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Full Length Research Paper

Hygroscopic properties of aerosols in the Sahel: preliminary results

Mouhamadou Bedou[1], Abdourahamane Konare[1], Ibrah Seidou-Sanda[2], Paul Assamoi[1] and Arona Diedhiou[3]

[1]LAPAMF, Université de Cocody-Abidjan, BP 231 Abidjan, Cote d'Ivoire.
[2]Université Abdou Moumouni, Faculté des Sciences, BP 10662 Niamey, Niger.
[3]IRD, BP 11416 Niamey, Niger.

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Approximately three years of sunphotometric measurements carried out in the locality of Bidi (13.36°N; 2.30°W) in Burkina Faso (West Africa) from October 1986 to January 1989 were used to estimate the atmospheric precipitable water vapour (APW) and the Angstrom exponent values α. A study of the relationship between these two parameters on a seasonal time scale shows that an increase of water vapour in the Sahel is associated with a decrease of α values, indicating hygroscopic growth of aerosol particles. This result shows that the Sahel aerosol particles may grow in size through water vapour absorption due to hygroscopic properties.

Key words: Aerosol, optical depth, angstrom coefficient, atmospheric water content and hygroscopic growth.

INTRODUCTION

Aerosols scatter and absorb solar radiation and thereby significantly reduce the amount of sunlight reaching the surface. Aerosols also modify the transfer of thermal radiation in the atmosphere and play an important role as cloud condensation and ice nuclei, contributing then to the formation of clouds (Hudson, 1993; Graham, 2000; Roelofs et al., 2004).

In West Africa in general and in the Sahelian zone in particular, aerosols are made up in large part of soil dust particles. These particles originate from the principal source regions of dust located in the Sahara desert and in the arid lands of Sahel (D'Almeida, 1987; Clark et al., 2004). Uplifted by strong surface winds, these particles are transported by the large-scale atmospheric circulation toward the southern and western Sahara as far as the American coast by the African Easterly Waves (Prospero et al., 1981, Diedhiou et al., 1999; Jones et al., 2003). Hygroscopic particles are in majority soluble particles, which have the capacity to absorb water (Hanël, 1976). Particles with hygroscopic properties can grow in size through water absorption when the relative humidity reaches certain thresholds.

Marine salts and sulphate particles are known to be the most hygroscopic particles (Kerminen, 1997). The hygroscopic behaviour of aerosol particles has been investigated over different oceans (Mabling et al., 2003). However, up to now no such investigations have been carried out over West Africa. Previous studies (Faizoun et al., 1994, McTainsh, 1996; Tanré et al., 2003) have revealed that in the Sahel, the size of aerosol particles is greater during the rainy season than in the dry season.

In this study, we investigate possible links between the observed growth of aerosols size during the rainy season and the atmospheric relative humidity. The present work aims to study the hygroscopic characteristics of aerosols over Sahel using sunphotometric measurements. The study is not concerned with the chemical composition of the aerosols, but investigates relationships between APW and the Angström parameter α. However we are aware that solubility is the main factor that characterizes the affinity of chemical compounds for water, and according to the Kohler model, particle growth of the spherical due to water vapour condensation depends on the aerosol chemical composition and initial diameters. Since α is a good indicator of the aerosol particles, values of the correlation coefficient between APW and α are apt to quantify the APW of aerosol sizes.

*Corresponding author. E-mail: akonare@ictp.it.

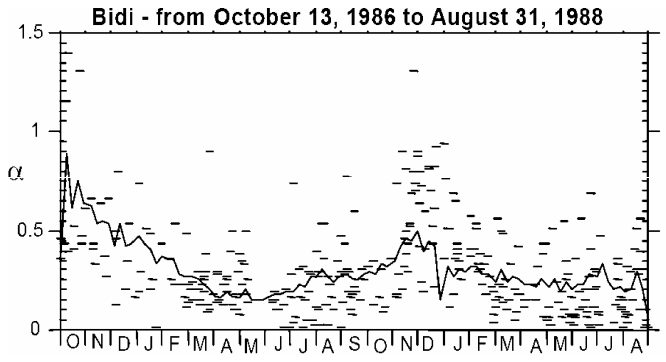

Figure 1. Evolution of the Angstrom wavelength exponent α at Bidi from October 1986 to August 1988. The continuous line represents the daily average.

