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Saharan dust flux and deposition rate near the Gulf of Guinea

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ABSTRACT

It has been estimated that 240 ± 80 Tg of Saharan dust are transported annually from Africa over the Atlantic Ocean to far away places such as the Amazon Basin and the Caribbean during the summer months of June to August. There are, however, few direct measurements of the dust transport towards the Gulf of Guinea (5°N) during the winter months of December–March. In this study, the Saharan dust flux and deposition to the Gulf of Guinea during the Harmattan (winter) season are estimated using the geographical area of Ghana (lying between latitudes 5° and 12°N) as the reference location. The flux and deposition rates were determined during the Harmattan dust episodes of 2002 and 2005 by measuring surface dust concentrations concurrently at two locations in northern and central Ghana. The average particle number concentration in 2002 was 21 cm^{-3} while in 2005, it was 30 cm^{-3} (although a few daily mean values were as high as 60 cm^{-3}). The corresponding mean mass concentrations were 543 $\mu g\ m^{-3}$ and 1383 $\mu g\ m^{-3}$ in 2002 and 2005, respectively. The deposition rates for the two winter seasons were estimated at 13 and 31 t $km^{-2}\ yr^{-1}$, respectively, corresponding to a dust deposition thickness of 5 μm in 2002 and 12 μm in 2005. The transit time for the dust aerosol to travel a distance of 320 km between the two measurement sites in a north–south direction was determined experimentally to be of the order of 1 d, a result which could serve as an early warning indicator for severe dust outbreaks travelling from higher to lower latitudes in the region. The results of this study may also be compared with any future simulation of the African dust plume towards the Gulf of Guinea.

1. Introduction

The seasonal influx of Saharan dust particles into the countries lying on the Gulf of Guinea in West Africa during the winter months of November to March has been previously reported (e.g. Kalu, 1979; McTainsh, 1980; d'Almeida, 1986; Afeti and Resch, 2000). The dry and hazy dust, known locally as the 'Harmattan', has its source in the Bodele depression of the Chad Basin, which is acknowledged as the most productive dust source on Earth at present (Prospero et al., 2002). However, few recent direct measurements of the dust physical characteristics and their transport towards the Gulf of Guinea exist. On the other hand, the transport of the African dust plume over the Atlantic Ocean to the Americas has been extensively studied using both satellite observations and simulation models and ground-based measurements (e.g. Prospero et al., 1981; Chiapello et al., 1995; Prospero, 1999; Chiapello and Moulin, 2002; Chiapello et al., 2005). Recently, Kaufman et al. (2005) using data from the Moderate Resolution Imaging Spectrometer (MODIS) space-based instrument estimated that 240 ± 80 Tg of dust are transported annually from Africa to the Atlantic Ocean, about half of which are deposited in the Atlantic Ocean. Ginoux et al. (2001) have also reported that the total maximum global emission of dust into the atmosphere from all the Earth's dust sources is almost 2 billion t yr^{-1}. The GOCART simulation model used by Ginoux et al. (2001) located the highest dust concentrations (above 250 $\mu g\ m^{-3}$) over western Sahara and the Sahel region and a deposition rate of 162 g $m^{-2}\ yr^{-1}$. This kind of information and data for the countries of West Africa on the Gulf of Guinea are scanty.

As is now well known, the transport and deposition of Saharan dust affects the Earth's radiation budget (Tegen et al., 2004) and photolysis rates (Martin et al., 2003). These effects are particularly severe in the sub-Sahel regions on the West African coast where farmlands become dry and hardened and difficult to cultivate during the Harmattan (winter) season, and the deposition of dust particles on agricultural plants results in chlorosis or yellowing of the leaves and subsequent reduction of plant yield. Saharan dust deposition over these areas, therefore, has implications for food security in the region.

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Afeti and Resch (2000) have measured the size and number distributions of the Saharan dust aerosol in Kumasi, central Ghana (6° 40′N; 1° 34′W). However, very little is known about the dust flux and deposition rate in the country. What quantity of Saharan dust is deposited every year on countries on the Gulf of Guinea? This paper reports the results of a study to estimate the dust flux and deposition rate by carrying out dust particle concentration measurements concurrently at two locations in central and northern Ghana, separated by a distance of about 320 km in a north–south direction during the Harmattan (winter) seasons of 2002 and 2005. Maps locating Ghana (with respect to the Gulf of Guinea) as well as the measurement sites of Tamale (9° 34′N; 0° 54′W) and Kumasi (6° 40′N; 1° 34′W) are shown in Fig. 1.

