3000 mm yr⁻¹, comparable with central Amazonia. In the central Congo Basin, the duration of the dry season varies with the distance to the equator in both hemispheres and also along an east-to-west gradient [19]. Mean monthly temperature has almost no variations through the season, and the average annual temperature generally stays below that of Amazonia owing to higher elevation of the Congo Basin [1].

African and Amazon rainforests also have been exposed to different drought patterns. The Amazon forests experienced two short-term, intense droughts in the past decade, while the African forests have been exposed to long-term reduction in precipitation over the past three decades, with occasional impacts by stronger drought events. The effects of long-term drought are more complex than the short-term droughts as forest composition and structure changes over time in order to adapt and respond to long-term reduction in rainfall. The recent study by Fauset et al. [20] showed that over the period of 20 years of exposure to a drying trend, the composition and structure of the Ghanaian forest species shifted from wetter forest affiliated vegetation to favour deciduous, drier forest canopy species with a need for intermediate light. Quantifying similar long-term effects over larger spatial scales requires a combination of field measurements and dedicated satellite observations sensitive to vegetation composition [18,21]. However, there has been no report of the response of the African rainforests over large spatial scales to drying trends and rainfall anomalies of the past decade. Here, we use satellite data to first quantify the extent and severity of rainfall anomalies and droughts in African rainforests in the past decade, and then to investigate the impacts of droughts and water stress on the forest. We will also analyse rainfall data over the past century to understand the severity of recent rainfall anomalies with respect to long-term patterns.

2. Data and methods

We used precipitation data from the Tropical Rainfall Measuring Mission (TRMM; 3B42-v6; monthly, 0.25° resolution) for the period of 1998–2010 to investigate the spatio-temporal distribution of rainfall and its seasonality for the past decade. The monthly, seasonal and annual rainfall anomalies on a pixel-by-pixel basis for each year were computed as a departure from the 1998–2010 mean, excluding the measurement from that year and normalized by the standard deviation (see methods in the electronic supplementary material). We calculated maximum water deficit (MCWD) as a complementary measure of drought severity using TRMM monthly rainfall data. MCWD is the maximum value of yearly-accumulated water deficit (WD) for each pixel based on the assumption that the tropical forests transpire approximately 100 mm month⁻¹ based on ground measurements of evapotranspiration in Amazonia [22–24], and using the method provided in Aragão et al. [25] (see the electronic supplementary material). The assumption suggests that when the monthly rainfall value falls below 100 mm, the forest will experience WD. The maximum WD (MCWD) provides the magnitude of WD signifying the intensity of drought and its spatial footprint over the landscape.

We included several other indices to examine the spatio-temporal patterns of droughts, such as (i) the duration of dry months (DMD) with the dry month being the month when the rainfall is less than 100 mm, (ii) driest quarter (DQ) rainfall as the rainfall of three consecutive driest month in each year, (iii) total annual rainfall (TAR) in each year, and (iv) wettest quarter (WQ) rainfall as total rainfall of three consecutive wettest months in each year.

We performed a similar analysis using long-term rainfall data from the Climate Research Unit (CRU TS 3.0: 1901–2009) ground-based gridded observation of precipitation. We used the CRU data over the period of 1950–1997 when there were a reasonably large number of ground stations in most of the African continent, and replaced the later years with TRMM 1998–2010 data. We performed the long-term analysis with the combined CRU and TRMM data over three large distinct regions in West Africa (region 1), west of the Congo Basin (region 2) and east of the Congo Basin (region 3) to avoid potential spatial artefacts caused by periodic loss of station data, in CRU data. The combined data were used to capture long-term WD values averaged over the three regions. The combined data were not used in studying long-term anomaly due to potential effect of the mismatch in the spatial rainfall pattern between CRU and TRMM, particularly over the Congo Basin. All anomaly calculations were performed separately with CRU and TRMM data.

