Rare ground data confirm significant warming and drying in western equatorial Africa

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Background. The humid tropical forests of Central Africa influence weather worldwide and play a major role in the global carbon cycle. However, they are also an ecological anomaly, with evergreen forests dominating the western equatorial region despite less than 2000 mm total annual rainfall. Meteorological data for Central Africa are notoriously sparse and incomplete and there are substantial issues with satellite-derived data because of persistent cloudiness and inability to ground-truth estimates. Long-term climate observations are urgently needed to verify regional climate and vegetation models, shed light on the mechanisms that drive climatic variability and assess the viability of evergreen forests under future climate scenarios.

Methods. We have the rare opportunity to analyse a 34-year dataset of rainfall and temperature (and shorter periods of absolute humidity, wind speed, solar radiation and aerosol optical depth) from Lopé National Park, a long-term ecological research site in Gabon, western equatorial Africa. We used (generalized) linear mixed models and spectral analyses to assess seasonal and inter-annual variation, long-term trends and oceanic influences on local weather patterns.

Results. Lopé’s weather is characterised by a cool, light-deficient, long dry season. Long-term climatic means have changed significantly over the last 34 years, with warming occurring at a rate of +0.25 °C per decade (minimum daily temperature) and drying at a rate of -75 mm per decade (total annual rainfall). Inter-annual climatic variability at Lopé is highly influenced by global weather patterns. Sea surface temperatures of the Pacific and Atlantic oceans have strong coherence with Lopé temperature and rainfall on multi-annual scales.

Conclusions. The Lopé long-term weather record has not previously been made public and is of high value in such a data poor region. Our results support regional analyses of climatic seasonality, long-term warming and the influences of the oceans on temperature and rainfall variability. However, warming has occurred more rapidly than the regional products suggest and while there remains much uncertainty in the wider region, rainfall has declined over the last three decades at Lopé. The association between rainfall and the Atlantic cold tongue at Lopé lends some support for the “dry” models of climate change.
for the region. In the context of a rapidly warming and drying climate, urgent research is needed into the sensitivity of dry season clouds to ocean temperatures and the viability of humid evergreen forests in this dry region should the clouds disappear.
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Abstract

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**Abstract (French)**

**Introduction:** Les forêts tropicales d’Afrique Centrale ont une influence sur le climat mondial et joue un rôle majeur dans le cycle global du carbone. Pourtant, ces sont des anomalies écologiques puisque ces forêts vertes dominent la région équatoriale de l’ouest malgré des pluies annuelle de moins de 2000 mm. Les données météorologiques d’Afrique Centrale sont connues pour être temporellement et géographiquement incomplètes. Les données climatiques de surface dérivées des données satellites sont souvent inexploitables au vu du couvert nuageux. Les observations climatiques sur le long terme sont donc urgemment nécessaires afin de confronter les différents modèles évolutifs du climat et de la végétation mettant en lumières les mécanismes de variation climatiques et de la survie de ces forêts dans un contexte de réchauffement climatique.

**Méthodes:** Nous avons eu l’opportunité rare d’analyser 34 années de données de précipitation et de température collectées dans le Parc National de La Lopé au centre du Gabon (et des périodes plus courtes d’humidité absolue, de vitesse du vent, de radiation solaire et de profondeur optique des aérosols dans l’atmosphère). Nous avons utilisé des modèles (généralisés) linéaire mixtes et des analyses spectrales afin d’observer les variations saisonnières et interannuelles, la tendance climatique sur le long-terme ainsi que l’influence de l’océan sur le comportement du climat local.

**Résultats:** Le climat de La Lopé est caractérisé par une longue saison sèche, froide à faible luminosité. Les moyennes climatiques ont changé de manière significative durant les trois dernières décennies, avec un réchauffement observé de +0.25 °C par décennie (température minimale journalière) and un taux d’assèchement de -75 mm par décennie (précipitation annuelle totale). La variabilité interannuelle à Lopé est fortement influencée par les conditions météorologiques. Les températures de la surface de les océans Pacifique et Atlantique sont fortement cohérentes avec la température de la Lopé et les précipitations sur une échelle de temps multi-annuelle.

**Conclusions:** Le relevé météorologique à long terme de la Lopé n'a pas été rendu public auparavant et est d'une grande valeur dans une région pauvre en données. Nos résultats appuient les analyses régionales de la saisonnalité climatique, du réchauffement à long terme et des influences des océans sur la variabilité des températures et des précipitations. Cependant, le réchauffement s'est produit plus rapidement que ne le suggèrent les produits régionaux et bien qu'il reste beaucoup d'incertitude dans la région élargie, les précipitations ont diminué au cours des trois dernières décennies à Lopé. Les données de la Lopé supportent l’hypothèse de « la langue froide » dans les modèles sec de changement climatique pour la région. Dans un contexte de réchauffement et d’assèchement rapide du climat, des recherches additionnelles portant sur la variabilité du couvert nuageux en fonction des températures océaniques sont urgemment nécessaires afin de prédire la survie des forêts vertes dans cette région sèche si les nuages venaient à disparaître.
Introduction

The humid forests of Central Africa make up 30% of the world’s tropical forests (Malhi et al. 2013), are a major carbon store (Lewis et al. 2013) and influence weather globally (Bonan 2008; Washington et al. 2013). Most African evergreen tropical forests are found in the western equatorial region where total annual rainfall is less than 2000 mm rainfall (Philippon et al. 2019). Evergreen forests can be maintained in this relatively dry region due to reduced water demand during seasonal drought associated with extreme cloudiness (Philippon et al. 2019). Long-term changes to climate and climatic variability in the region (James et al. 2013) are likely to have far-reaching impacts on the functioning of these evergreen tropical forests (Asefi-najafabady & Saatchi 2013; Zhou et al. 2014) with knock-on effects for the global carbon cycle (Mitchard 2018) and local human livelihoods (Niang et al., 2014).

However, evidence for changes in forest function linked to weather conditions in equatorial Africa is extremely rare, mainly due to missing long-term meteorological data. The number of rain gauge stations reporting data across Central Africa fell from a peak of more than 50 between 1950 and 1980 to fewer than ten in 2010 (Washington et al. 2013). This low density of observations and poor understanding of local landscape and climatic processes (Nicholson & Grist 2003) limits the accuracy of gridded observational data products (Asefi-najafabady & Saatchi 2013; Suggitt et al. 2017). Uncertainty is particularly high for rainfall patterns, which unlike temperature, are poorly conserved over space (Habib et al. 2001; Kidd et al. 2017). Because of missing ground data, climate and ecological models rely heavily on satellites despite major issues with this data source that include extreme cloudiness in the region and little opportunity for ground-truthing (Washington et al. 2013; Maidment et al. 2014; Wilson & Jetz 2016; Dommo et al. 2018). Empirical meteorological data are urgently needed to verify regional climate and vegetation models and shed light on the mechanisms that drive seasonal and long-term climatic variability in tropical Africa (Guan et al. 2013; Abernethy et al. 2016).

We have the rare opportunity to analyse a 34-year record of rainfall and temperature (and shorter periods of humidity, wind speed, solar radiation and aerosol optical depth) from a long-term ecological research site in western equatorial Africa. These local weather data have not contributed to the available climate products (such as the high-resolution gridded dataset from the Climate Research Unit) and are able to act as an independent control. In this paper we briefly review the published literature on drivers of weather variability and long-term climate trends in western equatorial Africa (~6°S-5°N, 8°-18°E, covering Cameroon, Republic of Congo, Central African Republic, Democratic Republic of Congo, Equatorial Guinea and Gabon). We then use our ground data to analyse seasonal, inter-annual and long-term weather patterns in this data-poor region with particular focus on rainfall for which uncertainty in regional products is high.

Seasonality

The climate of equatorial Africa is characterised by a bimodal rainfall pattern. Two rainy seasons occur each year coinciding with the boreal spring and autumn when the sun passes directly over the equator (March-May and October-November). Just 3% total annual rainfall falls during the
The major dry season, which extends from June to August/September (Balas et al. 2007). The primary influence on equatorial rainfall has historically been understood to be the Inter Tropical Convergence Zone (ITCZ), a band of clouds and high precipitation that migrates northwards and southwards over the equator following the sun (Nicholson 2018 and Fig. 1). However recent developments show the ITCZ to be a poor explanation of seasonal rainfall in Africa, with ITCZ-associated low-level convergence often decoupled from the rain belt in western and central equatorial regions (Nicholson 2018). Improved mechanistic models of the seasonal evolution of atmospheric conditions in the region are urgently needed.

In western equatorial Africa the rainy seasons coincide with bright conditions. Convection clouds develop into storms late in the day or night leaving clear skies during the daytime (Gond et al. 2013). By contrast, light is least available during the long dry season due to persistent low-lying cloud cover throughout the day (Philippon et al. 2019). The seasonal synchrony between light and precipitation in western equatorial Africa is in contrast to the central Congo Basin and the neotropics where dry seasons tend to coincide with peak irradiance (Wright & Calderón 2018; Philippon et al. 2019). In western equatorial Africa the long dry season is also the coolest time of year (Munzimi et al. 2015; Tutin & Fernandez 1993).

