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The Influence of Rainfall and Temperature on Total Column Ozone over West Africa

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Authors' contributions

This work was carried out in collaboration between all authors. Author EOE designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author AO managed the analyses of the study. Author MTD managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

This study aims at analyzing the influence of rainfall and temperature on Total Column Ozone (TCO) over West Africa. It provides adequate information on the spatial variability of total column ozone concentration, temperature distribution across latitudinal zones, monthly distribution and inter-annual variability of total ozone column and inter-relationship between monthly ozone and distribution of precipitation rate over West Africa. The result of this work shows that, there are significant interconnectivities between total ozone column variability with precipitation and temperature. The correlation between Annual coefficient of Relative Variation (ACRV) of Total Column Ozone (TCO) with average annual temperature and average precipitation shows that there is correlation in ACRV of total ozone column trends over West Africa with temperature and precipitation. A strong positive value correlation was observed between the ACRV of ozone and average annual temperature which increases from 25℃ to 29℃ at the hot arid north of the region and the mean monthly maximum ozone Coincides with the tropical summer rainfall over West Africa between June and September, which showed that there is a significant relationship between rainfall and total ozone column over West Africa. Temperature and ozone tend to increase across the latitude while rainfall decreases across the latitude. These observations suggest significant

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association between the atmospheric phenomena and total ozone redistribution over West Africa. Ozone distribution is mostly controlled by rainfall producing mechanism. The moist south westerly originating from Atlantic Ocean flows to enhance ozone accumulation as ozone maximum concentration occurs when it takes over the region. On the other hand, north easterly counterpart depletes ozone concentration thereby producing minimum ozone during the dry season.

Keywords: Ozone; ACRV; CRV; ultra violet; radiation.

1. INTRODUCTION

Ozone (O_3) is a triatomic molecule made up of three atoms of oxygen, and is mostly found in the stratosphere, where it protects us from the Sun's harmful ultraviolet (UV) radiation. Ozone is a constituent of the atmosphere and also one of the important atmospheric gases. It is produced mainly through photochemical reactions, but it can also be formed when silent electric discharge passes through oxygen [1]. As a result it can be produced in minute quantities during electric storms. Ozone levels change periodically as part of regular natural cycles such as the changing seasons, sun cycles and winds and the changes have implications on the climate, vegetation, animal and human lives [2]. Although it represents only a tiny fraction of the atmosphere, ozone is crucial for life on Earth. Ozone in the stratosphere (a layer of the atmosphere between 15 and 50 kilometer) acts as a shield to protect Earth's surface from the sun's harmful ultraviolet radiation. Without ozone, the Sun's intense ultra violet (UV) radiation would sterilize the Earth's surface. However, near the surface where we live and breathe, ozone is a harmful pollutant that causes damage to lung tissue and plants. This "bad" ozone forms when sunlight initiates chemical reactions in the air involving pollutants, particularly a family of gases called nitrogen oxides (released from vehicles and industry during the combustion process) and with volatile organic compounds (carbon-containing chemicals that evaporate easily into the air, such as petroleum products). Both the stratospheric and tropospheric Ozone is largely produced naturally through photochemical and chemical reactions [3]. The balance between production and loss determines the magnitude of ozone surplus or deficit at any location. The production and depletion appeared to be less problematic since both are sufficiently slow and thus capable of removing any irregularity in either of the ways. Anthropogenic depletion of ozone by ChloroFluoroCarbon (CFC) that finds its way to the stratosphere is the source of concern because the process is fast and the depleting agents are abundant [4]. Ozone varies across the latitudinal and longitudinal and also varies hourly, daily, monthly, seasonally and yearly.

2. MATERIALS AND METHODS

2.1 Study Area

The study area is West Africa region which is shown in Fig. 1. The latitudinal zone of West Africa, stretches across five latitudinal zones of 5° each namely zones 0 - 5°N, 5 - 10°N, 10 - 15°N, 15 - 20°N and 20 - 25°N. West Africa has bi-modal rainfall pattern due to the latitudinal oscillation of the Inter-tropical Discontinuity (ITD). The period of dry season starts in October and extends to March of the following year while period of wet season commences in April and ends in September. On some exposed slopes of West Africa Mountain and the other peaks of the West African region, rainfall is almost constant and in some places a value of 10,000 mm (400 in) a year are recorded. In the semi-arid mid-north, annual rainfall averages about 380 mm (about 15 in). The far northern portion of West Africa is hot and arid and stretches into the Sahara desert with rainfall averaging about 250 mm (about 10 in) and less than 127 mm (5 in) in the Sahara desert region of the farthest north. The duration of the dry season get prolonged as one moves farther north. The average temperature in the south is 25°C, on the plateau it is 21°C and in the north it is 34°C [5]. The climate system encompasses complex interactions between the different subsystems such as the oceans, land surface, ice coverage of land and oceans, thus incorporates many feedbacks. The traditional view in climatology has been that the stratosphere can only play limited role in climate change. However, there has been increasing evidence that the stratosphere is a sensitive component of the climate system, which can affect the troposphere through coupling mechanisms [6,7]. The other mechanism by which the stratosphere influence the tropospheric climate takes into account the basic dynamical fact that tropospherically forced waves propagate upwards, while zonal mean anomalies propagate down. The stratosphere

