Harmattan Dust Deposited in Ghana within 2000–2005

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Abstract

Between 2000–2005, a monitoring system for the collection of harmattan dust over Ghana was established. Three methods were used to sample the harmattan dust: i) bowls with water, ii) plastic mats and iii) plates made of plywood. This paper describes the establishment of the monitoring system, and the regional distribution of harmattan dust trapped in various agro-ecological zones by the bowls with water and the mats. The bowl values represent the total amount of dust falling over a unit area, and the mat values represents the amount of dust retained by vegetation. The amount of harmattan dust captured is largest in the north where the mats retained about 20 g/cm^3 compared to 5 g/cm^3 in the south. The amount of dust retained differs significantly from year to year, and the particle-size of the dust becomes finer towards the south and with an increasing amount of organic matter. In the north, the median diameter was slightly above 15 μm and the organic carbon content was about 5% while in the south the median diameter was slightly above 5 μm and the organic carbon content was between 10 and 15%.

Introduction

In West Africa, along the Gulf of Guinea, a dry wind, the harmattan, blows from the Sahara Desert in parts of the year. In Ghana the dust-laden harmattan wind is experienced in November–March, when it replaces the south westerly monsoon winds. During that period, storm activities in the Bilma and Faya Largeau area in the Chad basin raise large amounts of dust into the atmosphere which then is carried southwest by the predominant winds (Kalu, 1979; Mc Tainsh, 1980; Mc Tainsh & Walker, 1982; Cox *et al*., 1982; d'Almieda, 1986; Afeti & Resch, 2000).

In publications on harmattan dust, dust samples were collected in many ways, but mostly in different types of containers or funnels, some others filled with water or other liquids like paraffin (Mc Tainsh & Walker, 1982; Tiessen *et al*., 1991; Mc Tainsh *et al*., 1997; Adetunji *et al*., 2001) or on different types of plates (Møberg *et al*., 1991; Tiessen *et al.*, 1991). The question is, which sampling technique gives the most accurate measure of the amount of dust that settles on the landscape? Stoorvogel *et al*. (1997) showed that in the tropical rain forest in the Taï National Park in Ivory Coast, the harmattan dust deposition was twice as high using a canopy drip method compared to the dust captured in wet basins. This shows that the dust samplers should express the land surface cover as much as possible. Thus, in order to measure the amount of dust that settles on the landscape, it is important to use samplers which, as much as possible, mirror the vegetation cover.

Some investigations have been carried out in Ghana on the harmattan dust. Tiessen *et al.* (1991) investigated some soils in northern Ghana and compared their chemistry with the chemistry of the harmattan dust captured on plastic sheetings or in funnels. Resch (2000) measured, over a 3-year period at Kumasi in southern Ghana, the particle size, number and mass concentration in the air by means of a Pacific-Scientific Hiac/Royco 5250A. But none of these investigations measured the regional variation of dust deposition over several years. The objective of the paper is to demonstrate the spatial and annual variation of the harmattan dust deposition over Ghana.

Materials and methods

Study area

Ghana is located in West Africa on the Gulf of Guinea and lies between 6° and 11° N and 1° E and 3° W. The monthly mean temperature is between 25 °C and 30 °C. In the south, two pronounced rainy seasons exist, one in April-June and the other in September-November. The minor dry season is in July-August, while the major dry season is in December-February. In the north of Ghana, there is only one rainy season from July to October, followed by a long dry season.

In the coastal area in the southeast the annual precipitation is lower than 1000 mm and a narrow coastal savanna zone with grasses and few trees are found. In the southwestern corner of Ghana, the vegetation is tropical rain forest (Fig. 1). This is surrounded by a moist semi-deciduous tropical forest with a pronounced litter fall in the dry season. Towards the north the moist semi-deciduous tropical forest turns into a Guinea savanna with grasses, scrubs and a few trees. In the dry north, the Guinea savanna zone turns into the Sudan savanna zone.