2. Flux determination

A theoretical expression for the dust flux and deposition rate can be obtained by representing the dust transport in a control volume analysis as shown in the diagram below. The control volume is delimited by the vertical (north–south) distance L between Tamale (entrance Section 1) and Kumasi (exit Section 2), the thickness h of the atmospheric boundary layer and a unit length taken in the east–west direction (Fig. 2).

The particle mass concentration is M_1 at the entrance to the control volume and M_2 at the exit. The mass concentrations are assumed constant throughout the vertical boundary layer at both cross-sections. We also assume that the mainstream flow is steady and that there no extraneous particle inputs into the control volume through the top and bottom walls. However, the mass flow entering the control volume loses some of its particles due to sedimentation along the length of the control volume. Thus, on average, M_2 is different from M_1. The deposition velocity V_d is also different from the gravitational settling velocity since it takes into account the effects of turbulence as well. We assume that the mainstream velocity U is constant throughout the entire control volume. The deposition flux per unit area, F_d, is given by

$$F_\mathrm{d} = V_\mathrm{d} M_1, \tag{1}$$

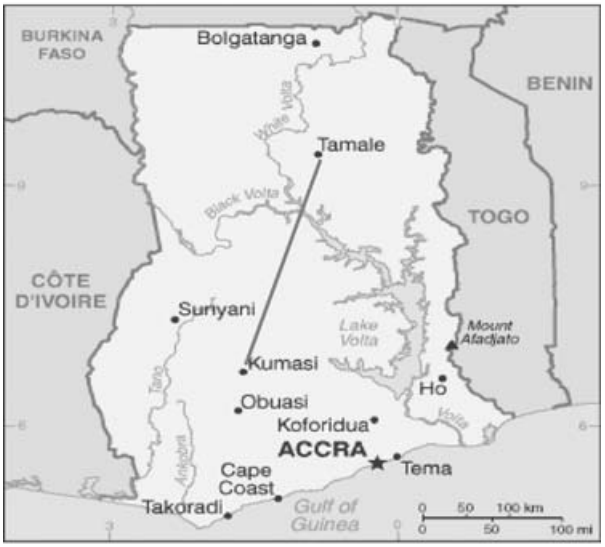
where V_d is the unknown deposition velocity.

In order to calculate V_d, we apply the principle of conservation of mass to a volume element of length dx, height h and unit width for which the concentration varies from $M(x)$ at a point x to $M(x + \mathrm{d}x)$ at the horizontal distance $x + \mathrm{d}x$. The fluxes entering and leaving the volume element (dx, h, 1) are, respectively, $M(x)Uh$ and $M(x+\mathrm{d}x)Uh$, while the deposition flux is $V_\mathrm{d}\,M(x)\mathrm{d}x$. Thus, according to the principle of conservation of mass, it is easy to show that:

$$M(x + \mathrm{d}x)Uh - M(x)Uh = -V_\mathrm{d} M(x)\mathrm{d}x.$$

From this equation, we can obtain the expression $\frac{\mathrm{d}M_{(x)}}{M_{(x)}} = -\frac{V_\mathrm{d}}{h}\mathrm{d}t$

(a) West Africa



(b) Ghana

Fig. 1. Maps showing (a) the location of Ghana in West Africa near the Gulf of Guinea and (b) the experimental sites of Tamale and Kumasi.

which, when integrated over the entire volume, from Section 1 to Section 2 and from 0 to T, where T is the transit time between Sections 1 and 2, gives

$$V_\mathrm{d} = \frac{h}{T} \ln \frac{M_1}{M_2}. \tag{2}$$

Knowing M_1, M_2, h and T, the deposition velocity, V_d, can be determined and hence the deposition flux, $F_\mathrm{d} = V_\mathrm{d}\ M_1$ (eq. 1). The transit time T is given by $T = L/U$ while U is taken conventionally as $U = V_{15}/0.8$ (Slinn, 1983; Hasager and Jansen, 1999), where V_{15} is the velocity measured at a height of 15 m.