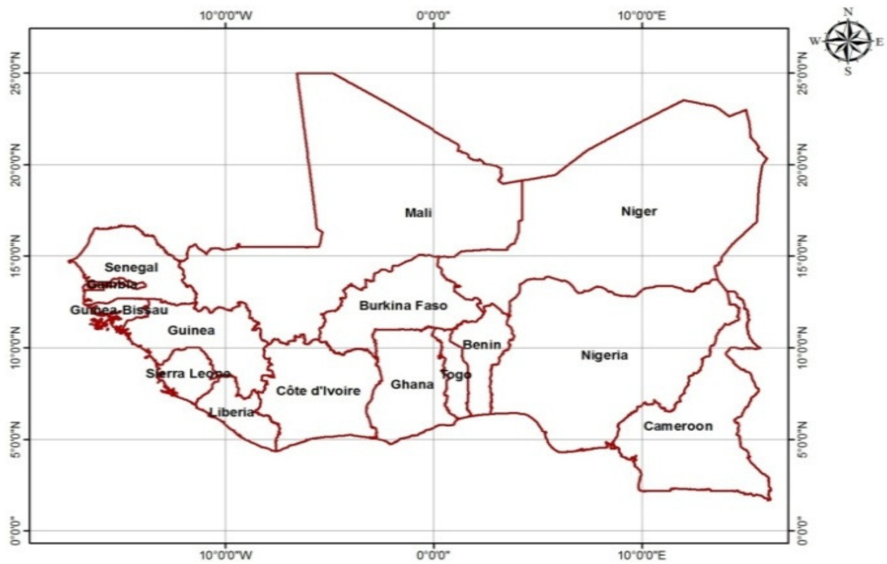

Fig. 1. Map of West of Africa showing the latitude and longitude of study area

affects the "upper boundary condition" of the troposphere by influencing the characteristics of tropospheric wave's propagation. Thus observation of the redistribution of ozone in the atmosphere has some link with the weather pattern variation.

2.2 Data

The data used in this research are; monthly total column ozone (1979-2005), temperature (1979-2005) and rainfall (1981-2005). However, there are no ozone data for the 1994 and 1995. One of the ways of detecting total ozone content in the Earth's atmosphere is by means of satellite measurements. Such measurements have been made by the Total Ozone Mapping Spectrometer (TOMS) on Nimbus–7 and the TOMS on Meteor–3 since late 1978 till present. TOMS/Earth Probe measures total column Ozone by observing both incoming solar energy and backscattered UV radiation at six wavelengths. 'Backscattered' radiation is solar radiation that has penetrated to the Earth's lower atmosphere. There, it is scattered by air molecules and clouds back through the stratosphere to the satellite sensors [8]. It is important to note that TOMS cannot measure ozone below clouds. To correct for this, the data reduction algorithm assumes a standard tropospheric ozone distribution [9] and estimates a cloud height based on cloud climatology and on the reflectance that it measures. Summaries of the TOMS instrumental and operational characteristics and ozone data products can be found in [10] and [11]. The TOMS dataset has been extensively validated against primarily Northern Hemisphere ground–based measurements, and the errors are reasonably well understood [12]. TOMS data have been found to agree reasonably with ground – based measurements and other satellite platforms [13]. The data used was extracted for each grid point of resolution 1° latitude by 1.25° longitude within which each of the surface stations lies. The TOMS data are measured in Dobson Units (DU). Temperature and Rainfall data used for the research was retrieved from Climate Research Unit. The data used was extracted for each grid point of resolution 0.5 ° latitude by 0.5. The monthly mean of Temperature in Kelvin and Precipitation in Millimeter was computed.