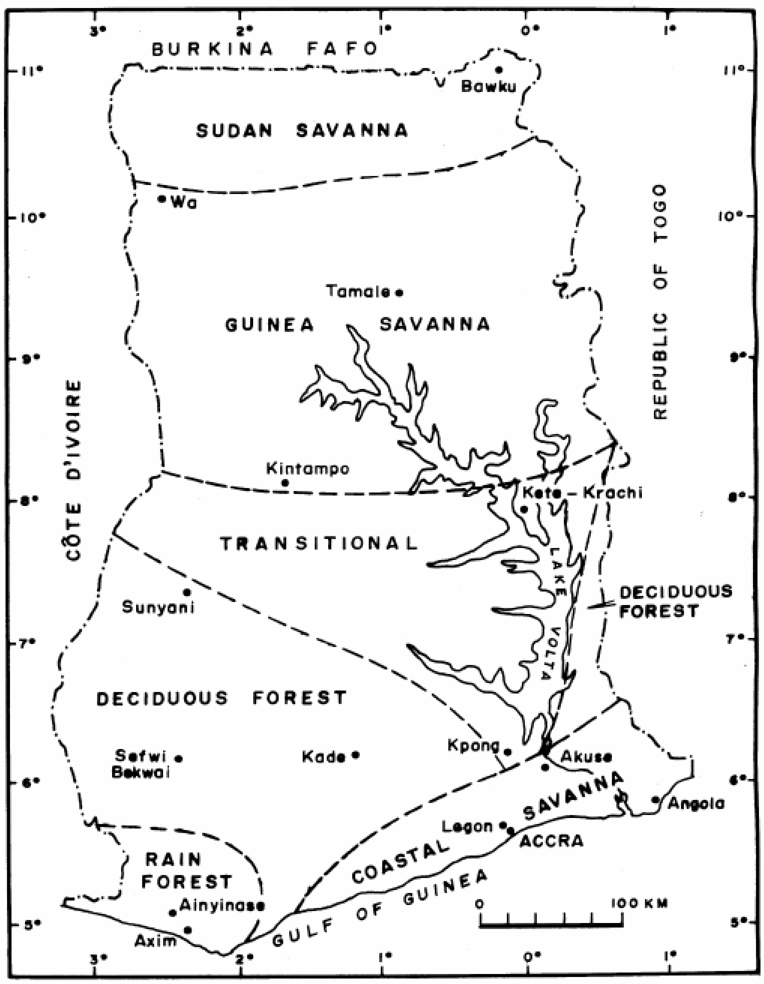

Fig. 1. Map of Ghana showing the ecological zones, the location of the climatic stations mentioned in Table 1 and the location of sampling sites for collecting harmattan dust

In December–February the north-eastern harmattan wind dominates in the northern part of Ghana, while the south-westerly monsoon wind dominates southern Ghana. The location of the border between the two wind systems – The Intercontinental Convergence Zone (ITCZ) – is not lying stable during the harmattan period, it moves and, sometimes, the north-easterly harmattan wind reaches the Gulf of Guinea. Table 1 shows the dominant wind direction on monthly basis for three harmattan seasons 2001–2002, 2002–2003 and 2003–2004. At the northern stations, Tamale and Wa, the north-easterly harmattan winds were dominant over the 3-year period.

TABLE 1

The dominant wind direction on monthly basis for seven climatic stations in Ghana. Their location is shown in Fig. 1

	2001-2002			*2002-2003*			*2003-2004*		
	Dec.	*Jan.*	*Feb.*	*Dec.*	*Jan.*	*Feb.*	*Dec.*	*Jan.*	*Feb.*
East Ghana									
Tamale (n)	NE	NE	NE	NE	NE	NE	NE	NE	NE
Kete Krachi (m)	S	N	SW	NE	N	S	N	N	S
Akuse (s)	SW	SW	SW	SW	SW	SW	NW	NW	SW
Accra (s)	SW	W	W	W	W	W	W	W	W
West Ghana									
Wa (n)	NE	NE	NE	NE	NE	NE	NE	NE	NE
Sunyani (m)	SW	SW	SW	SW	SW	SW	SW	SW	SW
Axim (s)	SW	SW	SW	SW	SW	SW	SW	SW	SW

(n) north Ghana, (m) mid Ghana, (s) south Ghana

In mid-Ghana the harmattan reached the eastern part each year although it did not dominate in all the 3 months. In mid-west, the south-west monsoon dominates each year in all the 3 months. In the south-east of Ghana the south-west monsoon dominates through out the year at the coast (Accra), but at Akuse, about 50 km north of Accra, the harmattan dominated in December and January 2004. At the south-western Ghana, the south-west monsoon dominated throughout the three harmattan periods. Although the south-west monsoon dominates in the south, the harmattan often has a break through for some days and reaches the coast. On the other hand, a substantial part of the dust trapped in the south is local dust and not dust transported from the Sahara.

