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Daily Levels of the Harmattan Dust near the Gulf of Guinea over 15 Years: 1996-2011

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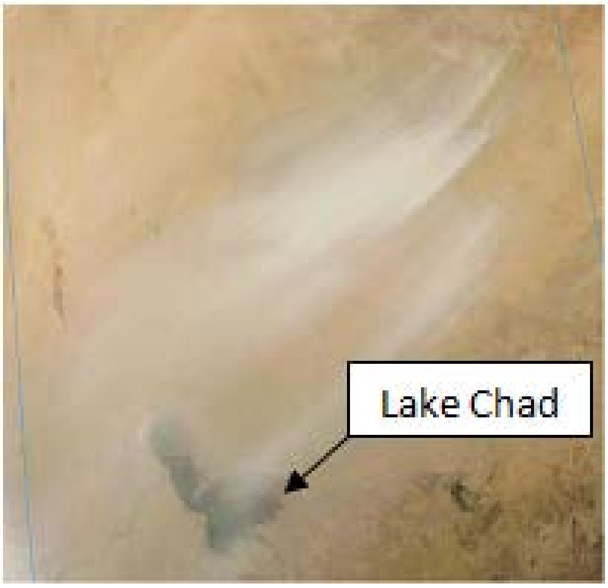
Abstract The Saharan dust which is transported over many countries in West Africa near the Gulf of Guinea (5°N) during the northern winter, known as the Harmattan period, is presented. The Harmattan dust phenomenon has influence on the climate of the region. The dust has been studied over a 15-year period, between 1996 and 2011, using a location at Kumasi in central Ghana (6° 40′N, 1° 34′W). The suspended Saharan dust particles have been sampled in situ by an optical particle counter, and the particle size and concentrations within the particle size range, 0.5–25 µm were analysed. The highest daily average particle diameter, number and mass concentrations during January-February reached 3.17 µm in Harmattan 2005, 148 particles/cm^3 in Harmattan 1997 and 6199 µg/m^3 in Harmattan 2005 respectively. It was found that the daily mean size has increased from D=1.01 µm in the period, 1996-2000, to D=1.76 µm in 2001-2011. The mass concentration has also increased from M=370 µg/m^3 over the period, 1996-2000 to M=1262 µg/m^3 in the period, 2001-2011. The increased particle size and corresponding concentrations are likely due to increased stronger winds. The diurnal characteristics of the peak Harmattan which is a period of 4-13 consecutive days of highest concentration within January – February, were also anlaysed over the 15 years. This allows the study of the trends of the physical characteristics of the suspended dust.

Keywords Atmospheric Aerosol, Harmattan Dust, Particle Size, Sahara Dust, Particle Concentrations

1. Introduction

Atmospheric dust pollution is a common environmental problem in most parts of West Africa. The atmosphere appears polluted with dust particles from various sources including vehicle exhaust, untarred road, construction sites, road construction, agricultural bush burning, soil and rock material haulage, open refuse burning and livestock movements. These sources mainly arise from human activities also known as anthropogenic sources. The airborne particles occur in different forms, such as dust, fume, mist, smoke, fog or smog. However, in addition to the normal condition, the atmospheric environment in most parts of West Africa is characterized by abnormally high suspended and deposited natural dust levels everywhere during the northern winter season. This occurrence is a result of the dusty northeast winds known as the Harmattan, which blows across the Sahara Desert through West Africa with the windblown dust particles entrained from the dust sources in the Sahara-Sahel regions. The Sahara Desert has many dust sources including the Bodélé Depression which is a well-known Sahara dust reserve that continuously eject and build up dust reservoirs in the atmosphere [1-5]. The prevailing wind over the Depression during the Harmattan period is the Northeast winds, which entrain the emitted Sahara dust and blows it towards the Gulf of Guinea and beyond. The Bodélé Depression is located in the Chad basin (Figure 1a). A typical Harmattan trajectory starting from the dust source at a height of about 300 m above ground level ending on the sampling site at 500 m above ground level at Kumasi in Ghana is shown in Figure 1b while a characteristic NE winds pattern over the region during northern winter is shown in Figure 1c.



(Lake Chad arrowed) (NASAimage courtesy the rapidfire.sci.gsfc.nasa.gov MODIS rapid response team at NASA GSFC).
Figure 1a. Bodèlè depression and the Sahara dust plume