Table 1. Data and their sources details

Data	Spatial resolution	Temporal resolution	Sources	Units
Ozone	1.0 x1.25	Monthly	TOMS Mirrador	Du
Precipitation	0.5 x 0.5	Monthly	CRU	Mm
Temperature	0.5 x 0.5	Monthly	CRU	°C

2.3 Statistical Analysis

The ozone data were divided into different latitudinal zone (0 -5°N, 5– 10°N, 10 -15°N, 15 – 20°N, 20–25°N) and then averaged. Monthly means for Total Ozone column (TCO), Temperature and Rainfall were computed and calculated from the monthly means of the parameters under investigation and used throughout the work. In order to investigate the relationship between climate and total ozone variability over West Africa, the annual coefficient of relative variation (ACRV) of total ozone distribution was computed and to evaluate the ozone concentration over West Africa, Seasonal Percentage Variability, A (i) of annual ozone Concentration was computed and also the annual mean of ozone was derived from the monthly Total Ozone data assuming that they are representative of the monthly means. To study the long trends, a linear regression analysis was used on monthly mean and the multiannual mean of Total Column Ozone concentration and Percent variability was also studied using Standard Deviation, Annual Standard deviation, Coefficient of Relative Variation and Annual Coefficient of Relative over West Africa. The Coefficient of Relative Variation (CRV), Annual Coefficient of Relative Variation and Seasonal Percentage Variability, A (i) of annual ozone Concentration were calculated using the Monthly and Multiannual means of TCO as follows

$$CRV = \frac{SD}{\bar{X}} * 100$$

$$ACRV = \frac{ASD}{\bar{X_a}} * 100$$

where, CRV is the coefficient of relative variation, ACRV is the annual coefficient of relative variation, SD is the monthly standard deviation, asd is the annual standard deviation, $\bar{X}$ is the monthly mean, $\bar{X}_a$ is the annual mean coefficient of variation (pv), the percentage variability and average variability was calculated on the annual mean to relate the dependence of ozone on weather activity percent variability a (i) at each zone for each year was also calculated as follows:

$$A(i) = \frac{R(i)}{Q(i)} * 100$$

$$\frac{ASD}{Q(i)} * 100$$

Where *i* = Months of the year (1, 2 , … 12), *A (i)* = Percent Variability of Total Ozone concentration for month (*i*), *R (i)* = Range of Total Ozone concentration for month (*i*) in the six years studied, *Q (i)* = Maximum Ozone concentration

3. RESULTS AND DISCUSSION

3.1 Spatial Variability of Total Ozone Concentration

The graphs below show the spatial variability of ozone concentration across the latitudinal belts over West Africa. Fig. 2 (a-e) shows the Annual Coefficient of Relative Variation (ACRV) of ozone from 1979-2005. The Figures reveals significant change in ACRV across latitudinal zones. Within the years of study, Ozone ACRV value of between 1.12% and 5.71% was observed. Minimum average ACRV value of 3.73% was observed at zone 5 – 10 o N and maximum average ACRV value of 4.1% at zone 15 – 20 o N. Minimum inter-annual fluctuation of 1.15 in Ozone ACRV occurred at zone 0 – 5 o N (Fig. 2b) while maximum fluctuation of 6.71 occurred at zone 20 – 25 (Fig. 2 e). The ACRV of Ozone when correlated with average zonal temperature reveals a significant positive trends over West African except in the year 1979,1 980, 1983 and 2000. The negative correlation recorded in the year 1979, 1980, 1983 and 2000 shows a notable inverse relation between temperature and the average ACRV.

(Table 2.). The average zonal temperature increased from 26 o C at the equatorial zone 0 – 5 o N to about 30 o C at the zone of 20 – 25 o N (Table 3.). This is in accordance with previous researches that variation observed in total Ozone concentration among other things, is directly linked with photo-chemical coupling between Ozone and temperature (Azeem et al. 2001) and that ozone variability responds to seasonal transport from one location to the other is due to seasonal atmospheric circulations.

3.2 Monthly Distribution of Total Ozone Column

Statistical analysis of the total ozone distribution (Table 4) shows that the mean monthly maximum ozone concentration was found to be 266.1Du occurring between July and August, which coincides with the rainfall season over

West Africa, which peaks between June and September as can also be observed in Fig. 3. This shows that there is a relationship between the rainfall patterns and the total ozone variability over West Africa. Ozone concentrations generally grow from January and reach a peak in June/July which then diminishes thereafter to December [14]. The occurrence of maximum ozone concentration with the peak tropical rainfall could possibly be attributed to the active weather system during the months. Active weather ensures strong mixing and vigorous transport which causes the transportation of ozone from the tropical stratosphere into the mid and high latitudinal region [8]. The tropical rainfall season is characterized with minimum surface temperature and evaporation. An average monthly minimum ozone concentration is found to be 246.6 DU occurring between November and March. This coincides with the period of dry season over West Africa which is characterized