Methods of dust collection

In order to determine the dust deposition rate in the different agro-ecological zones, four test sites were established in the year 2000; one at Bawku in the Sudan savanna zone, one at Tamale in the Guinea savanna zone, one at Kade in the moist semi-deciduous forest zone and one at Kpong in the coastal savanna zone (Fig. 1). In 2001, these four test sites were increased with several sites covering the entire country. Table 2 shows the stations and the years of sampling. The period 2000-2001 can be considered as a pilot study and, based on this, a nation-wide coverage of stations were established and functioned for 3 years. Based on the results obtained for the 3 years, the number of stations was reduced in 2004-2005 but still a reasonable coverage of the country was maintained.

TABLE 2

The location of the harmattan dust sampling sites 2000-2005

	2000-2001	*2001-2002*	*2002-2003*	*2003-2004*	*2004-2005*
Bawku	*	*	*	*	*
Wa		*	*	*	
Tamale	*	*	*	*	*
Kintampo			*	*	*
Sunyani		*	*	*	
Kete Krachi		*	*	*	*
Sefwi Bekwai		*	*		
Kade	*	*	*	*	*
Kpong	*	*	*	*	*
Ainyinase		*	*	*	*

Legon	*	*	*	*
Anloga	*	*	*	

Some of the sampling sites were situated at agricultural experimental stations; others were located at local farmers' fields or similar places. Each of the sampling sites were covered with vegetation, and they were located far from public roads and major towns (except Legon) in order to minimize the input of local dust (Tiessen *et al*., 1991; Erell & Tsoar, 1999). Thus, it is believed that most of the local dust might be generated from ploughed fields as well as grazing and other similar land uses. Three types of samplers were used to trap the dust (Fig. 2).

Fig. 2a. Mat sampler and bare wood sampler in frame with drainage system;

Fig. 2b. Bowl with water and a mat sampler in frame with drainage system

1. Plastic bowls about 40 cm deep with an inlet area of 0.23 m^2. The bowls were filled with water up to 10 cm to the top and was refilled once a week to 10 cm to the top. Except for the harmattan seasons of 2001-2002 when tap water was used to trap the dust, distilled water was used for the remaining years. In order to avoid birds, mice and other animals from drinking and polluting the water, a thin grid cover with a mesh width of about 1 cm was used to cover the mouth of the bowl. It is believed that the results from this type of sampler reflect the total amount of dust per harmattan season, as the dust trapped cannot be blown out again as would happen in a dry surface. Further-more it gives an indication of the dust retained in lakes and other water bodies, which is important in Ghana as it hosts one of the biggest man-made lakes in the world, the Volta Lake (Fig. 1).
2. Plastic mats covering 0.63 m^2, 70 cm broad and 90 cm long. The mats have plastic straws like a grass lawn. There are eight plastic straws per square centimetre. Each straw is 1.5 cm long and has a surface area of about 1 cm^2. Thus, the surface area of the mat is about eight times the surface area of bare ground. The mats are placed in a 2-cm high wooden frame. A drain is fitted by connecting a tube to a drilled hole in the frame in order to drain the water from erratic showers which might occur during the harmattan period, especially in the south. The tube leads the water to a 36-litre plastic container (Fig. 2). From the season of 2003-2004, another type of mat sampler was introduced at the sampling sites in the south where erratic showers occur during the harmattan that more than fill the 36-litre plastic containers and, thereby, reduces the possibility of accurately calculating the amount of dust retained. A plate of plywood with a diameter of about 55 cm was placed in a bowl 2 cm from the top. Holes for drainage were drilled in the plate and on the plate a mat fitting the size of the plywood was placed. When it rained the water passed through the holes in the plywood and collects in the bowl. These samplers can easily absorb all the precipitation in the erratic showers and are, therefore, more reliable than the mats in frames. The plastic mats are believed to give an estimate of the dust

which is captured by the vegetation and if harvested after the end of the harmattan period gives an approximate measure of the dust fallen to the ground and retained there.

3. Wooden plates covering 0.63 m^2, 70 cm broad and 90 cm long. If harvested at the end of the harmattan dust period, these plates are believed to retain dust in an amount similar to those falling on bare ground or consolidated areas like towns, asphalt roads, airports, etc.

The samplers were installed at the end of November and harvested about 1 March the following year. They were at all the sites established one metre above the ground, but at selected sites, samplers were also installed at other heights for special experiments. In this paper only the results for the bowl and mat samplers installed at 1 m height are reported and discussed.

At the end of the sampling time the mats were placed in plastic bags to avoid contamination during their transportation to the laboratory in Accra. Most of the water in the bowls was decanted on location and the remaining water with the sediment was stored in 1.5-litre plastic bottles. It was obvious that biological activity had taken place in the bowls with tap water and distilled water since the water had turned greenish due to algae.