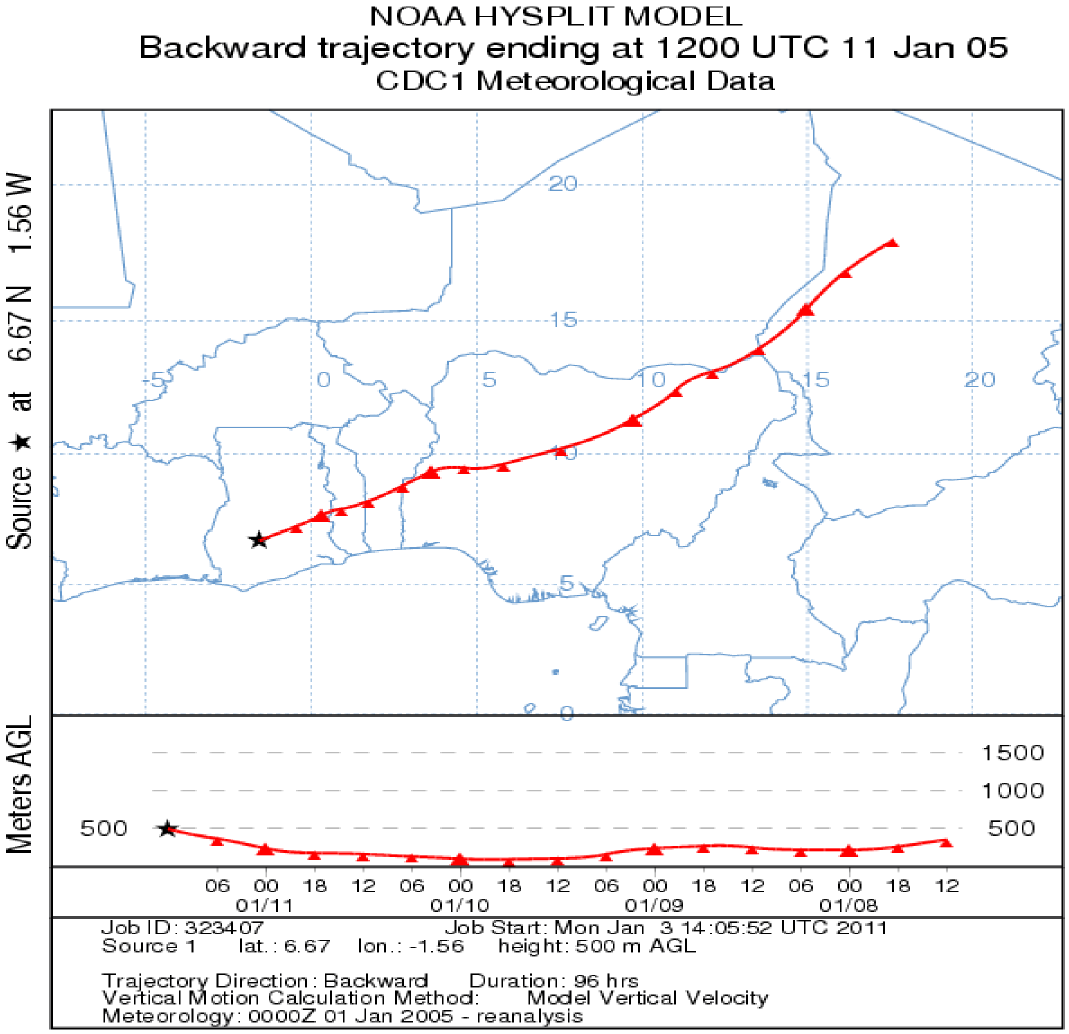


Figure 1b. A typical Harmattan trajectory derived from NOAA HYSPLIT model of 96 h (4-day) backward trajectory of winds ending in the Bodele depression on Jan. 11, 2005 from Kumasi (shown in star ★). After [6].

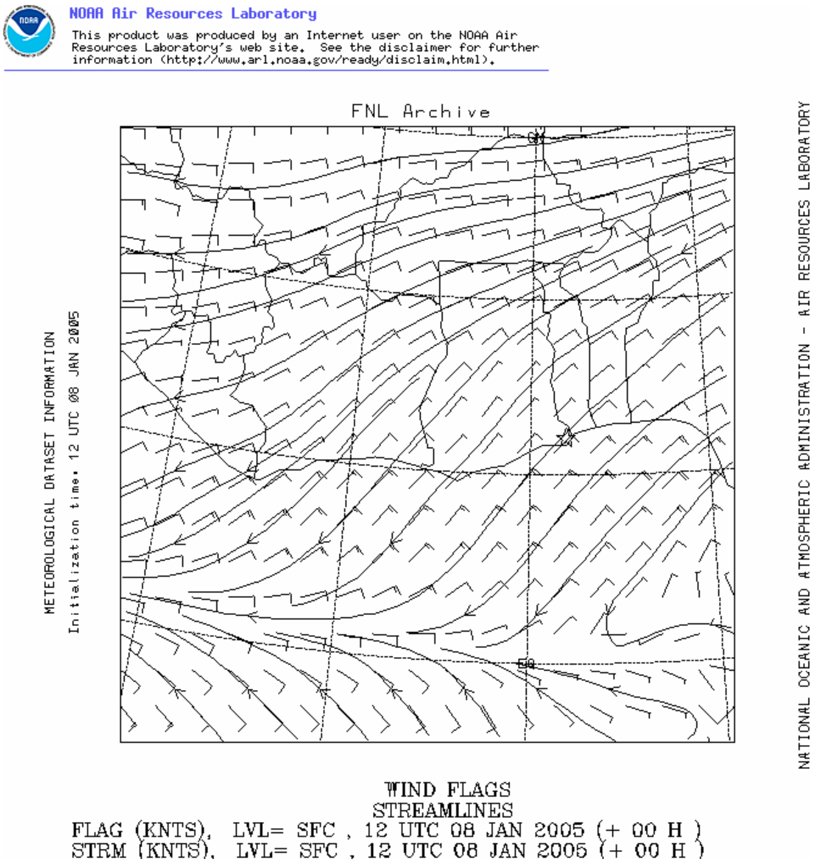


Figure 1c. Typical wind streamlines during winter in West Africa, derived from NOAA ARL.

Images taken by the Moderate Resolution Imaging Spectroradiometer (MODIS), aboard NASA satellites, indicate that the dust storms move across the Bodélé Depression at about 13 to 10 m/s [7]. The pattern of air flow is so steady that the winds have scoured a straight path on the ground, in the Bodele depression, marking the northeasterly direction of the winds [1].

One direction of these highly concentrated dusty winds ensuing from the Bodélé Depression reduces visibility over the Atlantic Ocean, off the coast of Western Sahara/ Senegal, affects the Barbados and sampled in Miami [5]. Elsewhere within the West Africa region, the reduction of visibility due to the suspended dust is often cited as the cause of road and aviation accidents as well as disruption of aviation schedules [8]. It is well known that the transport and deposition of the Saharan dust affects the Earth's radiation budget [9-11] and photolysis rates [4]. The settling dust can also have serious implication for open sun-dried agricultural produce as for example, Resch et al., observed that deposited Harmattan dust produce ground surface dust layers ranging from about 5 μm to 12 μm in 2002 and 2005 Harmattan seasons respectively [12]. Furthermore, the suspended dust affects air quality, while the deposition of the fine dust particles on exposed surfaces soils clothes, the skin, buildings and monuments.

The Harmattan dust production and transport has been studied in various study areas such as the dust sources, soil texture and strengths, period of transport, wind patterns, climate and large scale weather features including the ITCZ, the nature of the deflation, transport, and deposition of the aeolian dust material, the dust effect on the environment, air quality, climate visibility, etc. [2, 3, 6, 8, 11, 13-25].

The production of dust in the desert has been related to variables of surface soil texture, wind speed, vegetation, vegetative residue, surface roughness, soil aggregate size distribution, soil moisture and rainfall [3-5, 9, 17, 19, 26]. Wind deflation is a factor of mobilisation of loose dust particles from the dust sources. The stronger the wind, the more dust particles are mobilised. The wind forces are directly related to the wind speed which is responsible for the entrainment, advection and dispersion of the entrained dust particles. Thus stronger winds will cause larger quantities of deflated dust particles to be entrained and dispersed. Three mechanisms have been identified to be responsible for wind entrainment of sand sized particles [3]. For large sized particles (> 0.5 mm in diameter), motion is by creep which is rolling or sliding of the particles along the surface. With stronger winds, larger portions of the creeping particles will be entrained and the creeping distance will be longer. For moderate sized soil particles in diameter range (0.1 – 0.5 mm), the particles are deflated and travel by saltation or bouncing to a height of about 1.5 m above the surface. For stronger winds at the dust sources, many large sized particles are involved in the saltation movement. For particles smaller than 0.1 mm in diameter, the particles are ejected into the atmosphere beyond the saltation level into the prevailing surface winds. The particles advect with the winds in suspension. Stronger winds will suspend larger sized particles which will travel with the wind for longer distances and will remain in suspension for longer time periods before settling to the ground. Strong winds and turbulence affect the dust aerosol characteristics at a location within the Northeast trade winds regime. Stronger winds will cause the number concentration and size distribution of the suspended and settling particles to increase. Meanwhile, increase in the dust source strength in the Sahara may also be significant as this has been observed to be associated with the drought in the Sahel and agricultural use of the lands adjacent to the Desert dust sources [16, 27-30].

