IOP Publishing Environ. Res. Lett. 14 (2019) 034007 https://doi.org/10.1088/1748-9326/aaf5d8

Environmental Research Letters

RECEIVED
23 September 2018

REVISED
22 November 2018

ACCEPTED FOR PUBLICATION
4 December 2018

PUBLISHED
11 March 2019

LETTER

The light-deficient climates of western Central African evergreen forests

Nathalie Philippon[1,10], **Guillaume Cornu**[2], **Lou Monteil**[3], **Valery Gond**[2], **Vincent Moron**[4,5], **Julien Pergaud**[6], **Geneviève Sèze**[7], **Sylvain Bigot**[1], **Pierre Camberlin**[6], **Charles Doumenge**[2], **Adeline Fayolle**[8] **and Alfred Ngomanda**[9]

[1] IGE, University of Grenoble Alpes, CNRS, IRD, Grenoble INP, 70 rue de la Physique, F-38400 Saint Martin d'Hères, France
[2] F&S, CIRAD, F-34000 Montpellier, France
[3] Département de Géographie, Université de Laval, 2045 rue de La Terrasse, Québec, Canada
[4] Aix Marseille Univ, CNRS, IRD, INRA, Coll France, CEREGE, F-13000 Aix-en-Provence, France
[5] IRI, Columbia University, Palisades, United States of America
[6] Biogeosciences, UBFC, 6 bvld Gabriel, F-21000 Dijon, France
[7] LMD, IPSL, UPMC, CNRS, EP, ENS, 4 place Jussieu, F-75000 Paris, France
[8] Biose Department and TERRA research Unit, Gembloux Agro-Bio Tech, Université de Liège, Passage des Déportés 2, B-5030 Gembloux, Belgium
[9] Institut de Recherche en Ecologie Tropicale (IRET), BP 13354 Libreville, Gabon
[10] Author to whom any correspondence should be addressed.

E-mail: nathalie.philippon@univ-grenoble-alpes.fr

Keywords: tropical forests, central Africa, irradiance, diurnal cycles, cloudiness

Supplementary material for this article is available online

Abstract

Rainfall thresholds under which forests grow in Central Africa are lower than those of Amazonia and southeast Asia. Attention is thus regularly paid to rainfall whose seasonality and interannual variability has been shown to control Central African forests' water balance and photosynthetic activity. Nonetheless, light availability is also recognized as a key factor to tropical forests. Therefore this study aims to explore the light conditions prevailing across Central Africa, and their potential impact on forests' traits. Using satellite estimates of hourly irradiance, we find first that the four main types of diurnal cycles of irradiance extracted translate into different levels of rainfall, evapotranspiration, direct and diffuse light. Then accounting for scale interactions between the diurnal and annual cycles, we show that the daily quantity and quality of light considerably vary across Central African forests during the annual cycle: the uniqueness of western Central Africa and Gabon in particular, with strongly light-deficient climates especially during the main dry season, points out. Lastly, using an original map of terra firme forests, we also show that most of the evergreen forests are located in western Central Africa and Gabon. We postulate that despite mean annual precipitation below 2000 mm yr^{-1}, the light-deficient climates of western Central Africa can harbour evergreen forests because of an extensive low-level cloudiness developing during the June–September main dry season, which strongly reduces the water demand and enhances the quality of light available for tree photosynthesis. These findings pave the way for further analyses of the past and future changes in the light-deficient climates of western Central Africa and the vulnerability of evergreen forests to these changes.

1. Introduction

The climate conditions under which forests grow in Central Africa are still not well known, as it is one of the most under-studied climatic areas of the world. This relates mainly to the dramatic lack of *in situ* climatic measurements (Washington *et al* 2013, Bigot *et al* 2016).

As compared to Amazonian and southeast Asian forests, Central African forests grow under lower rainfall thresholds: mainly below 2000 mm yr^{-1} although noteworthy spatial variations exist between wetter west and east margins (>2000 mm), and drier north and south ones (~1500 mm, figures S1(a), (e) is available online at stacks.iop.org/ERL/14/034007/mmedia).

This explains that rainfall is acknowledged as the main environmental factor controlling forest photosynthesis and functioning in Central Africa (Gond *et al* 2013, Guan *et al* 2015, Cherrington *et al* 2016). Contrarily to Amazonian forests where the mean seasonality in photosynthetic activity is mostly driven by light availability, i.e. the highest photosynthesis levels are recorded during the luminous dry season (Huete *et al* 2006, Myneni *et al* 2007, Bi *et al* 2015, Wagner *et al* 2017), in Central Africa, the two seasons of highest (lowest) photosynthesis, i.e. March–May and September–November (December–February and June–August), are concomitant with the two rainy (dry) seasons (Gond *et al* 2013, Philippon *et al* 2016). Indeed, below 2000 mm yr^{-1} on average, the water stored during both rainy seasons is not expected to meet the main dry season water demand and to maintain evergreen forest.

However, recent studies also show that the western part of Central Africa is one of the most cloudy region across the tropics (Wilson and Jetz 2016, Dommo *et al* 2018), which accounts for its low mean incoming solar radiation (irradiance hereafter) at the surface (figures S1(b), (f)). Moreover an analysis of the diurnal cycles for northern Congo (Philippon *et al* 2016) shows that neither the two rainy seasons nor the two dry seasons resemble each other in terms of cloud cover, irradiance and rainfall, which translates into different levels of photosynthetic activity. In spite of that, a clear picture of the light conditions prevailing across Central Africa is still lacking.

It is also noteworthy that forests are usually seen as a uniform green block across the whole Central Africa (Hansen *et al* 2008, Verhegghen *et al* 2012). According to authors 'lowland rainforests' or 'dense moist forests' might encompass a huge variety of forest types from wet Atlantic forests toward moist semi-deciduous forests further inland (Caballé 1978, White 1983, Letouzey 1985, Fayolle *et al* 2014b). Further divisions have also been observed locally (Viennois *et al* 2013) according to the geological substrate and disturbance history (Fayolle *et al* 2012, 2014a). A forest typology, i.e. evergreenness versus deciduousness, at the regional scale is currently lacking despite its importance for the improvement of the modelling of land–atmosphere interactions.

Here, we examine for the first time light available for trees across Central Africa and its potential control on forest traits, particularly forest evergreenness.

To that aim and expanding on a previous study (Philippon *et al* 2016), we extract first the main types of diurnal cycles of irradiance. Then we explore their implication on variables important for forests such as potential evapotranspiration (PET) (i.e. water demand) and diffuse irradiance (i.e. quality of light). Lastly, accounting for scale interactions between the diurnal and annual cycles, we develop a novel irradiance-based climatic regionalization for Central Africa, that we cross with an original map of forests types. The main hypothesis of our study is that the low irradiance recorded in western Central Africa by reducing the water demand but associated with a better quality of light, enables the existence of evergreen forests under conditions which are drier than in Amazonia and southeast Asia.

