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Tropospheric Ozone Pollution in Some Major Cities of West Africa and its Relationship with Atmospheric Circulations

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ABSTRACT: This study utilizes a decade long (2005-2014) monthly data of Total Column Tropospheric Ozone (TCTO) in Dubson units to evaluate the spatial and temporal trend of LAO over some major cities of West Africa, namely Lagos, Accra, Niamey, Abuja, Bamako, Dakar, Agadez, Conakry, Kano, and Ouagadougou which are either capital cites or major commercial hubs, where the population ranges from 0.09 million (Agadez, Niger) to over 9 million (Kano and Lagos, Nigeria). The mean (long term average) of TCTO in Lagos (Nigeria) was 34.4±0.6 DU (α=5%) for the entire period, being the highest in all major cities of this study. The lowest TCTO, 30.4±0.5 DU (α=5%), occurred in Bamako (Mali). It was also observed that the concentrations of TCTO vary seasonally. The seasonal changes in TCTO was investigated by categorizing months of the year to very dry months of December, January, and February (DJF), onset of rainy season months of March, April, and May (MAM), wet season months of June, July, and August (JJA), and end of rainy season months of September, October, and November (SON). Seasonal mean of TCTO is higher in all cities, close to the coast during DJF, and cities, north of latitude 12^{o} N, during MAM, compared to rest of the seasons. Elevated TCTO concentrations can be attributed to transport mixing, due to the flow direction of well-known wind regime over the study area. This was established from the analysis of correlation coefficient between the mean of zonal, meridional winds, vertical wind speeds and divergence, and TCTO over region.

Keywords: atmospheric divergence, circulations, tropospheric ozone, West Africa, wind regimes.

INTRODUCTION

Tropospheric Ozone Pollution (TOP) has been attributed to various sources, ranging from stratospheric–tropospheric exchanges, altitude of a location, photochemical reactions with Volatile Organic Compounds (VOCs) in presence of sunlight to atmospheric phenomena such as Quasi–Biennial Oscillation (QBO), and deep convective clouds (Oluleye and Okogbue, 2013). In the troposphere, Ozone is harmful to human health as it can induce breathing problems, reduce lung function, and aggravate asthma as well as other lung diseases. TOP is not emitted directly, even though it is formed in the atmosphere when precursor gases such as nitrogen oxides (NOx) and volatile organic compounds (VOCs) pass through the process of photochemical reactions. In addition to fine particulate matter ($PM_{2.5}$), TOP is a major component of smog formation that reduces horizontal visibility, delaying and cancelling

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flights' operations. In urban areas, where population density is high, it is anticipated that vehicular emissions will be the major cause of elevated TOP. On the other hand, in the grassland and densely-forested areas of the world, where bush burning is prevalent, it can also be predicted that emission releases from bush burning will be a potent source; however, the strength of TOP identifiable sources strongly depends on seasons and atmospheric parameters. The seasonal dependence of ozone has been reported by Ryu and Jenkins (2004), who noted that elevated value of ozone is found over the Atlantic ocean during December, January, and February (DJF), while there is a low value near West Africa in the northern hemisphere, where the biomass burning is widespread during that period. On the other hand, during June, July, and August (JJA) when the biomass burning region is shifted to the southern hemisphere, the high value of ozone is observed over the Atlantic ocean near the West Africa in the northern hemisphere as well as off the coast of the central Africa. Poppe et al. (1998), van der Werf et al. (2006), Haywood et al. (2008), and Piero et al. (2015) also linked the formation of ozone to biomass burning, occurring during moderately dry to very dry periods. Model simulation, conducted in West Africa by Saunois et al. (2009) revealed that the lower values of ozone on vegetation are essentially controlled by dry deposition of trees and that the ozone maximum is clearly a consequence of higher NOx mixing ratios, north of 12^{o}N.

The findings of Altshuller (1986), Chameides et al. (1987), Sillman (1999), Saunois et al. (2009), Yin et al. (2016), and others provide an insight to urban ozone formation photochemistry that linked vehicular emissions of NOx and volatile organic compounds to elevated ozone pollution. In West African cities, population growth and industrial activities have led to more vehicles plying on the roads which depending on the vehicle type, fuel type, and year of manufacture, gives rise to the emission of more pollutants, mainly ozone precursors. More emission of such pollutants from vehicles in growing West African cities may be exacerbated by a lack of emission abatement and control measures (Pudasainee et al., 2006). Based on urban atmospheric chemistry between ozone and its precursors, it is expected that the level of ozone pollution in cities should increase too. The main aim of this study, therefore, is to assess spatial and temporal levels of ozone pollution in some major cities of West Africa, based on their rapidly developing nature. As a result of car emission, ozone production alone is not a sufficient factor of urban TOP without dispersion, transport, and exchanges between the tropospheric and stratospheric ozone circulation. The ozone profile analysis by Dale (2003), Abbas et al. (1987), and Gizaw et al. (2013) reveals that stratospheric ozone accounts for more than 85% of the total column ozone in the atmosphere and that highest ozone concentration can be found around 25 km altitude. Thus, in high altitude locations, elevated ozone pollution may be attributed to stratospheric effect, in other words, high altitude locations will be subject to more ozone pollution, simply because of their heights above sea level. In addition to location altitude, the role of meteorological variables, responsible for mixing, transport, and dispersion, is critical for the evaluation of urban ozone pollution level. Vertical mixing or ozone exchange between lower and upper atmosphere is a function of upward and downward transport by the vertical velocity and subsidence, or sinking motion. One may expect less-polluted air when there is widespread strong vertical transport by advection and vice versa during strong subsidence. This paper has surveyed the role of circulation-related fields of vertical velocity, zonal, meridional wind speeds, and horizontal divergence in West Africa in order to appropriately determine how these meteorological parameters affect seasonal accumulation or depletion of TOP circulation. Specific attention has been paid to divergence and vertical velocity, in addition to mean zonal and meridional winds, because while divergence is a measure of circulation, determining the rate of pollutants' dispersion, vertical velocity is a coupling parameter responsible for the exchange of material (momentum, moisture, ozone, etc.) across vertical levels throughout the atmosphere.

AREA OF STUDY

West Africa lies approximately within the longitude of 20°W and 20°E, extending from equatorial latitude (0°) to about 25°N, as shown in Figure 1. The climate of this region is controlled by a number of factors, but the individual influence subsumes the contrasting south-westerly and north-easterly wind regimes. The former generally blows from Atlantic Ocean to the coast, filled with moisture, then to move further inland, reaching its northernmost limit at about 21°N, during July/August. Under the influence of northward advance of the south-westerly wind, moisture depth increases towards the equator. The dynamics of the way, south-westerly winds combine with other factors to organize precipitation in West Africa has been dealt with in Grist and Nicholson, (2001), Grist et al. (2002), and other related works. North-easterly wind blows through the Sahara desert into the West African region, bringing mineral dust. It is accompanied by the Harmattan, during the dry period of November to February/ March of the following year. The interplay of these two wind systems produces the weather in West Africa region. The meeting line of these winds is referred to as Inter-Tropical Discontinuity (ITD) Zone, south of which lies a region of intense thunderstorms that sometimes develop to reach tropopause or beyond (Oluleye and Okogbue, 2013). These tall towers of thunderstorm mix tropospheric constituents with stratospheric air. North of ITD is a region of dry, sometimes cold, air which overlays relatively warm air at the surface that causes instability, lifting the dust from the loose top soils of Sahel and Sahara Deserts. The wind system is also responsible for transporting atmospheric constituents from the source region to other locations in the sub-continent. The fact that the northern areas of ITZ are dry, make it susceptible for bush burning, a good source of lower atmosphere ozone precursor gases.

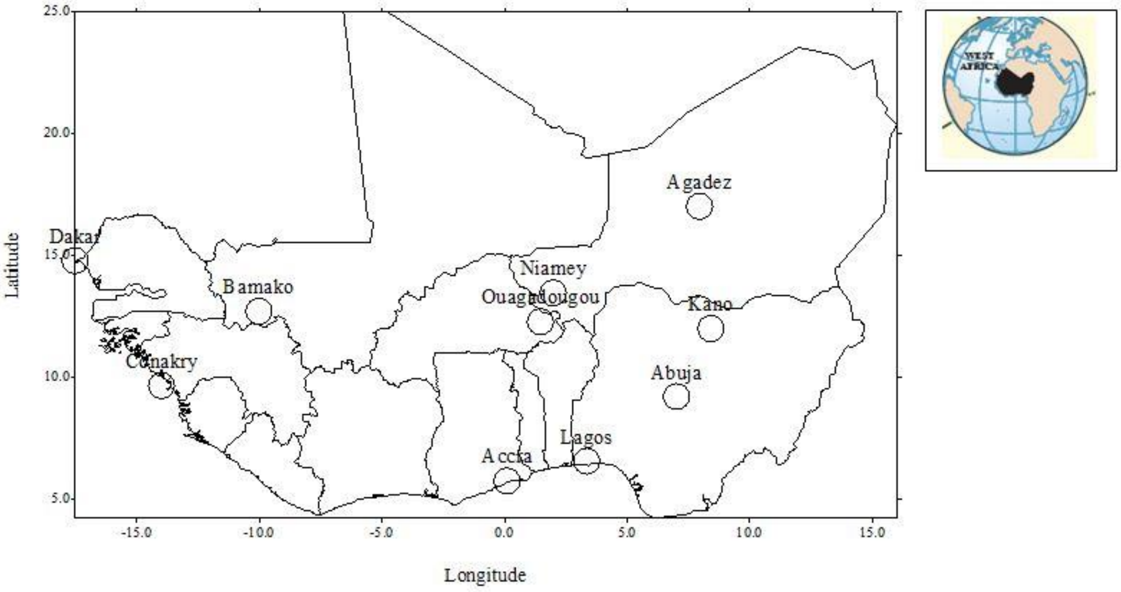


Fig. 1. Map of West Africa showin the major cities selected for this study

There are substantial elevated surfaces as well as low level surfaces in West Africa. In the south, bordering the Atlantic Ocean, which extend from Lagos through Accra, Conakry to Dakar are low elevated areas. While the elevation of cities along the coast of Atlantic Ocean ranges from 12 to 61 m above sea level, as we move inland the high elevation areas are widespread in the guinea savannah, namely Sudan savannah and Sahel regions of West Africa. In places like Abuja (Guinea savannah), Niamey (Sahel), Kano (Sudan) and Agadez (Sahel) have high elevations, ranging between 400 and 840 m above sea level. These cities are very populated, because of the important purposes they serve in the respective regions. For example in Table 1 the populations of Lagos and Kano (both in Nigeria), are high (> 9 million people). While the former served as the capital city of Nigeria until 1990 and the hub of industrialization in the sub-Sahara region of West Africa, the latter is a centre of commerce of the entire northern region of Nigeria. The cities, as a result of their strategic economic importance, attract migrants from many places in the sub-region. Other cities, mainly capital cities and commercial centers, have populations ranging from 0.09 million (Agadez) to more than 2.3 million (Accra) and are still growing. The rapidly-growing population of cities in West Africa has a huge impact on the pollution level of each city as well as the entire region. This study examines the temporal trends of TCTO in these cities in the last decade (2004-2014) along with the role of large-scale weather circulation in transport and dispersion of the pollutant.