With increase in population and human activities in the Sahara-Sahelian region, the ancient natural Saharan dust phenomenon is now being influenced by human activities including agriculture and animal movement, and therefore the dynamics of the dust sources and the suspended dust properties need to be studied. The nature of the deflation, transport, and deposition of the aeolian dust material from the Sahara is episodic and has aslo been linked to seasonal and annual rainfall as well as large-scale weather features such as the Inter-Tropical Convergence Zone and the North Atlantic Oscillation [3, 18, 19, 31]. During summer (May-October), the areas affected by the N-E winds with the dry dust load are restricted to above 20°N and the Saharan dust laden winds do not reach the Gulf of Guinea [3].

The suspended dust particles begin to settle immediately after entrainment with the largest particles dropping out first. Stronger winds would extend the travel distance for the suspended particles. The emerging dust aerosol that is involved in the long-range transport towards the Gulf of Guinea is composed of mainly smaller particles (1-2 µm mean size), which can remain in suspension for long-periods and hence be transported across the Atlantic towards South-East America, Barbados and the Caribbean [8, 20, 30, 32]. The inter-annual and intra-seasonal particle size distribution and concentration are not uniform. The varying dust particle distributions may affect climate change and this work shows the analysis of these variations.

In Ghana, the Harmattan dust plumes arrive through the north (12^oN) in November. The ITCZ, which serves as floating barrier delimits the areas affected by the Harmattan. Areas south of the ITCZ are shielded from direct onslaught of the dusty plume. The movement of the ITCZ, which is the convergence of the dry northeast Harmattan and wet southwest monsoon winds, reaches its lowest or southernmost latitude of about 5^oN and sometimes around the equator during very severe Harmattan months of January and February [3]. Sunnu et al. (2008) have shown the variation of the measured daily mean particle number concentrations (N/cm^3) with the daily ITCZ position (P degrees Latitude) at Kumasi as $P = -1.76\text{Ln}(N) + 13$ during the Harmattan 1997-2005 seasons [8].

The impact of Saharan dust relates climate-oriented effects, which focus on the physical properties of the dust aerosols to which this article also contributes. The dust generally has been identified as an important component in the global radiation balance [17, 22]. Aerosol particles can affect climate directly by scattering and absorbing solar radiation and indirectly by impacting on cloud processes. The current knowledge on these relationships of the Harmattan dust and the impact on climate are sparse. There is severe reduction in direct solar irradiance during the Harmattan periods due to the strong attenuating effect of the dust particles in accordance with the general behaviour of dust particles whose sizes are comparable to the wavelength of visible solar radiation [33]. It is important to know the dust trends in order to study and predict future dust related climate processes. However, the long term variability of the Harmattan dust haze is scanty. Therefore, in this paper, the daily dust particle concentration monitored over 15 years (1996-2011) is used to study the trend of the Harmattan dust phenomenon in Kumasi near the Gulf of Guinea.

2. Experimental Set-up and Data Acquisition

The first step to characterise the aerosol particles is their sampling. The key objective is to setup the sampling processes to obtain a representative sample so that the characteristics of the particles are not altered by the sampling technique. The sampling site is also selected to be beyond the reach of local dust movement.

In this study, the Harmattan dust was sampled in the city of Kumasi (6°40'N) which is about 200 km (crow-flight distance) from the Gulf of Guinea. Thus Kumasi is near enough to the Gulf of Guinea for the Saharan dust particle size distribution obtained there to give a clue to the dust physical characteristics that may ultimately reach the Gulf of Guinea and travel across the Atlantic Ocean. The measurement site was located at the concrete rooftop (of an abandoned cooling tower) of the classroom building of the Department of Architecture at the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi. The University is located about two kilometers away on the southeastern outskirts of the city. The Department of Architecture is at the south-eastern border of the KNUST. The detailed description of the sampling site is given in [3].

Data acquisition was done by means of a Pacific-Scientific Hiac/Royco 5250A airborne optical particle counter (OPC). The isoaxial inlet diffuser sampler was mounted on a tripod 0.6 m above the roof top of the department building and about 2.5 m above the particle counter, which was placed inside the building. The air suction line connecting the sampler to the counter was a Teflon-lined 1-cm diameter flexible rubber hose which was passed through a hatch in the concrete roof down to the floor below where the counter was mounted on a table. Adequate experimental precautions were taken to minimize losses in the suction line due to impaction and turbulence inertia. For example, the results of the 1996 campaign were corrected because of possible particle loss due to the 10 m long tube length used. Subsequently, the sampling hose length was made 2.5 m [3] for the sampling of the aerosol in the Harmattan 1997 to 2005. For the Harmattan period, 2006-2011 the hose was removed and the sampler was placed directly on the counter, which was then placed on a 0.8 m table above the rooftop, as the aerosol was aspirated directly through the counter without any interconnecting hose.

The sampling instrument incorporates a laser light source to illuminate the aerosol sample cell and a vacuum pump that provides the transport of atmospheric aerosol from the inlet through the sensor to exhaust. An electronic flow meter, downstream from the sensor assembly monitors the flow rate through the sensor. When aerosol particles are drawn into the sample cell, scattering of the laser light by the particles of sizes as small as 0.5 µm and extinction of the laser light by the bigger particles of sizes up to 25 µm are collected onto photodiodes producing an electrical pulse for each particle. These pulses are applied to the eight channel circuits, within the counter and for each pulse amplitude that exceeds the channel threshold setting, a count is triggered in that channel. Each channel counts pulses within a specified range; the ranges between the channels (channel 1 to 8) are contiguous. During and after the counting run, the channel counts are visually displayed on the LCD either differentially or cumulatively. The counts are also printed on a paper by the thermal printer and also on a data buffer *("Datalync")* for downloading and processing on a computer. The Mie scattering equations for particles between 0.05 µm and 50 µm are used to determine the distribution of scattered light. Practically, the electrical pulses are proportional in amplitude to the light intensity or extinction which is a measure of the particle size (diameter). Thus the instrument provides direct and continuous information about particle concentration numbers in the eight user-defined size channels within a particle size range of 0.5-25 µm ±5% sensitivity. The suction air flow-rate is about 0.5 ℓ/s and the maximum particle concentration capacity is 35 x 10^6 m^{-3}. This can be extended 50 times by connecting an isodiluter.