Data

The sunphotometric measurements used in this study were carried out in the Sahelian locality of Bidi (13.36°N, 2.30°W) in northern Burkina Faso from October 1986 to January 1989 by the Centre d'Etudes Spatiales de la Biosphère of Toulouse (CESBIO, France). The photometer (Faizoun et al., 1994) had a 3° field-of-view and five interferometric filters: three were centred on the wavelengths 450, 650 and 850 nm for the determination of the optical depth of aerosols, whereas the two others were centred on the wavelength 940 nm with different half-band width; one wide (50 nm) and the other narrow (10 nm). The last two filters were used to determine the APW.

Measurements were made from 7:30 am to 2:30 pm at intervals of 15 min in sunlight time. The situation is mostly cloudless, with only reduced cloud covers. Thus measurements are performed quite continuously. Measurements affected by clouds are systematically discarded (Konare et al, 1998).

Data sets are available approximately for three consecutive years, thus enabling to study the influence of air humidity on aerosol size distributions on a seasonal time scale through two parameters: the APW and Angström exponent, this latter being an indicator of particle size distributions. At Bidi in particular and in the Sahel in general, the dry season extends from November to May while the rainy season is from June to September.

The angstrom exponent α

We use the Angstrom (1964) formula defined below:

$$\tau_{a\lambda} = \beta\lambda^{-\alpha} \qquad (1)$$

To determine the Angstrom coefficients α and β where β represents the Angstrom coefficient of turbidity. The Angstrom coefficient is the wavelength exponent in the size distribution. It is the log scale linear fit parameter between the aerosol optical thickness and the wavelengths. The mathematical form of the relation between α and size distribution is discussed in Junge (1963). Small values of α correspond to weak dependence of optical thicknesses on wavelengths and thus to a greater proportion of large size particles in the atmosphere and vice versa (Junge, 1963; Mohamed and Frangi, 1986).

Values of α were determined with each of the three band combinations (*450 - 650 nm*, *450 - 850 nm* and 650 - *850 nm*). The method used to determine α values from Angström formula correspond to a "band combinations". The Figure 1 displays daily average of α obtained from the bands 450 nm and 650 nm combinations in Bidi from October 13, 1986 to August 31, 1988. α varies on a daily time scale. The lower values of α were obtained from May to September whereas the higher values were obtained during the period from September to April. This confirms that aerosol particles have larger sizes in the rainy season than in the dry season (Fouquart et al., 1987; Faizoun et al., 1994).

The atmospheric precipitable water vapour

Frouin et al. (1990) have developed a method to estimate the atmospheric precipitable water vapour (APW). This differential absorption method is based on the ratio of measurements performed in two spectral bands overlapping the same water vapour absorption band near 940 nm.

Let I^L and I^E be the intensities of signals measured by the radiometer through the larger filter (*L*) and the narrow filter (*E*). Assuming that the bandwidth of each filter is narrow with respect to the spectral variability of molecular and aerosol extinction we can write (Thomason et al. 1982):

$$I^L = I_0^L \exp\left[-m\left(\tau_a^L + \tau_R^L\right)\right] t_{H20}^L \qquad (2)$$

$$I^E = I_0^E \exp\left[-m\left(\tau_a^E + \tau_R^E\right)\right] t_{H20}^E \qquad (3)$$

where I_0 is the solar spectral irradiance that would be measured at the top of the atmosphere; *m* is the optical air mass; t_R and t_a are the Rayleigh scattering optical thickness and aerosol extinction optical thickness, respectively; t_{H2O} is the water vapour transmission. Considering that the two filters are centred at the same wavelength (940 nm), we can assume that $t_R^L = t_R^E$ and $t_a^L = t_a^E$. So, the ratio between measurements becomes:

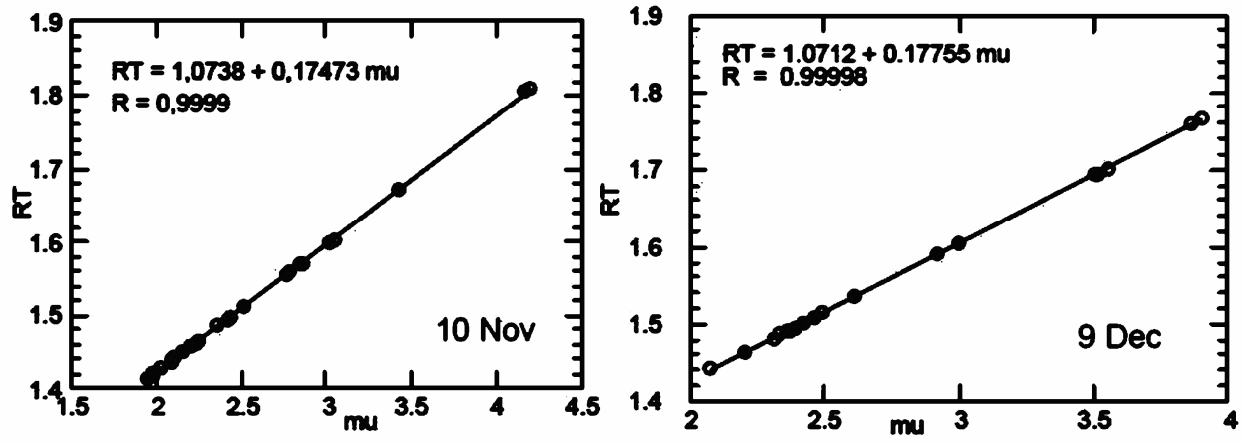

Figure 2. Illustration for two days (November 10 and December 9) of the relationship between the transmission ratio R_T and the product u.m of the optical air mass m and the water vapour content u established from measurements at Bamako (MALI) in 1991.

$$\frac{I^L}{I^E} = \frac{I_0^L t_{H2O}^L}{I_0^E t_{H2O}^E} \qquad (4)$$

Considering that aerosol optical thicknesses show a spectral decrease, the aerosols extinction is weak at 940 nm and using the ratio in equation (4) allows to eliminate the term due to the influence of aerosols in the measured signal expression. This ratio is influenced only by APW. However, use of the differential absorption method requires a model to approximate the total atmospheric water vapour transmission t_{H2O} and the filter functions of the photometer (Faizoun et al., 1994, Moskalenko, 1969).

In this preliminary study, we use a simple linear regression method as previously done by Konaré (1995), to approximate this ratio so as to follow APW temporal variability. From sunphotometric measurements performed in Bamako from November to December 1991 with a Cimel photometer, Konaré (1995) has established a relationship between the ratio $R_T = t_{H2O}^L / t_{H2O}^E$ relative to water vapour transmission, respectively through the large filter (t_{H2O}^L) and the narrow filter (t_{H2O}^E), and the product *um* between the APW *u* and optical air mass *m*. The atmospheric water vapour content calculated through this simplification gives results quite similar to the method described by Plana-Fattori et al. (1998) using the same data set. For November 10, 1991, a bias of only 3% was found on water vapour content.

Figure 2 shows a linear relation between these two parameters:

$$R_T = \frac{t_{H2O}^L}{t_{H2O}^E} = a + b\ u\ m \qquad (5)$$

Where *a* and *b* are constants. Thus, considering that $I_0^L / I_0^E \approx 1$, the ratio of measurements through the two filters is also linked to the product of um by a linear relation:

$$\frac{I^L}{I^E} = f(m) = q + k\ m \qquad (6)$$

where k = *b*' *u*; with *q* and *b*' constants. The ratio of measurements established for each sequence of measurements is a function of the optical air mass *m* as illustrated in Figure 3, which presents the ratio of the measurements versus the optical air mass for two days in Bidi.