Table 1. Population estimate and elevation above sea level of selected major cities of West Africa

Country	City	Population estimate (million)	Elevation above sea level
Senegal	Dakar	>2.3 (2001 estimate)	12m (39ft)
Nigeria	Lagos	>9.0 (2006 estimate)	41m (135ft)
Mali	Bamako	>1.8 (2009 estimate)	350m (1,150ft)
Ghana	Accra	>2.3 (2012 estimate)	61m (200ft)
Niger	Niamey	>0.8 (2001 estimate)	207 (679ft)
Niger	Agadez	>0.09 (2005 estimate)	520m (1,710ft)
Guinea	Conakry	>1.7 (2009 estimate)	13m (42ft)
Burkina Faso	Ouagadougou	>1.5 (2006 estimate)	305m (1,001ft)
Nigeria	Abuja	>0.8 (2006 estimate)	840m (2,760ft)
Nigeria	Kano	>9.3 (2006 etimate)	484m (3,920ft)

Source: Government website of respective countries

MATERIALS AND METHODS

Ground measurements of ozone at the lower levels in West Africa are still very sparse. Although there have been efforts to measure ozone in some cities, the network of stations are grossly coarse and inadequate. In Lagos, ground measurement by the Nigerian Meteorological agency (NIMET) focuses on the Total Column Ozone (TCO), being the only ozone monitoring station in the country. A similar scenario occurs in other cities of West Africa too. Several ozone measurement campaigns has been carried out in Africa but only TROPospheric Ozone experiment (TROPOZ) I and II have focused on West Africa between 11th - 22nd December 1987 and 9th January - 1st February, 1990 (Jonquieres et al., 1998; Sauvage et al., 2005). The African Monsoon Multidisciplinary Analyses (AMMA) Project (the focus of which is on West African Monsoon (WAM)) also has attempted to measure tropospheric ozone, though on a limited spatial and temporal scale (Ancellet et al., 2009; Murphy et al., 2010). The TCTO data for this study have been obtained from a rather longer period of global TCTO measurements from 2005 to 2014. Ziemke et al. (2005) and Ziemke et al. (2006) have given a detailed description of the measurement method of TCTO data set. Satellite measurements are based on a combination of the data from Total Mapping Ozone Spectrometer (TOMS) and Upper Atmosphere Research Satellite (UARS) Microwave Limb Sounder (MLS). Stratospheric Column Ozone (SCO) has been measured via MLS instrument on board Aura spacecraft, which is flown in a sun synchronous polar orbit at 705 km altitude (Waters et al., 2006). The residual method of Chandra et al. (2003) has been used to derive TCTO. The merit of this method over the others is explicit in Ziemke et al. (2006).

The first step in this research's analysis is to examine the temporal trend of ozone pollution, thus TCTO data set have been subjected to various statistical evaluations to determine any shift in their long term averages in the selected study area. Temporal trends of TCTO in the cities have also been examined with the aid of moving averages applied to the data. Furthermore, since the major concerns of this study is to determine TCTO pollution level in the selected cities and relate the same to atmospheric circulation, European Center for Medium range Weather Forecasting (ECMWF) ERA interim data of divergence, vertical velocity, zonal, and meridional wind speeds have been obtained. ERA interim data set, from 1989 to present day, are high-quality reanalyzed data, obtained from the combination of observations and forecasts (Uppala et al., 2005; Simmons et al., 2006; Barriford et al., 2009). ERA interim has uniform grid data set to make it very suitable for spatial characterization of circulation over a region, where ground-based measurements are sparse or not available such as in West Africa. The data, obtained for the period, have been covered by TCTO data set on a fixed grid of 1.5^o x 1.5^o. The reason for this grid spacing is that in our observations, it approximately matches the grid spacing of TCTO data. Correlation coefficient has been used to examine the relationship between TCTO and the circulation parameters. A weakness of Pearson's linear product-moment correlation coefficient is its inability to identify outliers in a data set, thus leaving room for outliers in the data to affect the coefficient, which usually results in a false conclusion about the true relationship between the variables. Experience has shown that the presence of outliers in a bivariate data causes dramatic bias in the estimation of correlation coefficients. To address this problem, several surrogate samples of the measurements are usually taken from the original data, on which the correlation coefficients have been obtained. This method is called bootstrapping (Schwanghart and Schütt, 2007).

In this study, 2000 re-samples surrogates have been taken from the data over each station in the study area. The data has been organized in a way to allow all January average measurements for the whole decade be correlated with corresponding decade-length data of atmospheric circulation, thereby obtaining correlation coefficient, based on long term climatology. Its advantage is that most variability, common to diurnal changes, is cut off (Rao et al. 1997; Oluleye and Okogbue, 2013). All stations in all months have been treated in the same way. The overall goal of this method is to obtain a sufficiently-reliable relation between the data sets that truly represent the influence of independent parameters (circulation parameters) on the dependent ones (tropospheric ozone).

RESULTS AND DISCUSSION

Monthly and Seasonal averages of TCTO

Based on ten years of data, the temporal variation of TCTO is presented in Figure 2, from where it is revealed that an approximate seasonal signature is evident. TCTO varies seasonally in the sense that higher TCTO values are noticeable during the months of

February to April/May and again in November/ December. Reduced TCTO concentrations are noticeable during the months of June to August in Lagos. This observation is general valid for all cities south of latitude 12^{o}N. But for locations, approximately north of this latitude, there is a shift in the months when high concentrations of TCTO are noticeable. Unlike the February-April period of elevated concentrations in coastal cities and those cities, located approximately south of latitude 12^{o}N, there is an extension to the number of months from February to June /July (Agadez for example). It should be noted that these months of elevated TCTO are dry months when very low amount of rainfall is prevalent. In some years of severe drought, these months may experience rainless conditions. Thus, the dry nature of this period is a major factor of moisture reduction both in the soil and plants, leading to an abundance of dry biomass. Since agricultural practices in West Africa depend strongly on rain, the dry period of the year preceding the onset of rain is devoted to land preparation when extensive bush burning is being carried out. Thus this period marks the period of active bush burning. Williams et al. (2010) in several simulations by means of Chemistry Transport Model (CTM) attributed the abundance of ozone in the lower atmosphere to biomass burning (BB) in the East and Equatorial Africa. Biomass burning produces a lot of ozone precursor gases and Carbon dioxide, making it the largest producer of ozone precursor gases across the region. The reduction in elevated level of TCTO during the wet season in West Africa can also be reasonably explained as a result of reduced biomass burning across the region and partly due to wet deposition of ozone precursor gases. In Lagos, for example, the mean monthly value of TCTO during the dry period of DJF is 35.8 DU with a standard deviation of 3.0 DU, according to Table 2. TCTO in Lagos is considerably high throughout the seasons, making other sources of ozone precursor gases important when determining the causes of elevated TCTO in the city. Apart from agriculture, other potent sources of TCTO in Lagos are traffic and petrochemical activities. Thanks to their measurements, Minga et al. (2010) found that petrochemical explosion in the neighboring city of Lagos contributed significantly to dramatic increase of ozone in Cotonou in 2005. Similarly, Lagos is a city hosting a population of more than nine million people with heavy traffic. Traffic in Lagos is capable of generating tons of NOx and VOCs on a daily basis. The duo of traffic emission and petrochemical activities are major sources of TCTO in Lagos, accounting for all-seasons elevated TCTO.

Accra and Abuja also show high all-seasons TCTO concentrations. The all-seasons high level of TCTO in these cities make biomass burning less important because far less or no biomass is available for burning during the wet season in these cities. Only traffic and industrial activities can sustain the all-seasons high TCTO; however, long range transport of biomass burning related gases from biomass burning-prone area is also a factor, though capable of being relegated to the background because of the different transformation that such pollutants undergo during transport. Nonetheless, this assertion is strictly valid to a large extent in cities, located to the south of the rain forest region. Cities in the savannah, where biomass is abundant, are significantly affected by bush burning throughout the seasons at varying degrees. Out of the duo of traffic and industrial activities in the southern cities, traffic appears more important because it is an all-seasons event. Lagos and other capital cities swank of high traffic density with most of the vehicles old and less efficient to burn fuel. As a result, they result in high pollutant concentrations in the atmosphere, contributing significantly to elevated level of TCTO.

Table 2. statistical characteristics of monthly averages of TCTO concentrations for a period of ten (10) years over the selected cities in West Africa. Max is the maximum value, Min is the minimum value, Ave is the average, StDev is the standard deviation from mean and conf is the confidence interval from the mean at confidence level of 5 % of the entire period of the data.

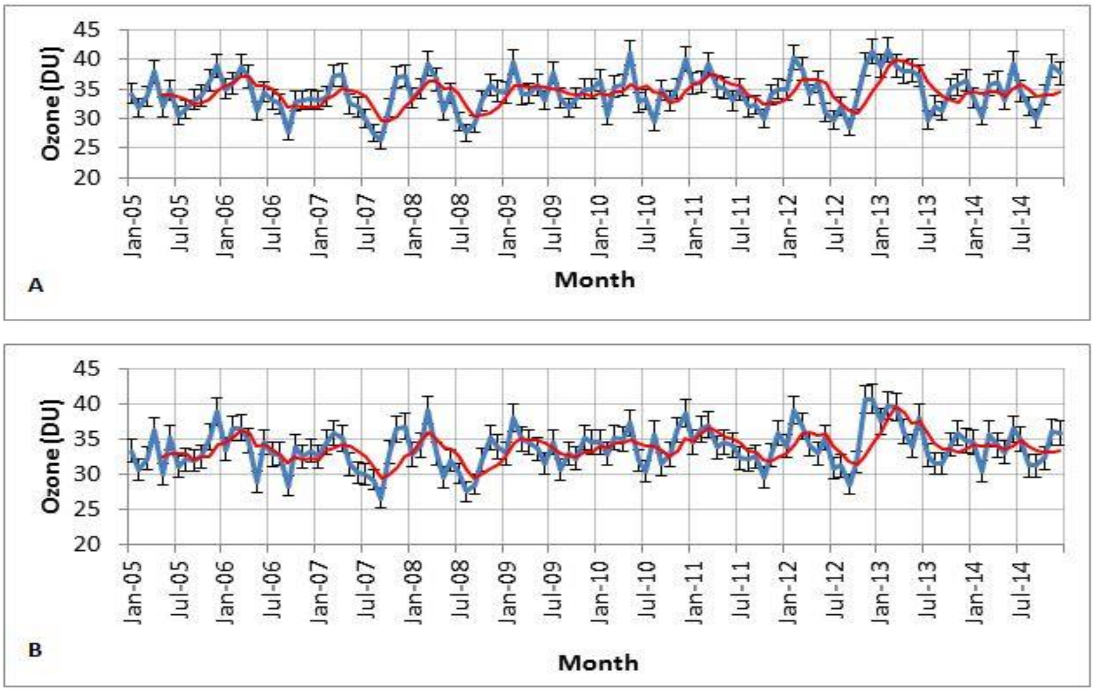
	Lagos	Accra	Niamey	Abuja	Bamako	Dakar	Agadez	Conakry	Kano	Ouagadougou
Max	41.7	40.7	39.1	41.1	38.4	37.9	38.7	41.3	38.5	38.3
Min	26.3	26.6	26.1	22.9	23.0	25.4	24.8	23.6	22.9	25.5
Ave	34.4	33.7	32.4	33.4	30.4	31.0	31.8	31.5	31.7	31.7
StDev	3.2	2.8	2.4	3.4	2.6	3.0	2.6	2.7	3.1	2.4
Conf $\alpha = 0.05$	0.6	0.5	0.4	0.6	0.5	0.5	0.5	0.5	0.6	0.4