The dust concentrations were measured continuously and averages determined automatically by the instrument at 1-hour intervals between the hours of 06:00 and 18:00 (GMT). The data was usually stable and only changing slowly over hours. Therefore, sampling was generally done during the daytime as the data variation did not appear to depend on the time of day whether nighttime or daytime [3]. Details of the experimental set-up and data acquisition procedure are given by Sunnu [3]. An eight-class size chosen for the Hiac/ Royco particle counter is (in µm): 0.5-0.7; 0.7-1; 1-2; 2-5; 5-10; 10-15; 15-25; > 25. The optical counter reports, for each sample run, the number concentration per cubic metre of air in each size class and the total concentration over the entire instrument size range (0.5-25 µm).

For most parts of Ghana, the Harmattan starts from the month of November, peaks around January – February and subsides in March [3, 8, 12]. The experiments were therefore conducted in the most productive Harmattan months of January and February of each year from 1996 to 2011, except 2004 when the equipment, which was sent out for servicing and calibration, arrived late after the Harmattan but was used to measure the background (monsoon) dust in October, 2004. The physical characteristics studied include: The average daily particle diameter (D µm), number (N in Number/cm^3) and mass concentrations (M in µg/m^3) of the background, Harmattan (January-February) and the selected peak Harmattan dust. The peak Harmattan dust particle size-frequency and the background are also studied.

3. Results and Discussion

3.1. Particle Number Concentrations

The average daily particle number concentration of the atmospheric aerosol sampled during the Harmattan period (January –February) and selected background dust sampled during the non Harmattan period (April – October) are plotted against the days in the 15 years (Figure 2a). The background dust concentration ranges between 1.33 and 10 particles/cm^3. The figure shows that the background dust levels are restricted to about 10 particles/cm^3 and the concentrations above this value constitutes the Harmattan dust, which gets to about 150 particles/cm^3 in Harmattan 1997. The diurnal average particle concentration observed during the period January –February over the 15 years is 29±19 cm^{-3}. A clearer illustration of the dust characteristic is obtained by calculating the periodic average number concentration (N) and the corresponding standard deviation (s) associated with each Harmattan (January-February) episode. This is shown for the various years in Table 1.

Table 1. The Harmattan dust average particle number concentration at Kumasi, Ghana (1996-2011).

Year	1996	1997	1998	1999	2000	2001	2002	2003	2005	2006	2007	2008	2009	2010	2011
Conc. N/cm^3	15	62	36	24	41	28	36	33	26	15	37	32	20	13	22
Std. Dev. s	4	33	28	10	35	6	14	12	13	6	13	11	8	4	6

The daily distributions of the Harmattan dust are observed to vary widely from day to day within the same season and from year to year at the same location. According to Sunnu et al. [8] this variation is linked to the movement of the ITCZ position with respect to the location. The particle concentration increases as the ITCZ migrates to lower latitudes and vice versa. Using the model, P=13 -1.76Ln(N), it means the ITCZ descended to Latitude 4.2^{o}N (at Long. 1.57^{o}W) on the Atlantic Ocean when the particle concentration reached 150/cm^3 in Kumasi. At this latitude (4.2^{o}N) most parts of the West African region would be plunged in severe Harmattan invasion and the wind streamlines would appear as in Figure 1c. The farther the ITCZ moves down south of the sampling location, the higher the particle number concentration at the location.

It should be noted that during the Harmattan period, (January-February) there are usually some days of little dust activity. Therefore, to critically study the inter-seasonal dust distributions, a derived data set of the highest daily average number concentrations of about 4-13 consecutive days in January-February of each year were assumed to be the actual Saharan dust and thus used to characterize the seasonal Harmattan. This is called the peak Harmattan where the daily concentrations remain reasonably stable at the highest levels. The average daily number concentrations recorded during the peak Harmattan period are shown in Figure 2b. The fluctuating character of the Harmattan dust still persists. The highest number concentration in the 15 year period occurred in 1997. The reason for the high number concentration in 1997 is probably due the low latitudinal position of the ITCZ, which has moved down to the equator two days earlier (on the 2nd February, 1997) before the 4th February, 1997 when the highest number concentration was observed. The concentration dropped gradually to a minimum in 1999 and then rises moderately in 2000. From 2001 to 2011 the inter-annual concentration varies a little less and oscillates around particle concentration of about 40 /cm^3. The peak Harmattan graph also shows that there is a marked change in concentration after Harmattan 2000. Between the years 1996 and 2001 the inter-annual variations are large while fluctuating around a higher value. Comparing, the distribution between the years 2001 and 2011 shows lower inter-annual variations and fluctuates around a lower value. The cause of this variation before and after Harmattan 2001 may be an indication of the topical global climate change which is manifested in the Harmattan dust episode. The surface wind speeds observed in the Harmattan periods before the year 2000 were generally low, between 1.2 and 1.4 m/s from years 1997 to 2002. While the wind speeds observed for the period after year 2000 were higher (between 1.5 and 1.9 from 2003 to 2011). Although the low ITCZ position favoured strong Harmattan with high dust concentrations, the low wind speeds favoured advection of smaller sized particle. The larger sized particles settled out of the suspension earlier on their way from the dust source before arriving at the sampling station. The dust particle characteristics of the two periods (before and after the year 2000) are therefore recorded. The average peak Harmattan daily number concentration over the 15-year period is 45±25 cm^{-3}. In the period 1996-2000, the peak Harmattan dust daily average number concentration measured 60±37 cm^3 which is higher than the peak daily average concentration of 37±12 cm^{-3} recorded for the latter period, 2001-2011.