2. Data and methods

Central Africa is defined here as the region encompassing latitudes 8°S–7°N and longitudes 8°E–30.5°E. Because we focus on the climate conditions under which forests grow, the non-forested land pixels and oceanic pixels are masked out. Only a rapid overview of data used is given hereafter as details are provided in the supplementary information. The study period is 2005–2013, dictated by the availability of irradiance data.

2.1. Data

The diurnal and seasonal cycles of light received at the surface are documented using mainly direct normalized irradiance data (DNI) produced by the CMSAF (Müller *et al* 2015) (Satellite Application Facility for Climate Monitoring).

To understand variations observed in DNI and their implications in terms of water budget and light quality, information on cloudiness, rainfall, land surface temperature, relative humidity, PET and photosynthetically active radiation (PAR) are analysed using various datasets. This enables the extraction of robust and coherent results across datasets, despite the uncertainties associated with the data. Cloudiness data come from the Satellite Application Facility for Support to Nowcasting and Very Short Range Forecasting Cloud Type (SAFNWC) product (Derrien and Le Gléau 2005). The TRMM 3B42v7 rainfall data is used as the reference rainfall dataset because its 3-hourly time resolution enables to document the diurnal cycle (Huffman *et al* 2007). Daily land surface temperatures come from the Berkeley Earth Temperature Study (Rohde *et al* 2013) while monthly relative humidity data originate from the Vmerge project database (Jones and Wint 2015). We also used daily PET provided by the (Senay *et al* 2008) National Oceanic and Atmospheric Administration's Global Data Assimilation System (GDAS) and monthly PET from WorldClim (Fick and Hijmans 2017). Total and diffuse PAR (400–700 nm) come from the Breathing Earth System Simulator (BESS) daily products (Ryu *et al* 2018).

Lastly, expanding on a forest typology proposed for northern Congo (Gond *et al* 2013), forests traits are documented using the enhanced vegetation index (EVI) at a 16-day temporal resolution issued from MODIS (Huete *et al* 2002), and crossed with forest inventory data and existing vegetation maps (see supplementary information).

2.2. Methods

2.2.1. Extraction of the four main types of DNI diurnal cycles

Following a methodology previously developed (Philippon *et al* 2016) and extending it for the whole of Central Africa, the detection of the four main types of diurnal cycles recorded over Central Africa for DNI relies on a classification of the whole set of 788 400 diurnal cycles of hourly DNI (365 days * 9 years from 2005 to 2013 and 2400 pixels), and not as commonly found on mean diurnal cycles computed on predefined seasons (Malhi *et al* 2002).

The extraction is done thanks to a k-means clustering algorithm which agglomerates data around randomly chosen seeds and iteratively finds the partition which minimizes the variance within clusters, for a given number of clusters (Michelangeli *et al* 1995). As preliminary steps, we (1) filter the diurnal cycles (low-pass band at 6 h), and (2) normalize them (by subtracting the annual hourly mean). Given the large number of observations available ($N = 2400$ pixels * 365 days * 9 years for 24 variables), the k-means is first performed on a subset of 2000 randomly chosen observations. The number of iterations, i.e. the number of random seeds is set to 200. The number of clusters varies from 3–5 and the 4-cluster solution is retained as the partition for which the four types seem, as expected, mostly driven by the first and second harmonics of the diurnal cycle, that is (1) the opposition between anomalously dark and bright conditions all along the day (~amplitude of the 1st harmonic) which is (2) superimposed on the temporal phase of the second harmonic (i.e. maximum near either the morning or the afternoon).

2.2.2. Regionalization of Central Africa according to DNI diurnal cycles

To delineate irradiance-based regions across Central Africa, a k-means clustering is applied to the daily frequency of the four types of DNI diurnal cycles across the 2400 forest pixels. First, the daily mean frequency over the 9 years of the study period, for the four types of diurnal cycles, is computed for each pixel. Then a 30-day low-pass filter is applied to remove the high frequency variability. We obtain four mean annual cycles, which are concatenated so that we attain a matrix of 365 days * 4 types as variables and 2400 forest pixels as observations to be clustered. We standardize the variables to zero mean and unit variance, then reduce the matrix dimensions and filter out the noise through principal component analysis, retaining ~75% of the total variance, i.e. eight principal components. The clustering model is therefore built in the EOF space with only eight variables taken into account. The number of clusters is varied from 2–9 and a classifiability index is applied to determine the appropriate number of clusters to be retained. This index rules out partitions into 2–3 clusters as not significant at the 95% level and we retain the partition into six clusters.

2.2.3. Compositing of other climatic parameters according to the four types of diurnal cycle and/or the six regions

The mean diurnal evolution of rainfall, and cloudiness, and mean daily values of PET, temperature and relative humidity, associated with each type of diurnal cycle of DNI are obtained by averaging values over the corresponding days (obscure, obscure AM …). The relationships between daily rainfall (from TRMM) and PET (from GDAS) as well as the one between daily direct and diffuse irradiance (either from DNI or PAR) have also been analysed for the 4 types of days. The conditional and marginal frequencies have been computed for deciles of daily rainfall, PET, direct and diffuse irradiance and PAR computed from all 2400 forest grid-points and 3285 days. For daily rainfall, we added a class for zero rainfall, which accounts for roughly 47% of all forest grid-points and days. The counts of observations are normalized by the grand total of forest grid-points and days. Then, we computed the conditional and marginal frequencies for the four daily types of irradiance and computed the relative anomalies versus the ones computed on all days. If the four types of days would not discriminate in terms of rainfall/PET and direct/diffuse irradiance deciles, anomalies would be close to zero and not significant.

The mean annual cycles of the parameters relative to climate (rainfall …) observed within each of the six irradiance-based regions are obtained by averaging values over the corresponding pixels (southwest Gabon, Cameroon …). For variables provided at a daily resolution, a 30-day low-pass filter is applied on the computed mean annual cycles to remove the high frequency variability (e.g. figures S6, S7, S8).

2.2.4. Identifying and mapping forest types according to EVI mean seasonal cycles plus elevation, soils, inventory data and vegetation maps

To identify and map forest types with similar trait and photosynthetic activity, we extended to the whole of Central Africa an approach previously developed for a restricted area in the Sangha River Interval, north of the Republic of Congo (Gond *et al* 2013).

The EVI value attributed to each 16-day period corresponds the best normalized difference vegetation index and the lowest zenith angle. Using the 'good' pixels only (i.e. pixels which are flagged 'no clouds') in the 12 years for each 16-day period, a mean seasonal cycle was computed from the 12-year database. An unsupervised iterative self-organizing data analysis technique (ISODATA) classification was applied on the EVI mean seasonal cycles. The ISODATA classification is a k-means algorithm which allows selecting clusters by splitting and merging the initial pixels dataset and has been previously applied for forests in Madagascar (Mayaux *et al* 2000).

Nine classes were finally retained which were crossed with elevation, soils and inventory data, and existing vegetation maps to corroborate their spatial extend, interpret them in terms of deciduousness and density, and label them. In particular we detected significant and consistent differences in forest structure and composition among the nine remotely-sensed forest types (see supplementary information for a description of datasets and of the nine types of forests).