Analyses

In the laboratory, the mats were carefully washed with distilled water. The water was evaporated in big glass beakers in order to get dry dust samples for analyses. The colour of the dried dust samples was determined by means of a Munsell Soil Color Chart. The bowl samples were also evaporated in big glass beakers. In some cases, the samples were contaminated with remnants of straw and starch from nearby fields. Before analyses, most of these were removed by a floating procedure, where the samples were put into water-filled beakers. The dust sank to the bottom while the plant remnants were floating at the water surface and skimmed off. The dried samples were weighed and g/m^2 of dust calculated. Because of the contamination of the mat samples with plant remnants and algae blooms in some of the bowls, which lead to an increase in total organic matter content, only the amount of the mineral part of the dust trapped is reported.

Particle-size was determined by use of a Malvern Mastersizer 2000 (laser diffraction method) as this method requires only small amount of soil material. Less than 1 g of dust sample was washed in hydrochloric acid to remove carbonates if present. Then the samples were treated with hydrogen peroxides for removal of organic matter. The samples were then dispersed with 0.1 *M* $Na_4P_2O_7$ and treated with ultrasound for 3 min. before analysis. A standard procedure was used for operating the Malvern Mastersizer 2000 and the diffraction pattern was converted to a grain size distribution using Mie diffraction theory (Mc Cave & Syvitski, 1991; Agrawal *et al.*, 1991; Operators Guide, 1998). Total carbon content was determined by dry combustion using an Eltra CS500-apparatus.

Results and discussion

Regional variation in the amount of dust retained by the water filled bowls

Information on the intensity of the Harmattan can be obtained from the amount of dust trapped in bowls with water. This is due to the fact that re-suspension from the bowl is almost zero, while re-suspension must be expected from the mats. Table 3 shows that, on average, the bowl samplers at Bawku in the north trapped about two and a half times the amount of dust trapped at Kpong in the south. There were big differences in the amount of dust trapped from harmattan season to harmattan season. The seasons 2001–2002 and 2004–2005 were very severe with high dust loads and, in the period investigated, the severe harmattan in the north occurred at the same times as in the south. As more than 10 stations have been equipped with water filled bowls, and they are spread over the country, it is possible to make maps showing in broad classes the intensity of the harmattan in various seasons.

TABLE 3

The amount of mineral dust trapped by bowl samplers at Bawku in the north and Kpong in the south during five harmattan seasons 2000-2005

	2000-2001 g dust/year	*2001-2002g g dust/year*	*2002-2003g g dust/year*	*2003-2004g g dust/year*	*2004-2005g g dust/year*	*Mean n=5*	*st. d.*
Bawku	15.9	80.7	30.7	14.6	42.8	37.0	27.0
Kpong	9.4	21.3	9.5	10.5	21.4	14.4	6.4

The results from the bowl with water samplers for the harmattan seasons 2001-2002, 2002–2003 and 2003–2004 are shown on Fig. 3. The lines are drawn based on the results from the different stations shown in Fig. 3. The three harmattan seasons represent years with strong, medium and weak dust-laden. The harmattan season 2001-2002 was the strongest in the 5 years of measurements. In the northern part of the savanna area (Bawku-Wa) the dust trapped in the bowls accounted for more than 80 g/m^2. Around Tamale, the dust deposition was relatively low (20-30 g/m^2) and far below the amount of dust trapped at Kete Krachi further to the south-east (above 40 g/m^2). Also, in the south, the dust collected is high, but not as extraordinary as found in the north. In the moist semi-deciduous forest zone the bowls trapped between 10 and 15 g/m^2. In the south-west, covered by tropical rain forest, less than 5 g/m^2 were trapped.