Oceanic influences

Large-scale patterns in sea surface temperatures (SSTs) are known to influence weather conditions across the tropics (Camberlin et al. 2001; Fig. 1). The El Niño Southern Oscillation (ENSO) refers to the state of the atmosphere and surface temperatures of the tropical Pacific Ocean. ENSO has a relatively straightforward, instantaneous effect on temperature throughout the African continent, with greater warming in El Niño years (Collins 2011). Central African rainfall is also strongly connected to SSTs (Otto et al. 2013), although interactions are complex and seasonally specific. In Table 1 we summarise six major studies of ocean influences on rainfall in western equatorial Africa (Todd & Washington 2004; Balas et al. 2007; Otto et al. 2013; Preethi et al. 2015; Nicholson & Dezfuli 2013; Dezfuli & Nicholson 2013). The main agreements between these studies are that (1) rainfall is below average from February to August in El Niño years (Camberlin et al. 2001; Todd & Washington 2004; Balas et al. 2007; Preethi et al. 2015; Nicholson & Dezfuli 2013), (2) rainfall positively correlates with the temperature of the Indian Ocean in January and February (Balas et al. 2007; Preethi et al. 2015) and (3) warm SSTs in the tropical south Atlantic enhance rainfall from April-September (Camberlin et al. 2001; Balas et al. 2007; Otto et al. 2013; Nicholson & Dezfuli 2013). We found no evidence in the literature for the influence of large-scale climate oscillations on other weather variables such as light availability, wind speeds or aerosols in the region.

Long-term trends

There is high confidence in the evidence for warming over African land regions (Niang et al. 2014). Satellite estimates for tropical Africa show an annual mean temperature increase of 0.15°C per decade from 1979-2010 (Collins 2011). A recent multi-model ensemble shows that
mean temperature for the whole continent is likely to continue to increase more than the global
average especially in the long dry season (James & Washington 2013).

Tropical land areas globally have seen no overall change in precipitation over the last century,
with a recent increase in precipitation (2003-2013) reversing a drying trend from the 1970s to the
1990s (Hartmann et al. 2013). Rainfall patterns are poorly conserved spatially and conflicting
trends are detected within the western equatorial region of Africa. A regionalised long-term
dataset for Africa constructed from historical records and rain gauge observations shows a sharp
reduction in rainfall in the Cameroon region from the late 1960s until the present and a
contrasting wetting trend in the Congo / Gabon region from 1980s until the present (Nicholson et
al. 2018). However a higher resolution analysis of the same dataset shows that within central
Gabon there has been a drying trend from the 1970s until 2000 and that there is no data
originating from this area for the last two decades (Nicholson et al. 2018). Flow data for the river
Ogooué – the largest river in western equatorial Africa - indicates that runoff in the region
declined from the 1960s until 2010 and that the flood peak has moved from May to April (Mahe
et al. 2013). Land-cover change has been minimal in the watershed during this period
(Abernethy et al. 2016) and so it is likely that reduced rainfall has been the biggest influence on
flow reduction.

Predictions of future rainfall vary widely across the African continent with high uncertainty in
the direction of change centrally due to the sparse network of observations and poor
understanding of local climate forcing (James & Washington 2013). Model projections mostly
show no change or a weak wet signal in the central Congo Basin, and a dry signal in the western
region in scenarios where warming is greater than 2°C (James et al. 2013). Models that support a
drying trend in western equatorial Africa show strong associations with Atlantic and Indian (but
not Pacific) SSTs. The construction of these dry models suggests that reductions in rainfall in
Gabon and surrounding countries are likely to be caused by a northward displacement of the
equatorial rain belt associated with the Atlantic cold tongue (Fig. 1B) and an eastward shift in
convection caused by contrasts between Indian and Atlantic SSTs (James et al. 2013).

As for surface solar radiation, once again the picture varies spatially within central Africa. In the
central Congo Basin (14E-30E) there has been a recent widespread decline in cloud optical
thickness and no change in aerosol optical thickness (MODIS, 2000 -2012) leading to an
increase in downward photosynthetically available radiation (CERES, 2003-2012; Zhou et al.
2014). For sunshine duration, there has been no change in the central region but a weak decline
(2-4 hours per decade) in western equatorial Africa from 1983-2015 (SARAH-2, Kothe et al.
2017). There is no published data on long-term changes in relative humidity or wind speed in the
region.

**Implications for the eco-region**

Humid evergreen forests currently dominate western equatorial Africa despite relatively low
precipitation compared to other closed canopy tropical forests (Reich 1995). As summarized by
James et al. (2013), intense rainfall seasonality alongside a drying and warming climate is likely
to lead to water stress and could push these ecosystems towards more open, fire prone, dry forest systems (as evidenced in this region over the last 3000 years; Brncic et al. 2006 and in West Africa in recent decades: Fauset et al. 2012) or even savanna (Willis et al. 2013). While elevated atmospheric carbon dioxide improves water use efficiency, the balance of gains for tropical forests related to carbon fertilization versus losses related to further warming and drying are poorly characterized in climate and vegetation models (Huntingford et al. 2013). Tropical forest species turnover or loss related to climate change will have serious consequences for people and animals dependent on forest resources in the region (Abernethy et al. 2016) while loss of tree cover will impact carbon storage and even feedback onto climate (Mitchard 2018).

Despite the risks associated with these scenarios few meteorological data are available, especially in recent decades, to understand if the climatic trends described above are witnessed on the ground and how quickly they are progressing. Using ground data from Lopé National Park (NP), Gabon, collected over a 34-year period we ask: How fast is the region warming? Is the region drying and how quickly? And how do the oceans influence rainfall and temperature variability? Answers to these questions will be important to predict the viability of evergreen forest ecosystems under future climates.

**Materials & Methods**

**Description of the study area and weather data recorded since 1984**

The Station d’Études des Gorilles et Chimpanzées (SEGC) research station is located at the northern end of Lopé National Park, Gabon (-0.2N, 11.6E). The station sits in a tropical forest-savanna matrix, at an elevation of 280m and within 10.5 km of the river Ogooué (the largest river in Gabon and the country’s main watershed). Ecological research activities including weather, plant and animal observations have taken place continuously at SEGC from 1984 until the present (>300 publications; 1984-2018).

Weather data have been recorded at Lopé using various types of equipment at two locations: a savanna site (the research station; 11.605E, -0.201N) and a forest site (800m from the research station and approximately 10m from the savanna/forest edge; 11.605E, -0.206N; Table 2). From 1984 to the present, a manual rain gauge was placed at the savanna site (50cm above ground and >5m from any tree or building) and used to record total daily rainfall at 8am each morning. There was a gap in data recording in 2013 and occasional missing days due to logistical constraints (e.g. availability of personnel). Since 1984 daily maximum and minimum temperatures and relative humidity were recorded using a manual thermometer and wet/dry bulb located at the forest site (1.5m aboveground under closed canopy), which were checked whenever field teams passed it or daily when logistics permitted. In 2002 all temperature recording at the forest site was transferred to continuous automatic units (ONSET HOBO® Data Loggers refhttps://www.onsetcomp.com/, these units also recorded relative humidity). At the same time temperature recording using the HOBO units also began in the savanna. Due to technical failures these units were replaced in 2006 with the original manual max/min thermometer in the forest and a digital max/min thermometer (Taylor 1441) in the savanna. These were in turn replaced by
another type of automated unit (TinyTag Plus 2, Gemini Data Loggers
https://www.geminidataloggers.com/data-loggers/tinytag-plus-2, some of which record both
temperature and relative humidity). TinyTags were deployed in the forest from 2007 and in the
savanna from 2008 and used until the present (with a gap at the forest site from mid-2015 to mid-
2016 and intermittent recording throughout 2017 partly due to equipment malfunctions caused
by termite infestation). Two weather stations were installed in the savanna (sited near the
research station, on a rock 4m from the ground) and collected data between 2012 and 2016. A
Davis VantagePro2 (https://www.davisinstruments.com/solution/vantage-pro2/) was installed in
January 2012 and recorded rainfall, temperature, relative humidity, pressure, wind speed and
direction, UV index and solar radiation every 30 minutes for two years until the equipment was
struck by lightning in January 2014. A SKYE MINIMET weather station
(https://www.skyeinstruments.com/minimet-automatic-weather-station/) was installed at the
same location in 2013 and collected temperature, relative humidity, wind speed and direction and
solar radiation (but not rainfall as the gauge was defective). The SKYE unit ran intermittently
until 2016 when the equipment was also damaged by lightning: data records between January
2014 and November 2014 were also lost. Finally, a sun photometer was installed at the research
station in April 2014 and used to record aerosol optical depth up to the present as part of the
NASA Aerosol Robotic Network (Aeronet; https://aeronet.gsfc.nasa.gov/; Holben et al. 1998).
Despite sustained effort, the remote and challenging environment at Lopé has led to a patchy
weather data record. This situation has been exacerbated since the introduction of automated
loggers, due to unreliable performance combined with difficulties and time delays in replacing or
repairing malfunctioning equipment and respecting annual calibration schedules with
manufacturers based in Europe or the USA. New equipment was often introduced out of
necessity when previous equipment failed, precluding the opportunity of collecting simultaneous
data for standardisation. Such problems have been experienced at many other field stations
across Africa (Maidment et al. 2017) and homogenisation is necessary in most long-term
instrumental climatic data sets (Peterson et al. 1998). It was therefore necessary to select and
standardise the Lopé data to reduce systematic biases between recording equipment. We
summarise the data selection steps we undertook below and provide further detail in the
accompanying Supplemental Information (Article S1 and Code S1). All Lopé data can be
downloaded from the University of Stirling’s DataSTORRE (http://hdl.handle.net/11667/133).

Data cleaning and preparation
We constructed a long-term record of daily rainfall totals (1984-2018) by calibrating the two
sources of data (manual rain gauge and Vantage Pro weather station) using a simple linear model
on simultaneous records and taking the mean value for days with multiple observations (resulting
in a dataset of 12,050 complete daily observations out of a possible 12419 over 34 years). Where
possible we interpolated missing daily values using the ten-day running mean for the time series
(resulting in a dataset of 12111 interpolated daily observations), however 11 months spread over
three calendar years remained incomplete. We used these interpolated daily data to calculate total
monthly and annual rainfall for the months and years with complete data (397 complete monthly
observations out of a possible 408 and 31 complete years out of a possible 34).