3. Results

3.1. Daily variations in direct irradiance in Central Africa

DNI strongly varies within a day as pictured by the four main types of diurnal cycles extracted (*see Methods*). Obscure days which are the most frequent (29%, figure 1(a)) display maximum DNI as low as <150 W m^{-2}. These days relate to a heavy cloud cover during daytime, from low to very high opaque clouds (figure S2) and above average hourly rainfall from midnight to noon (~4 mm h^{-1}, figure S3). In contrast, bright days display the largest values of DNI, 700 W m^{-2} at 12-13LT. They are associated with a high frequency of clear skies and are the driest (figure 1(d)). Days classified as obscure in the morning (figure 1(b), 'Obscure AM') have a peak value usually above 500 W m^{-2} at 14LT. These days are characterized by a high frequency of ultra-low and medium clouds, and below normal rainfall in the morning. Days classified as obscure in the afternoon (figure 1(c), 'Obscure PM') are associated with a high frequency of high to very high opaque clouds, and high rainfall intensities in the afternoon (more than 7 mm h^{-1} by 15LT), i.e. the typical end of afternoon, rain-bearing deep convective clouds, but they are nonetheless the less frequent (19%).

These four types of days translate into different relationships of PET versus rainfall (i.e. water demand versus supply) and direct versus diffuse irradiance (i.e. quantity versus quality of light) (figure 2, see also figure S4 for direct versus diffuse PAR). While obscure and bright days display the expected opposite rainfall versus PET and direct versus diffuse irradiance relationships (figures 2(a), (b) and (e), (f) respectively), i.e. higher rainfall and diffuse irradiance, and lower PET and direct irradiance recorded during obscure days as compared to bright days, this does not hold true for obscure AM and obscure PM days. Obscure AM days are usually characterized by low rainfall and low to medium PET whereas obscure PM days frequently record high rainfall and high PET (figures 2(c), (d)). High levels of diffuse irradiance associated with medium levels of direct irradiance are also more frequent during obscure AM days than obscure PM days (figures 2(g), (h)).

3.2. Seasonal and spatial variations across Central Africa

We identify wide spatial variations across Central Africa in the frequency of these four types of days across the mean annual cycle (*see Methods*). The western part of Central Africa ('SW Gabon' and 'Cameroon', figures 3(a)–(c)) display outstanding behaviour when compared to the other regions (figure S5): the cumulated frequencies of obscure and obscure AM days exceed 81% on average. In 'SW Gabon', the June–September season shows up with over 70% of obscure days, following a remarkable steep increase in May. Therefore, the forests of 'SW Gabon' grow under the lowest light levels recorded across Central Africa as attested by a DNI annual average of ~109 W m^{-2} (figure S6), and below 80 W m^{-2} in JJAS (figure 4(a)). Further inland, the four types of days are more evenly distributed, especially in 'Centre DRC' characterized by seasonal cycles of weak amplitude (figure 4(d)), and obscure PM days are relatively much more frequent (figure S5).

We also observe that forests of 'SW Gabon' exhibit the driest and longest dry season: less than 1 mm d^{-1} in June–August (figure 4(a)) whatever the rainfall estimates used (figure S6). Indeed, most of the days in June–September are rainless in 'SW Gabon', especially the obscure days (figure S7). Hence, we show that western Central Africa, and specifically 'SW Gabon', stands apart as the area in Central Africa where the main dry season is the most light-deficient season, whereas further inland the main dry season is, as usually expected, the brightest season (figure S6).

This peculiar seasonality of sunlight and rainfall in 'SW Gabon' is related to the presence of a uniform and opaque cover of low-level stratiform clouds in June–September (Dommo *et al* 2018) (figure S8, mean frequency of ~45%) which are mostly non-precipitating, and strongly filter the incoming solar radiation.

By decreasing the direct irradiance, a very direct effect of this June–September persistent low-level cloud cover is to lower the water demand (PET). In fact, the long dry season in 'SW Gabon' (June–September) records the lowest PET at the regional scale (<2.3 mm d^{-1}, figures 4(c) and S9). It is also the coolest (Tmax below 29 °C) and the moistest (RHmax ~90%, figure 4(d)) (concomitantly, Tmin and RHmin are the highest in 'SW Gabon', not shown). Comparatively, in the other regions, the long dry season (June–September for 'S DRC' and 'Centre DRC', and December–February for 'W&E Margins' and 'N DRC') is the season when the water demand and maximum temperature reach their highest level, and the maximum relative humidity its lowest level (note however that the high levels of PET maintain through the 1st part of the subsequent rainy season, i.e. September and March respectively).

A second effect of that persistent low-level cloud cover in 'SW Gabon' is a prominent modification of the quality of light available for trees photosynthesis (figure 4(b), in agreement with findings for the four types of diurnal cycles): the ratio between the direct and the diffuse irradiance in June–September varies between 0.4–0.8 (meaning that diffuse irradiance levels are 20% to 60% and up higher than those of direct irradiance). The relationship between PAR and PARdiff (figure S10)