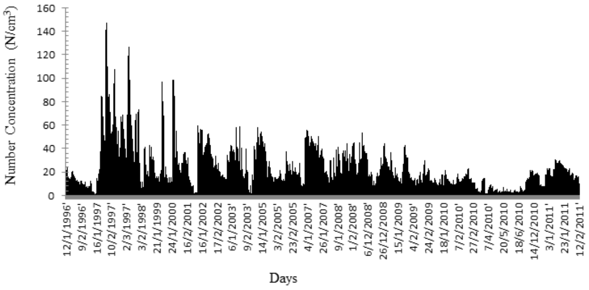


Figure 2a. Mean daily particle number concentration distributionat at Kumasi, 1996-2011

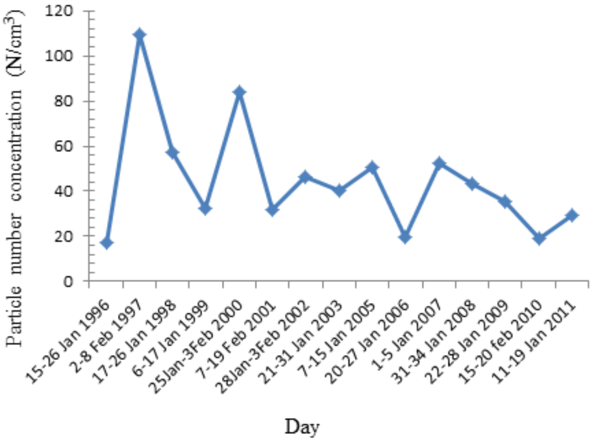


Figure 2b. Mean daily particle number concentration of the peak Harmattan at Kumasi, 1996-2011.

A further look at the average peak Harmattan distribution (Figure 2b.) shows a trend of a rise in number concentration after a lowest point is reached which appears to recur in periods of about 5 years as recorded in 1996, 2001, 2006 and 2010. Thus the Harmattan 2012 is expected to be stronger than Harmattan 2011 since the lowest point in the period (2011-2016) is already attained in Harmattan 2010.

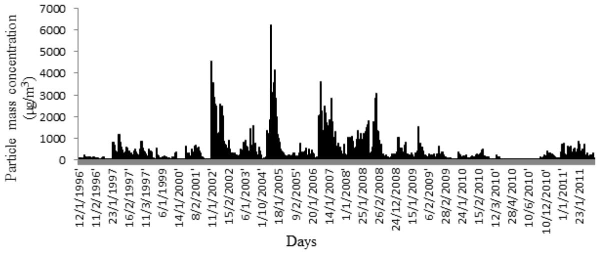


Figure 3a. Mean daily particle mass concentration distribution at Kumasi, 1996-2011

3.2. Mass Concentrations

The Saharan dust is assumed to be composed mainly of spherical quartz (silica) particles of density ρ ~2.65 g/cm^3, and the aerosol mass concentration is estimated using the average number concentration and mean diameter values within the size range of 0.5-*25* µm, as described by Sunnu et al. [6]. The mass distribution curve (Figure 3a) shows marked high points in Harmattan 2002, 2005, 2007 and 2008. The daily mass concentrations analysed for the Harmattan 1996 -2011 range from 17 to 6199 µg/m^3. The daily average dust particle mass concentration observed during the period January -February averaged over the 15 years is 571±722 µg/m^3.

The corresponding average peak Harmattan distributions are shown in Figure 3b. The distribution shows a gradual decrease from 1997 to 1999 and then a gradual increase to 2001. From Harmattan 2002 to 2007, large variations are observed followed by a gradual decrease to 2011. The average peak Harmattan dust particle mass concentration over the 15-year period is 965±946 µg/m^3. The distribution in the two periods, before and after the year 2000, is observed. The mass distributions show apparent low mass concentrations in the years 1996-2000 while higher mass concentrations are observed in the years 2002-2007 after which the mass concentration decreases gradually to the years 2010 and 2011. The average daily particle mass concentration recorded in the 'low mass' period 1996-2000 is 370±297 µg/m^3 which is far lower than the average mass concentration for the period 2001-2011 that measures 1262±1028 µg/m^3. The variation in wind speeds (shown in Table 2) may be responsible for the variation of the mass concentrations in the two periods. It is observed from the table that the wind speeds are between 1.2 and 1.4 m/s for the period 1997 to 2002 respectively. These values are lower than the wind speeds between 1.5 and 1.9 m/s for the years 2003 to 2010 respectively. The wind speed drops to1.3 m/s in 2011. Stronger winds are capable of entraining and suspending larger sized particles over longer distances and for longer periods. During the 'low mass' period, the winds are low and can only entrain and advect smaller sized dust particles. During the stronger wind regime, of the latter period, coarser dust particles are advected with the winds far away from the dust source as demonstrated by the mass concentration results in the period, 2003-2010.

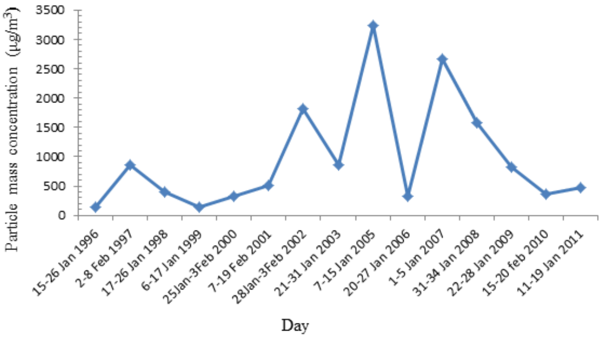


Figure 3b. Mean daily particle mass concentration of the peak Harmattan at Kumasi, 1996-2011.

The particle mass concentration pattern is different from the particle number concentration pattern. For example, the average peak mass concentration in 1997 (with 110 particles /cm^3) is 858 µg/m^3 and this is far less than the mass concentration of Harmattan 2005 (with 51 particles/cm^3) which is 3240 µg/m^3. As observed above in the particle number distribution, the period, 1996-2000, produced many more particle numbers than the period, 2001-2011, which produced fewer but larger sized particles. This makes the mass concentration for the latter period higher than the former as the particle mass is proportional to the particle number concentration and diameter cubed. Also, from the mass distribution, Figure 3b, the periodicity is not well defined. The bottom mass concentrations appear to occur in 1996, 2001, 2003, 2006, and 2010.

Table 2. Average wind speed at Kumasi Airport in Ghana during January-February (1996-2011)

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Wind speed (m/s)	1.3	1.2	1.2	1.4	1.2	1.2	1.9	1.8	1.5	1.5	1.8	1.5	1.5	1.8	1.3

