atmosphere

Supplementary Materials

The Variation in Atmospheric Turbidity Over a Tropical Site in Nigeria and its Relation to Climate Drivers

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G_0 was estimated using the expression [1-4]:

$$G_0 = \frac{24 \times 3600}{\pi} \times I_0 \times E_{0SC} \times \left(\cos\phi \cos\delta + \frac{\pi h_s}{180} \sin\phi \sin\delta\right) \quad \text{(S1)}$$

where I_0 is the solar constant with a value of $= 1367 \frac{W}{m^2}$, h_s is the sunrise hour angle, ϕ is the latitude of the measurement site, which is positively northward, δ is the solar declination angle and $\pi = 3.14286$. The units of Ψ, ϕ, λ_e and δ are degrees $(°)$.

The solar elevation angle was calculated using the expression:

$$\sin\Psi = \sin\phi \sin\delta + \cos\phi \cos\phi \cos h_s \quad \text{(S2)}$$

The solar declination angle, which represents the elevation of the sun above the equator at the time of observation, was calculated using the equation developed by [3-5]:

$$\delta = \phi_L \sin\left[\frac{2\pi(d_j - d_0)}{d_a}\right] \quad \text{(S3)}$$

where ϕ_L is the latitude of the Tropic of Cancer $23.45°$, $\pi = 180°$, d_j is the Julian day number of the year, which ranges from 1 on 1 January to 365 on 31 December, d_0 is a constant = 284, and d_a is the average number of days per year with a value of 365.

The eccentricity correction factor was computed using ([1,3,4]:

$$E_{0SC} = 1.000110 + 0.034221 \cos\Gamma + 0.001280 \sin\Gamma + 0.000719 \cos 2\Gamma + 0.000077 \sin 2\Gamma \quad \text{(S4)}$$

where Γ (unit is degrees) is the day angle and can be expressed as:

$$\Gamma = \frac{360(d_j - 1)}{d_a} \quad \text{(S5)}$$

The sunrise hour angle was estimated using:

$$h_s = \cos^{-1}(-\tan\phi \tan\delta) \quad \text{(S6)}$$

The daily values of the diffuse solar radiation (G_f, unit $\frac{W^2}{m}$) for the study area were calculated using equation (7) when $h_s > 81.4°$ and $0.3 \leq C_{tAVG} \leq 0.8$ ([3,4]:

$$G_f = G_{\downarrow}\left(1.311 - 3.022 CI_{AVG} + 3.427 CI_{AVG}{}^2 - 1.821 CI_{AVG}{}^3\right) \quad \text{(S7)}$$

where $G_{\downarrow}$ is the measured incoming solar radiation ($\frac{W^2}{m}$) and CI is the average value of the clearness index calculated using the mathematical expression:

$$CI = \frac{G_{\downarrow}}{G_0} \quad \text{(S8)}$$

The zenith angle was calculated using:

$$\theta = 90 - \Psi \quad \text{(S9)}$$

The auxiliary quantities and were using [6]:

$$b_1 = \frac{(f_0 + f_1 m_a)}{(1 + f_2 m_a)} \quad \text{(S10)}$$

$$f_0 = \frac{(1.6685 + 4.1257w + 0.018748w^2)}{(1 + 2.336w)} \quad \text{(S11)}$$

$$f_1 = \frac{(0.075379 + 0.066532w - 0.004263w^2)}{(1 + 1.9477w)} \quad \text{(S12)}$$

$$f_2 = \frac{(0.12867 + 0.24264w - 0.0087874w^2)}{(1 + 3.3566w)} \quad \text{(S13)}$$

$$b_2 = \frac{(j_0 + j_1 m_a + j_2 m_a^2)}{(1 + j_3 m_a^n)} \quad \text{(S14)}$$

$$j_0 = \frac{(-0.032335 - 0.0060424w)}{(1 + 0.023563w)} \quad \text{(S15)}$$

$$j_1 = \frac{(-0.38229 - 0.0009926w)}{(1 + 0.044137w^{0.594})} \quad \text{(S16)}$$