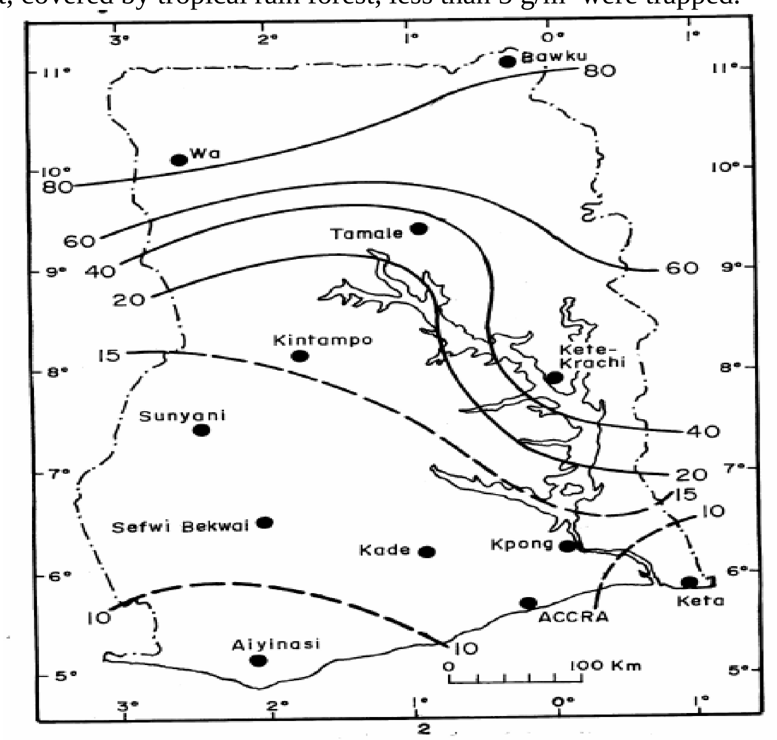

Fig. 3. The regional variation in the amount of harmattan dust trapped in bowls filled with water