The average wind speeds (January-February) over the study period between 1996 and 2011, taken from the Kumasi Airport at 10 m height are shown in the Table 2. The wind speeds, although generally very low (less than 2 m/s), are representative of the regional wind speeds and typical of the NE winds during the Harmattan period. Besides surface wind speeds, usually measured at 10 m above ground level, wind speeds within the planetary boundary layer (PBL) are strongly influenced by friction due to vegetation and topography. The PBL which is the lowest level of the atmosphere or the bottom of the troposphere is usually within a 1000 m of the surface and most of the suspended Saharan dust particles are transported within this layer. Wind speeds within the PBL increases exponentially with height above ground level. In order to estimate the wind speed at an elevation higher than the standard 10 m weather station anemometer, the following power law expression is used: $v_1/v_2 = (z_1/z_2)^p$, where v_1 and v_2 are wind speeds at the higher (z_1) and lower (z_2) elevations respectively. The exponent p is a dimensionless parameter that varies with atmospheric stability and the terrain surface roughness at the location of the 10-m weather station. Referring to Table 2, with surface winds less than 2 m/s, at the airport, during the dry season and assuming stable atmosphere, p can be approximated to 0.2. The lowest surface wind speed of 1.2 m/s corresponds to mid-PBL (500 m above ground level) speed of $v_1 = 1.2(500/10)^{0.2} = 2.6$ m/s. The highest wind according to Table 2 is 1.9 m/s which relates to a mid-PBL speed of $v_2 = 1.9(500/10)^{0.2} = 4.2$ m/s. Therefore the surface wind speed range of 1.2 – 1.9 m/s corresponds to 2.6 – 4.2 m/s in the mid planetary boundary layer. The stronger PBL winds may be turbulent and would sustain the suspended dust particles for the long-distance travel. It is generally observed that stronger NE winds transport higher numbers and larger sizes of particles toward the Gulf of Guinea [12, 34]. For example, Afeti et al. [34] observed wind speeds of 1-2 m/s for the 1996-1997 Harmattan while Sunnu et al, [8] observed wind speeds of about 3.5 m/s in Harmattan 2002 and 4 m/s in Harmattan 2005. The corresponding mean daily peak Harmattan mass concentrations are 858 µg/m^3 in 1997, 1811 µg/m^3 in 2002 and 3240 µg/m^3 in 2005, respectively. Therefore, it was found that the low NE wind speeds of the period 1996-2000 produced the low mass concentrations recorded in that period. Consequently, it is observed that the higher the NE wind speeds the higher the particle mass concentration and vice versa.

3.3. Frequency Size Distributions

The peak Harmattan dust was analysed to compute the particle size (diameter) and frequency distributions. The normalised frequency distribution curves, dN/(dlogD) and dM/(dLogD) as a function of the particle diameter, D for the Harmattan seasons are shown by Sunnu [15] for the Harmattan 1997-2009. In the present work, comparable frequency distributions of the Harmattan dust and the background (non Harmattan) aerosol (plotted on a log-log scale) are shown in Figure 4a & 4b.

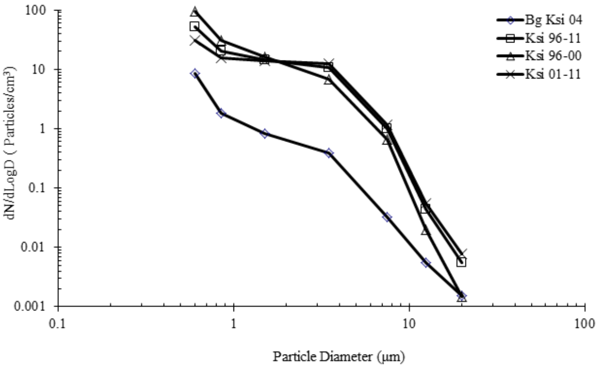


Figure 4a. Comparison of the particle number size-frequency for Kumasi (Ksi) during peak Harmattan periods, averaged over 1996-2011, 1996-2000 and 2001-2011 as well as the background (Bg Ksi 04) in October, 2004.

3.3.1. Number Size Frequency

The 15-year average daily number size-frequency distributions of the peak Harmattan dust concentrations over the period 1996-2011 are shown in Figure 4a. The number frequency distribution curves are plotted on the logarithmic scale with the ordinate d*N*/dlog*D*, where *N* is in the units of particles/cm^3 and *D* on the abscissa is the particle class mid-point size in micrometer (µm). In all cases like Sunnu [3], Resch et al. [12] and Sunnu [15], the particle number distribution graphs show that the smallest particles are in the highest concentrations. The spectra show a decrease in particle concentration with increasing particle diameters, as is typical of atmospheric aerosols. This observation agrees with related studies of Saharan dust characteristics closer to the source regions [35]. The 15-season average number frequency curve covers roughly five orders of magnitude across the particle (diameter) size of 0.6 µm to 20 µm. The contribution of the Saharan dust to the atmospheric particles by the various particle sizes are shown to lie between 1 and 2 orders of magnitude. The contribution of small particles ($D < 2$ µm) to the atmospheric dust is about one order of magnitude for Harmattan dust frequency distribution in the Harmattan 1996-2000 while the increment is half for the Harmattan 2001-2011. The average size-frequency distribution of peak Harmattan 2001-2011 shows that particles larger than 2 µm contribute about one and half orders of magnitude to the background while the addition of large particles narrows down to about one order of magnitude for particle sizes around D =20 µm. The overall average frequency distribution for the study period, Harmattan 1996-2011, lies between the small sized aerosol of Harmattan 1996-2000 and the larger sized aerosol of Harmattan 2001-2011.

3.3.2. Mass Size Frequency

The corresponding 15-year average daily mass size-frequency distributions of peak Harmattan 1996-2011, 1996-2000 and 2001-2011 are shown in Figure 4b. In the case of the mass distribution curves, a steep rise in concentration from the smallest particles (D = 0.6 µm) to the intermediate sizes (D = 3.5 µm) is visible. The peak concentration is situated between particle sizes 3.5 µm and 7.5 µm. The concentration decreases sharply for particle diameters between 7.5 and 20 µm. The particles in the medium size range 3.5-7.5 µm with a mode of about D = 5.5 µm are the main contributors to the suspended atmospheric dust particles for the Harmattan 1996-2000, adding about one and half orders of magnitude to the mass concentration. The mass frequency distribution for the peak Harmattan 2001-2011 shows that mainly silt particles (2 µm < D < 20 µm) added about one to one and half orders of magnitude to the atmospheric dust. For the size-frequency distribution of the Harmattan 2001-2011, the mode size is between 3.5 and 7.5 µm. The contribution of clay particles (D < 2 µm) in the Harmattan 2001-2011 is less than that of Harmattan 1996-2000. The long term average mass size-frequency distribution lies between the two periods, Harmattan 1996-2000 and 2001-2011 but closer to the Harmattan 2001-2011 graph. All the three curves meet near particle diameter D=2 µm.