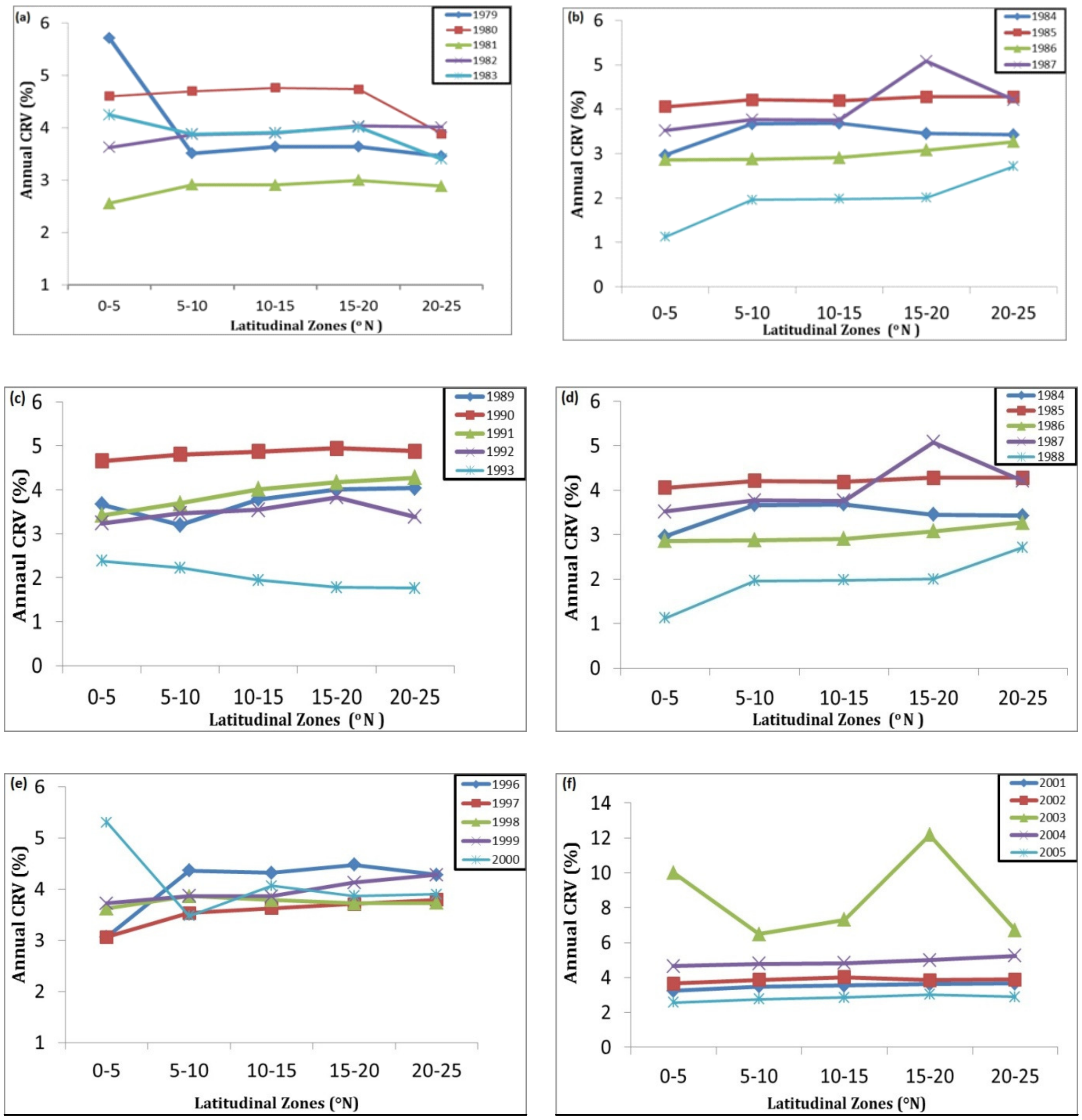

Fig. 2(a-e). Annual coefficient of relative variation (ACRV) of Ozone for 1979-2005 over West Africa

by high surface temperature and evaporation. With high temperature and maximum evaporation during this period, the atmospheric heat engine might be suggested to be at its peak performance in lifting of ozone rich air off the tropical stratosphere into extra tropical region, thus reducing the ozone amount in the tropics [15,16]. In West Africa,the period of dry season starts in October and extends to March of the following year while period of wet season commences in April and ends in September. This corresponds to a lag of two months between the onset of a season and minimum or maximum ozone concentration as the case may be. It was also noted that no station across the latitudinal belt recorded ozone concentration below 220 DU minimum mark otherwise known as ozone hole except in 2003. Although this mark is subjective but it is a good average for seasonal ozone minimum [17].