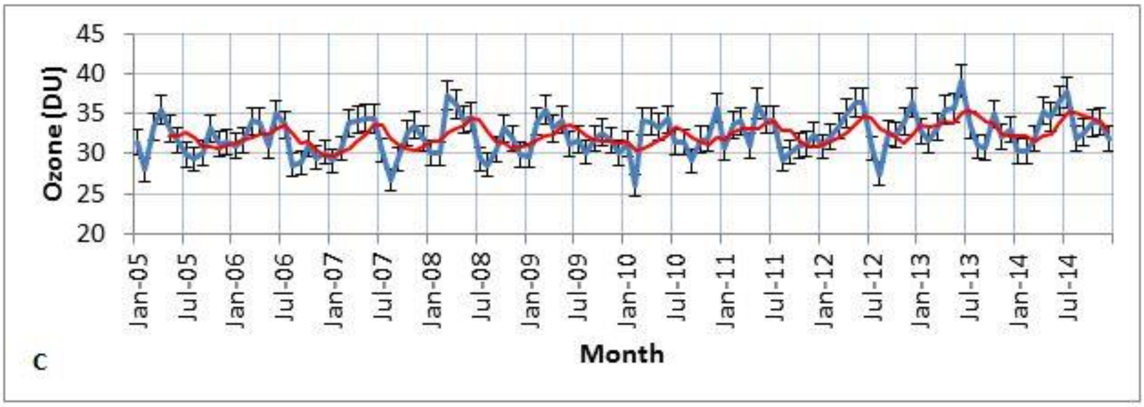
Table 3. same as in Table 2 but for seasonal averages

		Lagos	Accra	Niamey	Abuja	Bamako	Dakar	Agadez	Conakry	Kano	Ouagadougou
Max	DJF	41.7	40.7	36.4	41.1	34.2	33.2	34.8	34.8	38.5	35.5
Min		30.4	30.5	26.1	28.2	23.0	25.4	24.8	24.8	25.4	26.5
Ave		35.8	35.2	31.3	34.8	28.6	28.8	30.1	30.9	32.4	30.4
StDev		3.0	2.6	2.1	2.6	2.0	2.2	2.4	2.3	2.5	1.8
Conf $\alpha = 0.05$		1.1	0.9	0.7	0.9	0.7	0.8	0.9	0.8	0.9	0.6
Max	MAM	41.1	39.5	37.3	40.7	36.0	36.0	36.9	36.3	37.0	36.9
Min		31.4	28.9	31.0	31.4	29.8	27.5	28.8	29.4	29.1	27.1
Ave		36.0	34.5	34.3	35.6	32.2	32.8	33.8	32.9	33.9	33.3
StDev		2.5	2.5	1.5	2.2	1.5	2.1	1.8	1.8	1.8	1.8
Conf $\alpha = 0.05$		0.9	0.9	0.5	0.8	0.5	0.8	0.6	0.6	0.7	0.6
Max	JJA	39.4	38.1	39.1	36.2	38.4	37.9	38.7	41.3	36.3	38.3
Min		27.5	27.5	26.7	22.9	24.4	26.5	28.0	23.6	22.9	25.5
Ave		32.5	32.4	32.2	31.2	31.0	33.1	32.6	31.5	29.6	31.9
StDev		2.8	2.4	3.1	2.9	3.4	3.0	2.8	3.9	3.5	3.2
Conf $\alpha = 0.05$		1.0	0.8	1.1	1.1	1.2	1.1	1.0	1.4	1.2	1.1
Max	SON	39.1	40.6	35.0	37.0	32.3	32.9	34.0	35.8	34.5	35.3
Min		26.3	26.6	28.9	25.8	25.9	25.4	28.8	26.8	25.3	28.2
Ave		33.2	32.8	31.8	32.0	29.7	29.3	30.8	30.7	30.9	31.1
StDev		3.0	2.9	1.6	3.4	1.6	1.9	1.3	2.1	2.7	1.6
Conf $\alpha = 0.05$		1.1	1.0	0.6	1.2	0.6	0.7	0.5	0.7	1.0	0.6

Inter-annual temporal trend of TCTO

Moving the average of 6-month interval, depicted in Figure 2, shows a wave-like cycle of TCTO during the 10-year period. The period of maximum growth of TCTO concentration have strong link with prevalent weather conditions. It appears that weather condition, prevalent during the dry season, acts to reinforce lower atmospheric loads of TCTO, raising it to a value above average at each location. Similarly, there are such times corresponding to the wet season when lower atmospheric loads of TCTO fall below the average value. The contrasting load of TCTO, observed, is apparently a signature of daily weather changes, to be discussed further. However, it should be noted that locations, covered by this study, do not have uniform periods of both wet and dry seasons. For example wet season in Lagos is mainly in MAM and JJA while the dry season covers the remaining period of the year. The period of MAM and JJA in this location is a period of reduced atmospheric load of TCTO, which suggests that weather conditions during the period act to reduce the pollutant load within the troposphere. Although the results, obtained by Adeyewa and Oluleye (2011), indicated that total column ozone reaches maximum during this period, it appears tropospheric ozone is transported beyond the surface due to updrafts in tall clouds, accumulating at a certain layer in the stratosphere about 25 km from the surface. On the contrary, places like Conakry and Bamako exhibit elevated levels of TCTO, mostly during JJA due to favorable conditions. The inter annual variation of TCTO during the 10-year period have seasonal standard deviation of 5% confident level, ranging between 1.8 and 4 DU in the cities, covered in this study. The values of the standard deviations are considerably low, showing ‘no strong’ inter annual variations during the period of data coverage; however, separating the data into two equal 5-year periods, as shown in Figure 3, the frequency of TCTO concentration occurrence in each sub period is presented. Generally, there has been an increase (a positive shift) in the frequency of occurrence of TCTO in most of the cities between the sub-periods, an indication of increasingly polluted atmosphere. In the first sub-period, ‘most occurred’ values of TCTO are between 30 and 32 DU, ascending to 35 DU in the second sub-period. In Lagos and Accra for example, TCTO mode shifts significantly from 32 DU to 35 DU over a period of 5 years. Other cities have at least 1 DU shift in the mode of TCTO, except Ouagadougou where the shift is not noticeable. The mode shift of TCTO is perhaps an indication of more pollution in the atmosphere in these cities. Similar shift has been noted in China (Willem et al., 2015) A plausible explanation is that as the population of these cities grow, there is a tendency to expand infrastructure and there will be consequent increase in emission of pollutants from industrial and transportation sources.