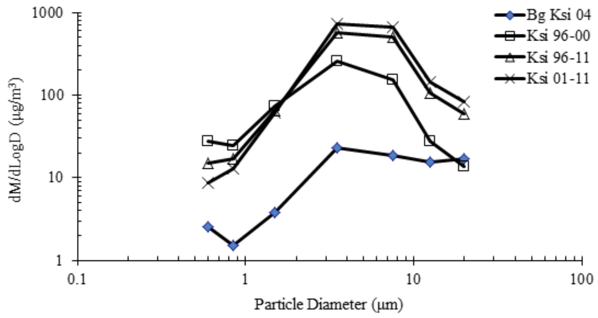


Figure 4b. Comparison of the particle mass size-frequency for Kumasi (Ksi) during peak Harmattan periods, averaged over 1996-2011 and the background in October, 2004 (Bg Ksi 04).

Generally, the spectra consist of clay and silt particles which are effective in attenuating solar radiation [3]. The suspended Harmattan dust therefore, is a major factor of the weather near the Gulf of Guinea and the adjoining Atlantic Ocean during the Northern Winter season. The number and mass size-frequency distributions show that the larger particles, though fewer in numbers, contribute much more to the overall dust load. The comparison between the size-frequency distributions of the Harmattan dust concentrations in 1996-2000, 2001-2011 and 1996-2011 shows that a change in particle concentration and size patterns has occurred around Harmattan 2001. This change could be an indication of climate change impacts on the Sahara dust transport towards the Gulf of Guinea. The change in dust distribution could also be a symptom of change of the dust source strength as a result of stronger winds. Therefore, the dust variations with respect to climate change variables will be studied in future.

3.4. Particle Diameter Distribution

The mean daily diameter was determined for each day using the average number concentration data for the day. The mean diameter is calculated by applying the method of weighted averages $\overline{D}$ (= $\sum n_i D_i / \sum n_i$) where n_i is the number of particles in the size class i having a midpoint size D_i and where $\sum n_i$ is the total number of particles in the class sizes (0.5 µm -25 µm). In Figure 5a, the daily mean (diameter) sizes are plotted against the days sampled over the 15 years. The background particle size (diameter) for the season is obtained as the arithmetic mean of all the daily mean diameters (January -February) in the study period. The daily mean diameter ranges from 0.72 µm to 3.17 µm. The lowest sizes are found in the background environment while the larger sizes come from the Harmattan dust episode. The background dust particle diameter range observed is 1.04-1.16 µm. In Figure 5b, the particle size distribution during the Harmattan periods is shown to range from 0.89 µm in Harmattan 1999 to 2.43 µm in Harmattan 2005. This variation is probably due to the variation in wind speed which is responsible for the dust transport. The 15-year mean size (diameter) observed over January-February is 1.35 ± 0.39 µm. The Harmattan dust is mainly clay particles (*D* < 2 µm) with few silt particles (2 µm < *D* < 4 µm). During high Harmattan winds of velocity around 4 m/s [12], the larger sized particles arrive at the Gulf of Guinea. This spectrum of mean sizes 1.35 ± 0.39 µm make the Harmattan dust effective in solar radiation attenuation and visibility reduction as these are controlled by particles in the size range, 0.1 µm to 2.0 µm [36]. As rain cloud is suspended water droplets formed around dust nuclei, the dust may also affect the characteristic size distribution of rain cloud droplets and their optical properties.

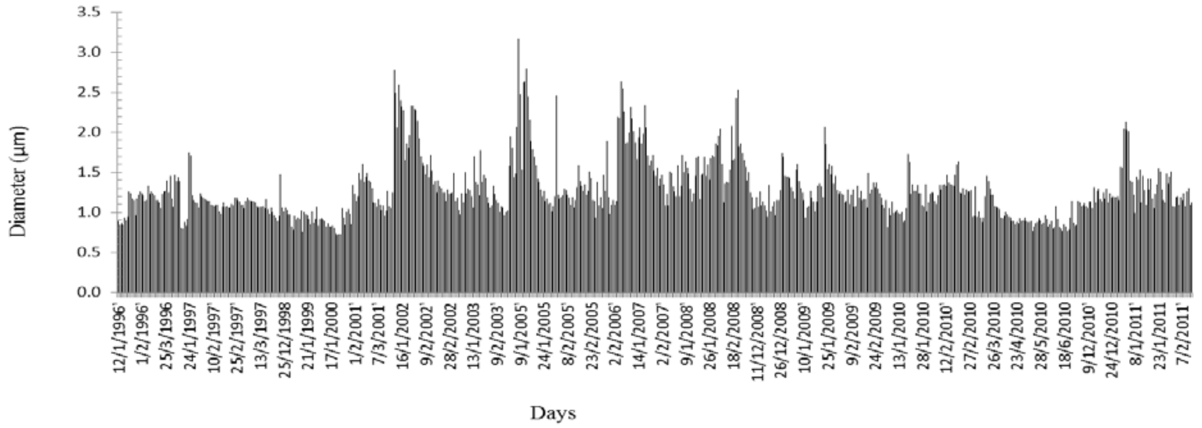


Figure 5a. Mean daily particle size distribution at Kumasi, 1996-2011

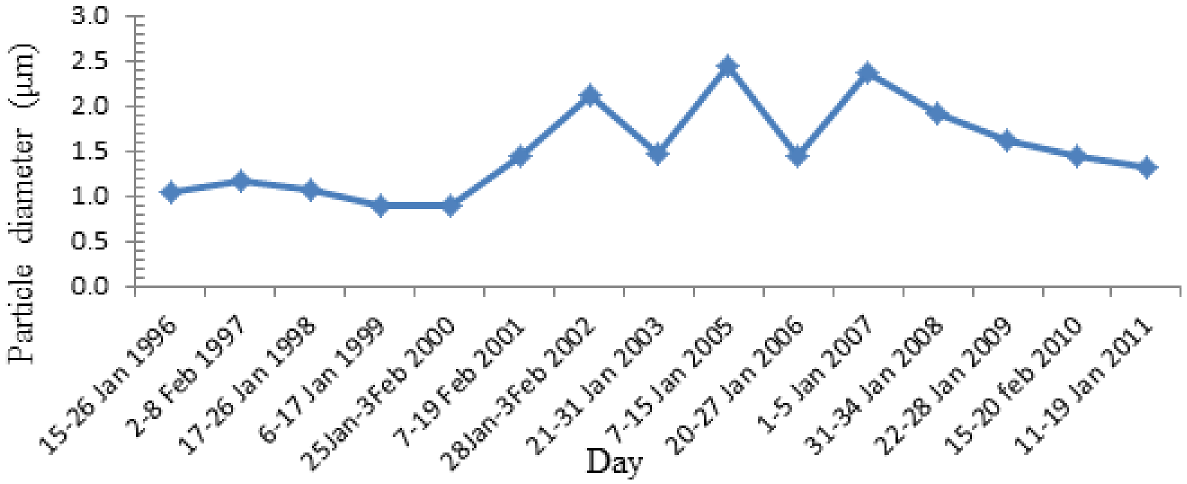


Figure 5b. Mean daily particle size of the peak Harmattan at Kumasi, 1996-2011.