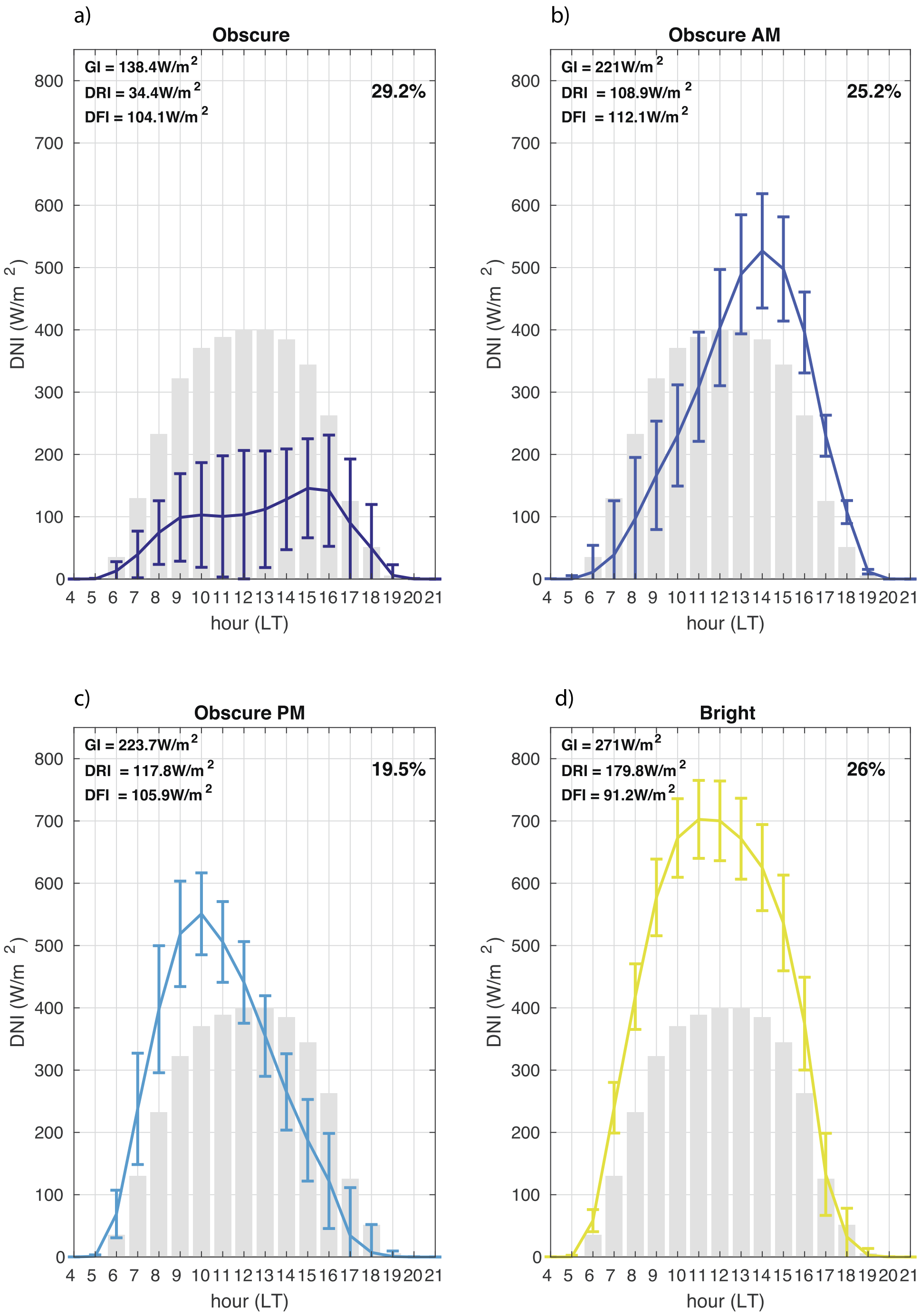

Figure 1. The four main types of diurnal cycles of the DNI. (a) Obscure, (b) obscure in the morning ('Obscure AM'), (c) obscure in the afternoon ('Obscure PM'), and (d) bright days. Coloured curves give the mean value (average over days and pixels), error bars the 0.5 std (with $N = 1837\,830/1422\,368/1895\,203/2128\,900$ respectively), and grey bars the overall average (all days and pixels available). In bold, the frequency of occurrence (in %) of each type over the study period (2005–2013) and the mean daily values of global (GI), direct (DRI) and diffuse (DFI) irradiances.

shows that forests in 'Cameroon' and 'SW Gabon' grow under much more days with low PAR and medium to high PARdiff than forests further inland (note also in figure 4(b), the DRI/DFI ratio below 1 during part of the March–May and September–November rainy seasons).

3.3. Links with forest trait

The six irradiance-based regions identified (figure 3(a)) are crossed with a regional map of terra firme forests (figure 5(a)) developed independently based on EVI seasonality and forest inventory data (see *Methods*). Nine different types of forests are identified across Central Africa which differ in terms of photosynthetic activity (i.e. showing mean annual cycles of EVI with different levels, amplitudes and phases, figure S11), structure (i.e. dense/degraded/secondary) and composition (i.e. evergreen/semi-deciduous/deciduous, table S3).

We find that the spatial distribution of these nine types of forests is in good agreement with the six

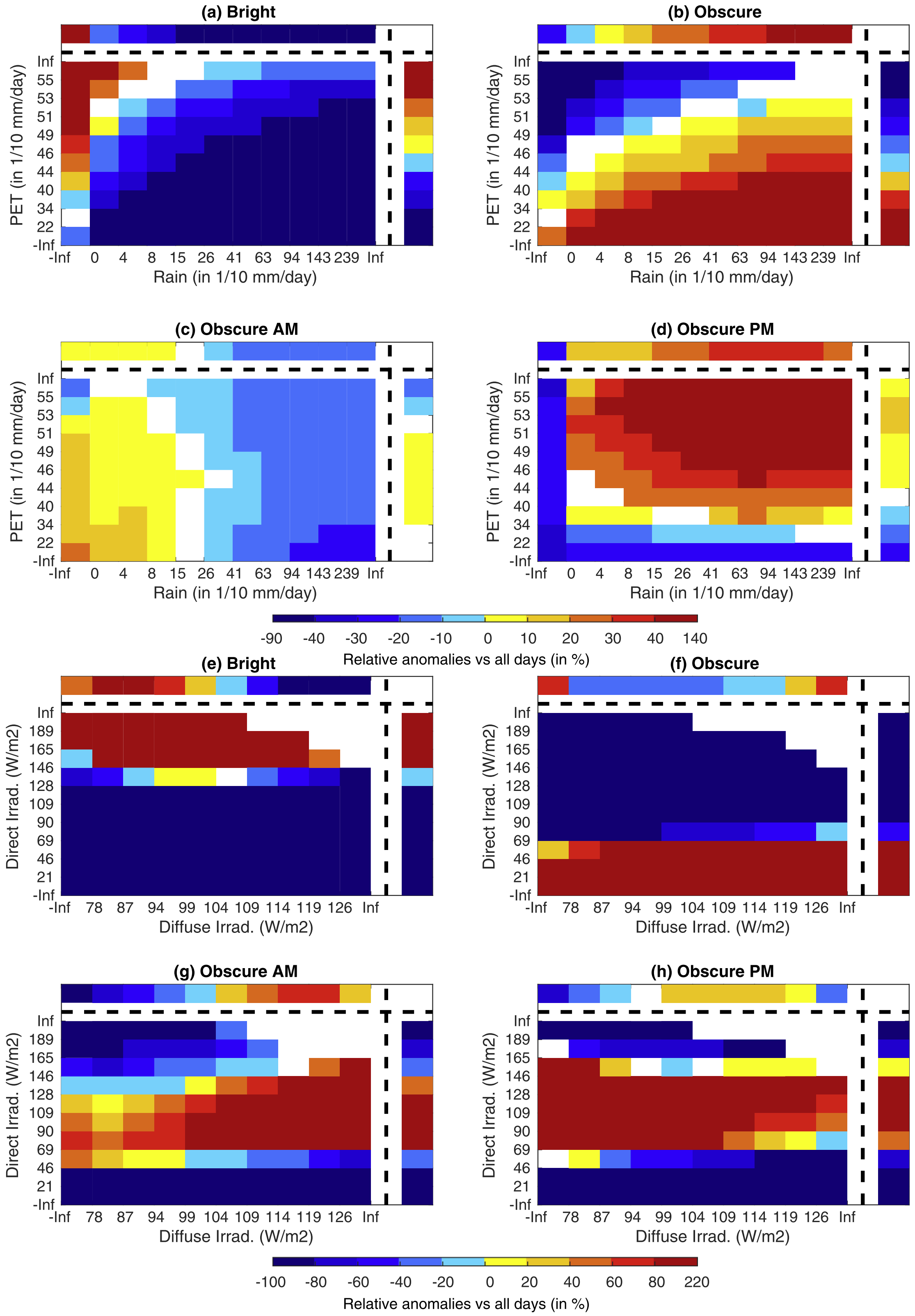

Figure 2. Water demand versus rain, and light quantity versus quality during the four types of diurnal cycles of irradiance. Conditional frequencies (expressed in relative anomalies versus all days) for deciles of PET and rainfall (in tenth of mm per day, panels (a)–(d)) and of diffuse and direct irradiance (in W m^{-2}, panels (e)–(h)). The marginal frequencies are given for reference in the rightmost column for PET or direct irradiance and upper row for rain or diffuse irradiance. Blank squares indicate non-significant anomalies at the two-sided 95% level (see Methods).