Temperature data were recorded using six different types of equipment across two sites
(recorded in the forest from 1984 to 2018 and in the savanna from 2002 to 2018). Where there
were multiple observations from overlapping data records we calculated mean daily maximum
and minimum values for each site and day in the time series, and used this dataset to demonstrate
temperature seasonality at each site (resulting in a dataset of 7058 daily observations out of a
possible 12419 over 34 years at the forest and 4878 daily observations out of a possible 5844
over 16 years at the savanna). To create continuous time series for periodicity analyses we
calculated mean monthly maximum and minimum daily temperatures for each month in the time
series with more than five observations (resulting in a dataset of 327 monthly observations out of
a possible 408 from the forest site and 166 monthly observations out of a possible 192 at the
savanna site). Minimum daily temperatures are recorded during the night and thus avoid errors
associated with direct solar radiation (which we found to vary between our equipment, Article
S1). Because of this we chose to use minimum daily temperatures to assess long-term trends and
inter-annual variation. We constructed a long-term daily record by calculating mean daily
minimum temperature using data from both sites combined (8217 daily observations out of a
possible 12419 over 34 years). We summarized these data to a monthly mean time series for
months with more than five observations (372 monthly observations out of a possible 408 over
34 years).

Finally, we used the shorter (and/or patchier) periods of data available for relative humidity
(2002-2018), solar radiation (2012-2016), wind speed (2012-2016) and aerosol optical depth
(2014-2017) to assess seasonality and periodicity for these climate variables. We used night-time
relative humidity records (6pm-6am) to avoid errors associated with direct solar radiation and
converted to absolute humidity (g/m$^3$) using simultaneous temperature records within the R
package humidity (Cai 2008). We extracted aerosol optical depth data at wavelengths relevant for
photosynthetic activity (440, 500 and 675nm).

Gridded regional temperature datasets

Because of missing data and lack of simultaneous recording between temperature equipment at
Lopé we also downloaded two widely used gridded regional data products with which to
compare the Lopé data: daily minimum air temperature from the Gridded Berkeley Earth Surface
Temperature Anomaly Field (1° resolution; Rohde et al. 2013) and monthly mean daily
minimum temperature from the Climate Research Unit’s Time-Series v4.01 of high-resolution
gridded data (CRU TS4.01; 0.5° resolution; University of East Anglia Climatic Research Unit et
al. 2017; Harris et al. 2014). Both were downloaded from http://climexp.knmi.nl/start.cgi for the
grid-cell overlapping the SEGC location (0.2N, 11.6E).

Ocean Sea Surface Temperatures (SSTs)

We downloaded data for four oceanic SST indices from commonly used data sources: the
Multivariate ENSO Index (MEI; Wolter & Timlin 1993; Wolter & Timlin 1998) sourced from
the NOAA website (https://www.esrl.noaa.gov/psd/enso/mei/index.html), the Indian Ocean Dipole (IOD) Dipole Mode Index (Saji & Yamagata 2003) sourced from the NOAA website (https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/DMI/) and deseasonalised SSTs for the tropical north Atlantic (NATL, 5°–20°N, 60°–30°W) and the south equatorial Atlantic (SATL, 0°–20°S, 30°W–10°E) sourced from the NOAA National Weather Service Climate Prediction Center (http://www.cpc.ncep.noaa.gov/data/indices/). We rescaled all four SST indices by subtracting the mean and dividing by one standard deviation to allow direct comparison of their effects. Positive values for MEI indicate El Niño conditions; positive values for NATL and SATL indicate warm SSTs in those regions while positive values for IOD indicate cool SSTs in South Eastern equatorial Indian Ocean and warm SSTs in the Western equatorial Indian Ocean.

Analyses

Seasonality

To characterise the seasonality of each weather variable we calculated mean values from empirical daily data at three different scales: the mean value for each day of the calendar year (DOY, fine-scale), the ten-day running mean of DOY (medium-scale) and the mean value for each calendar month (coarse-scale). To formally assess the periodicity of each variable we used Fourier analysis. The Fourier transform is a form of spectral analysis used to calculate the relative strength of all possible regular cycles in time series data (Bush et al. 2017). We created standardized, complete time series by filling missing values in monthly time series using the mean value for the corresponding calendar month and standardizing the data by subtracting the mean and dividing by its standard deviation. We then computed the Fourier transform for each time series using the *spectrum* function from the R Stats package (R Core Team, 2019) and inspected the spectra plots for peaks that represent strong regular cycles in the data (Bush et al. 2017).

Long-term trends

We used a linear regression framework to test whether rainfall and minimum temperature had changed over the observation period (1984-2018) using non-interpolated daily data. We fitted compound Poisson generalized linear mixed models (CPGLMM) for daily rainfall and linear mixed models (LMM) for minimum daily temperature to account for their respective data distributions. CPGLMMs are exponential dispersion models based on the Tweedie distribution and are recommended for daily or monthly rainfall data which is positive and continuous with many exact zeros (Hasan and Dunn 2010). We fit CPGLMMs using the *cplm* R package (Zhang 2013) and LMMs using the *lme4* R package (Bates et al. 2015). DOY was included as a random intercept in all models to account for seasonality and the hierarchical structure of the data. We fitted initial models with Year (continuous, rescaled) as the predictor (representing long-term change) and compared these to intercept-only models (representing no long-term change) preferring simple models (few parameters) with lowest AIC (significantly different if delta AIC >2). See R-style model notation below with $\varepsilon$ representing residual error not accounted for by the predictors of the model.
We repeated the same procedure for gridded temperature data for Lopé from the daily Berkeley and monthly CRU datasets. DOY was included as a random intercept within the models with daily response data and Month was included as a random intercept within the models with monthly response data.

Next we investigated whether trends in rainfall and minimum temperature at Lopé differed by season. Various seasonal definitions are used throughout the tropics, usually related to the annual rainfall cycle. We defined our seasons according to Lopé rainfall climatology where the long dry season extends into September, i.e. October-November (ON, the short rainy season), December-February (DJF, the short dry season), March-May (MAM, the long rainy season) and June-September (JJAS, the long dry season; Fig. 2A). We included Year (continuous, rescaled), Season (factor with four levels as above) and their interaction as predictors in initial models to represent long-term change varying by season. We fitted subsequent models without the interaction term to represent long-term change not varying by season and compared the models using AIC values. DOY was included as a random intercept in all models, as before.

To estimate the magnitude of the trend in each season, rather than comparing to the global intercept, we modified the best models by temporarily removing the global intercept. For all models described above we inspected the residuals to check for temporal autocorrelation using the R package *itsadug* (van Rij 2017). None of the median autocorrelation functions (autocorrelation calculated for each DOY or Month respectively) showed significant temporal autocorrelation.
Periodicity over time

We used Wavelet analyses to assess if and how the periodicities of the rainfall and temperature time series have changed over time. The Wavelet transform extends the Fourier transform into the time-frequency domain and allows identification of cyclic behavior that may be transient or change over time (Torrence and Compo 1998). We used the complete, standardised monthly time series for rainfall and minimum temperature (with missing values interpolated from the long-term calendar month mean) and computed the Wavelet transform using the function \texttt{wt} from the R package \texttt{biwavelet} (Gouhier et al. 2018). From the wavelet transform we plotted the power (higher power denotes greater fidelity to a certain cycle), significance (a cycle is significant if $>0.95$, $X^2$ test) and cone of influence (denoting the unreliable region at the beginning and end of the time series due to edge effects). We extracted the power of the biannual, annual and multiannual (mean of the 2-4 year periods) components from the wavelet spectra to further assess how these dominant cycles have varied over time and contributed to the trend (Adamowski et al. 2009). We constrained the upper limit of the multiannual component to four years because longer cycles were heavily influenced by edge effects.

Oceanic influences

We used wavelet coherence to assess if and how the local weather system at Lopé is associated with SSTs of the major oceans at interannual scales (Pacific: MEI, Indian Ocean: IOD and Atlantic Ocean: NATL and SATL). Wavelet coherence is an approach derived from bivariate wavelet analysis and calculates a measure of the correlation (from 0 to 1) between two time series ($x$ and $y$) at all periodicities through time. Wavelet coherence can be used to identify common oscillatory behavior, even if that behavior is inconsistent (i.e. the time series are “non-stationary”; Grinstead, et al. 2004). According to Grinstead, et al. (2004), strong coherence and consistent phase relationships between two carefully selected time series indicate that there may be a causative relationship. In this study we computed wavelet coherence for all eight combinations of $x$ (rainfall or minimum temperature monthly time series) against $y$ (MEI, IOD, NATL or SATL monthly time series) using the function \texttt{wtc} from the R package \texttt{biwavelet} (Tarik, et al. 2019) with 1000 Monte Carlo randomisations. To summarise and compare the wavelet coherence between each time series pair we calculated the “global” time-averaged coherence for each period (Chang, et al. 2019).

R code to accompany all analyses described above is made available in Supplemental Information (Code S1). Permission to conduct this research in Gabon was granted by the Centre International de Recherches Medicales de Franceville (CIRMF) Scientific Council and the Ministry of Water and Forests (1986 – 2010), and by Gabonese National Parks Agency (ANPN) and the National Centre for Research in Science and Technology (CENAREST; 2010 - present).

Results

Seasonality
Mean total annual rainfall at Lopé from 1984-2018 was 1466 mm ± 201 sd. Rainfall in this period followed a biannual cycle (Fig. S1) with broad peaks in the rainy seasons (MAM and ON) when mean daily rainfall was always greater than 5 mm (Fig. 2A). The long dry season (JJAS) was very consistent, with a 90-day period (mid-June to mid-September) in which the ten-day running mean was never greater than 1 mm (Fig. 2A). The short dry season (DJF) by contrast was much less dry (ten-day running mean greater than 1 mm) and more variable between years (Fig. 2A).