Table 2. Correlation of annual CRV of ozone with average annual temperature and rainfall over West Africa

Year	Correlation of annual CRV of ozone with average annual temperature	Correlation of annual CRV of ozone with average annual rainfall
1979	-0.22	0.68
1980	0.53	0.42
1981	0.49	-0.71
1982	0.21	-0.93
1983	0.41	0.66
1984	0.36	-0.30
1985	0.16	-0.73
1986	-0.47	-0.87
1987	0.32	-0.73
1988	-0.32	-0.85
1989	0.32	-0.85
1990	0.59	-0.86
1991	0.26	-0.99
1992	0.75	-0.55
1993	-0.12	0.99
1996	0.48	-0.63
1997	0.23	-0.86
1998	0.30	-0.09
1999	-0.13	-0.92
2000	-0.25	0.47
2001	0.37	-0.92
2002	0.53	-0.63
2003	0.46	-0.12
2004	-0.22	-0.90
2005	0.69	-0.64

Table 3. Temperature distribution (°C) across latitudinal belts over West Africa

Year	0-5	5-10	10-15	15-20	20-25
1979	25.4	26	27.2	27.5	27.5
1980	25.3	25.8	27.1	26.9	26.9
1981	25.4	25.7	26.8	26.7	26.7
1982	25.3	25.9	26.9	26.8	26.8
1983	25.4	26	27.1	27	27
1984	25.4	25.7	27.2	26.9	26.9
1985	25.3	25.5	26.8	26.7	26.7
1986	25.4	25.8	27.1	26.9	26.9
1987	25.8	26.3	27.4	27.4	27.4
1988	25.9	26.2	27.3	27.1	27.1
1989	25.4	24.5	26.2	26.9	26.9
1990	25.4	24.1	27.1	26.9	26.9
1991	25.4	25.7	27.2	27.2	27.2
1992	25.7	25.9	27.7	27.1	27.1
1993	25.6	25.9	26.8	26.6	26.6
1996	25.4	25.8	27	27.3	27.3
1997	25.3	25.6	26.6	27.2	27.2
1998	25.1	25.5	27.3	26.6	26.6
1999	25.6	25.9	27.3	27.1	27.1
2000	25.6	25.9	26.9	27.2	27.2
2001	25.5	25.9	27.4	27.1	27.1
2002	25.4	25.7	27.6	27.5	27.5
2003	25.9	26.3	26.1	27.1	27.1
2004	25.6	26.1	26.9	27.7	27.7
2005	25.5	25.9	26.9	27.2	27.2

3.3 Inter-annual Variability of Total Ozone Column

Fig. 5 shows the anomalous changes in the magnitude of variability in Ozone trend. The inter-annual variation presents an interesting feature in which ozone concentrations oscillate between years. The figure shows that the equatorial zone of 0 – 5°N recorded inter-annual fluctuation of above 2% between year 1979 and 1983 (Fig. 4a), of above 1% between year 1984 and 1988, (Fig. 4b), of above 2% between year 1989 – 1993, (Fig. 4c), of above 3% between 1996 and 2000, (Fig. 4d) and of above 32% between 2001 and 2005 (Fig. 4e). This may be related to all year round atmospheric dynamics in the equatorial zone generated by temperature gradients which result in continuous atmospheric circulation. The graphs showed that, zone 5 – 10 °N recorded inter-annual fluctuation of above 3% between year 1979 and 1983 (Fig. 4a), of above 2% between year 1984 and 1988, (Fig. 4b), of above 2% between year 1989 – 1993, (Fig. 4c), of above 4% between 1996 and 2000, (Fig. 4.d) and of above 3% between 2001 and 2005 (Fig. 4e), zone 10 – 15 °N, recorded inter-annual fluctuation of above 3% between year 1979 and

1983 (Fig. 4a), of above 2% between year 1984 and 1988, (Fig. 4b), of above 2% between year 1989 – 1993, (Fig. 4c), of above 4% between 1996 and 2000, (Fig. 4.d) and of above 2% between 2001 and 2005, (Fig. 4e), zone 15 – 20 ^{o}N, recorded inter-annual fluctuation of above 3% between year 1979 and 1983, (Fig. 4a), of above 2% between year 1984 and 1988, (Fig. 4b), of above 2% between year 1989 – 1993, (Fig. 4c), of above % between 1996 and 2000, (Fig. 4d) and of above 12% between 2001 and 2005, (Fig. 4e),this is quite different from what has been experienced in the latitudinal belt in the previous years. Zone 20 – 25 ^{o}N, recorded inter-annual fluctuation of above 3% between year 1979 and 1983 (Fig. 4a), of above 3% between year 1984 and 1988, (Fig. 4b), of above 3% between year 1989 –1993, (Fig. 4c), of above 4% between 1996 and 2000, (Fig. 4d) and of above 3% between 2001 and 2005, (Fig. 4e). In the five West African zones, maximum Ozone inter-annual variability observed to be between 6 and 10% occurred December and February, coinciding with the dry Harmattan season, while the minimum of between 2 and 4% occurred between June and August (Table 2) coinciding with the raining season [18]. December to February coincided with the peak winter period in the northern hemisphere when the planetary wave causes strong coupling of the stratosphere and the troposphere resulting in large year-to-year or inter-annual ozone variability [19]. The observed maximum inter-annual fluctuations in ozone column from December to February may be associated with the variation in the strength of the local Harmattan wind, a prevailing atmospheric dynamics over West Africa during that period. The dry cold Harmattan wind is a polar-continental air mass that originates from the high northern latitude towards Africa. The wind carries along with it a lot of dust from the Sahara desert and flows over West Africa towards the Atlantic Ocean. The year-to-year variability in intensity of the planetary scale atmospheric dynamics responsible for driving the Harmattan wind could be suggested to be responsible for the high inter-annual fluctuation in total ozone column observed between December and February.