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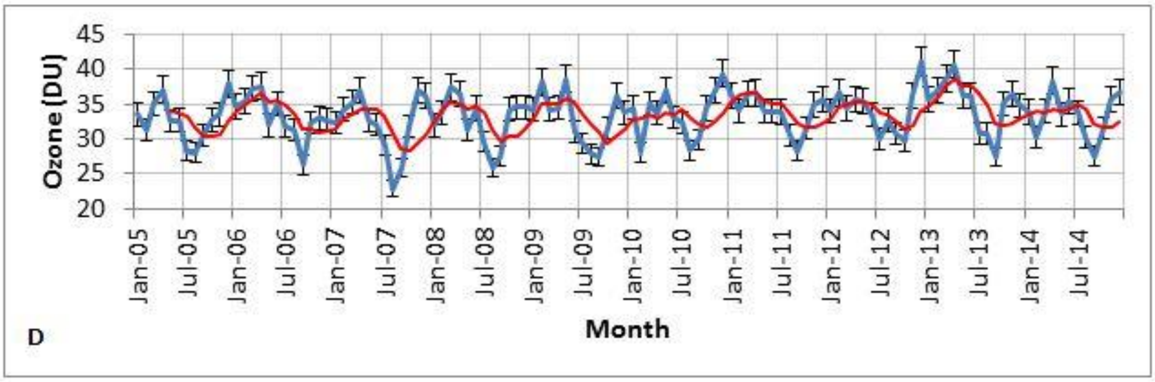
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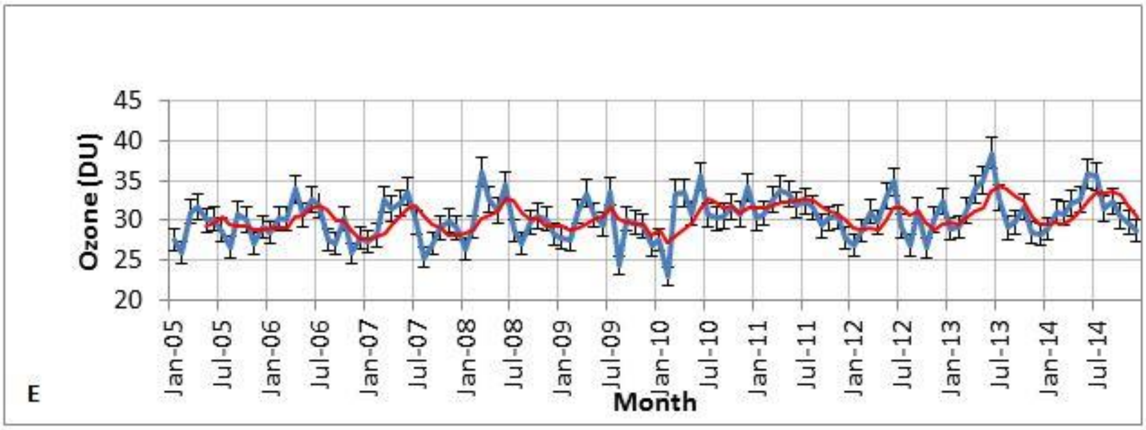
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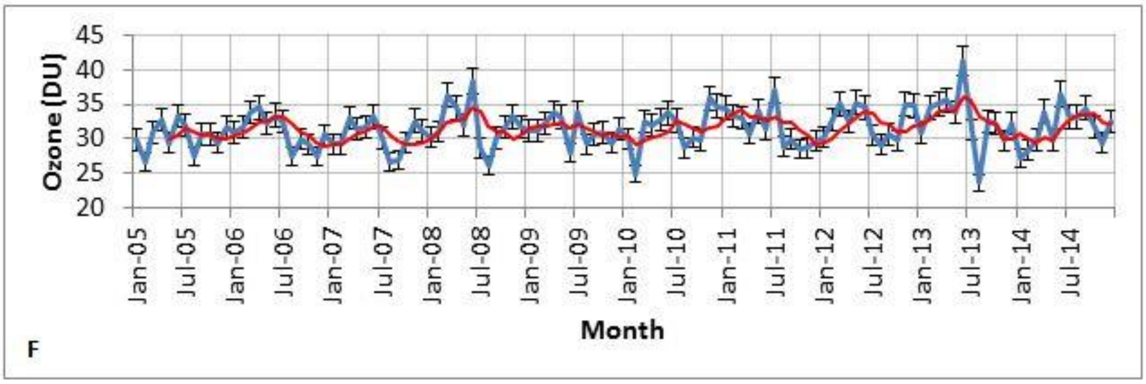
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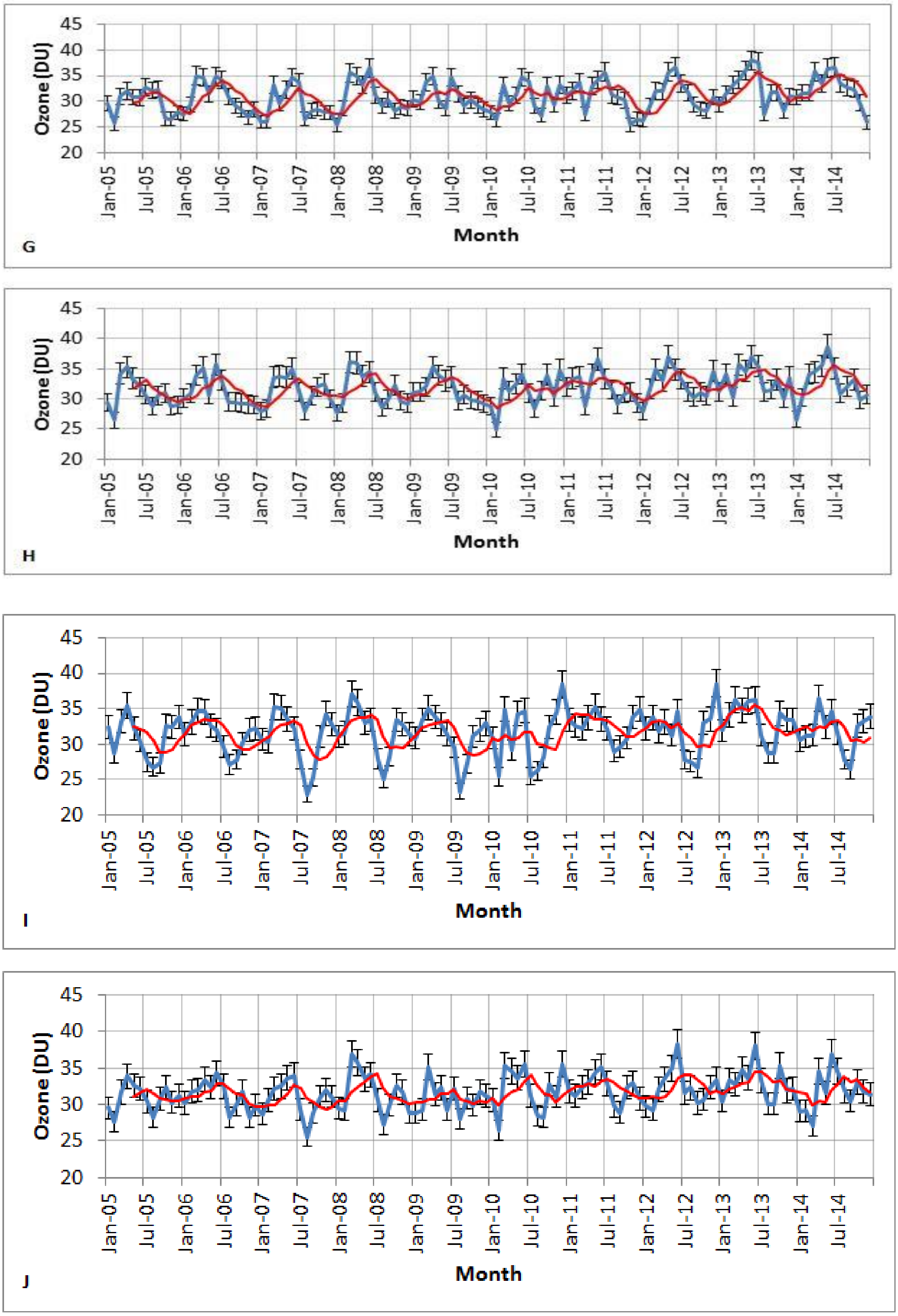
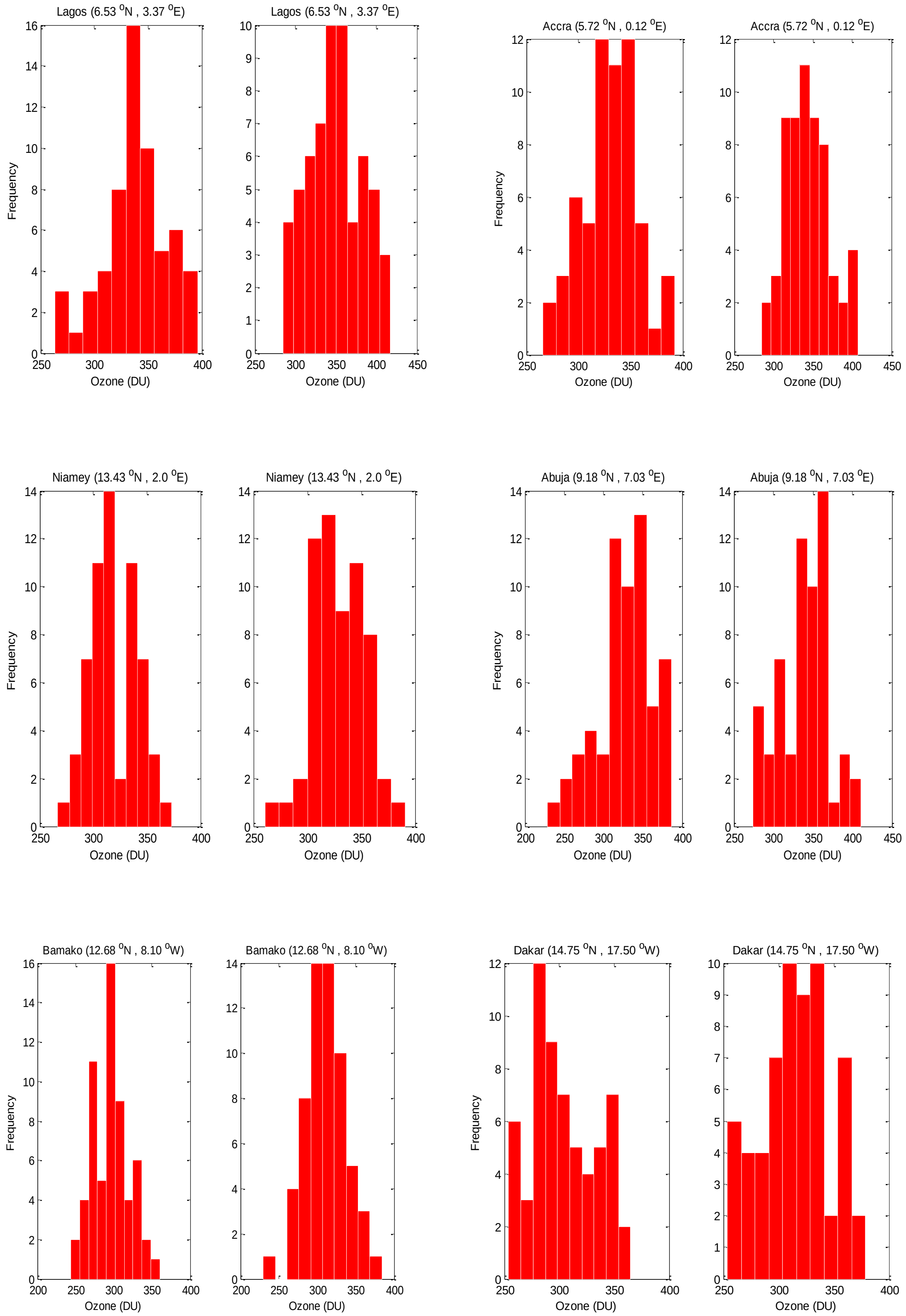


Fig. 2. Temporal variation of TCTO monthly averages. The red line is the six month moving average of the data. The error bars were estimated as 5% at each data point. The plots A-J are for (A)Lagos, (B)Accra, (C) Niamey, (D)Abuja, (E)Bamako, (F) Dakar, (G)Agadez, (H)Conakry, (I)Kano and (J)Ouagadougou respectively.


Lagos (6.53 ^{o}N , 3.37 ^{o}E)
Lagos (6.53 ^{o}N , 3.37 ^{o}E)
Accra (5.72 ^{o}N , 0.12 ^{o}E)
Accra (5.72 ^{o}N , 0.12 ^{o}E)
Niamey (13.43 ^{o}N , 2.0 ^{o}E)
Niamey (13.43 ^{o}N , 2.0 ^{o}E)
Abuja (9.18 ^{o}N , 7.03 ^{o}E)
Abuja (9.18 ^{o}N , 7.03 ^{o}E)
Bamako (12.68 ^{o}N , 8.10 ^{o}W)
Bamako (12.68 ^{o}N , 8.10 ^{o}W)
Dakar (14.75 ^{o}N , 17.50 ^{o}W)
Dakar (14.75 ^{o}N , 17.50 ^{o}W)
Frequency
Ozone (DU)
0
2
4
6
8
10
12
14
16
200
250
300
350
400
450

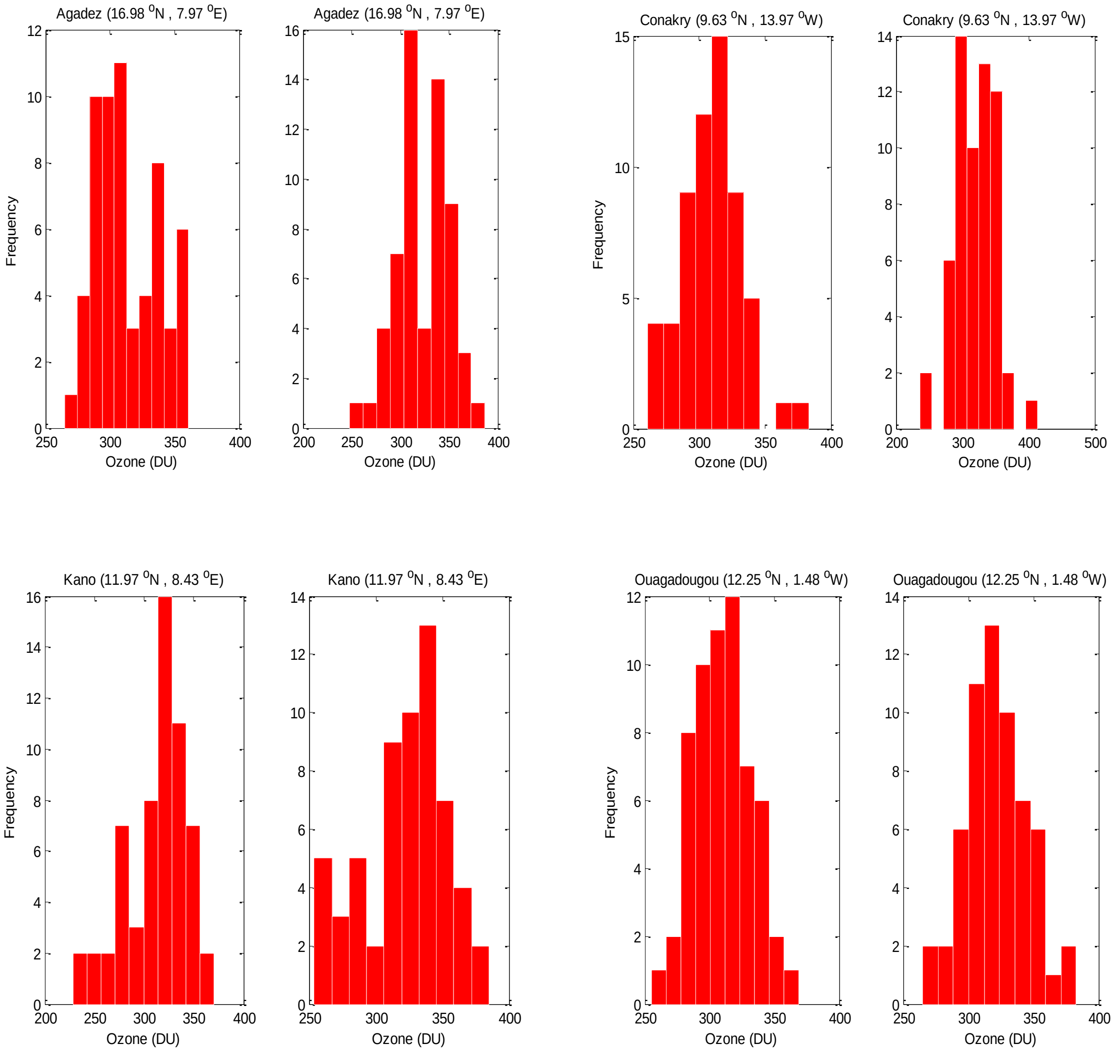


Fig. 3. Frequency distribution of TCTO concentration (x 10) in some major cities of West Africa. The right and left panels are monthly average distribution between 2005-2009 and 2010-2014 respectively.