Mean daily maximum and minimum temperatures at Lopé were 28.1°C ± 2.2 sd and 21.9°C ± 1.1 sd respectively at the forest site (1984-2018) and 31.6°C ± 2.9 sd and 22.0°C ± 1.2 sd at the savanna site (2002-2018). Daily temperature range was greater in the savanna than under the forest canopy (Fig. 2C and 2D). Maximum daily temperature in the forest showed strong annual and bi-annual cycles while in the savanna only the annual cycle appeared dominant (Fig. S1). The difference between the two sites occurred during the short dry season when temperatures were maintained in the savanna at similar levels to the rainy seasons (ten-day running mean always greater than 31.7°C from October to May in the savanna; Fig. 2C). In the forest, the highest peaks in maximum daily temperature occurred in April and September (mean monthly maximum daily temperatures were 29.5°C and 28.6°C respectively; Fig. 2D). Annual cycles dominated the minimum daily temperature record for both the forest and the savanna (Fig. S1). Minimum daily temperatures were relatively constant from September to June (~22.5°C) followed by a cool period during the long dry season reaching an annual trough in July (mean monthly minimum daily temperature is 20.6°C in both the savanna and forest; Fig. 2C and D). The forest was more humid than the savanna throughout the year (mean absolute humidity is 21.40 g/m³ and 20.35 g/m³ respectively; Fig. 2E and F). Humidity follows the same annual cycle in both locations (Fig. S1), dropping during the long dry season to reach a minima in August and increasing throughout the short rains (ON) to reach a plateau from January to May (Fig. 2E and F).

Both surface solar radiation and wind speed were dominated by annual cycles at Lopé (Fig. S1), with the long dry season coinciding with low irradiance (mean monthly solar radiation for July = 129.3 W/m²; Fig. 2G) and elevated wind speeds (mean monthly wind speeds for August and September are 1.3 m/s and 1.4m/s respectively; Fig. 2B). Aerosol optical depth cycled twice yearly (Fig. S1), being elevated during the dry seasons and suppressed during the rainy seasons (Fig. 2H). In contrast to the solar radiation cycle, which reached its minima during the long dry season (JJAS), the strongest peak in aerosol optical depth occurred in the short dry season (mean monthly aerosol optical depth at 500nm for February = 0.97). Aerosol optical depth at 440 and 675nm wavelengths is similar to that at 500nm (Fig. S2).

**Long-term trends**

Total annual rainfall decreased by -75 mm per decade, a change of -5.5% relative to mean annual rainfall for the time period (CPGLMM, Estimated index parameter = 1.6, Estimated dispersion parameter = 9.7, Estimate = -0.05, SE = 0.02, Z = -2.22, 95% CI = -0.10: -0.01; Table 3 and Fig. 3A). However, the slope of the decline was seasonally dependent (Tables 4 and 5) with no
change in daily rainfall in DJF and ON and significant decline in JJAS (-0.07 mm per day per
decade, equating to -6.35\% of mean JJAS daily rainfall).

Minimum daily temperature at Lopé increased at a rate of +0.25°C per decade, equivalent to
+1.1\% relative to mean minimum temperature for the time period (LMM, Estimate = 0.24; SE =
0.01; T = 24.84; 95\% Confidence Interval = 0.22: 0.26; Table 3 and Fig. 3B). The rate of
warming also varied by season (Tables 4 and 5) with minimum temperature increasing most
quickly in ON and DJF (+0.31°C and +0.30°C per decade respectively) and most slowly in JJAS
(+0.18°C per decade).

Minimum daily temperature at Lopé increased at a rate of +0.16°C per decade (LMM, Estimate = 0.34, SE = 0.01, T = 23.4, 95\%
Confidence Interval = 0.31: 0.37) while the CRU interpolated record (0.5° resolution) increased
by +0.19°C per decade (LMM, Estimate = 0.63 SE = 0.06, T = 11.2, 95\% Confidence Interval =
0.52: 0.74).

Periodicity over time

Wavelet analyses gave further indication of the nature of these changes. The dominant six-month
cycle for rainfall was, on average, four times as powerful as the annual component and 66 times
as powerful as the multi-annual component and remained significant for most of the time period
(Fig. 3C). However, the signal of the biannual cycle decreased on three occasions (1996-97,
2004 and 2006; Fig. 3C). Over time, the signal of the biannual rainfall cycle appeared to
decrease while the annual cycle strengthened (Fig. 3E). The annual cycle for minimum
temperature was, on average, three times as powerful as the biannual component and 23 times as
powerful as the multi-annual component (Fig. 3F). The signal of the annual cycle remained
dominant throughout most of the time period with patches of low power at the end of the 1980s
and between 2007 and 2010 (Fig. 3D). There were patches of high power in the multiannual
component around 2000. The signal of both the annual and semi-annual components appear to
have been increasing in strength over time (Fig. 3F).

Oceanic influences

Wavelet coherence analyses showed that the ENSO index (MEI) had the strongest coherence
with both rainfall and temperature at Lopé over the last three decades at multi-annual scales (2-4
years; Fig. 4 and Fig. S3). However, the influence of ENSO has been patchy through time;
Coherence between ENSO and rainfall was particularly strong pre-1990 and between 2007 and
2012 (Fig. 4A) while coherence between ENSO and minimum temperature was fairly consistent
up to 2000 and has become weaker since (Fig. 4B). SSTs of the southern tropical Atlantic
showed strong coherence with Lopé rainfall pre-2000 while SSTs of the northern tropical
Atlantic showed strong coherence with Lopé rainfall post-2000 at multi-annual scales (4-8 years;
Fig. 4C and E and Fig. S3). SATL cycled in phase with Lopé rainfall (arrows point to the right)
while NATL cycles in anti-phase during the 2005 to 2010 period (arrows point to the left;
Figures 4C and E). Within the reliable region of the wavelet coherence plots (away from edge
effects) the IOD does not appear to have had a particularly strong or consistent relationship with either rainfall or temperature at Lopé (Fig. 4G and H and Fig. S3).

Discussion

Our results

Lopé weather has changed significantly over the last three decades, warming at a rate of +0.25°C per decade (minimum daily temperature) and drying at a rate of -75 mm per decade (total annual rainfall; Figure 3A and 3B). Both trends are seasonally dependent (Table 4); with significant warming occurring in all seasons, being most pronounced from October to February (see model estimates in Table 5). The rainfall decline occurred predominately between March and September, incorporating both the long rainy season and the long dry season (see model estimates in Table 5). The drying trend at Lopé supports observations of reduced Ogooué river flow from March to September (Mahe et al. 2013) and precipitation declines evident from gridded gauge-data for the Gabon/Cameroon region (-1% total annual rainfall, 1968-1998; Malhi & Wright 2004). However, the Lopé total annual rainfall decline of -5.5% per decade exceeds the trend estimated from the regional gauge-data. While the strength of the biannual cycle in rainfall appears to be declining at Lopé along with the overall long-term trend, the annual component is getting more powerful. Declines in rainfall in the long dry season (June-September) but not the short dry season (December-February) are likely to be contributing to an increased contrast between the two dry seasons and enhancing the overall annual rainfall cycle (Table 5).

The warming trend recorded at Lopé is greater than that estimated for the location over the same time period using the Berkeley and CRU gridded datasets (+0.16°C and +0.19°C respectively) and that identified using satellite data for mean annual temperature for all tropical Africa (+0.15°C, 1979-2010; Collins 2011). However, it is lower than the change estimated from gridded observational data (CRU) for mean annual temperature specifically for African tropical forests (+0.29°C per decade, 1976-1998; Malhi & Wright 2004). While there remain issues with the Lopé temperature data record (lack of simultaneous recording to calibrate data recorded using different equipment), there is good evidence from supporting datasets and the literature that the warming trend observed at the site since 1984 is real. The slower warming trend in the already cool, long dry season is likely to account for the apparent increase in the power of the annual cycle for Lopé minimum temperature.

Our analysis of seasonality at Lopé further serves to emphasise the ecological importance of the long dry season in western equatorial Africa; three to four months of dry (almost no rainfall for 90 consecutive days), cool (mean maximum daily temperature is 2.5°C lower in July compared to April) and windy conditions with low humidity and limited light availability (Figure 2). Such a defined dry season poses specific constraints to the biota and is likely to act as a temporal marker for ecological events, similar to a winter event in temperate regions, while the response of the plant community to recurrent and predictable seasonal drought during the long dry season
could be used to estimate the long-term response to drying over multi-annual time scales (Detto et al. 2018).

Reduced light availability during the long dry season in the Gabon region is most strongly associated with seasonal low-level cloud cover (Philippon et al. 2019). Aerosol load may also have a seasonal influence on light availability as aerosol optical depth and solar radiation appear to cycle in anti-phase although we are not able to tease apart their relative importance in this analysis (Figure 2). Low direct solar radiation and cool temperatures will reduce water demand during these months (e.g. potential evapotranspiration is less than 2.3mm per day during the long dry season in SW Gabon; Philippon et al. 2019) and are likely contributors to the forest’s ability to maintain an evergreen canopy despite seasonal drought. Unsurprisingly, the savanna and forest experience different microclimates because the forest canopy creates a more humid, cooler climate throughout the year with a reduced range between daytime and night-time temperatures (Figure 2). It is possible that the forest may also directly enhance water supply for plants during periods of low precipitation / high cloud cover due to foliar interception of low-lying clouds. At another tropical forest site (~1000m above sea level), foliar interception has shown to contribute an additional 40% of moisture compared to rainfall (Hutley et al. 1997) meaning that rain gauge data does not always accurately represent the water balance of the forest ecosystem (Philippon et al. 2019). While we do not have information on foliar interception of clouds at our study site (~280m above sea level), the hydroclimatic conditions of the region do not predict occurrence of cloud-affected forest here (Oliveira et al. 2014). We can assume that the impact of cloud interception on water supply is negligible, although it may occur on forested hills above 600m (e.g. the hill local to the study station known as The Camel which reaches 678m) and a dedicated research agenda would be needed to assess the any direct contribution of clouds to moisture availability, especially during the cloudy dry seasons.