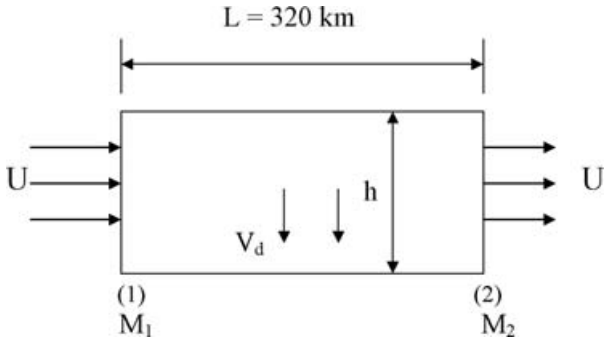


Fig. 2. Control volume representation of dust flux and deposition phenomenon.

The 'box model' we have adopted in this study to estimate the deposition rate assumes that a certain degree of homogeneity of the dust flow exists horizontally and vertically. Concerning the vertical homogeneity, we have chosen an average boundary layer thickness of $h = 1000$ m, since it is known that the atmospheric boundary layer thickness varies between 800 and 1200 m. This choice of $h = 1000$ m is quite common in the litterature (e.g. Fairall and Larsen, 1984; Carruthers and Choularton, 1986; Smith et al. 1991). With regard to the assumption of horizontal homogeneity, we have used the experimental determination of the transit time for the dust plume to travel between the two measurement stations as supporting evidence. In effect, as we shall see later, the experimentally determined transit time is of the same order of magnitude as the displacement time (L/U) of the dust plume.

3. Experimental measurements

The main measuring equipment was a Pacific Scientific Hiac/Royco 5250A automatic optical airborne counter with eight user-select size channels within the instrument size range of 0.5–25 μm $\pm$ 5% sensitivity. In this experiment, the size channels were chosen such that the channels are centred around the following diameters : 0.6, 0.85, 1.5, 3.5, 7.5, 12.5 and 20, all in μm. Two of these counters were used to monitor the dust particle concentrations concurrently at the two experimental sites located, respectively, on top of the airport control tower at Tamale and on top of one of the Faculty buildings of the Kwame Nkrumah University of Technology at Kumasi. With only four take-offs and landings a day, the airport at Tamale is not a busy one and the top of the control tower, at about 15 m from ground level, provides a panoramic and unobstructed view of the savannah landscape over several kilometres, devoid of any industrial activity or vehicular traffic. The Kumasi site is similarly protected against locally generated dust particles at a height of 15 m from ground level and located at about 2 km away on the southeastern outskirts of the city. The particle concentrations were monitored concurrently at Tamale and Kumasi between January and March during two separate Harmattan seasons in 2002 and 2005. Particle data were obtained on a continuous basis and averaged automatically by the Hiac/Royco machine at 1-h intervals over several hours a day. The Hartmattan season is characterised by dry weather, no rains and low humidity (less than 20%).

4. Results and discussion

4.1. Particle number and mass distributions

The particle number and mass concentrations are plotted in Figs. 3 and 4, respectively. The average number and mass concentrations were 21 cm^{-3} and 543 μg m^{-3}, respectively, in 2002 and 30 cm^{-3} and 1383 μg m^{-3} in 2005. The strong daily interannual variability of the dust concentrations can also be observed. In order to quantify the strength or severity of each Harmattan (winter) dust episode, we selected, for each year, a few consecutive days (6–9 d) when the daily dust concentrations remain reasonably stable at the highest levels. We then used the selected data associated with each year to calculate the mean maximum concentration for that year. The particle number and mass frequency distributions shown in Figs. 5(a) and (b) are associated with data corresponding to these selected days. The periods selected were 28 January–3 February (Julian day 28–34) in 2002 and 7 January–15 January (Julian day 7–15) in 2005.

The dust concentrations are much higher than those earlier reported by Afeti and Resch (2000) for 1997 and 1998. These values may also be compared with a mass concentration of 900 μg m^{-3} measured by Bertrand et al. (1974) during a severe dust outbreak in Ivory Coast in the same geographical area as Ghana. These results confirm the observed interannual variability of the Saharan dust transport (Chiapello et al., 2005). Such discrepancies are also linked to the range of dust sizes that are covered by the measuring instruments or simulation models. Although the contribution of other aerosol types by biomass burning, which is common during the winter season (Chin et al., 2002) cannot be entirely dismissed, their contribution to the overall dust load is negligible. The smoke particles are generally smaller than 2 μm in diameter. In addition, the interannual variability and intensity of human-induced dust may be difficult to quantify.