SeaWinds scatterometer data onboard QSCAT (2000–2009) was used to examine the impact of the precipitation anomaly and WD on the forest. QSCAT is an active radar sensor operating in microwave frequency (13.4 GHz) and provides daily (6.00 and 18.00) measurements of the backscatter signal from the top layer of the forest canopy. QSCAT observations are not impacted by cloud cover, atmospheric aerosol and radiation condition, and are sensitive to the structure and water content of forest canopy, providing a reliable remote sensing technique.
to monitor impact of climate on tropical forests \cite{17,18,26}. Given the high frequency (2.2 cm) and the steep incidence angle (46° – 54°) of the QSCAT radar, the backscatter measurement over dense tropical forests is sensitive only to the top canopy structure and moisture and has relatively no information about the underlying soil moisture \cite{27–31} (see the electronic supplementary material). We used 4-day composited QSCAT backscatter data ($\sigma_0$) with enhanced resolutions of 4.45 km at H polarization in ascending mode from morning passes (6.00 LST) to create backscatter anomalies of monthly, seasonal and DQ (averaged backscatter values of three consecutive months with lowest monthly backscatter values) for the entire time series. We limited the pixel extraction from QSCAT and TRMM rainfall metrics to include only the tropical forest regions by using a mask developed from the latest MODIS land cover map (see the electronic supplementary material for methods). The global wall-to-wall acquisition of QSCAT data stopped in November 2009, limiting our analysis of the impact of droughts on forest canopy up to 2009.

### 3. Results and discussion

#### (a) Rainfall patterns

Over Sub-Saharan Africa, we found significant differences of spatial patterns of rainfall measurements from CRU and TRMM. We compared climatology of rainfall metrics derived from 1998 to 2009 by CRU and TRMM, including DMD, DQ and TAR. The spatial pattern of the metrics suggests that the satellite observation of rainfall from TRMM has been able to capture patterns of rainfall magnitude and seasonality undetected by CRU due to lack of operating ground stations, particularly over the past decade \cite{1}. The largest difference between the two datasets exists in an area in the central Congo Basin and eastern Democratic Republic of the Congo (DRC) along the southern reaches of the Congo River. TRMM data show a spatial pattern along the Congo River with low TAR (TRMM: 1200 mm versus CRU: 1800 mm), and with distinct DQ and DMD different from the rest of the Central Africa (figure 1). The changes in rainfall patterns reverse along eastern mountains of DRC, around the borders with Burundi and Rwanda, and Lake Tanganyika, showing higher rainfall (TRMM: 2200 mm versus CRU: 1200 mm) and shorter dry season. Differences also exist in coastal regions of West Africa, particularly in Ivory Coast, Liberia and Sierra Leone where CRU interpolated rainfall data shows higher annual rainfall (TRMM: 1200 mm versus CRU: 2200 mm), shorter dry months and lower rainfall during dry months (figure 1).

The observed differences are probably due to insufficient working ground stations or potential problems in reporting to international centres from different regions of Central and West Africa (see the electronic supplementary material, figure S1). The recent processing of TRMM data (3B43 product) includes ground observations to improve the magnitude of TRMM retrieval of rainfall, and the products are calibrated and scaled to match the global monthly rain data. Although there may still be errors in TRMM data, the most recent products have relatively low bias in magnitude and errors in capturing rainfall spatial patterns \cite{32–34}. Contrary to TRMM data, CRU gridded data are based on available station data and spatial modelling, interpolating rainfall gauge measurements to large distances (up to 1000 km) and potentially missing legitimate rainfall patterns in areas with paucity of station data \cite{35}. In areas of large differences between the two datasets, no station data were reported after 1990 to provide points in model interpolation such as in

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central DRC because of regional political conflicts (see the electronic supplementary material, figure S1). Similarly, in West Africa, the number of stations dropped significantly over the last decade (see the electronic supplementary material, figure S1). The differences in magnitude and seasonality of rainfall observed by TRMM and missing in recent CRU data may have significant implications for the science community developing models to understand and predict climate interactions with the land surface in the region.

(b) Short-term rainfall anomalies
Climate variations of the past decade were detected from three rainfall metrics, DQ, WQ and MCWD, using 12 years of the TRMM dataset. Together, these measures are strong predictors of drought intensity and provide complementary spatial information on the extent of droughts [25,36], which correlates with tree mortality [10]. In Africa, major drought signatures appeared in three consecutive years, 2005, 2006 and 2007 (figure 2). In 2005, the low rainfall of the dry season resulted in high MCWD values (greater than 700 mm) in these regions, which persisted in 2006 with slightly less severity in central regions and followed in 2007 along the forest–savanna regions in northern DRC, western Africa and southern Gabon (figure 2).

In 2005, widespread rainfall anomalies of less than minus 1.5 s.d. (\(<-1.5\sigma\)) appeared in DRC, Cameroon and southern Gabon. Anomalies persisted in the northern edge of the African forests through October, November, December and January, February, March of the following year of 2007 (dry season in northern African forests; see the electronic supplementary material, figure S3). Strong negative rainfall anomalies during the dry season of 2005, 2006 and 2007 resulted in widespread MCWD (less than \(-700\) mm) and strong anomalies of \(<-1.5\sigma\) over these regions (figure 2).