Table 4. Statistical analysis of ozone over West African

S/N	Year	Mean	Max.	Month (Max)	Min.	Month(Min.)	ASD	ACRV	% Var.
1	1978	261.9	274.9	Nov.	258.4	Nov.	43.5	16.3	6
2	1979	265.2	280	July	248.4	Jan	45.5	17.2	11.3
3	1980	265.3	281.2	Aug	247.8	Feb	44.2	16.6	11.9
4	1981	266.1	275.9	Sept.	242.8	Jan	44.3	16.6	12
5	1982	268.2	281.9	July	247.4	Jan	44.7	16.7	12.2
6	1983	259	272.5	Aug.	242.4	Feb.	43.1	16.3	11
7	1984	261.9	272	Aug.	250.9	Jan.	43.5	16.6	7.8
8	1985	265.1	275.9	Sept.	242.8	Jan.	44.1	16.6	12
9	1986	262.5	271.9	July	249.2	Jan	43.7	16.7	8.3
10	1987	264.3	276.7	July	247.9	Jan.	43.9	16.6	10.4
11	1988	263.2	271.1	July	253.5	Nov.	43.8	16.6	6.5
12	1989	267.2	277.9	July	247.6	Dec.	44.5	16.4	10.9
13	1990	267.2	285	July	245.9	Jan	44.6	16.6	13.7
14	1991	267.8	279.3	July	250.6	Jan	44.5	16.7	10.3
15	1992	260	273.7	July	244.7	Jan	43.3	16.6	10.6
16	1993	254.6	260	April	250	Jan	41.9	16.5	3.8
17	1996	198.4	272.2	Aug.	251	Dec	1.92	0.97	7.8
18	1997	258.6	269.9	Aug.	243.4	Dec	42.9	16.6	9.8
19	1998	249.5	273.4	Aug	244	Jan.	39.8	15.9	10.8
20	1999	271.3	284.4	July	253	Jan	45.6	16.8	11
21	2000	264.2	281.3	June	247.5	Dec	39.9	15.1	5.9
22	2001	264.7	272.2	Sept.	247.8	Jan	43.6	16.6	9
23	2002	270.5	285.1	July	251.9	Jan	46.4	17.2	11.6
24	2003	258.6	276.9	August	195.9	Mar	52.7	21.6	29.3
25	2004	271.3	288.5	June	251.7	Jan	43.9	16.2	12.8
26	2005	269.5	278.7	July	255.6	Nov	43.6	16.1	8.3