4.2. Dust flux and deposition rate

From eq. (1) and (2), using the mass concentration data obtained from the measurements at Tamale (M_1) and Kumasi (M_2) and taking h as the height of the boundary layer (assumed to be 1000 m by convention), the total deposition flux can be calculated for particles in the size range of 0.5–25 μm. The transit time, $T = L/U$ is obtained by taking L as 320 km (distance between Tamale and Kumasi in a straight north–south direction). The mainstream velocities for the dust episodes in 2002 and 2005 were obtained from the expression $U = V_{15}/0.8$, where V_{15} was 2.78 m s^{-1}

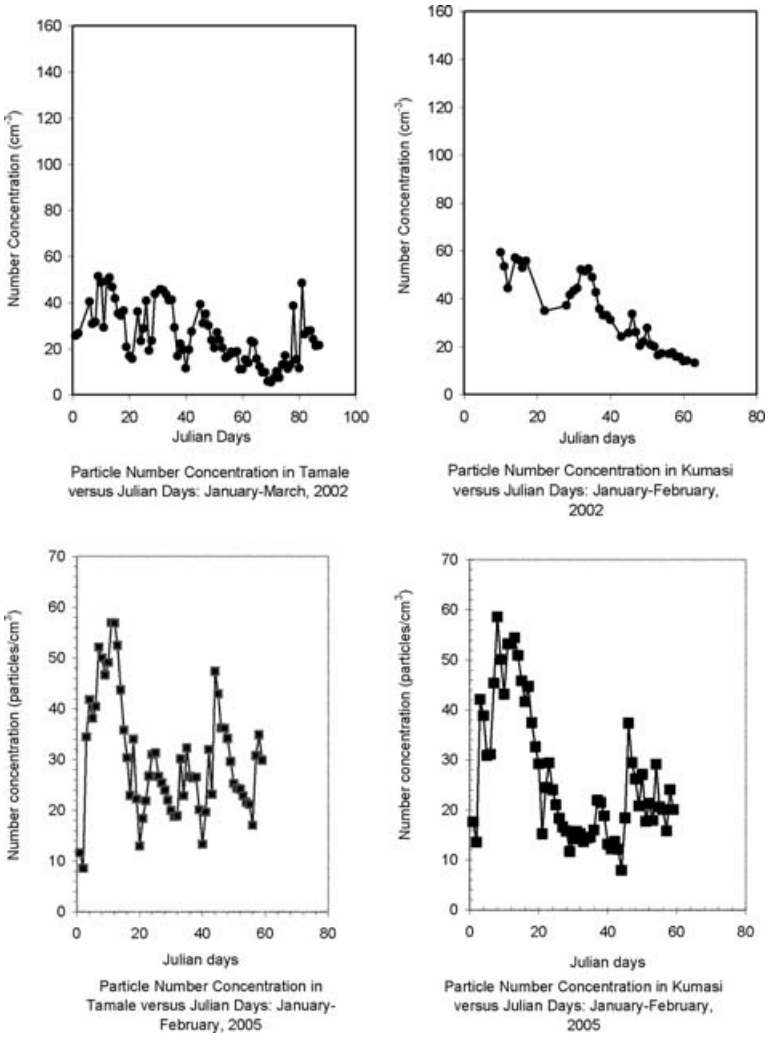


Fig. 3. Daily particle number concentrations at Tamale and Kumasi during 2002 Harmattan season.

in 2002 and 3.2 m s^{-1} in 2005. The corresponding mainsteram velocities were 3.48 and 4.0 m s^{-1}, respectively.