The rainfall of DQ did not increase above 150 mm over almost the entire African forests (see the electronic supplementary material, figure S4). The lowest values of rainfall in the DQ were observed in central DRC, the southern edge of the Central African rainforest, southern and western Gabon, and in the West African forests. In the wet season, rainfall remained low (less than 400 mm) in the central DRC and northwestern regions (less than 300 mm); however, other regions including Gabon experienced higher rainfall (greater than 1000 mm) during the wet season (see the electronic supplementary material, figure S4).

(c) Long-term rainfall patterns
The short-term analysis of rainfall patterns and interannual variability may be impacted by an overestimation of the strength of the anomalies due to the short length of the analysis (approx. a decade). To examine this effect and understand the recent magnitude and distribution of anomalies with respect to long-term patterns, we developed a longer time series, using the CRU monthly rainfall dataset from 1950 to
has large interannual variability, but the last decades (starting
extreme WDs. drying trend that started in the 1970s resulting in frequent
ved by TRMM have been a continuation of an increasing
appears that the drought events of the past decade obser-
stations were available in the region. Remarkably, it
rainfall data prior to the year 1998 are reliable as more
Using the aggregated dataset, we computed monthly WD
regions to provide stable average rainfall measurements.
last decade (derived from TRMM data). The aggregated data-
y by dividing the entire African forests into three major zones
2009 and used aggregated rainfall values for three large forest
areas of these regions were determined
Over the three regions in Central and West Africa, we
extracted the monthly QSCAT backscatter and TRMM WD
anomalies over the forested pixels (figure 4) by eliminating
deforested pixels captured by the MODIS land cover map
and MODIS continuous field percent tree cover data [38].
Over the combined Central and West African forest regions,
QSCAT and WD anomaly stayed decoupled and showed no
significant correlation ($p < 0.1$), suggesting the rainfall
anomalies caused no significant impact on forest canopy.
Region 1 in West Africa, covering tropical forests of Ghana,
Ivory Coast, Liberia and Sierra Leone experienced a severe
WD anomaly from 2005 to 2008 with the largest deficit in
mid-2007 (greater than $-3.0 \sigma$; electronic supplementary
material, figure S2). During this period, QSCAT backscatter
anomaly gradually became negative with a moderately
strong response in January, February, March 2007 (greater
in the 1970s) show the strongest deviation from long-term
mean. Particularly in forests in West Africa (region 1) and
the Congo Basin east (region 3), recent low WDs appear to
be the strongest of the past 108 years. On average, region 3
experienced approximately threefold deviation from the
long-term mean (less than 50 mm deficit). Relatively, region
1 has the largest mean WD (approx. 200 mm) compared
with the other regions, indicating the forests are in a strong
seasonal environment. Since the 1970s, the WD in region 1
has increased gradually. However, during the last decade,
low rainfall years causing about four times larger WDs
have impacted region 1 in West Africa for several years.
We performed a time-series analysis using the Breaks in
Additive Season and Trend (BFAST) algorithm [37], based
on the iterative decomposition of time-series data, and
found no major significant break in the time-series data
suggesting a major shift in the rainfall patterns. However,
the trend analysis showed significant negative trend in WD
and monthly rainfall in West Africa since the early 1970s
($R^2 = 0.16, p < 0.05$). The other regions had no significant
long-term trends but showed more frequent extreme WD
events during the last two decades in region 3 and compara-
tively moderate WDs in region 2. In general, region 2 had the
lowest WD, but highly fluctuating, with large WDs occurring
on an approximately decadal cycle.

(d) Changes in canopy backscatter
Despite the strong and prolonged (more than six months)
drought in 2005 and 2006, areas that experienced significant
rainfall and WD anomalies showed no significant negative
backscatter anomalies, which would have indicated water
stress on forests altering canopy properties (structure and
water content; figure 2). Negative anomalies of $<-1.5 \sigma$ only
appeared in scattered patches in DRC, Gabon and Cameroon
from April, May, June 2005 to October, November, December
2006 (see the electronic supplementary material, figure S2).
This result is in contrast to what was observed in the
Amazon forests during and after the 2005 drought, in which
severe QSCAT backscatter anomalies resulted from the
impact of strong WDs in southwestern Amazonia [17,18].
Strong canopy backscatter anomalies of less than $-2.0 \sigma$ were
observed following the rainfall anomalies of October, Novem-
ber, December 2006 and January, February, March 2007,
in western African forest, across northern DRC and over
the forest–savanna boundary regions (see the electronic
supplementary material, figure S2).
4. Discussion