We have also shown that variability in temperature and rainfall at our site is strongly influenced by global weather patterns. The most important influence on Lopé temperature is the Pacific ENSO index, with our analysis showing strong coherence between these two datasets on multi-annual scales, especially pre-2000 (Figure 4). This result is supported by a continent-wide study showing warming throughout Africa in El Nino years (Collins 2011). None of the other oceanic indices appeared to influence Lopé temperature in a consistent way (Figure 4). As for Lopé rainfall, the most important influence appears to be the tropical Atlantic. Rainfall cycled in phase with southern tropical Atlantic SSTs pre-2000 and in anti-phase with northern tropical Atlantic SSTs post-2000 on multi-annual scales (Figure 4). The phase relationships between these data series indicate that higher than average rainfall at Lopé coincides with warm conditions in the south tropical Atlantic and cool conditions in the north tropical Atlantic. This result is supported by a number of other studies; Camberlin et al. (2001) show the Atlantic dipole (cool temperatures in the north Atlantic and warm temperatures in the south tropical Atlantic) to be associated with higher than average rainfall in the region during March-May. Similarly, Balas et al. (2007) and Otto et al. (2013) demonstrate how warm conditions in the southern equatorial...
Atlantic (especially the Benguela coast) coincide with enhanced rainfall in the region during the
dry seasons. ENSO also appears to have some influence on Lopé rainfall although the
relationship is patchy (Figure 4). The anti-phase relationship during periods of strong coherence
in our analysis indicate that rainfall decreases at Lopé during El Nino events. A similar result
was found among the major studies summarized in Table 1. Finally, we found little evidence of
the influence of the Pacific Ocean on Lopé rainfall despite published data showing reduced
rainfall in western equatorial Africa coinciding with positive IOD modes (Dezfuli & Nicholson
2013; Nicholson & Dezfuli 2013; Otto et al. 2013).

Model projections of future rainfall in western equatorial Africa cover a broad spectrum and as a
result, averaged model trends are close to zero. However, those models that predict drying in the
region incorporate a northward shift of the rainbelt, related to cool conditions in the Gulf of
Guinea (the Atlantic Cold Tongue; James et al. 2013 and Fig. 1). The strong coherence between
Lopé rainfall and SSTs of the southern equatorial Atlantic (0°- 20°S) at multi-annual scales in
our study provides some support for the mechanisms behind these “dry” models. Indeed, Atlantic
SSTs and circulation patterns have been an important influence on Congo Basin precipitation for
the past 20,000 years (Schefuss et al. 2005). Overall, our work supports the idea that the drivers
of rainfall variability in western equatorial Africa are highly complex, with strong local and
seasonal forcing from the major oceans. Land topography (e.g. the highlands of Gabon,
Cameroon and eastern Africa) is also likely to be a major influence on highly localised
expressions of rainfall and rainfall variability in the region (Balas et al. 2007; Dezfuli et al.
2015).

Data quality and availability

One of the major issues with climate analyses in Central Africa is the already limited and
declining amount of publicly available data from weather stations in the region: The nearest
weather stations to Lopé listed on the Global Historical Climatology Network (GCHN) Daily
Database (Menne et al. 2012) are between 136 and 185km away and there are no public data
available since 1980. The World Meteorological Organisation has a minimum recommended
density of weather stations eight times higher than the modern density of weather stations in
Africa (Collins 2011). This lack of data has a direct impact on the quality of gridded climate data
products (Suggitt et al. 2017) and leads to an inability to calculate daily climatic indices for the
extremes (Niang et al. 2014). Gabon is also one of the cloudiest places on earth
(http://www.acgeospatial.co.uk/the-cloudiest-place/) which leads to large uncertainties in
satellite estimates, with some satellite algorithms overestimating rainfall in the region by at least
a factor of two (Balas et al. 2007). Finally, poor correlation between Central African rainfall and
neighbouring regions, as well as variability between individual stations, suggests much local
influence and further confounds the challenges of sparse data (Balas et al. 2007).

The importance of maintaining long-term study sites and improving the quality and type of
weather measurements in the region has been known for some time (Clark 2007). However, the
region is remote and there are many financial, logistical and political challenges to face when
servicing field stations. One such issue is that western equatorial Africa has the highest
frequency of lightning strike in the world (Balas et al. 2007) leading to difficulties and great
expense maintaining equipment. Lightning damage is an issue regularly confronted at Lopé and
has led to major gaps in our data record. While automatic continuous measurements can provide
vast amounts of detailed data relevant for ecological studies, they are also inherently more
susceptible to technical failures that need expert fixes. In our experience, data gaps are more
likely to go unnoticed with automatic data collection and so while we welcome new automatic
methods, we recommend maintaining long-term manual records alongside for consistency.

Conclusions
The long-term Lopé weather record has not previously been made public and is of high value in
such a data poor region. Our results support regional analyses of climatic seasonality, long-term
warming and the influences of the oceans on temperature and rainfall variability. However, there
are some surprises; warming has occurred more rapidly than the regional products suggest and
while there remains much uncertainty in the wider region, reduced rainfall over the last three
decades at Lopé is in agreement with drying trends evident from less recent observational data
for western equatorial Africa. The influence of the southern equatorial Atlantic (Atlantic cold
tongue) on rainfall at Lopé lends support to the mechanism behind “dry” models of future
rainfall in the region.
With a climatic regime delivering on average less than 1500 mm per year, Lopé is a globally
anomalous region for the persistence of evergreen tropical forest (Reich 1995). Reduced water
demand during the cloudy, light-deficient long dry season is likely to be the major factor
facilitating persistence of evergreen forests despite seasonal drought (Philippon 2019). It is
essential that we understand the sensitivity of this seasonal cloudiness to ocean temperatures, and
the viability of forest in this dry region should the clouds disappear and thus water demand
increase during the seasonal drought.
We know from historic analyses that, while forests in this region have been resilient to certain
levels of climatic change, they have also been susceptible to shifts back and forth between
evergreen humid forests and open, fire-prone, dry forest systems and even savannas when
changes tip over certain thresholds (Brncic et al. 2006; Willis et al. 2013). The community shifts
associated with drier and warmer climates have often been non-linear and dependent on
ecosystem-specific resilience at local and regional scales (Willis et al. 2013). Carbon fertilisation
and dry season cloudiness may be shielding African humid forests from the impacts of drying
and warming at present. However, we urgently need reliable information on current climate and
forest function and reduced uncertainties in future projections of change to inform climate
change risk assessments for the western equatorial region of Central Africa.

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References

Abernethy, K., Maisels, F. & White, L.J.T. (2016). Environmental Issues in Central Africa. *Annual Review of Environment and Resources,* 41, 1–33.

Adamowski, K., Prokop, A. & Adamowski, J. (2009). Development of a new method of wavelet aided trend detection and estimation. *Hydrological Processes,* 23, 2686–2696.

Asemi-najafabady, S. & Saatchi, S. (2013). Response of African humid tropical forests to recent rainfall anomalies. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences,* 368, 20120306.

Balas, N., Nicholson, S.E. & Klotter, D. (2007). The relationship of rainfall variability in West Central Africa to sea-surface temperature fluctuations. *International Journal of Climatology,* 27, 1335–1349.

Barlow, J., França, F., Gardner, T.A., Hicks, C.C., Lennox, G.D., Berenguer, E., Castello, L., Economo, E.P., Ferreira, J., Guénard, B., Gontijo Leal, C., Isaac, V., Lees, A.C., Parr, C.L., Wilson, S.K., Young, P.J. & Graham, N.A.J. (2018). The future of hyperdiverse tropical ecosystems. *Nature,* 559, 517–526.

Bates, D., Maechler, M., Bolker, B. and Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software,* 67(1), 1-48. doi:10.18637/jss.v067.i01.

Behera, S., Brandt, P. & Reverdin, G. (2013). The tropical ocean circulation and dynamics. *International Geophysics vol. 103,* pp. 385–412. Academic Press.

Bloomfield, P. (2000). *Fourier analysis of time series: an introduction.* John Wiley & Sons.

Bonan, G.B. (2008). Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science (New York, N.Y.)*, 320, 1444–1449.

Borchert, R., Renner, S.S., Calle, Z., Havarrete, D., Tye, A., Gautier, L., Spichiger, R. & Von Hildebrand, P. (2005). Photoperiodic induction of synchronous flowering near the Equator. *Nature,* 433, 627–629.

Brncic, T.M., Willis, K.J., Harris, D.J. and Washington, R., 2006. Culture or climate? The relative influences of past processes on the composition of the lowland Congo rainforest. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 362(1478), pp.229-242.

Bush, E.R., Abernethy, K.A., Jeffery, K., Tutin, C., White, L., Dimoto, E., Dikangadissi, J.T., Jump, A.S. & Bunnefeld, N. (2017). Fourier analysis to detect phenological cycles using tropical field data and simulations. *Methods in Ecology and Evolution,* 8, 530–540.

Cai, J., 2018. humidity: Calculate Water Vapor Measures from Temperature and Dew Point. R package version 0.1.4. Available at: https://github.com/caijun/humidity.

Camberlin, P., Janicot, S. & Poccard, I. (2001). Seasonality and atmospheric dynamics of the teleconnection between African rainfall and tropical sea-surface temperature: Atlantic vs. ENSO. *International Journal of Climatology,* 21, 973–1005.
Chang, X., Wang, B., Yan, Y., Hao, Y. and Zhang, M., 2019. Characterizing effects of monsoons and climate teleconnections on precipitation in China using wavelet coherence and global coherence. *Climate Dynamics*, 52(9-10), pp.5213-5228.

Clark, D.A. (2007). Detecting Tropical Forests’ Responses to Global Climatic and Atmospheric Change: Current Challenges and a Way Forward. *39*, 4–19.

Collins, J.M. (2011). Temperature variability over Africa. *Journal of Climate*, 24, 3649–3666.