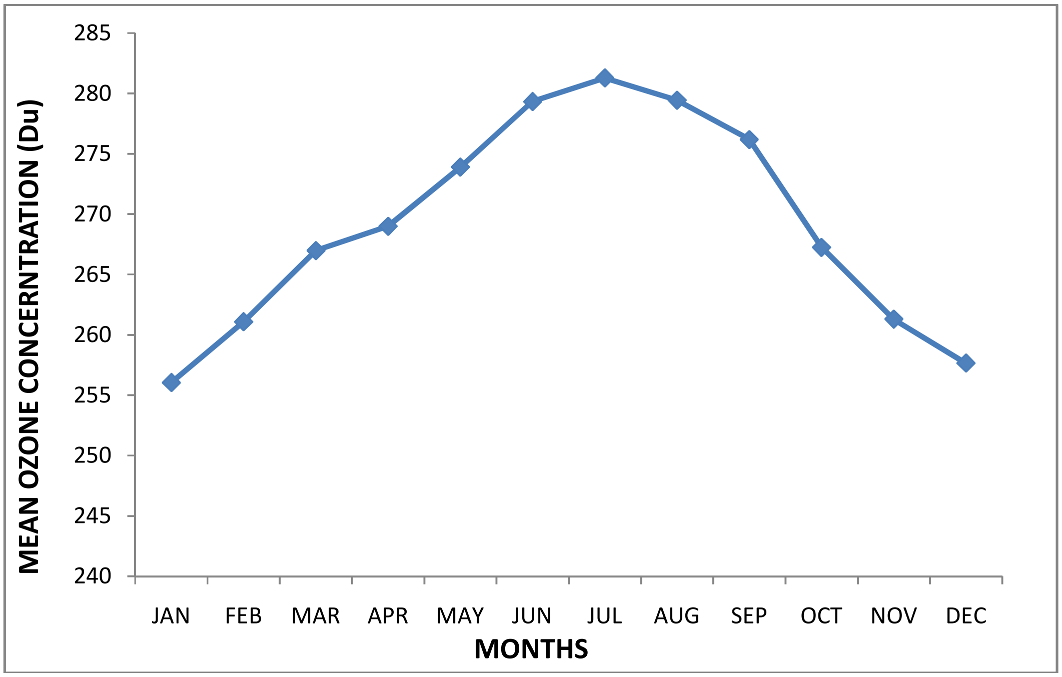

Fig. 3. Monthly distribution of total ozone column over West Africa For 1979-2005

3.4 Inter-relationship between Monthly Ozone and Distribution of Precipitation Rate over West Africa

Fig. 5, shows the monthly distribution of Precipitation rate over West Africa. It presents results for April, May, June, (AMJ) and July, August and September (JAS). The focus is on AMJ and JAS because, West Africa is known to have bi-modal seasonal rainfall, that is April – June and September – November. JAS is the peak of the monsoon season, a critical period for the West African economy and thus a critical period [18]. The Figure shows the mean rainfall over tropics to be peak between June and September (JJAS) and lowest between December and February (DJF). The mean monthly maximum ozone coincides with the tropical summer rainfall over West Africa between June and September (Fig. 3). This showed that there is a significant relationship between rainfall and total ozone column over West Africa. A prominent feature in the rainfall distributions is a band of maximum rain associated with the ITCZ in the Atlantic Ocean [18]. The cycle starts with a minimum during the period of dry season DJFM and gradually assumes a maximum during the period of wet season AMJ and JAS. Minimum and maximum ozone concentrations over each station are found to occur principally in January and June respectively. However in West Africa the period of dry season starts in October and extends to March of the following year while period of wet season commences in April and ends in September. This corresponds to a lag of two months between the onset of a season and minimum or maximum ozone concentration.

Table 5. Latitudinal zones of West Africa and the corresponding ACRV, temperature and rainfall

Latitudinal zones (N)	Avg. ACRV ozone (%)	Avg. Temp. (℃)	Avg. annual rainfall (mm)
20 – 25	3.85	29	2.415771
15 – 20	4.14	28	16.51615
10 – 15	3.84	27	58.65104
5 – 10	3.73	26	119.171
0 – 5	3.82	25	142.594