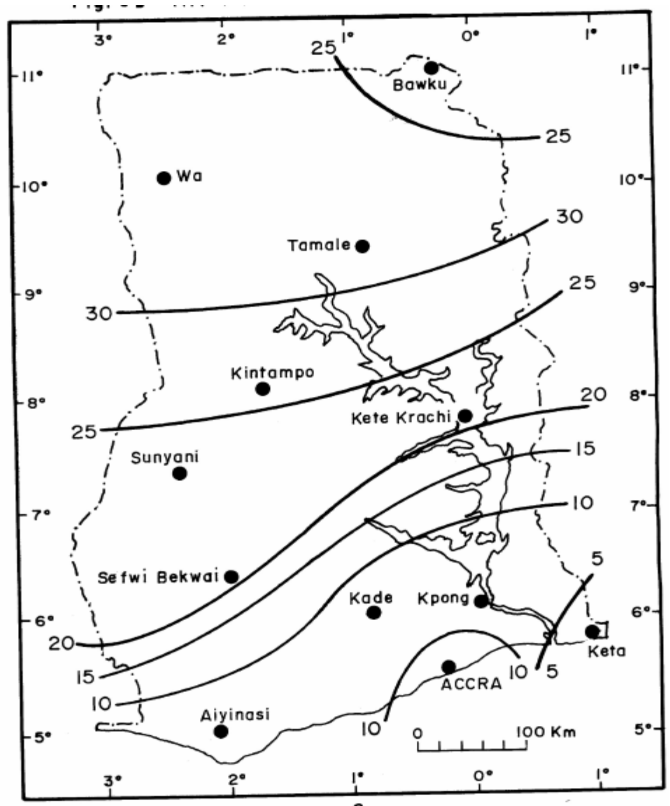

Fig. 3a. g dust/m² in the harmattan season 2001–2002

Fig. 3c HARMATTAN DUST DISTRIBUTION

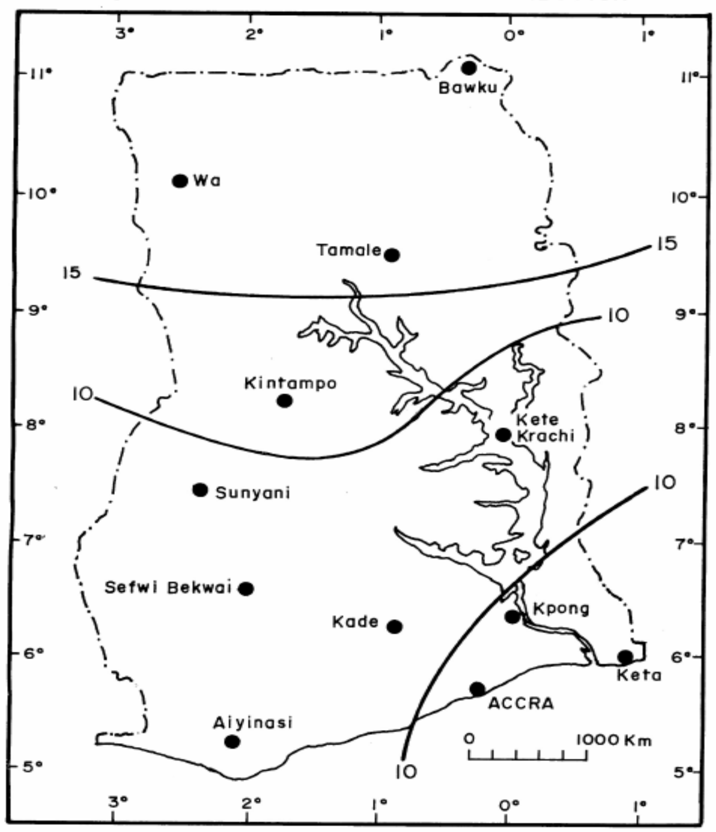

Fig. 3c. g dust/m² in the harmattan season 2003–2004

The harmattan season 2002–2003 expressed a medium harmattan period. The dust retained in the bowls in the north was about 30 g/m² with maximum value of 36 g/m² in Wa. The dust load decreased towards the south and in the northern part of the moist semi-deciduous forest zone it was about 20 g/m² and less than 15 g/m² in the southern part. The lowest values were recorded in the south-eastern corner at Anloga with 3 g/m².

The harmattan season 2003–2004 was very weak in the north. The dust retained accounted for 15–20 g/m² and decreased towards the south, and in the moist semi-deciduous forest it was about 5–10 g/m². In the south-east, in the coastal savanna zone, the amount of dust retained was 10–15 g/m².

Regional variation in the amount, texture and carbon of dust retained by the mats

The amount of dust retained by the mats is a measure of the dust captured by the vegetation (Breuning-Madsen & Awadzi, 2005). Table 4 shows the amount of dust trapped on the mats in the period 2000–2005. In general, the harmattan dust deposition rate was highest in the north and decreased towards the south. The savanna area, Bawku, Wa, Tamale and Kintampo, had an average deposition per harmattan season of slightly above 16 g/m² while the sampling sites in the moist semi-deciduous forest area, Sunyani, Kete Krachi and Kade, is slightly above 5 g/m².

TABLE 4

The amount of the mineral portion of dust trapped on the mats for five harmattan seasons

	2000-2001 g/m²	*2001-2002 g/m²*	*2002-2003 g/m²*	*2003-2004 g/m²*	*2004-2005 g/m²*	Average g/m²	st.d.
Bawku	15.7	25.1	17.2	15.7	19.6	18.7	3.9
Wa	–	23.9	13.6	23.0	–	20.2	5.7
Tamale	12.0	14.4	12.5	11.9	15.2	13.2	1.5
Kintampo	–	–	– 12.3	13.6		–	
Keta Krachi	–	–	6.7	5.3	7.8	6.6	1.3
Sunyani	–	5.8	5.0	4.4	–	5.1	0.7
Kade	–	2.3	2.4	7.7	5.5	4.5	2.6
Ainyinase	–	–	–	4.4	3.5		–

Based on the mat samples from Bawku and Tamale, the harmattan seasons 2000–2001 and 2003–2004 were very weak, while the harmattan season 2001–2002 was the most dust-laden in the north. It is also supported by the results from Wa. On the other hand, the dust deposition in Wa was rather severe in 2003–2004 where the deposition rate in Bawku-Tamale was low. In the south the variation from year to year is low in absolute figures but in average the dust trapped in the two last seasons seems to be a little higher than the years before. This means that there is no connection between the seasons in the north and south for maximum dust retention.

The grain size distribution of the dust trapped on mats in the harmattan season 2003–2004 is shown in Table 4. In the north (Wa, Bawku and Tamale) the median grain size (D_{50}) is about 16 μm and the mean grain size is about 13 μm. The grain size distribution is rather close to a log normal distribution but with a little tail of coarser materials (Breuning-Madsen & Awadzi 2005). The organic carbon content is lowest in the north-east with about 3% organic carbon increasing to about 7% in Wa and Tamale. In the middle section (Kintampo, Sunyani, Kete Krachi) the grain size distribution became finer and the D_{50} and the mean value dropped to about 10 μm, indicating a more log normal distribution than in the north. The organic carbon content increased to about 15%. Further to the south D_{50} and the mean value dropped to about 6 μm with an organic carbon content of about 13%, which is almost at the same level as in the middle section. Thus, the general trend is that the grain size distribution is finer towards the south, while the organic carbon content is lowest in the north.

As the grain size analyses were carried out using the laser diffractometry method, it is difficult to compare the laser results with dust analyses carried out with the pipette or hydrometer method. A comparison of the pipette method and laser diffractometry method shows that the two methods give almost the same result when looking at the sand fraction, but the laser diffractometry method overestimates the silt content and underestimates the clay content compared to the pipette method. This discrepancy is, among other things, due to different principles where the pipette method defines the particle diameter as equivalent to that of quartz sphere settling in a liquid, while the laser diffraction method calculates the diameter based on the particle diffraction pattern. Konert & Vandenberghe (1997) demonstrate that the percentage share less than 2 μm, determined by the settling method, correspond well with the percentage share less than 8 μm, determined by the laser diffractometry method. If so, the dust settled in northern Ghana will have about 30% clay, while that in the south will have about 50% clay if the texture was determined by the pipette method.