The dust deposition rate was found to be of the order of 13 t km^{-2} yr^{-1} in 2002 and 31 t km^{-2} yr^{-1} in 2005. Assuming that the dust particles were mainly silt or quartz with a density of 2650 kg m^{-3}, the corresponding dust layer thickness δ deposited on the ground in a year can be estimated from the expression $m = \rho A \delta$, where m is the mass of dust deposited and A is the surface area covered by the dust particles: δ is found to be about 5 μm in 2002 and 12 μm in 2005. The deposition rates we have calculated here are much smaller than those obtained by McTainsh and Walker (1982) in Kano (Nigeria) which were in the range of 137–181 t km^{-2} yr^{-1}. Again, we cannot ignore expected interannual variabilities or the considerable differences in distance of the measuring sites from the dust sources. We note that Kano is much closer to the Saharan dust source in the Bodele depression than Tamale and Kumasi.In fact, the distance between Tamale and Kano is about 1200 km and Kano is situated about half-way between Tamale and the dust production zones in the Bodele depression. Using the turbulent dry deposition model for various aerosol particle sizes given by Smith et al. (1991) and the expression for the deposition velocity (eq. 2), it can be shown that the mass concentrations at Kano are 7–10 times higher than at Tamale. The deposition rates of 13–31 t km^{-2} yr^{-1} that we have obtained in this study are therefore consistent with the measurements at Kano. Elsewhere, Ginoux et al. (2001), using a simulation model, obtained a dust deposition of 162 t km^{-2} yr^{-1} over western China while Zhang et al. (1998) reported a value as high as 450 t km^{-2} yr^{-1} at Taklimakan (40°N, 85°E) also in China.

Although the dust deposition rates we have obtained in this study seem reasonable, it can be seen from Fig. 5b that particles of different sizes contribute differently to the total deposition flux. From the figure, it appears somewhat parodoxical that for some particle sizes the deposition flux is negative, suggesting a possible injection of particles of these sizes into the dust plume from local non-Saharan dust production sources. However, these negative flux components are not significant and it is clear that

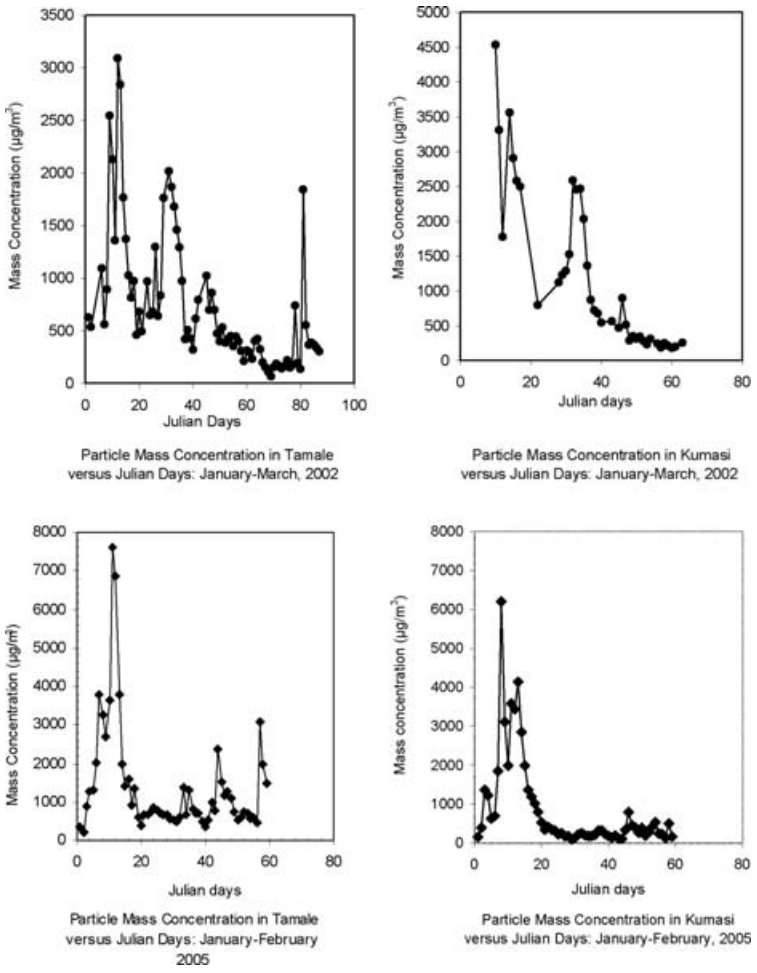


Fig. 4. Daily particle mass concentrations at Tamale and Kumasi during 2002 and 2005 Harmattan seasons.

within the range of particle sizes considered, the total flux is indeed a deposition flux, even if for certain class sizes the situation is less obvious. In any case, it is the total mass flux that really accounts for the quantity of dust particles that finally gets deposited on the ground and other surfaces.