Correlation between TCTO and atmospheric circulation

The relation between TCTO and atmospheric circulation is critical to the accumulation or dispersion of the pollutant concentrations. A favorable atmospheric condition will ensure quick dispersion of pollutants, thus ensuring improved air quality. Spatial distribution of monthly horizontal divergence, meridional wind speeds, zonal wind speed, and vertical velocity is presented in this section which covers the entire West African Space within a longitude of 20^{o}W to 20^{o}E and latitude of 0^o to 25^{o}N at two pressure levels of 1000 hpa and 850/ 700 hpa in the atmosphere, representing surface layer and near the top of atmospheric boundary layer respectively. Incidentally, the 700 hpa pressure level coincides with the height at which the African Easterly Jet (AEJ) is located over West Africa. Appearance, latitudinal location, and the strength of this jet modify atmospheric flows over the sub region (Grist and Nicholson, 2000). At the surface in January (Fig. 4), air converges principally in the stations, located south of latitude 12^o N with pockets of convergence apparently due to local factors to compensate for widespread divergence. North of the latitude, it appears that divergence is predominant, though with pockets of convergence. The pattern of divergence-convergence in January intensifies in February, but starts to change in March. At this period, convergence is only strong near the coastline of West Africa, probably due to the wind blowing from the sea into the land. Low level convergence is a marked feature of sea breeze, which in this case might be responsible for the near permanent low level convergence along the coast. Between April and September, during the summer rain, the region of strong divergence extends from the south (excluding the coastline, where convergence is still very strong) to latitude 16^{o}N and beyond and later return to January situation, beginning the change from October. The predominance of divergence during the boreal summer is primarily due to outflow from tall rain-bearing clouds At upper level near 700 hpa, as shown in Figure 5, horizontal convergence in January appears to be dominant across the latitudinal belt approximately between 7^{o}N and 12^{o}N, (Guinea and sudanian savannah) which is strongest at the fringes around mountainous areas; however, in the mountainous regions of Cameroon to the east and fouta Djallon to the west, there is strong divergence, apparently due to the presence of the mountains. Also along the coastline, bordering the ocean, divergence is predominant. Across the Sahelian latitudinal belt between 11^{o}N and 16^{o}N, the atmosphere is predominantly divergent. Divergence and convergence pattern in February is similar to what has been obtained in January. In March, this pattern in the sub-region changes, manifesting areas of strong convergence between latitude 7^{o}N and 12^{o}N while divergence prevails over the coast and the sahelian regions. This condition becomes widespread in April, thereby leading to the extension of upper level convergence from Sudanian Savannah to the Sahelian region. Between May and September, the condition in West Africa is predominantly convergent with patches of divergence apparent due to local factors; however, starting again from October an opposite situation begins to show up. The results of correlation obtained between divergence at the surface and upper atmosphere and TCTO through bootstrapping in each location of interest are depicted in Table 4a & b. We define significant correlation as $r = \frac{1}{e}$ (Oluleye and Akinbobola, 2010). By this definition a value of ±0.37 is chosen as the limit of correlation which is more robust than choosing arbitrary value of ±0.2 as adopted by Schwanghart and Schütt, (2007). The relation between divergence and TCTO reveals significant negative correlation coefficients in locations, where divergence is strong along with positive values where divergence is weak. For example, in January, February, and March in Abuja correlation coefficients are strong and positive, (0.43, 0.43, and 0.37). During this period horizontal convergence is very strong in Abuja at the surface. It should be noted also that these months are dry periods in Abuja. However, at the upper level correlation coefficients are weak and negative during the same period, indicating relatively moderate divergence which is explained as the interplay between divergence and convergence. Although there is a weak convergence in Abuja, the surrounding areas showed a strong divergence. The existence of a strong divergence around the station ensures material transport *'away'* from the area, thus reducing TCTO concentrations and the negative weak correlation coefficients. Overall, the domination of weak negative correlation coefficients between divergence and TCTO in most areas and for greater portion of the year in West Africa both at the surface and near the tropopause indicates that divergence disperses TCTO concentrations in the atmosphere with relatively weak convergence.

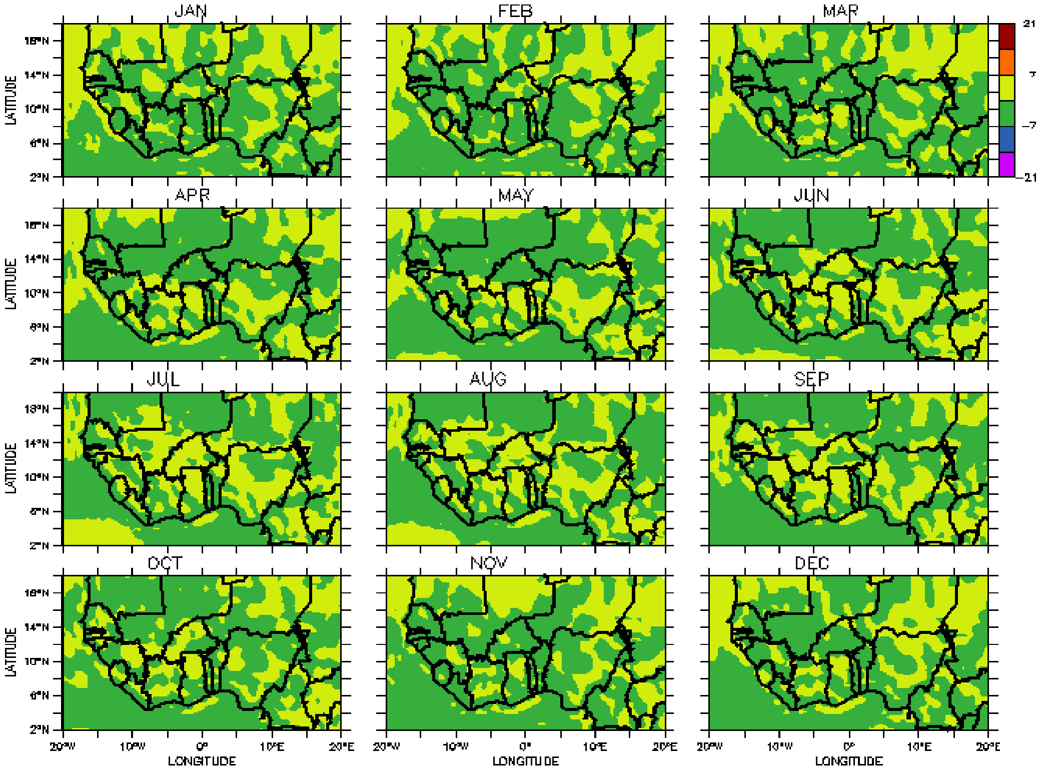


Fig. 4. Surface (1000 hpa) divergence

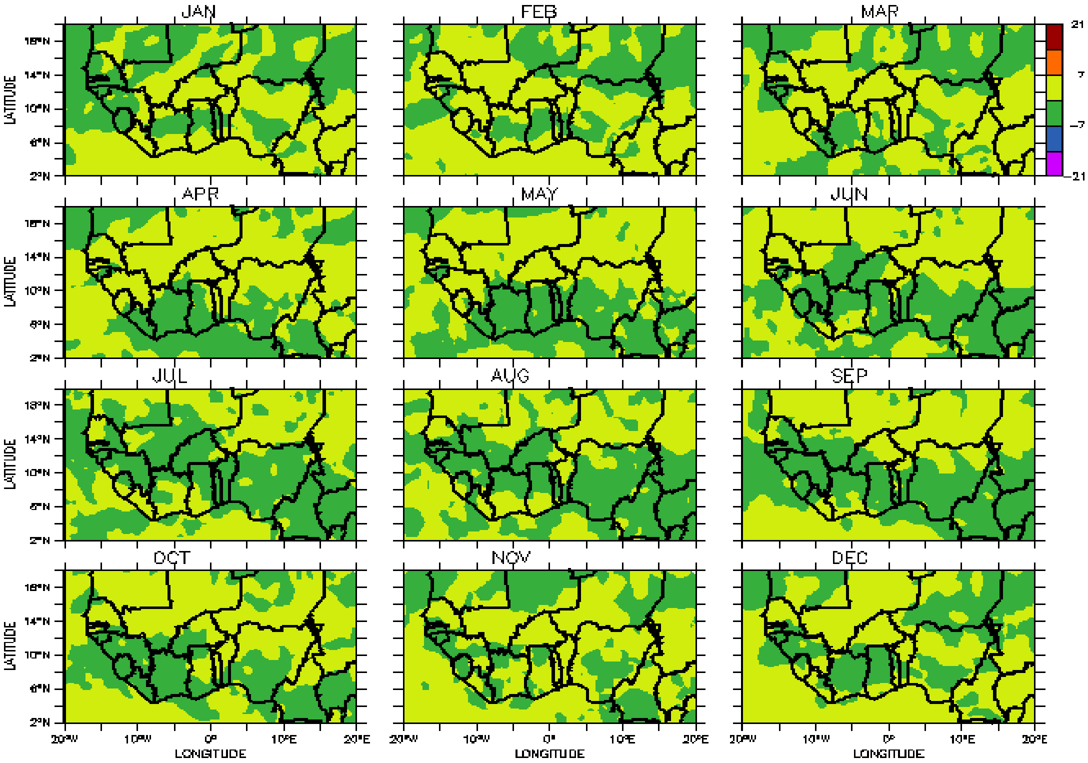


Fig. 5. Upper level (700 hpa) divergence

Table 4a. bootstrap correlation coefficient between TOMS tropospheric ozone and horizontal divergence at 1000 hpa level. Bold are significant correlations

Cities	Lat	Lon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abuja	9.18	7.03	**0.43**	**0.43**	**0.37**	0.20	-0.19	-0.18	-0.04	**-0.44**	-0.09	-0.07	**0.82**	-0.08
Lagos	6.53	3.37	-0.13	-0.08	-0.11	-0.14	0.13	0.21	0.25	0.22	0.29	-0.24	-0.31	-0.27
Accra	5.72	0.12	**0.74**	0.30	0.11	**-0.43**	0.27	**-0.46**	0.00	0.15	**0.59**	-0.01	**-0.57**	**0.56**
Agadez	16.98	7.97	0.31	0.03	**-0.38**	**0.58**	-0.05	**-0.50**	-0.10	-0.15	-0.23	**-0.42**	**0.45**	**0.47**
Bamako	12.68	-10	**-0.47**	-0.27	0.26	0.25	-0.34	0.13	**0.54**	0.02	**0.47**	0.10	0.12	0.03
Conakry	9.63	-13.97	0.13	**0.44**	**0.50**	**0.53**	**-0.58**	0.15	0.29	0.26	-0.06	0.34	0.21	-0.11
Dakar	14.75	-17.5	**-0.34**	-0.15	-0.24	-0.09	-0.25	-0.24	-0.15	**-0.57**	**-0.75**	-0.02	**-0.38**	-0.26
Kano	11.97	8.43	0.09	-0.02	-0.16	-0.09	0.01	0.07	0.18	**0.38**	**-0.43**	**0.42**	-0.21	0.14
Niamey	13.43	2	**-0.52**	0.07	0.14	0.25	-0.14	0.05	0.32	-0.36	0.02	**-0.39**	-0.12	0.23
Ouagadougou	12.25	1.48	-0.18	**0.47**	**-0.42**	0.27	**-0.59**	**0.41**	**0.40**	-0.19	0.28	0.30	-0.22	0.28