$$j_2 = \frac{(-0.0059467 - 0.0054054w)}{(1 + 0.91487w)} \quad \text{(S17)}$$

$$j_3 = \frac{(0.21989 + 0.041897w)}{(1 + 0.35717w)} \quad \text{(S18)}$$

$$n = \frac{(1.3211 + 2.2036w)}{(1 + 1.9367w)} \quad \text{(S19)}$$

The precipitable water content (w) was estimated using [7]:

$$w = 0.493 \frac{RH}{T} exp\left(26.23 - \frac{5416}{T}\right) \quad \text{(S20)}$$

where T is the temperature in Kelvin and RH the relative humidity in fractions of one. The unit of w is centimeter (cm)

$$C_A = \frac{G_{\downarrow M}}{G_{\downarrow C}} \quad \text{(S21)}$$

where $G_{\downarrow M}$ is the measured incoming solar radiation at the surface and $G_{\downarrow C}$ is the calculated incoming solar radiation under cloudless sky condition expressed by as:

$$\begin{cases} I_o \tau_K \sin \Psi, & \Psi > 0 \\ 0, & \Psi < 0 \end{cases} \quad \text{(S22)}$$

where I_0 is the solar constant =1367 W/m², Ψ is the solar elevation angle between 0º and 90º, which is ≥ 0 and ≤ 0 for daytime and night-time conditions, respectively, and τ_K is the atmospheric transmissivity expressed for clear sky conditions as $\tau_K = 0.6 + 0.2 \sin \Psi$ by [8,9].

The statistical parameters for the Linke turbidity factor (TL), the calculated Ångström turbidity coefficient (βEST), Schüepp (SCH), and Unsworth–Monteith (KAUM) for January–December, 2016 at Ile-Ife, Nigeria is presented in Table S2. The standard deviation for the monthly average values of TL, βEST, SCH, and KAUM presented in this table vary between 0.04 and 2.21; 0.006 and 0.14; 0.015 and 0.15; and 0.02 and 0.11, respectively. These fluctuations are likely due to the short-term variations in air pollution or more unstable weather conditions, with the higher values recorded during the dry season and lower values recorded in the wet months. Notably, the minimum standard deviation values observed in the wet months indicate more stable atmospheric conditions during this season. The annual average values presented in this table for TL, βEST, SCH, and KAUM are 39.79 ± 9.36, 4.79 ± 0.64, 5.14 ± 0.77, and 4.70 ± 0.72, respectively, while they are 38.05, 4.81, 5.13, and 4.72 for the median, respectively. The monthly average values of TL, βEST, SCH, and KAUM presented in this table vary between 0.48 and 9.62, 0.20 and 0.60, 0.22

and 0.65, and 0.11 and 0.62 with the corresponding median values ranging from 0.47 and 9.21, 0.21 and 0.59, 0.23 and 0.63, and 0.11 and 0.62.

Table S1. List of sensors used in this study.

Parameter	Device	Instrument (model and manufacturer)	Accuracy[1], sampling time, and averaging Interval
Incoming Solar Radiation	Pyranometer (4-Component Net Radiometer)	SR01 (NR01), Hukseflux, USA	< 2.4% (solar radiation), < 7% (longwave radiation), 10 seconds, 1 minute
Global Radiation	Pyranometer	CS300, Campbell Scientific, USA	±5% (for daily total radiation), 10 seconds, 1 minute
Aerosol Optical Depth	Sun Photometer	Calitoo, Tenum, France (λ_1 = 465 nm, λ_2 = 540 nm, λ_3 = 619 nm)[3]	$\overline{AOT_{AERONET} - AOT_{Calitoo}}$ [2]: ≈ 0.4 (λ_1 = 465 nm, λ_2 = 540 nm) ≈ 0.2 (λ_3 = 619 nm), instantaneous
Wind Components	3D Ultrasonic Anemometer	CSAT3, Campbell Scientific, USA	Horizontal wind speed: < ±8.0 cms^{-1}, wind direction: ±0.7° at 1 m/s (for horizontal wind), 10 Hz, 30 min
Air Temperature and Relative Humidity	Temperature (Pt resistance) and Relative Humidity (capacitance) Probe	HMP45C, Campbell Scientific, USA	Temperature (t): <±0.3 °C (10°C < t < 40°C) Relative humidity, (RH) at 20 °C: ± 2% (0 to 90% RH) ± 3% (90 to 100% RH), 10 seconds, 1 minute

[1] According to the manufacturers' manuals, if not noted otherwise.