irradiance-based regions (figure 5(b)). The 'SW Gabon', with its dark long dry season with a low water demand, and where diffuse radiation dominates during a large part of the year, harbours most of the evergreen and dense forests of Central Africa: the 'dense evergreen forests', 'dense evergreen and semi-deciduous forests'

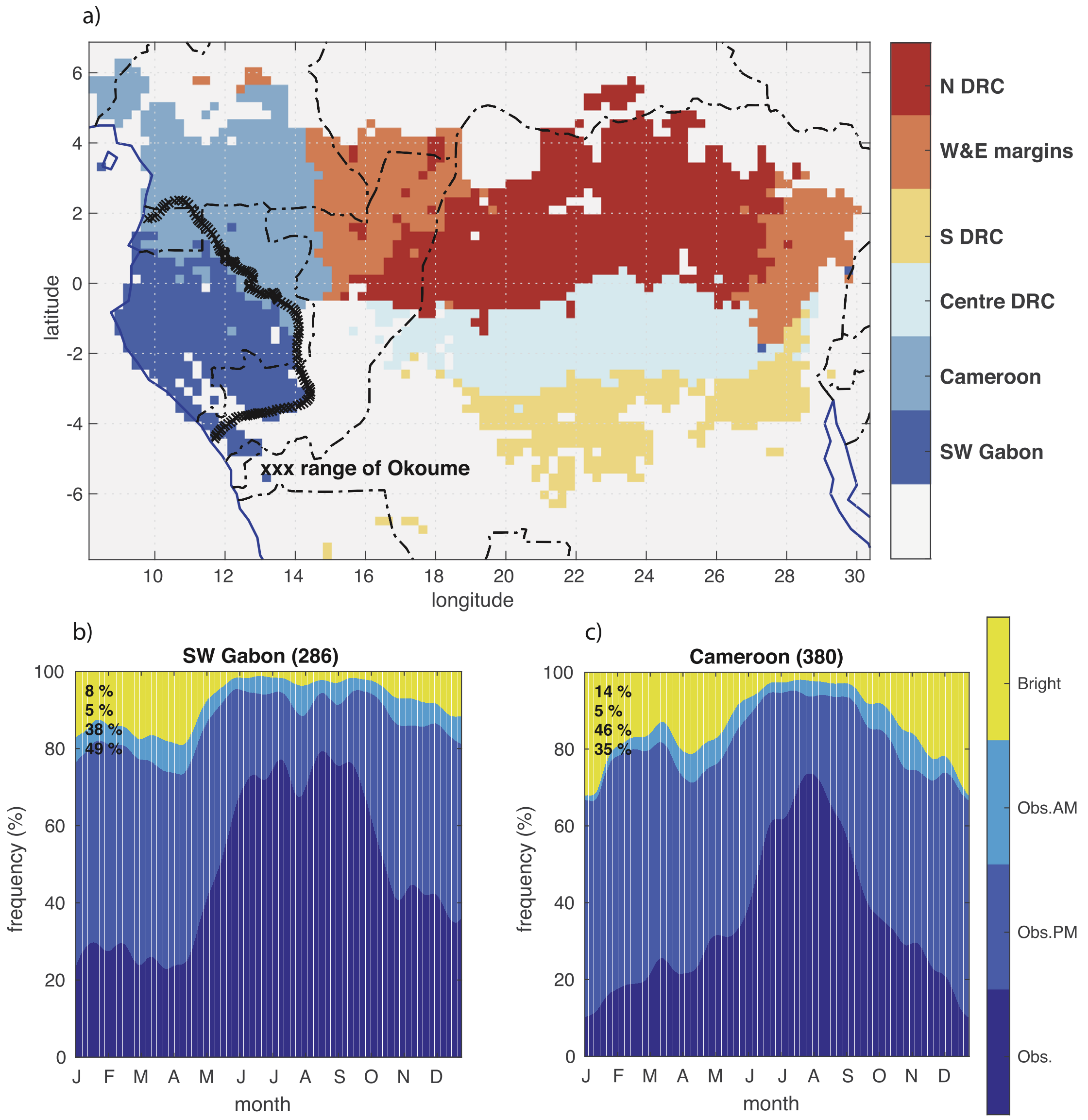

Figure 3. Irradiance-based regionalization of Central Africa according to the frequency of the four types of diurnal cycles of DNI. (a) The six regions are labelled 'SW Gabon', 'Cameroon', 'Centre DRC', 'South DRC', 'W&E margins' and 'North DRC' plus the range of Okoumé as black crosses. (b), (c) Frequency of the four types of diurnal cycles of DNI across the annual cycle for the 'SW Gabon' and 'Cameroon' regions (results for the four other regions are provided in figure S5). Into brackets the number of 0.25° * 0.25° pixels comprised into each region. Percentages give the mean annual frequency of the four types ('Obscure' to 'Bright' from bottom to top).

and 'dense semi-deciduous forests' of western Central Africa (i.e. forest types 1, 3 and 4) are the most represented. But it is also remarkable that the 'SW Gabon' region closely matches the range of the Okoumé (*Aucoumea Klaineana* Pierre, figure 3(a)), a pioneer evergreen tree encountered as mono-dominant stands after shifting cultivation or savannahs, and one of the most important timber-producing native tree of western Central Africa (White *et al* 2000).

4. Discussion

In this study, we propose an original analysis of light conditions prevailing in Central African forests, and their implication on variables relevant for forests' functioning and traits. This analysis relies on the diurnal cycles of irradiance, the associated levels of rainfall, ETP and direct versus diffuse light, and the evolution of their frequency along the annual cycle. It leads to the first irradiance-based regionalization of Central African forests.

Our irradiance-based regionalization highlights western Central Africa, and more specifically the southwestern Gabon, as an area standing apart from the rest of Central Africa in terms of mean climate functioning: indeed, an important finding is that the 'SW Gabon' is much darker than the other regions, especially during its main dry season which is also the driest and longest at the regional scale. This contrasts with most previous climatic regionalizations based on the mean annual cycles of rainfall only (Dezfuli 2011, Badr *et al* 2016): they mainly picked-up zonal patterns driven by the gradual lengthening, on each side of the