Cusack, D., Karpman, J., Ashdown, D., Cao, Q., Ciocchina, M., Halterman, S., Lydon, S. & Neupane, A. (2013). Global change effects on humid tropical forests: Evidence for biogeochemical and biodiversity shifts at an ecosystem scale. *Review of Geophysics*, 54, 523–610.

Detto, M., Wright, S.J., Calderón, O. & Muller-landau, H.C. (2018). Resource acquisition and reproductive strategies of tropical forest in response to the El Niño–Southern Oscillation. *Nature Communications*, 9, 913.

Dezfuli, A.K. & Nicholson, S.E. (2013). The Relationship of Rainfall Variability in Western Equatorial Africa to the Tropical Oceans and Atmospheric Circulation. Part II: The Boreal Autumn. *Journal of Climate*, 26, 66–84.

Nicholson, S.E. (2018). The ITCZ and the seasonal cycle over equatorial Africa. *Bulletin of the American Meteorological Society*, 99, 337–348.

Nicholson, S.E. & Dezfuli, A.K. (2013). The Relationship of Rainfall Variability in Western Equatorial Africa to the Tropical Oceans and Atmospheric Circulation. Part I: The Boreal Spring. *Journal of Climate*, 26.

Nicholson, S.E., Funk, C. & Fink, A.H. (2018). Rainfall over the African continent from the 19th through the 21st century. *Global and Planetary Change*, 165, 114–127.

Otto, F.E.L., Jones, R.G., Halladay, K. & Allen, M.R. (2013). Attribution of changes in precipitation patterns in African rainforests. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 368, 20120299.

Dezfuli, A.K., Zaitchik, B.F. & Gnanadesikan, A. (2015). Regional atmospheric circulation and rainfall variability in south equatorial Africa. *Journal of Climate*, 28, 809–818.

Dommo, A., Philippon, N., Vondou, D.A., Seze, G. & Eastman, R. (2018). The June – September Low Cloud Cover in Western Central Africa: Mean Spatial Distribution and Diurnal Evolution. *31*, 9585–9603.

Farnsworth, A., White, E., Williams, C.J.R., Black, E. & Kniveton, R. (2011). Understanding the Large Scale Driving Mechanisms of Rainfall Variability over Central Africa. *African Climate and Climate Change*, pp. 101–122. Springer, Dordecht.

Fauset, S., Baker, T.R., Lewis, S.L., Feldpausch, T.R., Affum-Baffoe, K., Foli, E.G., Hamer, K.C. and Swaine, M.D., 2012. Drought-induced shifts in the floristic and functional composition of tropical forests in Ghana. *Ecology letters*, 15(10), pp.1120-1129.

Gond, V., Fayolle, A., Penneck, A., Cornu, G., Mayaux, P., Doumenge, C., Fauvet, N., Gourlet-fleury, S., B, P.T.R.S. & Camberlin, P. (2013). Vegetation structure and greenness in Central Africa from Modis multi-temporal data. *Philosophical transactions of the Royal
Gouhier, T.C., Grinsted, A. & Simko, V. (2018). R package biwavelet: Conduct Univariate and Bivariate Wavelet Analyses.

Grinsted, A., Moore, J.C. and Jevrejeva, S., 2004. Application of the cross wavelet transform and wavelet coherence to geophysical time series. *Nonlinear processes in geophysics*, 11(5/6), pp.561-566.

Guan, K., Wolf, A., Medvigy, D., Caylor, K., Pan, M. & Wood, E.F. (2013). Seasonal coupling of canopy structure and function in African tropical forests and its environmental controls. *Ecosphere*, 4, 1–21.

Habib, E., Krajewski, W.F. & Ciach, G.J. (2001). Estimation of Rainfall Interstation Correlation. *Journal of Hydrometeorology*, 2, 621–629.

Harris, I., Jones, P.D., Osborn, T.J. & Lister, D.H. (2014). Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset. *International Journal of Climatology*, 34, 623–642.

Hartmann, D.L., Klein Tank, A.M.G., Rusticucci, M., Alexander, L. V., Brönnimann, S., Charabi, Y.A.R., Dentener, F.J., Dlugokencky, E.J., Easterling, D.R., Kaplan, A., Soden, B.J., Thorne, P.W., Wild, M. & Zhai, P. (2013). Observations: Atmosphere and surface. *Climate Change 2013 the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex & P.M. Midgley), pp. 159–254. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Hasan, M.M. and Dunn, P.K., 2010. A simple Poisson–gamma model for modelling rainfall occurrence and amount simultaneously. *Agricultural and forest meteorology*, 150(10), pp.1319-1330.

Helder, C., Sousa, R. De, Hilker, T., Waring, R., Moura, Y.M. De & Lyapustin, A. (2017). Progress in Remote Sensing of Photosynthetic Activity over the Amazon Basin. *Remote Sensing*, 9, 148.

Holben, B.N., Eck, T.F., Slutsker, I., Tanré, D., Buis, J.P., Setzer, A., Vermote, E., Reagan, J.A., Kaufman, Y.J., Nakajima, T., Lavenu, F., Jankowiak, I. & Smirnov, A. (1998). AERONET—A Federated Instrument Network and Data Archive for Aerosol Characterization. *Remote Sensing of Environment*, 66, 1–16.

Huntingford, C., Zelazowski, P., Galbraith, D., Mercado, L.M., Sitch, S., Fisher, R., Lomas, M., Walker, A.P., Jones, C.D., Booth, B.B. and Malhi, Y., 2013. Simulated resilience of tropical rainforests to CO2-induced climate change. *Nature Geoscience*, 6(4), p.268.

Hutley, L.B., Doley, D., Yates, D.J. and Boonsaner, A. (1997). Water balance of an Australian subtropical rainforest at altitude: the ecological and physiological significance of intercepted cloud and fog. *Australian Journal of Botany*, 45(2), pp.311-329.

James, R. & Washington, R. (2013). Changes in African temperature and precipitation associated with degrees of global warming. *Climatic Change*, 117, 859–872.
James, R., Washington, R. & Rowell, D.P. (2013). Implications of global warming for the climate of African rainforests. Philosophical Transactions of the Royal Society B: Biological Sciences, 368, 20120298.

Kidd, C., Becker, A., Huffman, G.J., Muller, C.L., Joe, P., Skofronick-Jackson, G. & Kirschbaum, D.B. (2017). So, how much of the Earth’s surface is covered by rain gauges? Bulletin of the American Meteorological Society, 98, 69–78.

Kothe, S., Pfiffastroth, U., Cremer, R., Trentmann, J. & Hollmann, R. (2017). A Satellite-Based Sunshine Duration Climate Data Record for Europe and Africa. Remote Sensing, 9, 429.

Laraque, A., Mahé, G., Orange, D. & Marieu, B. (2001). Spatiotemporal variations in hydrological regimes within Central Africa during the twentieth century. Journal of Hydrology, 245, 1–117.

Lewis, S.L., Sonké, B., Sunderland, T., Begne, S.K., Lopez-gonzalez, G., Heijden, G.M.F. Van Der, Phillips, O.L., Affum-baffoe, K., Baker, T.R., Banin, L., Bastin, J., Beeckman, H., Boeckx, P., Bogaert, J., Cannière, C. De, Clark, C.J., Collins, M., Djagbletey, G., Djuikouo, M.N.K., Doucet, J., Ewango, C.E.N., Fauset, S., Feldpausch, T.R., Ernest, G., Gillet, J., Hamilton, A.C., Harris, D.J., Hart, T.B., Haulleville, T. De, Hladik, A., Hufkens, K., Huygens, D., Jeanmart, P., Jeffery, K.J., Leal, M.E., Lloyd, J., Lovett, J.C., Makana, J., Malhi, Y., Andrew, R., Ojo, L., Peh, K.S., Pickavance, G., Poulsen, J.R., Reitsma, J.M., Sheil, D., Simo, M., Steppe, K., Taedoumg, H.E., Talbot, J., James, R.D., Taylor, D., Thomas, S.C., Toirambe, B., Verbeeck, H., Vi, E.M. De, Lee, J., White, T., Wilcock, S., Woell, H., Zemagho, L., B, P.T.R.S., Sonke, B., Poulsen, R. & Thomas, C. (2013). A new, long-term daily satellite-based rainfall dataset for operational monitoring in Africa. Scientific Data, 4, 1–19.

Malhi, Y. & Wright, J. (2004). Spatial patterns and recent trends in the climate of tropical rainforest regions. Philosophical Transactions of the Royal Society B: Biological Sciences,
Menne, M.J., Durre, I., Vose, R.S., Gleason, B.E. & Houston, T.G. (2012). An Overview of the Global Historical Climatology Network-Daily Database. *Journal of Atmospheric and Oceanic Technology*, 29, 897–910.

Mitchard, E.T.A. (2018). The tropical forest carbon cycle and climate change. *Nature*, 559, 527–534.

Munzimi, Y., Hansen, M., Adusei, B. & Senay, G. (2015). Characterizing Congo Basin Rainfall and Climate Using Tropical Rainfall Measuring Mission (TRMM) Satellite Data and Limited Rain Gauge Ground Observations. *Journal of Applied Meteorology and Climatology*, 54, 541–555.

Nagai, S., Ichie, T., Yoneyama, A., Kobayashi, H., Inoue, T., Ishii, R., Suzuki, R. & Itioka, T. (2016). Usability of time-lapse digital camera images to detect characteristics of tree phenology in a tropical rainforest. *Ecological Informatics*, 32, 91–106.

National Weather Service. (2018). Inter-Tropical Convergence Zone. *Jet Stream - An Online School for Weather*. URL https://www.weather.gov/jetstream/itcz [accessed 3 December 2018]

Niang, I., Ruppel, O.C., Abdarbo, M.A., Essel, A., Lennard, C., Padgham, J. & Urquhart, P. (2014). Africa. *Climate Change 2014: Impacts, Adaptation and Vulnerability - Contributions of the Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (eds V.R. Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea & L.L. White), pp. 1199–1265. Cambrdige University Press, Cambirdge, UK and New York, NY, USA.