Table 4b. bootstrap correlation coefficient between TOMS tropospheric ozone and horizontal divergence at 700hpa level

Cities	Lat	Lon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abuja	9.18	7.03	-0.15	-0.18	-0.19	-0.27	-0.29	**-0.42**	**-0.35**	0.10	-0.11	-0.16	**-0.54**	**-0.47**
Lagos	6.53	3.37	0.02	0.28	0.23	0.28	0.23	**-0.45**	-0.11	0.11	0.17	0.15	0.23	**0.39**
Accra	5.72	0.12	0.13	-0.15	0.18	**-0.50**	**0.39**	-0.08	**-0.67**	**0.43**	**0.38**	0.18	-0.06	0.20
Agadez	16.98	7.97	0.04	**-0.51**	-0.15	0.02	-0.14	**0.70**	-0.02	**-0.35**	0.12	**0.52**	-0.32	-0.22
Bamako	12.68	-10	**0.52**	-0.14	**-0.52**	**0.37**	-0.12	**-0.43**	0.18	**-0.38**	**-0.42**	0.00	0.08	**0.38**
Conakry	9.63	-13.97	0.27	-0.32	0.31	0.25	**0.79**	0.17	-0.34	-0.06	**0.41**	0.12	**0.37**	**0.53**
Dakar	14.75	-17.5	**0.86**	-0.05	-0.03	**0.49**	0.10	0.05	-0.18	0.19	**0.44**	0.18	-0.18	0.07
Kano	11.97	8.43	**0.43**	0.18	-0.02	**-0.44**	-0.03	-0.10	**0.75**	-0.36	-0.05	**-0.69**	0.18	0.25
Niamey	13.43	2	0.27	0.27	-0.17	-0.02	-0.24	0.02	0.05	-0.25	0.09	**-0.43**	0.33	0.23
Ouagadougou	12.25	1.48	0.30	**-0.48**	**0.53**	-0.18	**0.62**	**-0.49**	**-0.74**	0.27	0.08	**-0.63**	-0.19	0.10

Furthermore, we have examined the relation between mean zonal and meridional wind speeds and TCTO concentrations. Zonal winds are flow from west to east or from east to west. Their values are positive in the former case (easterly) and negative in the latter (westerly). Similarly, meridional winds flow from the south to north or from north to south and their values are positive in the former and negative in the latter. Figure 6 presents the monthly mean pattern of flow for both the zonal and meridional winds at the surface (1000 hpa). In January westerly flows are prevalent over the region south of latitude 8^{o} N, which persisted till March with gradual extension pole-ward. The meridional component also took south to north direction during the same period, becoming stronger in succeeding months of April through June. The west-east flows of the zonal winds are not '*directly*' straight from west to east and similarly, the south-north flows of meridional are not so. The two wind regimes interact and cause the directions of flow to adjust in south-westerly or north-easterly direction. At the upper level, as shown in Figure 7, the flow is predominantly easterly for zonal and north-southerly for meridional winds in January and becomes stronger in subsequent months with the appearance of core of wind maximum (a Jet) in May around latitude 10^{o}N, persisting until October. This wind maximum is the well-known African Easterly Jet (AEJ) that occurs as a consequence of surface thermal stratification between south and north over West Africa (Diedhiou et al., 1998; Grist and Nicholson, 2001; Diongue et al., 2002; Sultan et al., 2003). Thus, while the surface winds are south-westerly, the upper winds are predominantly north-easterly. The wind flow regime has severe implication on the distribution of TCTO in the region. Correlation coefficients in Table 5a obtained among the surface zonal winds, indicate that strong positive relation exists such that the wind flows tend to enhance TCTO concentrations by transporting it from one location to another. The correlation coefficients are particular strong in the raining season months of May to September, perhaps due to sufficiently strong winds strengthened by downdraft winds from matured tall clouds; however, during the months of transition from dry season to wet season (March and April), there are weak negative correlations due to stronger winds, decreasing TCTO concentrations. During these transition periods, clouds develop, though without precipitation most of the time; therefore, the winds associated with the clouds disperse TCTO at the surface, hence the negative weak correlation. At the 700 hpa level, relation is generally negative (Table 5b) correlated and strongest in May with r>0.70. The role of zonal winds at this level in the atmosphere appear to be that of washing out, which can only be understood when considered in line with entrainments into the stratosphere from tall clouds. In addition, there exist at this level fast east-ward moving winds (AEJ) transporting atmospheric contents; therefore, the chance of accumulation is greatly reduced. Meridional winds have the same effects as that of zonal winds on TCTO because the correlation between TCTO and the winds are basically negative (Tables 6a & b).

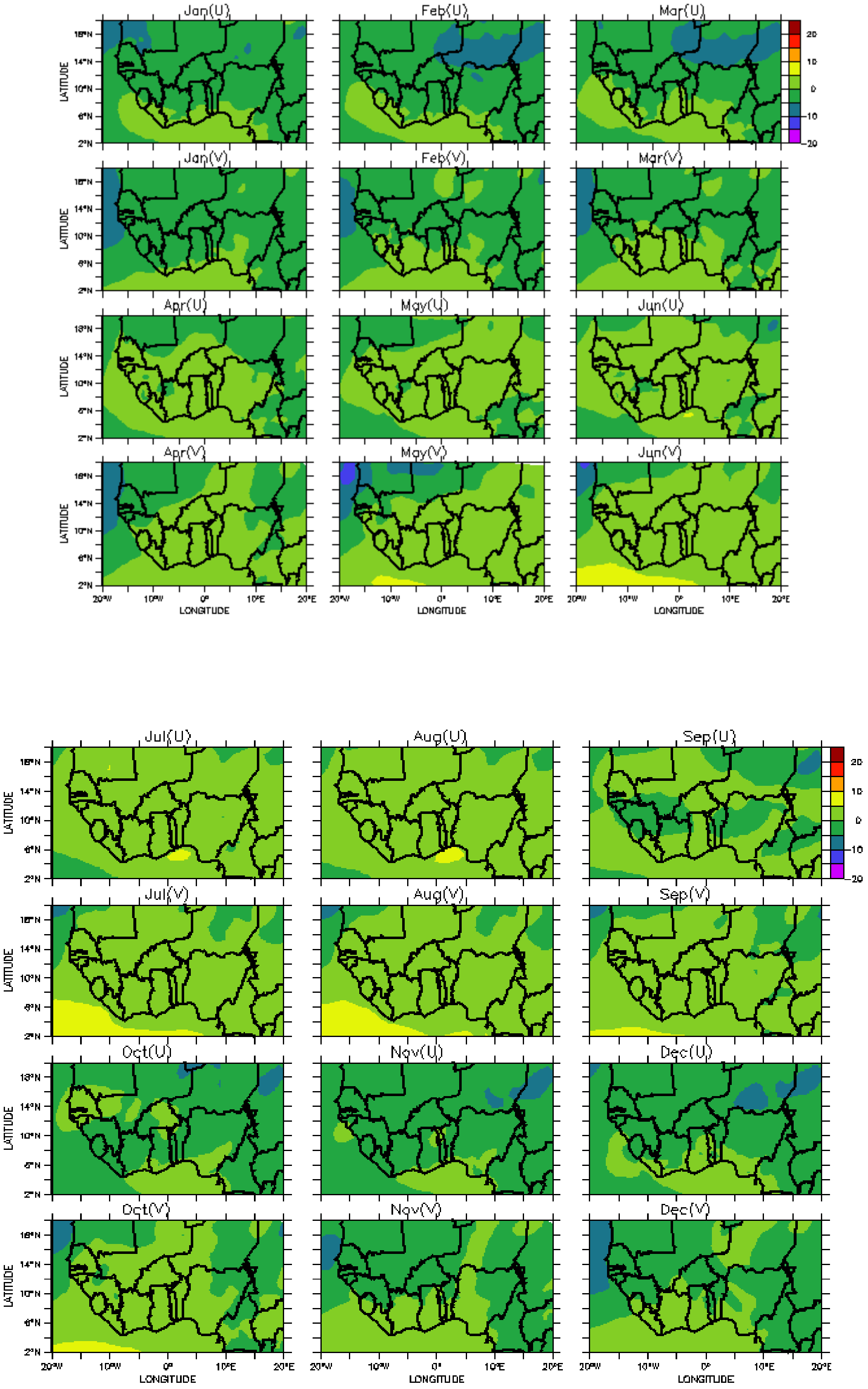


Fig. 6. monthly average zonal (U) and meridional (V) wind speeds at the surface (1000 hpa). The first and third rows are zonal winds while 2nd and 4th rows are meridional winds

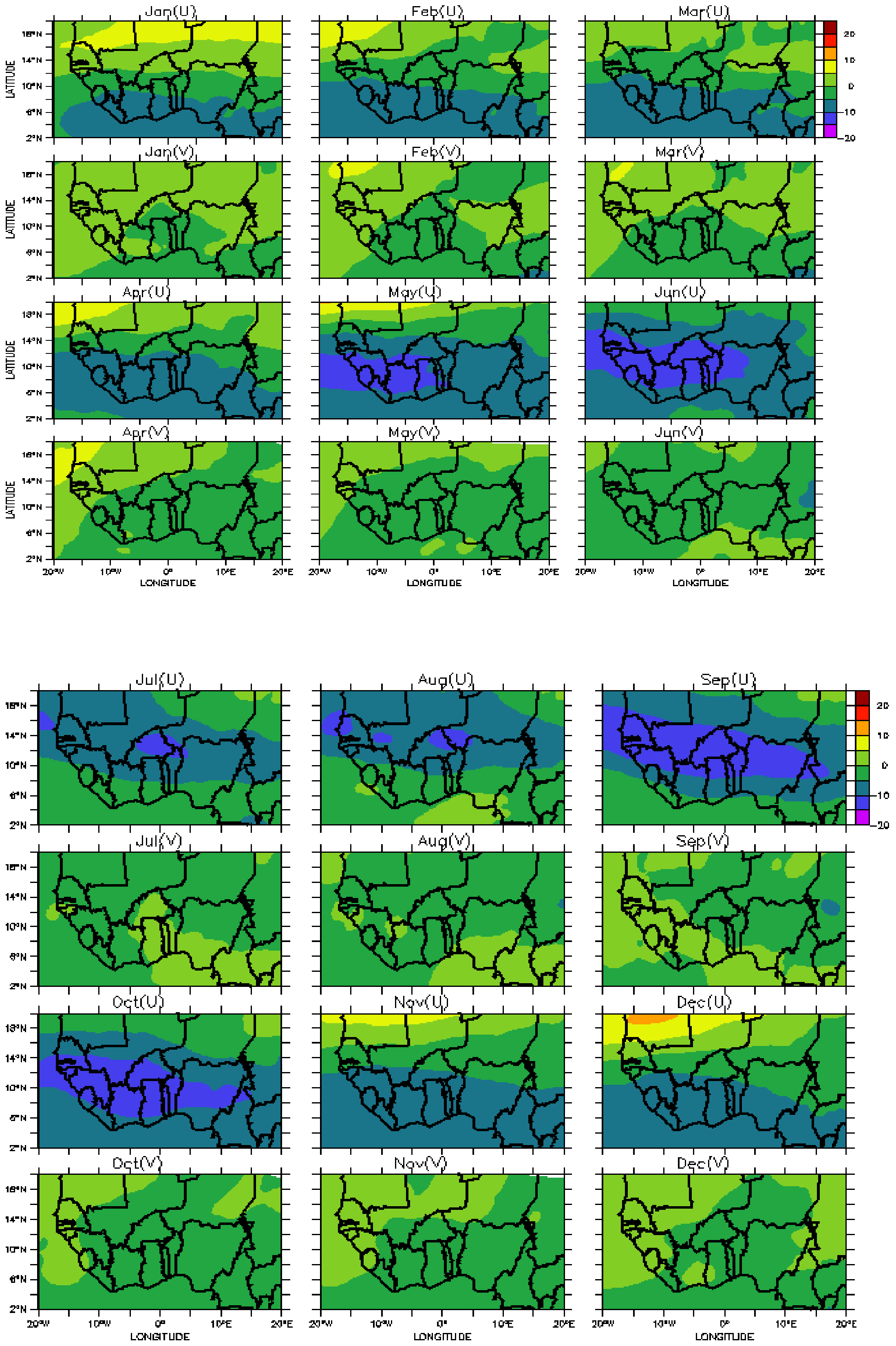


Fig. 7. monthly average zonal (U) and meridional (V) wind speeds at the surface (750 hpa)