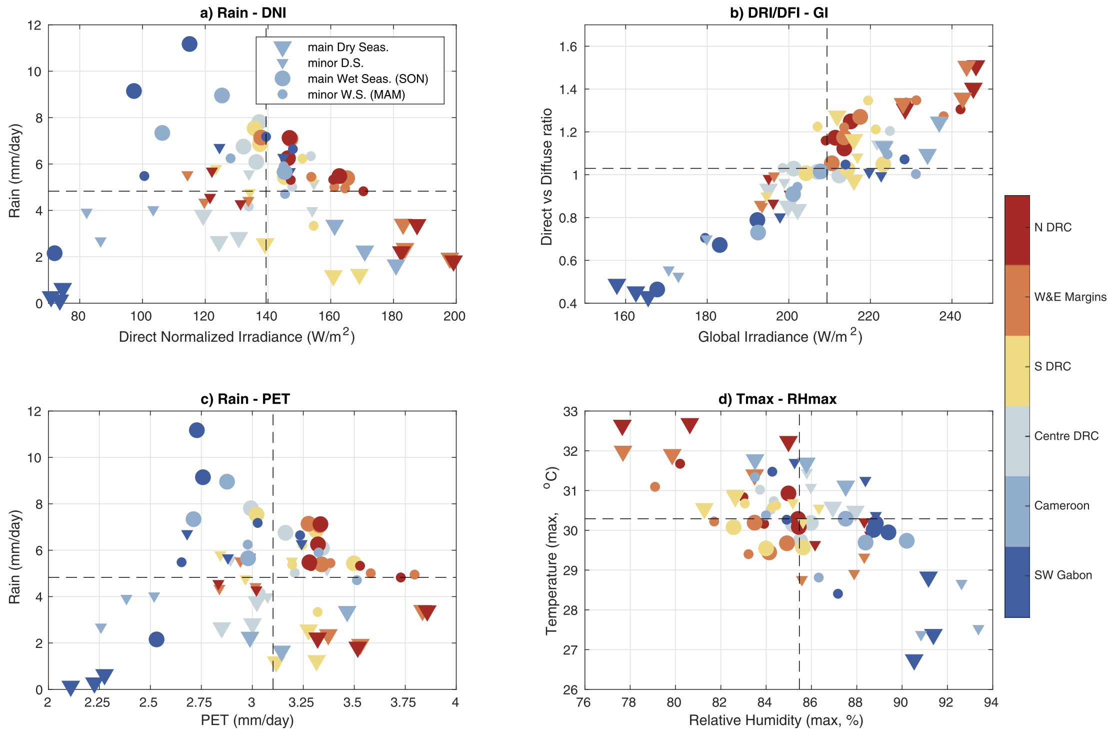

Figure 4. Relationships between irradiance, rainfall, potential evapotranspiration, temperature and relative humidity in the six regions. Scatter-plots of the mean monthly values of (a) DNI and rainfall, (b) GI and DRI/DFI, (c) PET and rainfall, (d) RHmax and Tmax. The vertical and horizontal black dashed lines denote the mean annual value across the six regions. The two dry (DJF and JJA) and two wet (MAM and SON) seasons are pictured with different markers.

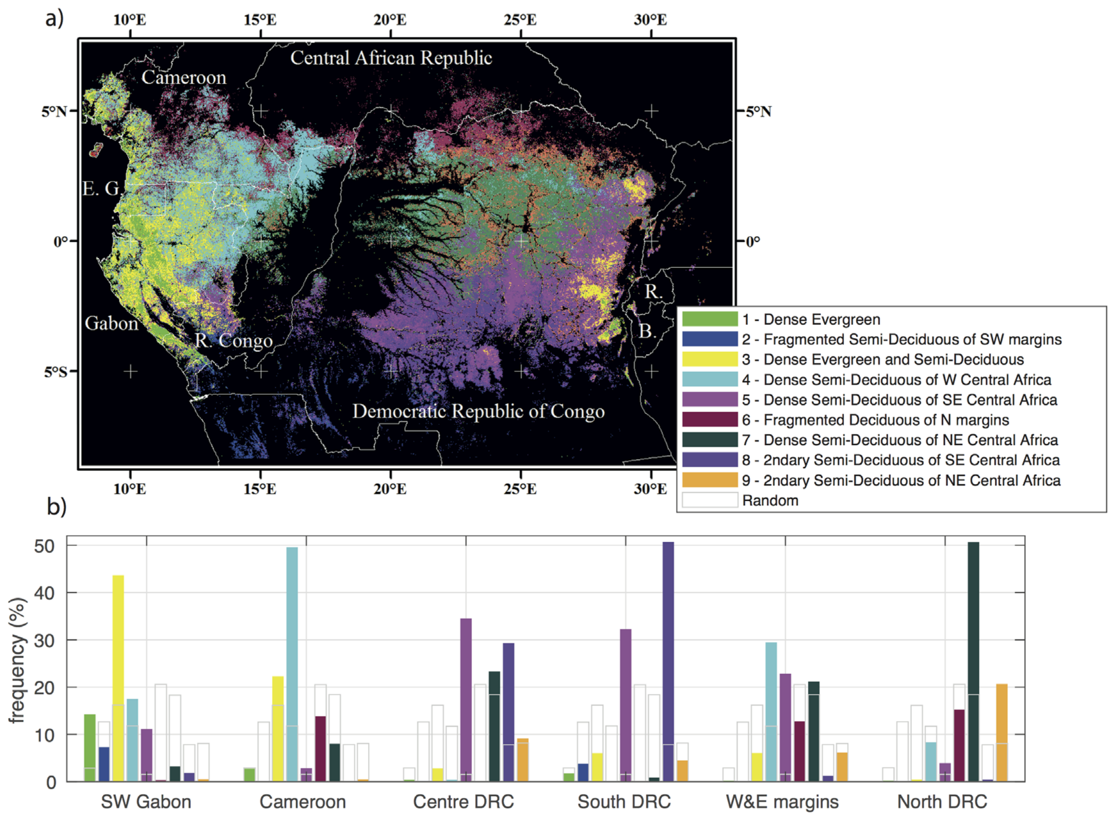

Figure 5. The nine types of terra firme forests of Central Africa and their distribution within the six climatic regions. (a) Location of the nine types of terra firme forests of Central Africa detected based on cross-analyses of inventories data, vegetation maps and mean annual cycles of EVI. (b) Frequency (in %) of the nine types of forests within the six climatic regions. The forests types' colour is the same as in (a). Empty grey bars give the frequency of the nine forests types within the six regions as obtained from a random permutation of forests pixels across Central Africa. Chi square equals 2.98 × 10^7 against a theoretical value of 25.2 for 10° of freedom and 99.5% level of significance.

equator, of the main dry season (and the corresponding shortening of the secondary dry season) as a result of the latitudinal shift of the ITCZ, but fail to mention the darkness of the long dry season in western Central Africa, thus its low water demand and high levels of diffuse light.

A second key finding is that the light-deficient climates of western Central Africa harbor most of the evergreen forests of Central Africa. Despite the relatively low mean annual rainfall (<2000 mm against 2500 mm and up in Amazon and southeast Asia) and long dry season (3 months below 30 mm), evergreen forests might have been favoured by the limited water demand during the long dry season due to the extensive low cloud cover. Rainfall above 2000 mm yr^{-1} has indeed been shown to sustain evergreen forests worldwide though most tropical forests in Central Africa (including the evergreen forests) are found below this climatic threshold (spatial variations of mean annual rainfall among the six regions do not exceed 170 mm, i.e. ~10% of the mean annual amount, figure S6). We further hypothesize that in western Central Africa, the June–September rainfall amounts recorded in rain-gauges or estimated through remote-sensing are far from being representative of the actual amount of water available to forest ecosystems, since they do not take into account cloud water interception and water foliar interception (Oliveira *et al* 2014). At the annual scale, water inputs resulting from fog are estimated to represent up to 20% of the total precipitation in the Gabon highlands (Bruijnzeel *et al* 2011). This ratio might be even higher in June–September given the high frequency of low clouds likely to be regularly trapped in the canopy and the high relative humidity levels, and might help at balancing the water demand.