Nicholson, S.E. (2018). The ITCZ and the seasonal cycle over equatorial Africa. *Bulletin of the American Meteorological Society*, 99, 337–348.

Nicholson, S.E. & Dezfuli, A.K. (2013). The Relationship of Rainfall Variability in Western Equatorial Africa to the Tropical Oceans and Atmospheric Circulation. Part I : The Boreal Spring. *Journal of Climate*, 26.

Nicholson, S.E., Funk, C. & Fink, A.H. (2018). Rainfall over the African continent from the 19th through the 21st century. *Global and Planetary Change*, 165, 114–127.

Nicholson, S.E. & Grist, J.P. (2003). The seasonal evolution of the atmospheric circulation over West Africa and equatorial Africa. *Journal of Climate*, 16, 1013–1030.

NOAA. (2018). U.S. Daily Climate Normals (1981-2010). *National Centers for Environmental Information*. URL https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00823 [accessed 26 November 2018]

Oliveira, R.S., Eller, C.B., Bittencourt, P.R. and Mulligan, M. (2014). The hydroclimatic and ecophysiological basis of cloud forest distributions under current and projected climates. *Annals of botany*, 113(6), pp.909-920.

Otto, F.E.L., Jones, R.G., Halladay, K. & Allen, M.R. (2013). Attribution of changes in
precipitation patterns in African rainforests. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, **368**, 20120299.

Peterson, T.C., Easterling, D.R., Karl, T.R., Groisman, P., Nicholls, N., Plummer, N., Torok, S., Auer, I., Boehm, R., Gullett, D. and Vincent, L., 1998. Homogeneity adjustments of in situ atmospheric climate data: a review. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, **18**(13), pp.1493-1517.

Philippon, N., Cornu, G., Monteil, L., Gond, V., Moron, V., Pergaud, J., Sèze, G., Bigot, S., Camberlin, P., Doumenge, C., Fayolle, A. & Ngomanda, A. (2019). The light-deficient climates of western Central African evergreen forests. *Environmental Research Letters*, **14**, 34007.

Preethi, B., Sabin, T.P., AdeDay of Yearin, J.A. & Ashok, K. (2015). Impacts of the ENSO Modoki and other tropical indo-pacific climate-drivers on African rainfall. *Scientific Reports*, **5**, 1–15.

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Reich, P.B. (1995). Phenology of tropical forests: patterns, causes, and consequences. *Canadian Journal of Botany*, **73**, 164–174.

Rohde, R., Muller, R.A., Jacobsen, R., Muller, E., Perlmutter, S., Rosenfeld, A., Wurtele, J., Groom, D. & Wickham, C. (2013). A new estimate of the average Earth surface land temperature spanning 1753 to 2011. *Geoinfor Geostat Overview 1*, **7**, 2.

Saji, N.H. & Yamagata, T. (2003). Possible impacts of Indian Ocean dipole mode events on global climate. *Climate Research*, **25**, 151–169.

Sakai, S. (2001). Phenological diversity in tropical forests. *Population Ecology*, **43**, 77–86.

van Schaik, C.P., Terborgh, J.W. & Wright, J.S. (1993). The phenology of tropical forests: Adaptive significance and consequences for primary consumers. *Annual Review of Ecology and Systematics*, **24**, 353–377.

Schefuss, E., Schouten, S. & Schneider, R.R. (2005). Climatic controls on central African hydrology during the past 20,000 years. *Nature*, **437**, 1003–1006.

Suggitt, A.J., Platts, P.J., Barata, I.M., Bennie, J.J., Burgess, M.D., Bystriakova, N., Duffield, S., Ewing, S.R., Gillingham, P.K., Harper, A.B., Hartley, A.J., Hemming, D.L., Maclean, I.M.D., Maltby, K., Marshall, H.H., Morecroft, M.D., Pearce-Higgins, J.W., Pearce-Kelly, P., Phillimore, A.B., Price, J.T., Pyke, A., Stewart, J.E., Warren, R. & Hill, J.K. (2017). Conducting robust ecological analyses with climate data. *Oikos*, **126**, 1533–1541.

Suzuki, T. (2011). Seasonal variation of the ITCZ and its characteristics over central Africa. *Theoretical and Applied Climatology*, **103**, 39–60.

Tarik C. Gouhier, Aslak Grinsted, Viliam Simko (2019). R package biwavelet: Conduct Univariate and Bivariate Wavelet Analyses (Version 0.20.19). Available from https://github.com/tgouhier/biwavelet

Todd, M.C. & Washington, R. (2004). Climate variability in central equatorial Africa: Influence from the Atlantic sector. *Geophysical Research Letters*, **31**, 1–4.
915 Torrence, C. and Compo, G.P., 1998. A practical guide to wavelet analysis. *Bulletin of the American Meteorological Society, 79*(1), pp.61-78.

916 Tutin, C.E.G. & Fernandez, M. (1993). Relationships between minimum temperature and fruit production in some tropical forest trees in Gabon. *Journal of Tropical Ecology, 9*, 241–248.

917 University of East Anglia Climatic Research Unit, Harris, I.C.. & Jones, P.D. (2017). *CRU TS4.01: Climatic Research Unit (CRU) Time-Series (TS) version 4.01 of high-resolution gridded data of month-by-month variation in climate (Jan. 1901- Dec. 2016).*

918 van Rij J, Wieling M, Baayen R, van Rijn H (2017). “itsadug: Interpreting Time Series and Autocorrelated Data Using GAMMs.” R package version 2.3.Washington, R., James, R., Pearce, H., Pokam, W.M. & Moufouma-Okia, W. (2013). Congo Basin rainfall climatology: can we believe the climate models? *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 368, 20120296.

919 Willis, K.J., Bennett, K.D., Burrough, S.L., Macias-Fauria, M. & Tovar, C. (2013). Determining the response of African biota to climate change : using the past to model the future. *Philosophical transactions of the royal society, 368*, 20120491.

920 Wilson, A.M. & Jetz, W. (2016). Remotely Sensed High-Resolution Global Cloud Dynamics for Predicting Ecosystem and Biodiversity Distributions. *PLOS Biology, 14*, e1002415.

921 Wolter, K. (2018). Multivariate ENSO Index (MEI). URL https://www.esrl.noaa.gov/psd/enso/mei/ [accessed 24 July 2018]

922 Wolter, K. & Timlin, M.S. (1998). Measuring the strength of ENSO events: How does 1997/98 rank? *Weather, 53*, 315–324.

923 Wolter, K. & Timlin, M.S. (1993). Monitoring ENSO in COADS with a seasonally adjusted principal component index. *Proc. of the 17th Climate Diagnostics Workshop*, pp. 52–57.

924 Wright, S.J. & Calderón, O. (2018). Solar irradiance as the proximate cue for flowering in a tropical moist forest. *Biotropica, 50*, 374–383.

925 Zhang, Y., Tan, Z., Song, Q., Yu, G. & Sun, X. (2010). Respiration controls the unexpected seasonal pattern of carbon flux in an Asian tropical rain forest. *Atmospheric Environment, 44*, 3886–3893.

926 Zhang Y (2013). “Likelihood-based and Bayesian Methods for Tweedie Compound Poisson Linear Mixed Models.” _Statistics and Computing_, *23*, 743-757.

927 Zhou, L., Tian, Y., Myneni, R.B., Ciais, P., Saatchi, S., Liu, Y.Y., Piao, S., Chen, H., Vermote, E.F., Song, C. & Hwang, T. (2014). Widespread decline of Congo rainforest greenness in the past decade. *Nature, 508*, 86–90.
Figure 1

Global climatic influences on western equatorial Africa

A. The forested region of central Africa is indicated by a layer of green pixels (>25% tree cover in 2000 from Hansen et al. 2013 - available from http://earthenginepartners.appspot.com/science-2013-global-forest). The Northern (July) and Southern limits (January) of the Inter Tropical Convergence Zone (ITCZ) are drawn from Barlow et al. (2018). The blue zones indicate patterns in oceanic sea surface temperatures (SSTs) known to influence weather in western Central Africa: the Pacific Ocean El Niño Southern Oscillation (ENSO); North and South Tropical Atlantic SSTs (NATL and SATL) and the Indian Ocean Dipole (IOD). In conventional El Niño years the tropical Eastern Pacific is abnormally warm, in El Niño Modoki the warming occurs in the central Pacific. The IOD is the difference between SSTs of the western and eastern tropical Indian Ocean. B. Lopé National Park (our study site) is indicated by a black dot and the limits of western equatorial Africa as defined in this paper are indicated by the grey rectangle (including the humid forests of Gabon, Equatorial Guinea, Cameroon and the Republic of Congo). Also the location of the seasonal Atlantic cold tongue, a pool of cool surface water that develops in the eastern tropical Atlantic during the boreal summer (drawn from Tokinaga & Xie 2011). The grey world map was created by Layerace at Freepik.com.
Figure 2

Seasonal weather variability at Lopé NP, Gabon.

Mean seasonality for daily rainfall (1984-2018), maximum and minimum daily temperature (1984-2017), relative humidity (2007-2015), surface solar radiation (2012-2016), wind speed (2012-2016) and aerosol optical depth at 500nm (2014-2017). The thin grey lines indicate the mean values for each day of the calendar year (DOY). The thin black lines indicate the seven-day running means of DOY and the thick black lines indicate the monthly means. Vertical dotted lines indicate the alternating rainy and dry seasons.
Figure 3

Inter-annual variation, long-term trends and periodicity for rainfall and temperature at Lopé NP, Gabon.