The results trend also shows periodic differences. The mean particle sizes of the peak Harmattan in the period 1996-2000 comprise mainly particles of diameter less than 1.2 µm with a mean size of 1.01±0.12 µm whereas the peak Harmattan 2001-2011 comprise larger-sized particles between 1.5 µm and 2.5 µm with a mean of 1.76±0.42 µm. Is this difference a manifestation of climate change or is it due to increasing source strength? Droughts in the dust source areas including the Bodélé Depression that affects the West Africa in the past years may result in increased dust production. Effects of land use activities including Agriculture in the Sahel regions adjacent to the Sahara Desert should be investigated for possible expansion of the dust source. It would also be interesting to know the cause and effect of the turnaround of the dust distribution on the climate factors including the ITCZ and the North Atlantic Oscillation (NAO). The apparent recurring bottom size of the size-distribution pattern occurs in periods of about 5 years (1996, 2000, 2006 and 2011) as observed in the particle number concentration distribution. It is noteworthy that the particle characteristic diameter remained essentially uniform in the same period, being about 1 µm in 1996-2000 and 1.76 µm in 2001-2011. Since the Harmattan dust distribution shows systematic reduction of particle mean size from the dust source, the larger particle sizes observed in the period, 2001-2011, could be brought about by either a reduction in the dust source distance from the sampling station, increased source strength or stronger Harmattan winds. The surface wind speed is the only factor studied in this work. Within the size range covered by the measuring equipment, the results presented in this work compare favourably with the characteristics associated with Saharan dust measured by others, for example, Kalu [37] obtained 8.9 µm mean diameter at Kano (Lat. 12^o N) in Nigeria, Adeyefa [33] obtained 3.12 µm in Ile Ife (Lat. (7.5° N) also in Nigeria and in Accra (Lat. 5.5^oN), Oduro-Afriyie and Anderson [38] obtained a mean of 2.11 µm. A systematic reduction of particle mean size from the dust source is observed in these results.

3.5. The Harmattan Dust and Climate Change

The results show that the dust aerosols which are mainly clay (D <2 µm) in the Harmattan episode of the years

1996-2000 have changed composition to a more silt particle dust (2< D < 4 µm) in the Harmattan 2001-2011. This may be an emerging symptom of desertification due to agricultural use of the lands adjacent to the dust sources as observed by e.g. [27-29]. The increased suspended dust may increase scattering of solar radiation in the day time with the accompanying warming of the troposphere and rain clouds over the region. The phenomenon may also change the temperature profile, the thermodynamics of the troposphere and the atmospheric dynamics. The dust aerosol particle size and concentration have increased from the year 2001-2011 suggesting significant effect on cloud development and precipitation in the Gulf of Guinea. Increase in dust concentrations may also imply increased dust plume temperature, dust aerosol albedo and tropospheric temperature in the day time as well as increased reduction of the ground surface temperature. The radiative cooling in the night which produces the usual cold night temperatures will also be affected as this would be influenced by scattering of the long wave radiations from the earth by the suspended Harmattan aerosol which may become a key process over the region. Su et al. [10] estimate the contribution to the cloud radiative forcing by the dust effects using combined satellite observation and Fu-Liou model simulation. It is shown that the heating effect of the dust aerosols and the increased dust aerosol loading may suppress precipitation in the period 2001-2011 [31]. This, in turn, may reduce the probability of precipitation, resulting in more and uncertain climatic impacts. Hence, as a result of the increase in the dust aerosol, the interactions of the Harmattan dust with rain clouds and land surfaces can have significant impacts on the climate. These causes and climate impacts should be further investigated.

4. Conclusions

The material presented in this paper constitutes a significant contribution to the characterisation of the Saharan dust near the Gulf of Guinea over a long term and its possible impact on the climate of the region. The daily variations of the average size (diameter), number and mass concentrations of the Harmattan dust in January-February and the peak Harmattan dust have been determined over fifteen years. The atmospheric dust size (diameter) range observed is 0.72-3.17 µm; the number concentration vary from 1 to 148 particles/cm^3 and the mass concentration ranges from 4 to 6199 µg/m^3. The daily particle number and mass concentrations of the dust observed during the period January-February over the 15 years are 29±19 cm^{-3} and 571±722 µg/m^3 respectively. The peak Harmattan dust distribution shows that the average daily number concentration over the 15-year period is 45±25 cm^{-3} while the particle mass concentration is 965 ±946 µg/m^3.The peak Harmattan distribution shows a trend of a rise in number concentration after a lowest point is reached which appears to recur in periods of about 5 years as recorded in 1996, 2001, 2006 and 2010. The peak Harmattan dust particle distributions show a turning point around the year 2001 with a trend of small-sized particles in the peak Harmattan 1996-2000 while larger-sized particles are observed in the peak Harmattan 2001-2011. The mean size D=1.01±0.12 µm was observed for the peak Harmattan 1996-2000 while a mean of D=1.76±0.42 µm was observed for the peak Harmattan 2001-2011. The particle mass concentration also shows an increase in the peak Harmattan 1996-2000 with a mean mass concentration of 370±297 µg/m^3 while the mass concentration of 1262±1028 µg/m^3 was recorded for the peak Harmattan 2001-2011. The high dust concentration levels call for the use of nose/mouth filters to protect the respiratory system of the people.

Both the background dust aerosol and the Harmattan dust distributions follow the typical atmospheric dust particle distribution showing part of the accumulation mode and the coarse particle mode. The graphs show that the number and mass frequency distributions of the Harmattan dust are consistently higher, by about one to one and half orders of magnitude, than the corresponding background dust at almost all particle sizes. The average size-frequency distribution for the peak Harmattan 1996-2011 lies between the smaller-sized aerosol of Harmattan 1996-2000 and the larger-sized aerosol of Harmattan 2001-2011 but closer to the Harmattan 2001-2011 graph. All the three curves meet near particle diameter D=2 µm.

A possible cause of this seasonal difference between peak Harmattan parameters of 1996-2000 and 2001-2011 may be the manifestation of the change in the dust source characteristics including source strength and stronger wind speeds. This is the first detailed characterisation of the Harmattan (Saharan) dust aerosol in Ghana near the Gulf of Guinea over such a long term of 15 years. Thus the results reported here will provide useful experimental data for testing the Harmattan dust filter and any theoretical model of the Saharan dust transport toward the Gulf of Guinea and may also explain the regional climate change.

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