Another finding is the particularity of the light quality in western Central Africa, specifically in June–September, when the diffuse component represents an important part of the total irradiance. Although high rainfall/low water demand and low soil fertility are recognized as the main determinants of forest evergreenness (Givnish 2002, Ouédraogo *et al* 2013), the specificity of irradiance in western Central Africa raises question on the impact of light quality on forest trait (and also on photosynthetic activity levels although their estimation in June–September is uncertain because of the large cloud cover). Many studies suggest that diffuse irradiance is favourable to photosynthesis because it irradiates more of the subcanopy leaves and decreases light-saturation of the canopy top leaves (Mercado *et al* 2009, Doughty *et al* 2010, Rap *et al* 2015). Therefore, evergreenness in western Central Africa might be the most cost-effective way to cope with light-deficiency as the presence of mature leaves through a large part of the annual cycle might be the best adaptive strategy for gaining carbon (Schwartz 1993, Aerts 1995, Givnish 2002).

A last key finding is that the four types of diurnal cycles of direct irradiance extracted translate into different PET versus rainfall and direct versus diffuse light relationships. This is particularly so for obscure AM and obscure PM days although they have comparable daily levels of irradiance. Such relationships are not trivial given the uncertainties in the data. They also demonstrate that direct irradiance at the diurnal scale is a particularly comprehensive parameter which deserves much more attention in climatological studies especially those dedicated to plant functioning, and which we believe is easier to work with than cloudiness and rainfall which are intrinsically discrete.

5. Conclusion

Because mean annual rainfall in Central Africa is lower than in Amazonia and therefore recognized as the main controlling factor of forests functioning, little attention has been paid to solar radiation levels.

An irradiance-based regionalization of Central Africa reveals the uniqueness of western Central Africa and Gabon in particular, as an area with a strongly light-deficient main dry season because of an extensive low-level cloud cover. The low water demand and high quality of light observed during the main dry season might explain that western Central Africa sustains most of the evergreen forests of Central Africa when semi-deciduous and deciduous forests are mainly observed further east.

The questions are now how these light-deficient climates of western Central Africa will be impacted by global warming, and whether they will still be able to sustain most of the evergreen forests of Central Africa, their biodiversity and the ecosystem services they provide. This implies an appropriate simulation of the June–September low cloud cover and of the diurnal cycles of irradiance by climate models which is unfortunately one of their weak points (Nam *et al* 2012).

Acknowledgments

Authors thank S Gourlet-Fleury, N Bayol and the timber companies Alpicam, BPL, IFO-Danzer, DLH, IFB, Likouala Timber, Rougier, SEFCA, SCAD, SCAF and Vicwood for authorizing access to the inventory data collected and analysed in the framework of the ErA Net BiodivERsA 2008 CoForChange and ErA Net BiodivERsA 2013 CoForTips projects, funded by the National Research Agency (ANR) and the Natural Environment Research Council (NERC), see http://coforchange.fr and https://cofortips.org/.

They also acknowledge the AERIS/ICARE data center (http://icare.univ-lille1.fr/) for providing access to the SAFNWC CT data used in this study. This study was supported by the TOSCA/CNES and LEFE/INSU french national programmes. It is part of the International Joint Laboratory 'Dynamics of land ecosystems in Central Africa in a context of global changes' (LMI DYCOFAC). Calculations were performed using HPC resources from DNUM-CCUB (University of Bourgogne Franche Comté).

Authors contribution

NP has designed the study and performed climate analyses; GC, VG and LM have produced the forest traits map; VM has analysed the rainfall/PET and direct/diffuse irradiance relationships; JP and GS have helped with the retrieval and analysis of cloud data; PC has analysed PET data; AN has provided data for the Okoumé range; SB, CD and AF have helped with the interpretation of the results with regards to their field knowledge. All authors have contributed to the writing of the paper. The authors declare no conflicts of interest.

ORCID iDs

Nathalie Philippon https://orcid.org/0000-0003-3519-539X
Guillaume Cornu https://orcid.org/0000-0002-7523-5176

References

Aerts R 1995 The advantages of being evergreen *Trends Ecol. Evol.* **10** 402–7

Badr H S, Dezfuli A K, Zaitchik B F and Peters-Lidard C D 2016 Regionalizing Africa: patterns of precipitation variability in observations and global climate models *J. Clim.* **29** 9027–43

Bi J, Knyazikhin Y, Choi S, Park T, Barichivich J, Ciais P and Fu R 2015 Sunlight mediated seasonality in canopy structure and photosynthetic activity of Amazonian rainforests *Environ. Res. Lett.* **10** 064014

Bigot S *et al* 2016 État actuel des réseaux de mesures éco-climatiques en Afrique centrale: Les ambitions du projet de recherche international *FORGREENE 29ème colloque de l'Association Internationale de Climatologie* ed P Camberlin and Y Richard (Dijon) pp 101–6

Bruijnzeel L A, Mulligan M and Scatena F N 2011 Hydrometeorology of tropical montane cloud forests: emerging patterns *Hydrol. Process.* **25** 465–98

Caballé G 1978 Essai sur la géographie forestière du Gabon *Adansonia Ser.* **2** 425–40

Cherrington E A, Barbier N, Ploton P, Vincent G, Sabatier D, Berger U and Pélissier R 2016 Equatorial forests display distinct trends in phenological variation: a time-series analysis of vegetation index data from three continents *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **9** 3505–11

Derrien M and Le Gléau H 2005 MSG/SEVIRI cloud mask and type from SAFNWC *Int. J. Remote Sens.* **26** 4707–32

Dezfuli A K 2011 Spatio-temporal variability of seasonal rainfall in western equatorial Africa *Theor. Appl. Climatol.* **104** 57–69

Dommo A, Philippon N, Seze G and Vondou D A 2018 The June–September low cloud cover in western Central Africa: mean diurnal and spatial patterns and associated atmospheric dynamics *J. Clim.* **31** 9585–603

Doughty C E, Flanner M G and Goulden M L 2010 Effect of smoke on subcanopy shaded light, canopy temperature, and carbon dioxide uptake in an Amazon rainforest *Glob. Biogeochem. Cycles* **24** 1–10

Fayolle A, Engelbrecht B, Freycon V, Mortier F, Swaine M, Réjou-Méchain M, Doucet J L, Fauvet N, Cornu G and Gourlet-Fleury S 2012 Geological substrates shape tree species and trait distributions in African moist forests *PLoS One* **7** 12–4

Fayolle A, Picard N, Doucet J, Swaine M, Bayol N, Bénédet F and Gourlet-fleury S 2014a A new insight in the structure, composition and functioning of central African moist forests *For. Ecol. Manage.* **329** 195–205