(A) The grey lines indicate inter-annual variation and the black line indicates the long-term trend for total annual rainfall (1984-2018) derived from a compound poisson generalised linear mixed model. (B) The grey dots indicate raw daily data summarised to monthly means and the black line indicates the long-term trend for minimum daily temperature (1984-2018) derived from a linear mixed model. (C, D) Wavelet transforms of the standardised monthly time-series for total monthly rainfall and mean minimum daily temperature. The faded region indicates the “cone of influence” where end effects make the data unreliable. The colour indicates the power of the cycle at each time period, red = high power and blue = low power. Bold black lines indicate cycles with significant power (Chi-sq test). (E, F) Extracted wavelet components for the biannual, annual and multi-annual (mean of 2-4 years) periods from the wavelet transforms, adjusted for edge effects. Both E and F share the same legend.
Figure 4

The influence of oceanic sea surface temperatures on weather at Lopé NP, Gabon.

Wavelet coherence plots for all eight combinations of x (rainfall or minimum temperature) against y (MEI = Multivariate ENSO Index, NATL = northern tropical Atlantic SST, SATL= southern equatorial Atlantic SST, IOD = Indian Ocean Dipole). The coloured region indicates the reliable data within the “cone of influence” away from edge effects. The colour indicates the strength of coherency between the time series at each period through time, red = high coherency and blue = low coherency. Bold black lines indicate areas with significant coherency (derived from Monte Carlo randomizations). Arrows indicate the phase relationship between the time series within areas of strong coherency. Arrows pointing to the right mean that x and y are in phase. Arrows pointing to the left mean that x and y are in anti-phase. Arrows pointing up mean that y leads x by π/2. Arrows pointing down mean that x leads y by π/2.
Table 1 (on next page)

Major oceanic influences on rainfall in western equatorial Africa.
| Study                        | Description                                      | Ocean influences                                                                 |
|------------------------------|--------------------------------------------------|----------------------------------------------------------------------------------|
| Preethi et al 2015.          | Africa-wide; Satellite and gridded obs.; 1979-2010. | Pacific: Canonical El Niño reduces rainfall Jan-Sep. El Niño Modoki increases rainfall Mar-May. |
|                              |                                                  | Indian: Positive relationship between SSTs and rainfall Jan-Feb. No relationship between IOD and rainfall. |
| Camberlin et al. 2001.       | Sub-Sahara; Gridded obs.; 1951-1997.             | Pacific: El Niño negatively influences rainfall Apr-Jun.                        |
|                              |                                                  | Atlantic: South Atlantic SSTs positively influence rainfall Apr-Sep.              |
| Balas et al. 2007.           | WEA; Precipitation gauge dataset; 1950-1998.     | Pacific: El Niño negatively influences rainfall.                                |
|                              |                                                  | Indian: Weak positive relationship between SSTs and rainfall in all seasons except Mar-May when it is reversed. |
|                              |                                                  | Atlantic: Positive correlation between south Atlantic SSTs and rainfall Jun-Nov, negative influence Dec-Feb. Benguela coast influences rain Mar-May. |
| Todd & Washington 2004.      | CEA and WEA; Gridded obs. and discharge data Feb-Apr; 1901-1998. | Pacific: El Niño has weak negative influence on rainfall Feb-Apr.               |
|                              |                                                  | Atlantic: North Atlantic Oscillation negatively influences rainfall Feb-Apr.     |
| Otto et al. 2013.            | CEA and WEA; Simulated data. Dry seasons only.   | Pacific: ENSO influences rainfall in dry seasons.                               |
|                              |                                                  | Indian:IOD negatively influences rainfall in dry seasons.                       |
|                              |                                                  | Atlantic: Warm tropical Atlantic SSTs enhance rain in dry seasons.              |
| Nicholson & Dezfuli 2013;    | WEA. Regionalised obs. Rainy seasons only.      | Pacific: El Niño reduces rainfall in rainy seasons.                             |
| Dezfuli & Nicholson 2013.    |                                                  | Indian: Positive IOD modes associated with reduced rainfall in rainy seasons.  |
|                              |                                                  | Atlantic: Warm tropical Atlantic SSTs enhance rainfall in rainy seasons. Strong correlation with Benguela coast from Oct-Dec |

CEA = central equatorial Africa, WEA = western equatorial Africa, SST = sea surface temperatures, ENSO = El Niño Southern Oscillation, IOD = Indian Ocean Dipole.
Table 2 (on next page)

Weather station instrument record at Lopé NP, Gabon, 1984 - 2018.
| Instrument                          | Time period         | Location | Data                                      | Missing periods                                      |
|-----------------------------------|---------------------|----------|-------------------------------------------|-----------------------------------------------------|
| Manual rain gauge                 | 1984 - present      | Savanna  | Total daily rainfall.                     | Sep-2010 to Dec 2010; 2013; Odd days.                |
| Manual Max/Min thermometer        | 1984 - 2002; 2006 - 2007 | Forest  | Max. / Min. temp. since last reset.       | Jul-1998 to Jan-1999; Mar-2001 to Aug-2001; Intermittent throughout. |
| Wet/dry bulb                      | 1984 - 2002         | Forest  | Relative humidity.                        | Intermittent throughout.                            |
| HOBO Data Logger (ONSET)          | 2002 - 2006         | Forest + Savanna | Temperature Relative humidity.               | Jun-2003.                                          |
| Digital Max/Min thermometer (Taylor 1441) | 2006 - 2008 | Savanna  | Max. / Min. daily temp.                   | Odd days.                                           |
| TinyTag Plus 2 Data Logger (Gemini) | 2007 - present   | Forest + Savanna | Temperature; Relative humidity.              | Jun-2015 to Jun-2016 (Forest); Intermittent throughout 2017. |
| Vantage Pro2 Weather Station (Davis) | 2012 - 2014       | Savanna  | Rainfall; Temperature; Relative humidity; Pressure; Wind speed; Wind direction; UV index; Solar radiation. | Nov-2013; Feb-2014 to Jul-2014.                      |
| Minimet Weather Station (SKYE)     | 2013 - 2016         | Savanna  | Temperature; Relative humidity; Wind speed; Wind direction; Solar radiation.            | Jan-2014 to Nov-2014; Intermittent throughout.      |
| Sun Photometer (NASA Aeronet)      | 2014 - present      | Savanna  | Aerosol optical depth.                    | Intermittent throughout.                            |
Model comparisons to test for long-term trends in rainfall and minimum temperature at Lopé NP, Gabon (1984-2018).

We used a compound poisson generalised linear mixed model for daily rainfall and a linear mixed model for minimum daily temperature. Day of Year and was included as a random intercept in both models.
| Response    | Model                | Predictors | DF | AIC    | Delta AIC |
|-------------|----------------------|------------|----|--------|-----------|
| Rainfall    | Long-term change     | Year       | 4  | 40839.6| 0.0       |
|             | No long-term change  | Intercept only | 3  | 40842.3| 2.7       |
| Temperature | Long-term change     | Year       | 4  | 22909.5| 0.0       |
|             | No long-term change  | Intercept only | 3  | 23494.0| 584.5     |

AIC = Akaike Information Criterion, DF = Degrees of Freedom.
Table 4 (on next page)

Model comparisons to test for long-term trends in rainfall and minimum temperature varying by season at Lopé NP, Gabon (1984-2018).

We used a compound poisson generalised linear mixed model for daily rainfall and a linear mixed model for minimum daily temperature. Day of Year and was included as a random intercept in both models.
| Response            | Model                          | Predictors     | DF  | AIC       | Delta AIC |
|---------------------|--------------------------------|----------------|-----|-----------|-----------|
| Rainfall            | Long-term change by season     | Year * Season  | 10  | 40506.2   | 0.0       |
|                     | Long-term change not by season | Year + Season  | 7   | 40519.5   | 13.3      |
| Temperature         | Long-term change by season     | Year * Season  | 10  | 22572.8   | 0.0       |
|                     | Long-term change not by season | Year + Season  | 7   | 22582.4   | 9.6       |

AIC = Akaike Information Criterion, DF = Degrees of Freedom.
Table 5 (on next page)

Outputs from the best models for long-term trends in rainfall and minimum daily temperature varying by season at Lopé NP, Gabon (1984-2018).

The estimates derive from a compound poisson generalised linear mixed model for daily rainfall and a linear mixed model for minimum daily temperature. Day of Year was included as a random intercept in both models.
| Response | Predictor | Estimate | SE  | T     | Lower 95% CI | Upper 95% CI |
|----------|----------|----------|-----|-------|--------------|--------------|
| Rainfall | DJF      | 0.99     | 0.09| 10.45 | 0.81         | 1.17         |
|          | JJAS     | -0.82    | 0.09| -8.97 | -1.00        | -0.64        |
|          | MAM      | 1.67     | 0.09| 18.32 | 1.49         | 1.85         |
|          | ON       | 1.93     | 0.11| 17.42 | 1.71         | 2.15         |
|          | Year: DJF| 0.03     | 0.05| 0.62  | -0.07        | 0.13         |
|          | Year: JJAS| -0.28   | 0.06| -5.08 | -0.40        | -0.16        |
|          | Year: MAM| -0.06    | 0.04| -1.38 | -0.14        | 0.02         |
|          | Year: ON | 0.00     | 0.05| -0.06 | -0.10        | 0.10         |
| Temperature | DJF | 22.30   | 0.04| 534.23 | 22.22     | 22.38       |
|           | JJAS     | 21.22   | 0.04| 595.76 | 21.14     | 21.30       |
|           | MAM      | 22.33   | 0.04| 542.42 | 22.25     | 22.41       |
|           | ON       | 21.97   | 0.05| 433.78 | 21.87     | 22.07       |
|           | Year: DJF| 0.30    | 0.02| 15.13  | 0.26      | 0.34        |
|           | Year: JJAS| 0.17   | 0.02| 10.42  | 0.13     | 0.21        |
|           | Year: MAM| 0.25    | 0.02| 12.92  | 0.21     | 0.29        |
|           | Year: ON | 0.30    | 0.02| 12.33  | 0.26     | 0.34        |

SE = Standard Error, T = T value, CI = Confidence Interval