4.3. Transit time

In order to estimate the transit time for the dust particles to travel from Tamale to Kumasi, we studied carefully the particle number and mass distributions obtained at the two measurement sites during both the 2002 and 2005 Harmattan seasons. From these diagrams, Figs. 6 and 7, several peaks associated with significant dust spells can be observed. These observations point to several pairs of successive peaks linking the Tamale and Kumasi data. In 2002, the peak occurring on Julian day 31 (January 31) at Tamale corresponds to that detected on Julian day 32 (February 02) at Kumasi. Similarly, the peak of Julian day 45 (February 14) at Tamale corresponds to the peak recorded on Julian day 46 (February 15) at Kumasi. In 2005, the peak that was observed on Julian day 7 at Tamale was detected a day later on Julian day 8 at Kumasi. The other pairings are Julian day 11 and 44 at Tamale for Julian day 13 and 46 at Kumasi, respectively. It is estimated, therefore, that mean-size dust particles take between one and two days to travel from Tamale to Kumasi.

In order to verify this experimental observation, we calculated (in a first approximation) the dust transit time between Tamale and Kumasi, separated in a straight north–south direction by a distance of 320 km and using an average mainstream wind speed of $U = 3.48$ m s^{-1} for 2002 and $U = 4.0$ m s^{-1} for 2005. For the two cases, the calculated transit time is 22 and 25 h, respectively, or roughly 1–2 d, as observed experimentally. We note that the basic unit of time for our experimental method is one day, such that a time lapse of more than 24 h and less than 48 h is taken as 2 d.

5. Conclusion

The Saharan dust flux deposition rates of 13 and 31 t km^{-2} yr^{-1} determined for Ghana during two separate Harmattan (winter) seasons can be reasonably considered as typical values for geographical regions lying on the Gulf of Guinea between lati-

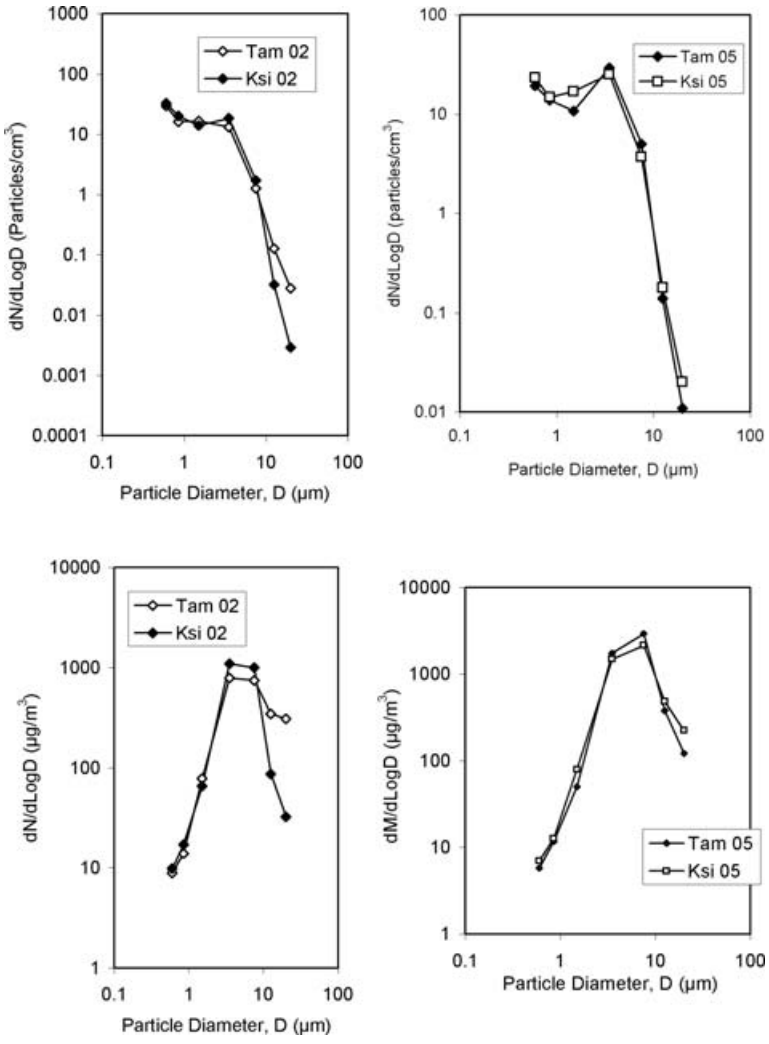


Fig. 5. Comparison of number and mass frequency distributions for 2002 and 2005.