The absence of any evidence of strong or persistent impact of severe droughts on the rainforests of Central Africa and West Africa suggests that these forests may be more adapted to tolerate high WD short-time events in comparison with the forests in other regions of moist tropics. QSCAT backscatter data have the capability of detecting any widespread changes of forest canopy properties such as damages or mortality of emergent trees as the first response to droughts [9,39]. These changes were readily observed in moist tropical forests of Amazonia almost immediately after an intense rainfall anomaly [17,18]. Our results focused over the past decade also show the QSCAT response to negative rainfall or WD anomaly on average (see the electronic supplementary material, figure S6b), and spatially (see the electronic supplementary material, figure S5c). These short-term changes in QSCAT backscatter data represent minor canopy disturbance or a decline of canopy water content during the extreme WD event. A comparison with 2005 and 2010 droughts in Western Amazonia [18] suggest that the MCWD in Central and West Africa during drought years (figure 2) was significantly larger than Amazonia by more than 200 mm. However, unlike Amazonia, the QSCAT response was relatively weak and not persistent over most of the African humid forest, providing a strong indication that these extreme events did not create major disturbance.

The longer time-series analyses of rainfall suggest that the lack of persistent QSCAT anomaly over the last decade is probably due to the long-term climate condition with frequent WDs and potential adaptability of vegetation characteristics of the region. A 60 year time-series analysis of the combined CRU and TRMM dataset (figure 3) showed the observed negative anomalies of the past decade are a continuation of a gradual drying and more frequent rainfall anomalies in most regions of the African forests, indicating the long-term exposure of the African forests to...
increasing levels of WD. On the other hand, Central African forests have lower annual rainfall and moderate seasonality with relatively small difference in rainfall between dry and wet season compared with tropical forests in Amazonia. African forests have experienced continuous wet and dry cycles over the past 3000 years [3]; therefore, it is possible that the African forests contain more drought-adapted species compared with other tropical forests [40,41]. This was particularly shown in a study by Fauset et al. [20] on the Ghanaian forests, where they found a 20 year drying trend caused a shift in composition and structure of the vegetation in favour of drought tolerant species, including canopy species with intermediate light requirements. In contrast, studies in Amazonia show an increase in mortality of large trees and canopy loss caused by short-term severe drought events [9,18]. Other factors such as lower evapotranspiration due to cooler temperature and lower and uniform distribution of rainfall, frequent cloud cover and potential differences in rooting depth, and complex biogeographic and edaphic factors may explain the adaptation of these forests to drought [10,42].

The analysis of the TRMM data showed higher resolution patterns of rainfall and WD over the African forests. Particularly, the pattern detected by the WD and the lower rainfall of the driest season along the southern reaches of the Congo River appeared consistently throughout the entire decade, suggesting a distinct climate pattern in this region that was partially obscured by low resolution and sparse ground stations used in CRU data. This pattern may be related to changes in the atmospheric convection layer associated with surface topography and changes of elevation in the eastern mountains of DRC along the Rwanda and Burundi borders. With this drier climatological pattern in the central Congo Basin, it is likely that forests in the region may also have adapted to stronger WDs and are tolerant to severe rainfall anomalies. A similar pattern observed in QSCAT averaged backscatter variation over the decade indicates that forests in this region may be relatively seasonal and have been weakly impacted by the persistent WD observed in rainfall data (see the electronic supplementary material, figure S7). It is important to note that long-term CRU rainfall dataset does not show any evidence of such a dry pattern in this region prior to 1998 (figure 3). We expect this is possibly due to the lack of enough rainfall stations. However, longer observations from TRMM are required to clarify the nature of rainfall climatology in this region.

Western African forests experience one long dry season with rainfall less than 10 mm for more than two months per year (see the electronic supplementary material, figure S8), which may support the higher vulnerability of the region to droughts [43]. Strong response to drought was observed in West Africa and the northern boundary of Central Africa (see the electronic supplementary material, figure S2). This may be attributed to the vulnerability of these forests due to logging, fragmentation, land use activities and the prolonged dry episodes in the last few decades in the Sahel region [23]. During the past three decades, African rainforests have been experiencing an increasing rate of negative WD anomalies related to climate variations. The causes of these variations are the subject of continuous debates [44].

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References