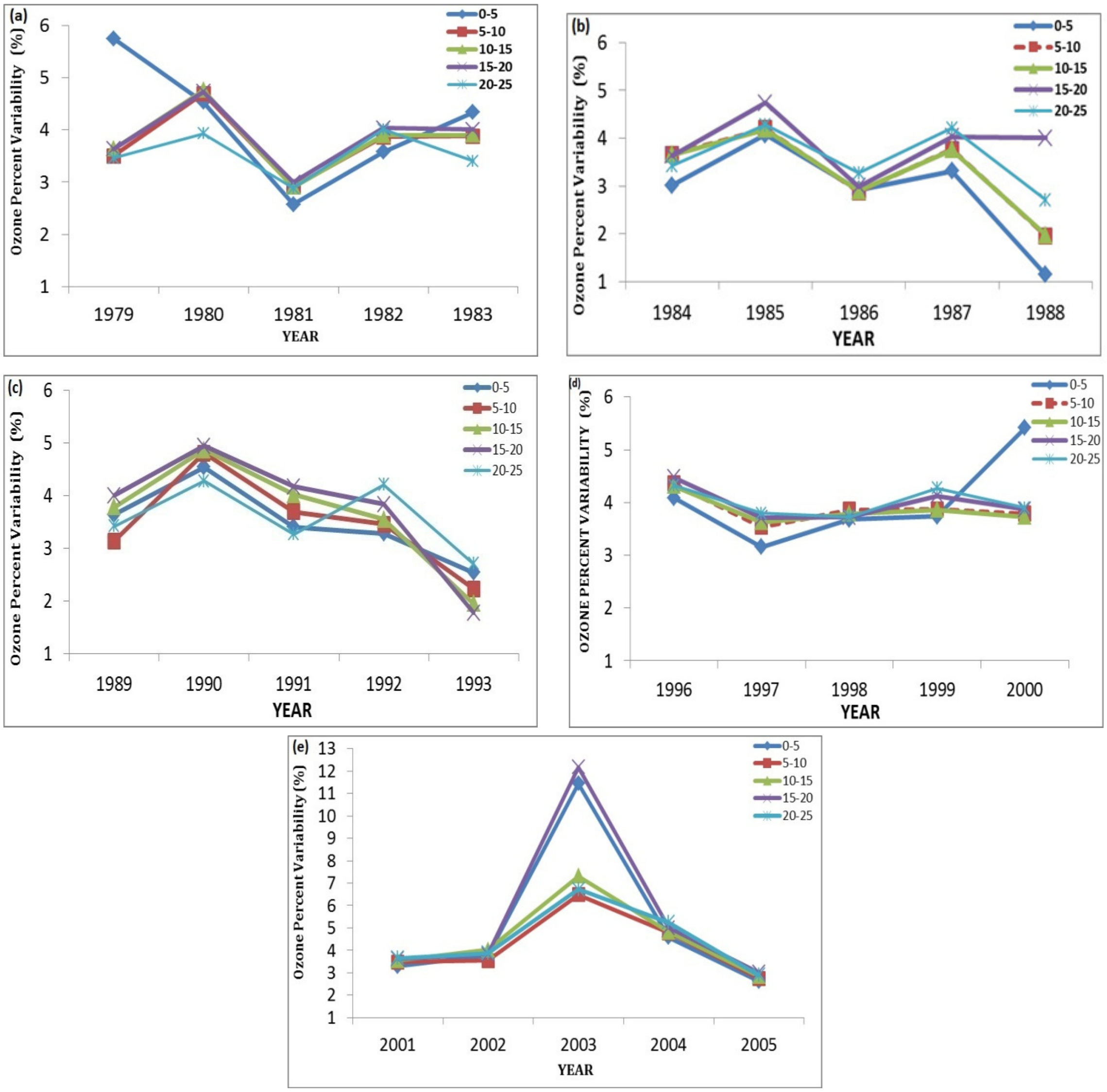

Fig. 4 (a-e). The inter annual fluctuation of ozone across latitudinal belts for 1979 – 2005

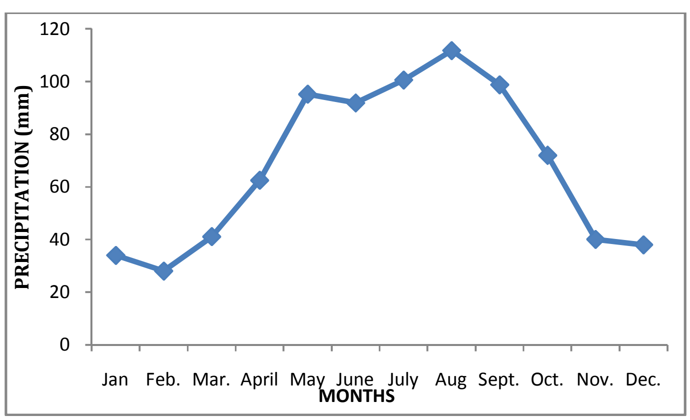

Fig. 5. Inter-relationship between monthly ozone and distribution of Precipitation rate over West Africa

4. CONCLUSION

Rainfall regime is basically the same over the entire region of West Africa, rainfall is of two regimes: a bi–modal maximum south of 10°N and a single maximum north of this latitude. We used rainfall as a proxy and measure of weather activity. The result of this work shows that, there are significant interconnectivities between total ozone column variability with precipitation and temperature. The significant positive and negative correlation between ACRV of total column ozone with temperature and precipitation reveals this interconnectivity over West Africa. The correlation between ACRV of total column ozone with average annual temperature and average annual rainfall in 1979 are -0.22 and 0.68 whereas for the 1980 are 0.53 and 0.53 and 0.42. There are similarities in ACRV of total ozone column trends over West Africa with temperature and precipitation and there are also notable inverse relationship between precipitation and temperature ozone over the region. These observations suggest significant association between the atmospheric phenomena and total ozone redistribution over West Africa. The role of latitudinal location also became explicit in that all the parameters tend to change across latitudinal belt. Temperature and ozone tends to increase across the latitude while rainfall decreases across the latitude. The role of rainfall producing mechanism has been stressed. Ozone distribution is mostly controlled by rainfall producing mechanism. The moist south westerly originating from Atlantic Ocean flows to enhance ozone accumulation as ozone maximum concentration occurs when it takes over the region. On the other hand, north easterly counterpart depletes ozone concentration thereby producing minimum ozone during the dry season.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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