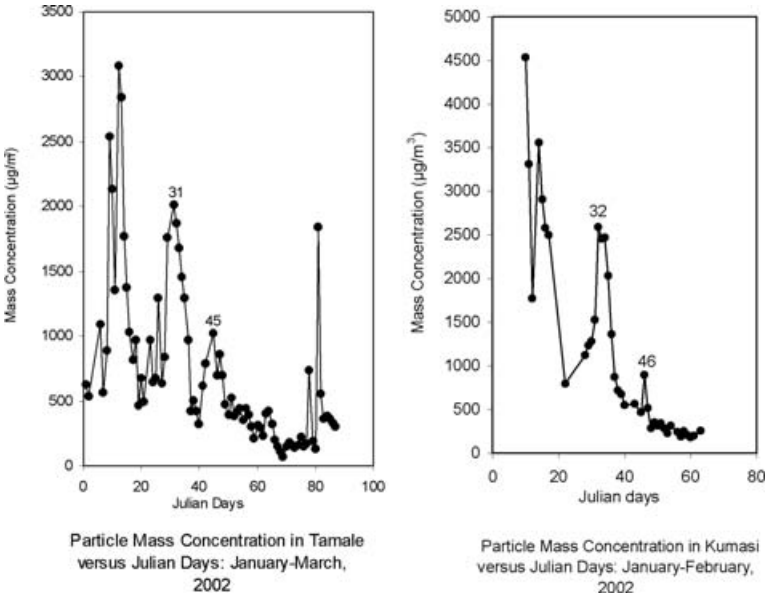


Fig. 6. Experimental determination of dust aerosol transit time between Tamale and Kumasi from 2002 data.

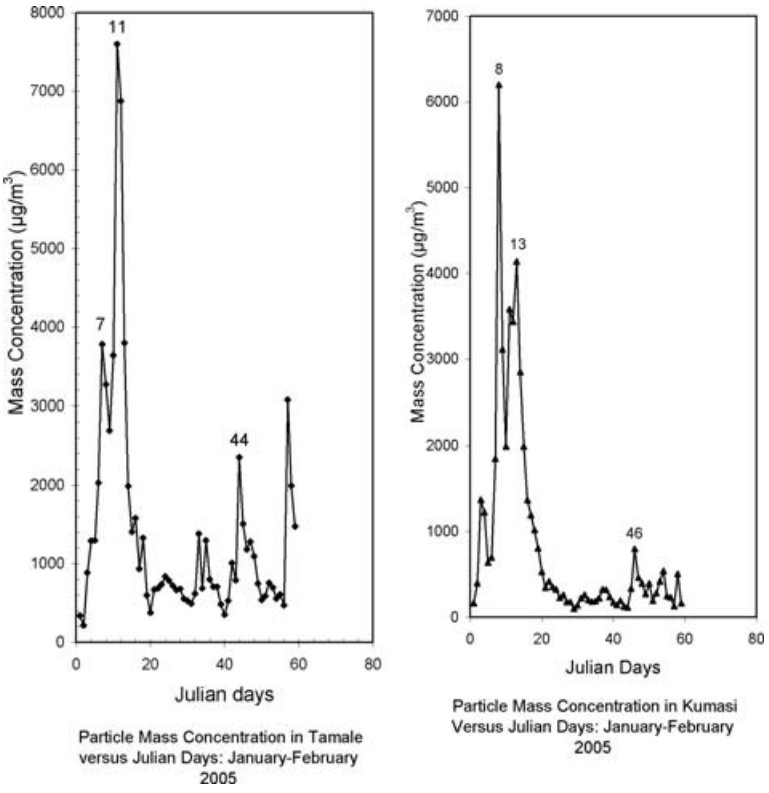


Fig. 7. Experimental determination of dust aerosol transit time between Tamale and Kumasi from 2005 data.

tudes 5° and 12°N during the winter. It is, however, possible that much higher or lower deposition rates may be experienced during very severe or milder dust episodes. The experimentally determined transit time of one day for the dust particles to travel from the north to the south of Ghana can serve as an early-warning indicator for precautionary measures to be taken, where necessary, against any massive influx of Saharan dust particles into the coastal areas of the country where the major industries and hospitals are located. The dust concentrations and deposition rates can also compared with any future simulation of the transport and deposition of the Saharan dust towards the Gulf of Guinea.

6. Acknowledgments

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