The relative increase in the organic carbon content towards the south might be due to differences in the sedimentation rate of the mineral and organic part of the dust and/or an enrichment of the dust with organic matter when passing through Ghana. The increasing content of organic matter towards the south is reflected in the colour of the dust. Using the Munsell colour notation the dust in the Bawku area is often pale brown to brown; in the Tamale area it is brown while in the south it is dark greyish brown. These colours indicate that the major part of the dust does not have its origin from red tropical soils, but probably, as proposed by Kalu (1979), Mc Tainsh (1980), Mc Tainsh & Walker (1982), Cox *et al*. (1982, d'Almieda (1986) and Afeti & Resch (2000), the dust originates from the Bilma and Faya Largeau area in the Chad basin. In that region, very large areas which were former lakes have evaporated leaving behind evaporites on the ground and fossils from the aquatic state.

Table 5

The particle size distribution and total carbon of the mat samples from the harmattan season 2003-2004

Location and height	*D(0.1) μm*	*D(0.5) μm*	*D(0.9) μm*	*Mean μm*	*Total C%*
Bawku	1.7	17.1	58.6	13.4	3.1
Wa	1.7	16.0	69.6	13.3	7.5
Tamale	1.6	15.3	58.6	12.3	6.0
Kintampo	1.7	11.3	45.9	10.2	14.6
Kete Krachi	1.8	10.7	40.1	9.5	15.6
Sunyani	1.3	8.2	72.0	9.0	14.9
Kade	1.0	5.4	25.7	5.3	11.9
Kpong	1.1	6.1	30.2	6.1	13.0
Anloga	1.3	7.4	43.7	7.7	14.5

Loess formation in Ghana

In Nigeria, closer to the source of the harmattan dust in the Sahara, Aeolian mantles of geological significance (Sombroek & Zonneveld, 1971; McTainsh, 1984) has been reported, and it is, therefore, obvious to investigate whether the severe Harmattan in the north can form loess deposits. The Memoir No. 5 of Soil Survey of Ghana (Adu, 1969) does not describe loess deposits in north-east Ghana, where high deposition rate of dust is found. An extensive survey between Bolgatanga and Bawku conducted in 2001 confirmed the work of Adu (1969) that no loess layer was found, and the soil surfaces were often gravelly or stony. Detailed soil profile investigation at the agricultural stations at Bawku (Tafeli and Kupela soil series) and Tamale (Tingoli soil series) revealed that the parent material was not loess as the profiles contained great amounts of gravel and coarse sand in both topsoil and subsoil, particle-sizes which should not be present in loess deposits.

Pye & Sherwin (1999) stated that a high dust accumulation rate is crucial if a loess layer is to develop. In semi-arid conditions, the threshold accumulation rate is more than 500 $g/m^2/yr$. Thus, the deposition rate of dust measured in the three harmattan seasons described supports the fact that no distinct loess layer was found. The maximum dust deposition in Ghana occurs in the north with average dust deposition of about 20 $g/m^2/yr$, while in the south the deposition rate is about 5 $g/m^2/yr^{-1}$ in the moist semi-deciduous tropical forest zone and in the coastal savanna zone. The 20 $g/m^2/yr^{-1}$ will form a loess layer of about 0.015 mm per year or 1.5 cm per 1,000 years if it is assumed that the bulk density of the layer is 1300 kg/m^3. Termites and ants can easily incorporate such a layer into the soil, and no loess layer will develop. Furthermore, the present day deposition rate is probably higher than it was about 100 years ago, because the cultivation of the semi-arid soils and other types of human disturbance to desert surfaces has caused significant increase in the scale of dust transport (Tsoar & Pye, 1987; Morales, 1979).

Conclusion

There are great regional differences in the amount of harmattan dust captured in Ghana. In general, the Harmattan is most severe in the north. The amount of dust retained differs significantly from year to year, and in the period investigated a severe Harmattan in the north did coincide with severe Harmattan in the south. The texture of the dust becomes finer towards the south and with increasing amount of organic matter. The amount of dust retained on the surface in the north is about 20 g/m^2. This gives a deposition rate of about 15 mm per 1000 years. This explains why loess layer has not developed in northern Ghana.