Table 5a. bootstrap correlation coefficient between TOMS tropospheric ozone and zonal wind speeds at 1000 hpa level

Cities	Lat	Lon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abuja	9.18	7.03	**0.47**	0.05	-0.08	0.13	**0.52**	0.32	**0.48**	**0.42**	0.26	-0.03	**0.62**	0.29
Lagos	6.53	3.37	**0.46**	0.21	0.17	**-0.61**	**0.73**	-0.23	0.30	0.01	**0.38**	-0.10	0.05	0.22
Accra	5.72	0.12	**0.74**	0.17	0.28	-0.15	**0.66**	**0.49**	0.33	0.21	0.30	-0.03	**0.39**	0.13
Agadez	16.98	7.97	-0.10	**0.49**	-0.26	-0.15	**0.70**	**0.72**	**0.73**	**0.77**	**0.49**	**0.47**	0.15	**0.63**
Bamako	12.68	-10	**0.47**	0.29	-0.16	-0.02	**0.83**	**0.70**	**0.46**	**0.65**	**0.51**	0.13	**0.44**	0.25
Conakry	9.63	-13.97	0.23	0.30	0.17	-0.01	**0.70**	0.10	0.26	0.15	0.29	0.15	0.35	**0.38**
Dakar	14.75	-17.5	0.12	**0.42**	-0.27	**-0.67**	**0.42**	**0.54**	**0.53**	**0.58**	0.35	**0.37**	0.32	**0.53**
Kano	11.97	8.43	0.09	-0.01	-0.15	-0.09	0.01	0.04	0.19	**0.38**	**-0.43**	**0.42**	-0.21	0.15
Niamey	13.43	2	**0.38**	0.25	**-0.58**	0.05	**0.74**	**0.71**	**0.56**	**0.39**	**0.52**	0.14	**0.42**	**0.65**
Ouagadougou	12.25	1.48	**0.37**	0.18	-0.34	0.23	**0.41**	**0.79**	**0.62**	**0.83**	-0.14	0.34	**0.60**	**0.57**

Table 5b. bootstrap correlation coefficient between TOMS tropospheric ozone and zonal wind speeds at 700 hpa level

Cities	Lat	Lon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abuja	9.18	7.03	**-0.46**	0.07	0.16	-0.25	**-0.46**	**-0.49**	**-0.61**	**-0.59**	-0.15	0.09	**-0.37**	-0.20
Lagos	6.53	3.37	**-0.48**	-0.30	-0.19	**0.45**	**-0.70**	-0.12	**-0.16**	**-0.39**	-0.21	-0.19	-0.35	-0.24
Accra	5.72	0.12	**-0.60**	**-0.51**	-0.32	0.19	**-0.71**	0.08	-0.02	-0.22	-0.36	**0.55**	-0.14	-0.22
Agadez	16.98	7.97	0.33	-0.34	-0.11	-0.16	**-0.48**	**-0.67**	**-0.58**	**-0.44**	**-0.45**	**-0.51**	**-0.39**	**-0.39**
Bamako	12.68	-10	-0.30	-0.30	0.00	0.00	**-0.70**	**-0.60**	**-0.60**	**-0.50**	**-0.40**	-0.10	**-0.40**	-0.10
Conakry	9.63	-13.97	0.08	-0.29	-0.07	-0.10	**-0.42**	**-0.37**	-0.25	-0.33	**-0.66**	-0.25	-0.02	**-0.39**
Dakar	14.75	-17.5	0.29	**-0.43**	0.20	-0.09	**-0.66**	**-0.77**	**-0.76**	**-0.69**	**-0.49**	**-0.41**	-0.12	**-0.42**
Kano	11.97	8.43	-0.14	-0.22	**0.53**	0.06	-0.23	**-0.77**	**-0.50**	**-0.69**	-0.14	**-0.40**	-0.28	**-0.43**
Niamey	13.43	2	-0.13	-0.27	**0.43**	-0.13	**-0.62**	**-0.80**	**-0.65**	**-0.37**	**-0.54**	-0.35	**-0.57**	**-0.47**
Ouagadougou	12.25	1.48	-0.19	-0.22	**0.39**	-0.20	-0.20	**-0.80**	**-0.70**	**-0.81**	0.01	**-0.40**	**-0.50**	**-0.41**

Table 6a. bootstrap correlation coefficient between TOMS tropospheric ozone and meridional wind speeds at 1000 hpa level

Cities	Lat	Lon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abuja	9.18	7.03	**0.58**	0.00	0.00	0.23	**0.56**	**0.35**	**0.45**	**0.57**	0.23	-0.17	**0.56**	**0.38**
Lagos	6.53	3.37	**0.56**	0.25	0.23	**-0.60**	**0.79**	-0.31	0.34	0.17	**0.36**	-0.23	-0.09	0.15
Accra	5.72	0.12	**0.57**	0.33	**0.43**	-0.33	**0.82**	0.17	0.15	0.20	0.26	-0.33	0.22	0.06
Agadez	16.98	7.97	0.20	**0.45**	-0.01	**-0.63**	**0.39**	**0.37**	0.32	**0.56**	-0.06	0.11	**0.47**	**0.36**
Bamako	12.68	-10	-0.36	**0.42**	0.24	-0.17	**0.41**	0.20	-0.03	-0.12	**-0.40**	**-0.42**	0.04	-0.23
Conakry	9.63	-13.97	-0.22	**0.41**	0.07	0.32	0.16	**0.54**	0.04	0.21	**0.69**	0.32	-0.05	0.29
Dakar	14.75	-17.5	-0.05	**-0.44**	0.04	**0.62**	**-0.42**	-0.25	-0.22	**-0.44**	0.20	-0.02	**-0.53**	**-0.45**
Kano	11.97	8.43	0.13	0.21	**-0.49**	0.05	0.23	**0.78**	**0.55**	**0.67**	0.11	**0.42**	0.35	**0.44**
Niamey	13.43	2	0.25	0.19	**-0.50**	0.01	**0.62**	**0.73**	**0.71**	**0.56**	**0.54**	0.26	**0.43**	**0.48**
Ouagadougou	12.25	1.48	**0.39**	0.14	-0.23	0.23	**0.39**	**0.74**	**0.66**	**0.75**	-0.20	0.30	**0.61**	**0.52**

Table 6b. bootstrap correlation coefficient between TOMS tropospheric ozone and meridional wind speeds at 700 hpa level

Cities	Lat	Lon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abuja	9.18	7.03	**-0.68**	-0.09	0.04	0.08	**-0.67**	0.00	-0.34	**-0.53**	**-0.52**	0.08	**-0.37**	**-0.40**
Lagos	6.53	3.37	**-0.56**	-0.25	-0.07	**0.67**	**-0.77**	**0.61**	-0.26	-0.04	**-0.51**	**0.39**	0.36	0.01
Accra	5.72	0.12	-0.18	-0.23	-0.02	0.28	**-0.45**	**0.63**	0.21	-0.05	-0.35	**0.37**	0.05	-0.04
Agadez	16.98	7.97	0.16	-0.03	-0.35	-0.28	0.36	0.05	0.28	0.34	**0.44**	0.33	0.05	**0.37**
Bamako	12.68	-10	-0.36	**-0.46**	0.11	-0.01	**-0.76**	**-0.69**	**-0.55**	**-0.54**	**-0.42**	-0.15	-0.15	0.01
Conakry	9.63	-13.97	0.24	-0.35	-0.19	**-0.43**	-0.23	**-0.59**	-0.01	-0.15	**-0.58**	**-0.37**	0.09	-0.20
Dakar	14.75	-17.5	0.28	0.00	-0.09	**-0.67**	-0.20	**-0.26**	-0.22	-0.17	-0.22	-0.14	0.20	-0.02
Kano	11.97	8.43	**-0.37**	-0.29	**0.55**	0.25	-0.29	**-0.73**	**-0.42**	**-0.76**	-0.34	-0.30	**-0.43**	**-0.71**
Niamey	13.43	2	-0.12	-0.36	**0.45**	-0.20	**-0.67**	**-0.81**	**-0.49**	-0.08	**-0.49**	**-0.41**	**-0.59**	**-0.49**
Ouagadougou	12.25	1.48	-0.16	-0.27	**0.50**	-0.32	0.05	**-0.68**	**-0.69**	**-0.74**	-0.17	**-0.37**	**-0.47**	**-0.42**

From the foregoing discourse, there exists a connection between surface and upper levels in terms of exchange of atmospheric contents. Accordingly, we examine the link between the two levels by considering a coupling parameter that connects the surface and upper layers together. Vertical velocity is a coupling parameter, thanks to its role in vertical transport of the materials. On the surface, there is a predominant ascent (negative values of vertical velocity) everywhere from the coast to latitude 10^oN, beyond which there are patches of descending motions **(**Fig. 8). This widespread ascent is understood to be a consequence of convection, caused by surface heating. The convection generates rising air parcels (thermals) that ascend to upper layers. During the ascent, the atmospheric content (TCTO) is lifted from the surface and transported aloft with the parcels of air, until the parcels form clouds that could either dissipate or rise further to form tall clouds entraining into the stratosphere. Correlations between surface vertical velocity and TCTO, shown in Table 7a, are significantly negative suggesting that the parameter's role, in this case, is to reduce surface TCTO in rising motion due to convection. Similarly, at the upper level (700 hpa), in January, as shown in Figure 9, a band of descending motion exists roughly between latitude 7^oN and 11^oN, where on both sides of the latitudinal band there is an ascending motion to the south and north, apparently as a compensation for the region of descending motion. An important consequence of the descending motion or subsidence is the suppression of cloud development. Thus, it should be understood that while there is some ascent on the surface, vertical transport of the materials from the surface is restricted to a certain level in the atmosphere (perhaps, not beyond the boundary layer height) as a result of suppressing subsidence aloft. This probably explains while low level clouds rarely grow tall during this period over West Africa. Starting from March, the latitudinal band of descending motion is being encroached by ascending from both south and north sides of the latitudinal band. This is a result of northward propagation of converging zone of north-east and south–west winds. As the zone moves northward, the ascending motion is strengthened until October, before retreating to its initial (January) situation, beginning from November. Correlations between upper level vertical velocity and TCTO, shown in Table 7b, shows inverse relationship, i.e. as the vertical velocity strengthens, TCTO concentrations reduce. However, the correlations are weak in most stations and in some months. For example, in February, all correlation coefficients are inverse, though none is significant. Similar situations occur when the ascent is weak and there are sections of subsidence. In fact, both ascent and subsidence occur in the atmosphere at all times, but the strength and dominance of either depend on triggering factors such as the ITD and wind regimes.