[2] According to http://www.calitoo.fr/index.php?page=qualification-2 (accessed 15 December 2023).

[3] with calibration factors:

λ_1 = 465 nm: CN0_465 = 3787, Rayleigh _465 = 0.19490, Ozone_465 = 0.00000
λ_2 = 540 nm: CN0_540 = 3368, Rayleigh _540 = 0.10637, Ozone_540 = 0.0128.

λ_3 = 619 nm: CN0_619 = 2655, Rayleigh _619 = 0.06281, Ozone_619 = 0.0154

Table S2. Statistical parameters for the Linke turbidity factor (T_L), the calculated Ångström turbidity coefficient (β_{EST}), Schüepp (SCH), and Unsworth–Monteith (K_{AUM}) for January–December, 2016 at Ile-Ife.

Months	T_L					β_{EST}					SCH					K_{AUM}				
	Mn	Md	Min	Max	CV (%)	Mn	Md	Min	Max	CV (%)	Mn	Md	Min	Max	CV (%)	Mn	Md	Min	Max	CV (%)
January	9.62± 2.21	9.21	6.24	15.21	22.95	0.59± 0.11	0.59	0.543	0.69	17.86	0.64± 0.11	0.63	0.58	0.74	17.88	0.58 ± 0.10	0.59	0.53	0.66	16.51
February	4.13± 0.90	4.04	2.82	7.31	21.80	0.52± 0.07	0.52	0.386	0.67	12.43	0.56± 0.08	0.56	0.41	0.72	14.70	0.48± 0.07	0.46	0.4	0.64	15.09

March	3.07± 0.52	3.01	2.52	5.54	17.00	0.39± 0.06	0.40	0.287	0.53	15.87	0.42± 0.07	0.43	0.31	0.57	16.42	0.47± 0.06	0.46	0.40	0.63	12.99
April	2.91± 0.73	3.02	1.87	5.42	24.92	0.37± 0.04	0.37	0.354	0.42	9.68	0.40± 0.07	0.39	0.38	0.45	16.75	0.43± 0.06	0.45	0.34	0.54	12.82
May	1.06± 0.25	1.08	0.52	1.65	23.94	0.34± 0.03	0.34	0.299	0.41	9.81	0.36± 0.04	0.36	0.32	0.44	9.81	0.36± 0.05	0.37	0.22	0.49	12.98
June	0.67± 0.11	0.63	0.52	0.93	17.08	0.30± 0.03	0.32	0.234	0.34	10.25	0.33± 0.04	0.34	0.25	0.37	11.39	0.21± 0.04	0.21	0.09	0.38	18.61
July	0.59± 0.10	0.58	0.44	0.81	17.14	0.23± 0.01	0.21	0.084	0.38	6.35	0.26± 0.03	0.24	0.004	0.82	12.77	0.15± 0.03	0.14	0.002	0.35	20.28
August	0.48± 0.04	0.47	0.41	0.66	8.74	0.20± 0.01	0.22	0.023	0.34	3.09	0.22± 0.02	0.23	0.02	0.36	7.07	0.11± 0.02	0.11	0.01	0.20	18.06
September	2.09± 0.44	2.08	1.35	2.92	21.22	0.35± 0.03	0.35	0.349	0.35	9.93	0.37± 0.04	0.37	0.37	0.37	9.86	0.39± 0.06	0.40	0.31	0.47	14.39
October	1.39± 0.45	1.29	0.82	2.54	32.25	0.35± 0.03	0.35	0.340	0.37	9.80	0.37± 0.04	0.37	0.36	0.39	10.33	0.36± 0.06	0.37	0.19	0.61	17.41
November	5.52± 1.44	5.15	3.21	10.14	26.18	0.54± 0.08	0.55	0.477	0.59	14.16	0.58± 0.10	0.58	0.51	0.64	16.94	0.54± 0.08	0.54	0.49	0.62	14.45
December	8.26± 2.16	7.49	5.52	14.00	26.09	0.60± 0.14	0.59	0.555	0.70	22.59	0.64± 0.15	0.63	0.59	0.74	22.63	0.62± 0.11	0.62	0.59	0.67	17.16
Annual	39.79 ± 9.36	38.05	26.24	67.13	259.31	4.79 ± 0.64	4.81	3.93	5.79	141.82	5.14 ± 0.77	5.13	4.10	6.61	166.56	4.70 ± 0.72	4.72	3.57	6.26	190.76