Fayolle A *et al* 2014b Patterns of tree species composition across tropical African forests *J. Biogeogr.* **41** 1–12

Fick S E and Hijmans R J 2017 WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas *Int. J. Climatol.* **37** 4302–15

Givnish T J 2002 Adaptive significance of evergreen versus deciduous leaves: Solving the triple paradox *Silva Fenn.* **36** 703–43

Gond V, Fayolle A, Pennec A, Cornu G, Mayaux P, Camberlin P, Doumenge C, Fauvet N and Gourlet-Fleury S 2013 Vegetation structure and greenness in Central Africa from Modis multi-temporal data *Phil. Trans. R. Soc.* B **368** 20120309

Guan K *et al* 2015 Photosynthetic seasonality of global tropical forests constrained by hydroclimate *Nat. Geosci.* **8** 284–9

Hansen M C, Roy D P, Lindquist E, Adusei B, Justice C O and Altstatt A 2008 A method for integrating MODIS and Landsat data for systematic monitoring of forest cover and change in the Congo Basin *Remote Sens. Drought Innov. Monit. Approaches* **112** 2495–513

Huete A, Didan K, Miura T, Rodriguez E P, Gao X and Ferreira L G 2002 Overview of the radiometric and biophysical performance of the MODIS vegetation indices *Remote Sens. Environ.* **83** 195–213

Huete A R, Didan K, Shimabukuro Y E, Ratana P, Saleska S R, Hutyra L R, Yang W, Nemani R R and Myneni R 2006 Amazon rainforests green-up with sunlight in dry season *Geophys. Res. Lett.* **33** L06405

Huffman G J, Adler R F, Bolvin D T, Gu G, Nelkin E J, Bowman K P, Hong Y, Stocker E F and Wolff D B 2007 The TRMM multi-satellite precipitation analysis: quasi-global, multi-year, combined-sensor precipitation estimates at fine scale *J. Hydrometeorol.* **8** 38–55

Jones P and Wint W 2015 The Vmerge Project Database (Oxford: Environmental Research Group)

Letouzey R 1985 Notice de la carte phytogeographique du Cameroun au 1:500 000 (Toulouse: IRA)

Malhi Y, Pegoraro E, Nobre A D, Pereira M G P, Grace J, Culf A D and Clement R 2002 Energy and water dynamics of a central Amazonian rain forest *J. Geophys. Res. Atmos.* **107** 1–17

Mayaux P, Gond V and Bartholomé E 2000 A near real-time forest cover map of Madagascar derived from SPOT VEGETATION data *Int. J. Remote Sens.* **21** 3139–44

Mercado L M, Bellouin N, Sitch S, Boucher O, Huntingford C, Wild M and Cox P M 2009 Impact of changes in diffuse radiation on the global land carbon sink *Nature* **458** 1014–7

Michelangeli P-A, Vautard R and Legras B 1995 Weather regimes: recurrence and quasi stationarity *J. Atmos. Sci.* **52** 1237–56

Müller R, Pfeifroth U, Träger-Chatterjee C, Trentmann J and Cremer R 2015 Digging the METEOSAT treasure—3 decades of solar surface radiation *Remote Sens.* **7** 8067–101

Myneni R B *et al* 2007 Large seasonal swings in leaf area of Amazon rainforests *Proc. Natl Acad. Sci. USA* **104** 4820–3

Nam C, Bony S, Dufresne J L and Chepfer H 2012 The too few, too bright tropical low-cloud problem in CMIP5 models *Geophys. Res. Lett.* **39** 1–7

Oliveira R S, Eller C B, Bittencourt P R L and Mulligan M 2014 The hydroclimatic and ecophysiological basis of cloud forest distributions under current and projected climates *Ann. Bot.* **113** 909–20

Ouédraogo D Y, Mortier F, Gourlet-Fleury S, Freycon V and Picard N 2013 Slow-growing species cope best with drought: evidence from long-term measurements in a tropical semi-deciduous moist forest of central Africa *J. Ecol.* **101** 1459–70

Philippon N *et al* 2016 Analysis of the diurnal cycles for a better understanding of the mean annual cycle of forests greenness in Central Africa *Agric. For. Meteorol.* **223** 81–94

Rap A *et al* 2015 Fires increase Amazon forest productivity through increases in diffuse radiation *Geophys. Res. Lett.* **42** 4654–62

Rohde R, Muller R, Jacobsen R, Perlmutter S and Mosher S 2013 Berkeley earth temperature averaging process *Geoinform. Geostat.* **1** 1–13

Ryu Y, Jiang C, Kobayashi H and Detto M 2018 MODIS-derived global land products of shortwave radiation and diffuse and total photosynthetically active radiation at 5 km resolution from 2000 *Remote Sens. Environ.* **204** 812–25

Schwartz D 1993 Les retombées de litière en tant que source du carbone et de l'azote du sol : quantification et périodicité des apports en relation avec les caractéristiques climatiques et édaphiques dans deux parcelles de forêt dense à Dimonika (Mayombe, Congo). *Echanges forêt-Atmosphère en Milieu Tropical Humide : Recueil de Travaux Effectués dans le Mayombe* ed B Cros, J Diamouangana and M Kabala (Paris: UNESCO) pp 141–58

Senay G B, Verdin J P, Lietzow R and Melesse A M 2008 Global daily reference evapotranspiration modeling and evaluation *J. Am. Water Resour. Assoc.* **44** 969–79

Verhegghen A, Mayaux P, De W C and Defourny P 2012 Mapping Congo basin forest types from 300 m and 1 km multi-sensor time series for carbon stocks and forest areas estimation *Biogeosci. Discuss.* **9** 7499–553

Viennois G, Barbier N, Fabre I and Couteron P 2013 Multiresolution quantification of deciduousness in west-central African forests *Biogeosciences* **10** 6957–67

Wagner F H, Hérault B, Rossi V, Hilker T, Maeda E E, Sanchez A, Lyapustin A I, Galvão L S, Wang Y and Aragão L E O C 2017 Climate drivers of the Amazon forest greening *PLoS One* **12** 1–15

Washington R, James R, Pearce H, Pokam W M and Moufouma-Okia W 2013 Congo Basin rainfall climatology: can we believe the climate models? *Phil. Trans. R. Soc.* B **368** 20120296

White F 1983 *The Vegetation of Africa: A Descriptive Memoir to Accompany the UNESCO/AETFAT/UNSO Vegetation Map of Africa* (Paris: UNESCO)

White L, Oslisly R, Abernethy K and Maley J 2000 L'Okoumé (Aucoumea Klaineana): expansion et déclin d'un arbre pionnier en Afrique Centrale Atlantique au cours de l'Holocène *Dynamique à Long Terme des Écosystèmes Forestiers Intertropicaux* ed M Servant and S Servant-Vildary (Paris: IRD) pp 399–411

Wilson A M and Jetz W 2016 Remotely sensed high-resolution global cloud dynamics for predicting ecosystem and biodiversity distributions *PLoS Biol.* **14** 1–20