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References

Adetunji M. T., Martins, O. and **Arowolo T. A.** (2001). Seasonal variation in atmospheric deposition of nitrate, sulphate, lead, zinc, and copper in southwestern Nigeria. *Commun. Soil Sci. Pl. Anal*. **32**: 65–73.

Adu S. V. (1969). *Soils of the Navrongo-Bawku area, Upper Region Ghana. Memoir No 5.* Soil Research Institute, Kumasi, Ghana.

Afeti G. M. and **Resch F. J.** (2000). Physical characteristics of Saharan dust near the Gulf of Guinea. *Atmosph. Envir.* **34**: 1273–1279

Agrawal Y. C., McCave I. N. and **Riley J. B.** (1991). Laser diffraction size analysis. In *Principles, methods and applications of particle size analysis.* (J. M. P. Syvitski, ed.), pp.119–128. Cambridge University Press, New York.

Breuning-Madsen H. and **Awadzi T. W.** (2005). Harmattan dust deposition and particle size in Ghana. *Catena* **63**: 23–38.

Cox E., Mazurek M. A. and **Simonei B. R. T.** (1982). Lipids in Harmattan aerosols in Nigeria. *Nature* **296**: 848–849.

d'Almieda G. A. (1986). A model for Saharan dust transport. *J. Climatol. appl. Meteorol*. **25**: 903–916.

Erell E. and **Tsoar H.** (1999). Spatial variations in the Aeolian deposition of dust – the effect of a city: A case study in Be'er-Sheva, Israel. *Atmospheric Envir*. **33**: 4049–4055

Kalu A. E. (1979). The African dust plume: Its characteristics and propagation across West Africa in winter. In *Saharan dust: Mobilization, transport, deposition.* (C. Morales, ed.), pp.95–118. Wiley, New York.

Konert M. and **Vandenberghe J**. (1997). Comparison of laser grain size analysis with pipette and sieve analysis: a solution for the underestimation of the clay fraction. *Sedimentology* **44**: 523–535.

McCave I. N. and **Syvitski J. P. M.** (1991). Principles and methods of geological particle size analysis. In *Principles, methods and applications of particle size analysis.* (J. M. P. Syvitski, ed.), pp. 3–21. Cambridge University Press, New York.

Mc Tainsh G. (1980). Harmattan dust deposition in northern Nigeria. *Nature* **286**: 587–588.

McTainsh G. (1984). The nature and origin of the Aeolian mantles of central northern Nigeria. *Geoderma* **33**: 13–37 .

Mc Tainsh G., Nickling W. G. and **Lynch A. W.** (1997). Dust deposition and particle size in Mali. *Catena* **29**: 307–322.

Mc Tainsh G. and **Walker P. H.** (1982). Nature and distribution of Harmattan dust. *Z. Geomorphol. N.F.* **26**: 417–435.

Morales C. (1979). *Saharan dust: Mobilization, transport, deposition*. Wiley, New York. 297 pp.

Møberg J. P., Esu I. E. and **Malgwi W. B.** (1991). Characteristics and constituent composition of Harmattan dust falling in Northern Nigeria. *Geoderma* **48**: 73–81.

Operators Guide (1998). *Malvern Mastersizer (2000).* Malvern Instruments Ltd. Worchestershire, UK.

Pye K. and **Sherwin D.** (1999). Loess. In *Aeolian environments, sediments and landforms.* (A. S. Goudie, I. Livingstone and S. Stokes, ed.), pp. 213–238. Wiley, New York.

Sombroek W. G. and **Zonneveld I. S.** (1971). *Ancient dune fields and fluviatile deposits in the Rima- Sokoto River Basin (N.W. Nigeria). Soil Survey Paper 6*. Soil Survey Institute. Wageningen.

Stoorvogel J. J., van Bremen N. and **Janssen B. H.** (1997). The nutrient input by Harmattan dust to a forest ecosystem in Côte d'Ivoire, Africa. *Biogeochem*. **37**: 145–157.

Tiessen H., Hauffe H.-K. and **Mermut A. R.** (1991). Deposition of Harmattan dust and its influence on base saturation of soils in northern Ghana. *Geoderma* **49**: 285–299.

Tsaro H. and **Pye K.** (1987). Dust transport and the question of dessert loess formation. *Sedimentol*. **34**: 139–153.

Whalley W. B. and **Smith B. J.** (1981). Mineral content of Harmattan dust from northern Nigeria examined by scanning electron microscopy. *J. Arid Envir.* **4**: 21–29.