Mn—Arithmetic Mean, Md—Median, Min—Minimum, Max—Maximum, CV—Coefficient of Variation. The frequency distribution of the atmospheric turbidity coefficients values at different categories are presented in Table S3. For the Linke turbidity factor, the distribution in the dry season was 1.7 % for values < 2.5, 29.8 % for the range of 3.5 to 4.5, and 68.6 % for values ≥ 5.5. In the wet season, the distribution was 45.7 % for values below 2.5, 11.8 % for the range of 3.5 to 4.5, and 0.8 % for values ≥ 5.5. For the entire year, the distribution of T_L was 59.0 % for values below 2.5, 1.7 % for the range of 3.5 to 4.5, and 23.2 % for values ≥ 5.5. Notably, all the frequency distributions for the calculated Ångström turbidity coefficient were 0.0 % 26.1 %, and 17.5 % for values < 0.3 in the dry season, wet season, and annual, respectively. However, for values above 0.3, the distribution of β_{EST} is 100.0 %, 73.9 %, and 82.5 % in the dry season, wet season and annual, respectively. Similarly, all the frequency distributions for SCH were 0.0%, 21.6 %, and 14.5 % for values below 0.3, and 100.0 %, 78.4 %, and 85.5 % for values above 0.3 in the dry season, wet season, and annual, respectively. For K_{AUM}, the distribution was 0.0 %, 43.1 %, and 28.9 % for values below 0.3, and 100.0 %, 56.9 %, and 71.1 % for values above 0.3 in the dry season, wet season, and annual, respectively. These results highlight that the atmospheric turbidity levels are generally higher during the dry season at the study site compared to the wet season.

Table S3. Frequency distribution of atmospheric turbidity coefficients values broken down into different categories for January–December, 2016 at Ile-Ife.

Frequency Distribution	Dry Season (%)	Wet Season (%)	Annual (%)
$T_L \leq 2.5$	1.7	45.7	59.0
$3.5 \leq T_L \leq 4.5$	29.8	11.8	1.7
$T_L \geq 5.5$	68.6	0.8	23.2
$\beta_{EST} < 0.3$	0.0	26.1	17.5
$\beta_{EST} > 0.3$	100.0	73.9	82.5
SCH < 0.3	0.0	21.6	14.5
SCH > 0.3	100.0	78.4	85.5
$K_{AUM} < 0.3$	0.0	43.1	28.9
$K_{AUM} > 0.3$	100.0	56.9	71.1

Table S4. Monthly mean values of sunshine duration R_s, air temperature T_A, relative humidity RH, water vapor pressure e_v, and precipitable water content w in Ile-Ife.

Months	R_S (hr)	T_A (ºC)	RH (%)	e_V (hPa)	w (cm)
January	6.0	28.2	61.4	19.1	3.4
February	5.7	28.2	61.1	22.1	3.6
March	5.9	28.2	73.3	25.6	4.6
April	6.6	27.0	78.9	26.8	4.8
May	5.4	25.8	81.5	27.2	4.8
June	4.9	25.4	83.7	27.5	4.3
July	3.3	24.9	85.0	30.1	4.4
August	2.0	24.4	85.0	28.9	4.2
September	4.2	25.4	83.9	27.6	4.4
October	5.7	25.8	79.4	27.0	4.3
November	6.6	27.4	76.1	26.3	4.4
December	5.9	26.9	75.4	25.6	4.4

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