It is apparent that accumulation or dispersion of TCTO depends on interacting circulation parameters. Certain scenarios, worthy of being considered, arise from the combined effects of atmospheric circulation parameters. First, convergence and ascent at the surface coupled with divergence and further ascent at the top will ensure outflow of TCTO into the stratosphere, where and when this occurs, (e.g., over the coastal cities between January and March) TCTO concentration is expected to be minimum. However, in Lagos and indeed cities close to the coast, this period corresponds to the time when TCTO seasonal average becomes maximum. A quick look at the wind, both at the surface and upper level suggests that north-bound south westerly flow is not developed beyond latitude 6^oN on the surface, whereas the opposite wind, north easterly, is strong and almost reaching the coast. Also at the upper level, the wind is predominantly easterly suggesting a condition, favourable to the accumulation of south-bound atmospheric constituents, its result being temporary stagnation in the coast during DJF and, hence, high TCTO concentrations. Secondly, during the wet period, south westerly wind is fully developed and strengthened, flowing pole-ward and breaking through DJF stagnation. This progress combined with the effect of surface ascent ensures dispersion and vertical transport of TCTO, thereby reducing TOP during the season.

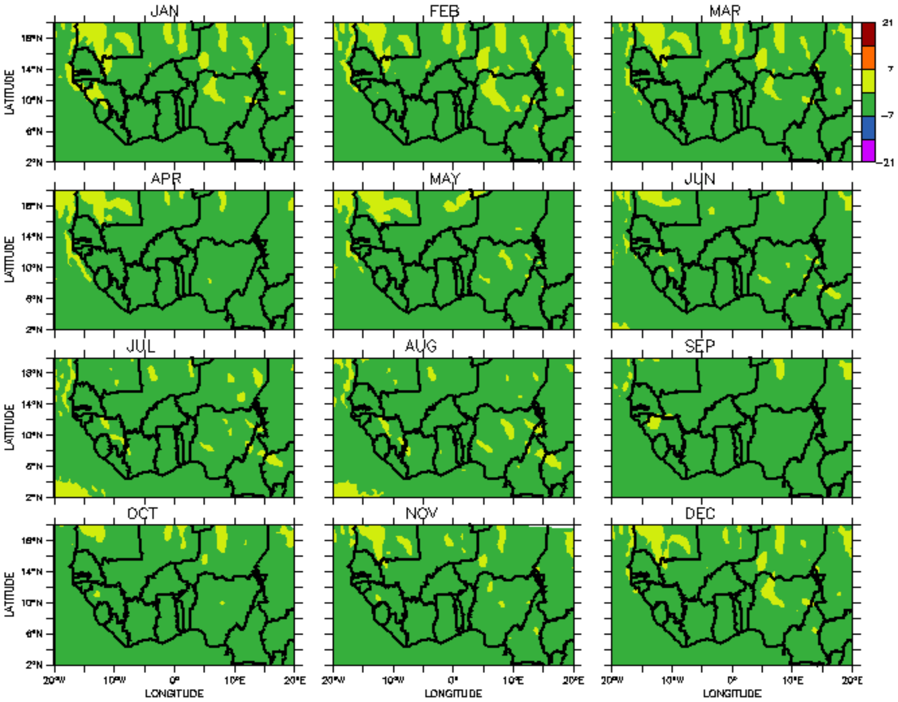


Fig. 8. Vertical velocity at the surface (1000 hpa)

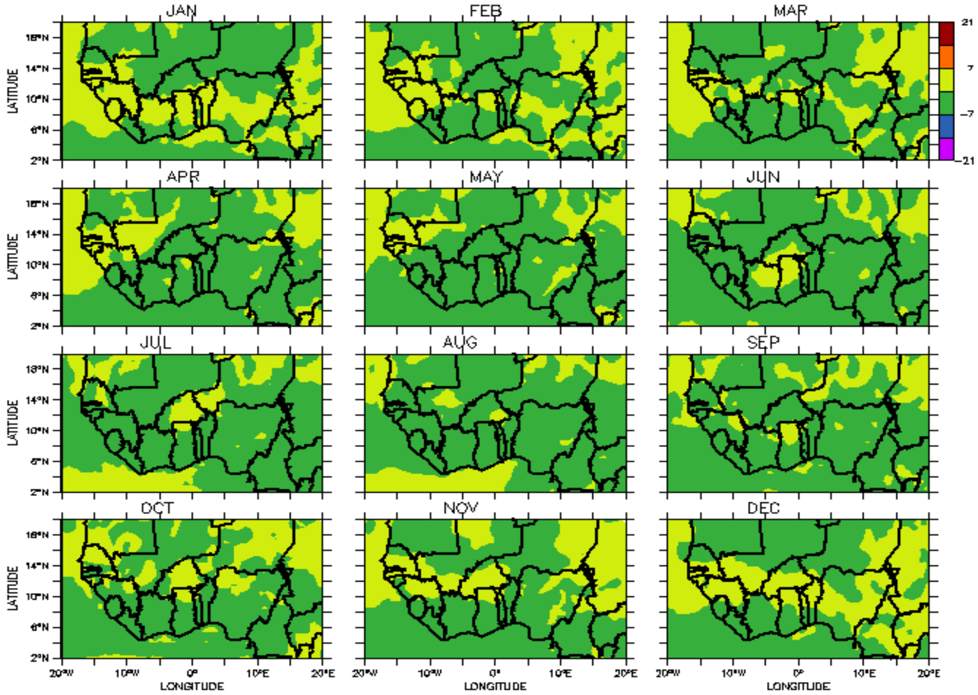


Fig. 9. Vertical velocity at the upper level (750 hpa)

Table 7a. bootstrap correlation coefficient between TOMS tropospheric ozone and vertical wind speeds at 1000 hpa level

Cities	Lat	Lon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abuja	9.18	7.03	**-0.51**	-0.04	0.05	-0.15	**-0.54**	-0.35	**-0.50**	**-0.49**	-0.27	0.06	**-0.60**	-0.31
Lagos	6.53	3.37	**-0.55**	-0.25	-0.18	**0.62**	**-0.79**	0.29	-0.30	-0.13	**-0.43**	0.21	0.09	-0.15
Accra	5.72	0.12	**0.43**	0.27	0.21	0.17	0.08	**0.75**	0.01	0.08	0.20	-0.35	0.16	0.19
Agadez	16.98	7.97	0.08	**-0.51**	0.22	0.22	**-0.70**	**-0.73**	**-0.73**	**-0.80**	**-0.44**	**-0.45**	-0.21	**-0.63**
Bamako	12.68	-10	**-0.62**	-0.16	0.20	-0.04	**-0.68**	**-0.62**	**-0.39**	**-0.64**	**-0.57**	-0.27	**-0.50**	**-0.40**
Conakry	9.63	-13.97	0.05	-0.33	-0.03	-0.18	**-0.39**	**-0.40**	-0.18	-0.30	**-0.67**	-0.36	-0.11	**-0.44**
Dakar	14.75	-17.5	0.21	-0.33	0.27	0.02	**-0.57**	**-0.68**	**-0.74**	**-0.61**	**-0.59**	**-0.47**	-0.16	**-0.45**
Kano	11.97	8.43	0.16	0.31	**-0.46**	0.04	0.26	**0.80**	**0.54**	**0.67**	0.15	**0.43**	**0.43**	**0.49**
Niamey	13.43	2	**0.38**	0.24	**-0.65**	0.06	**0.68**	**0.72**	**0.61**	**0.43**	**0.53**	0.23	**0.44**	**0.61**
Ouagadougou	12.25	1.48	0.32	0.26	**-0.53**	0.19	0.33	**0.83**	**0.66**	**0.86**	-0.09	**0.44**	**0.48**	**0.54**

Table 7b. bootstrap correlation coefficient between TOMS tropospheric ozone and vertical wind speeds at 700 hpa level

Cities	Lat	Lon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abuja	9.18	7.03	**-0.53**	0.08	0.23	0.09	**-0.49**	-0.34	**-0.54**	**-0.57**	-0.34	-0.09	**-0.50**	-0.34
Lagos	6.53	3.37	**-0.53**	-0.18	-0.22	0.35	**-0.63**	-0.26	-0.26	**-0.39**	-0.20	-0.25	-0.36	**-0.42**
Accra	5.72	0.12	**-0.58**	-0.26	**-0.43**	0.32	**-0.83**	-0.20	-0.23	-0.28	-0.28	0.25	-0.34	-0.17
Agadez	16.98	7.97	**-0.45**	-0.18	0.29	**0.67**	**-0.37**	-0.04	**-0.47**	**-0.66**	-0.07	0.15	-0.02	**-0.54**
Bamako	12.68	-10	-0.10	-0.09	0.00	-0.17	-0.10	-0.22	**-0.61**	0.00	-0.33	-0.19	-0.06	0.34
Conakry	9.63	-13.97	**0.37**	0.29	**0.48**	**-0.40**	0.17	-0.34	-0.18	**-0.39**	**-0.90**	**-0.72**	0.13	-0.30
Dakar	14.75	-17.5	-0.03	0.13	-0.07	**0.44**	**0.64**	0.05	0.36	**0.47**	0.28	0.20	0.05	0.30
Kano	11.97	8.43	-0.13	-0.28	**0.39**	-0.34	-0.05	**-0.62**	**-0.49**	**-0.73**	-0.07	**-0.50**	-0.20	**-0.39**
Niamey	13.43	2	-0.19	0.02	**0.56**	-0.26	-0.11	**-0.66**	**-0.77**	**-0.49**	**-0.55**	**-0.59**	**-0.42**	-0.21
Ouagadougou	12.25	1.48	0.08	-0.30	**0.74**	-0.31	0.10	**-0.76**	**-0.63**	**-0.80**	-0.29	**-0.51**	-0.24	-0.31

CONCLUSION

A decade–long measurement of total column tropospheric ozone in major cities of West Africa has been examined. Temporal analysis of the dataset has revealed a seasonal variation, in which maximum concentration is found in cities close to the coast in the months of December, January, and February. These months are dry periods when biomass burning is rampant in addition to local production of ozone precursor from car emissions. These observations are generally valid for all cities south of latitude 12^{o}N, but for regions approximately north of this latitude, there is a shift in the months when high concentrations of TCTO are noticeable, which is strongly connected to the atmospheric circulation in the study area. The correlation between atmospheric circulations, have been represented in the study by divergence, zonal, meridional, and vertical velocity. The interactions between these parameters are more important than the effect, produced by each. Although, correlation coefficients obtained by bootstrapping the dataset and obtaining 2000 replicates suggested a relationship between TCTO and each of the parameters, the combined effect summed in the two major wind regimes that appeared to dictate the seasonal accumulation or reduction of TCTO. Consequently, dry season is more polluted in study area than the wet one. Finally, we have compared a five–year monthly mean by dividing the decade into two. The second sub-period between 2010 and 2014 has had high frequency of elevated TCTO, attributable to increasing pollution related to population and infrastructure development.

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