This figure confirms that a linear relation with a correlation coefficient greater than 0.98 links the ratio of measurements to the optical air mass. Therefore, in equation 6, in which *q* is a constant depending only on the technical characteristics of the photometer, k represents the slope of the linear regression between the ratio $R_T = I^L / I^E$ and the relative optical air mass m. As shown in Figure 3, the constant q can be estimated to 5.520 ± 0.015 (average calculated with others fits as in Figure 3, not shown here). The values of the slope *k* are determined for each day and intermediate values can also be obtained from two successive sequences of measurements, in order to depict diurnal variations. In equation (6), k is proportional to APW *u* (*g/cm*^{2}) and *b*' is a constant depending only on the technical characteristics of the photometer.

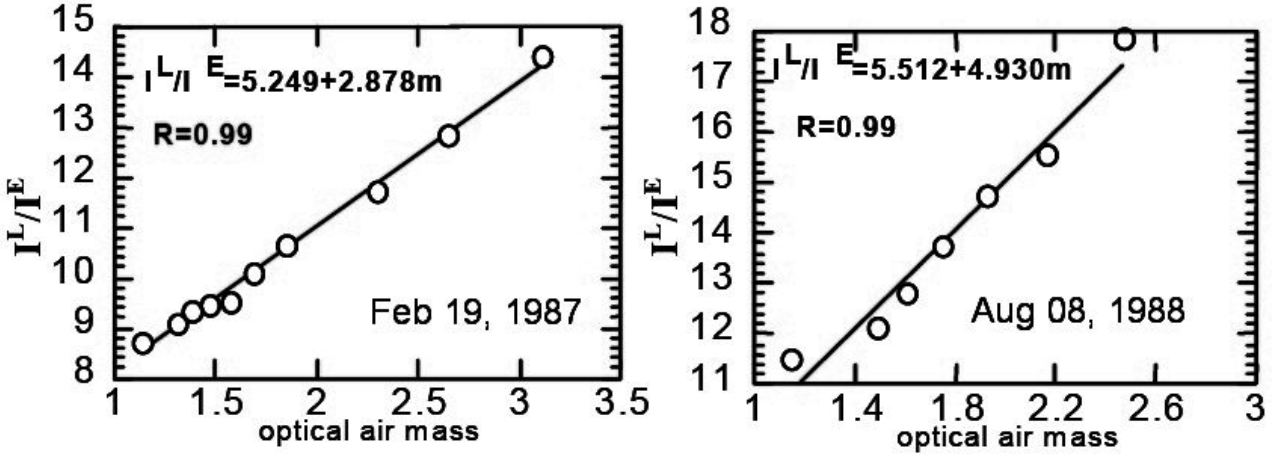

Figure 3. Illustration for two days of the relationship between the optical air mass m and the ratio of irradiance measurements through the wide and the narrow filters cantered at 940 nm.

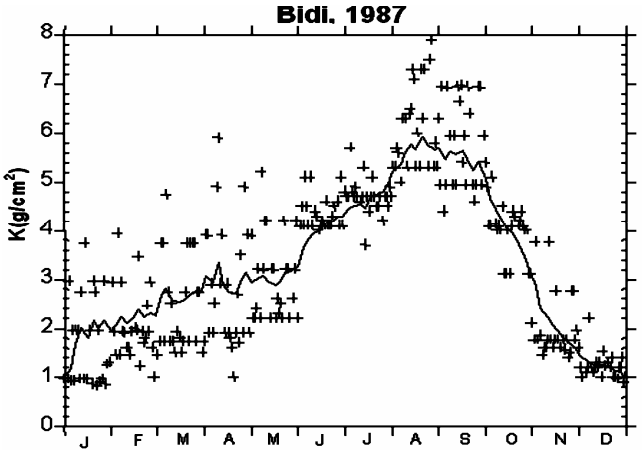

Figure 4. Evolution of the parameter k (g/cm^2) at Bidi for 1987. The continuous line represents the mean daily values.

RESULTS

In order to study the influence of atmospheric water vapour on particle size, a linear correlation coefficient was calculated between the Angstrom coefficient α and APW (represented by the parameter *k*).

We display in Figure 4 the annual evolution of the parameter k at Bidi in 1987. Values of k are higher during the rainy season (from May to September) than during the dry season (from November to April). We observe also, an increase of *k* values from March to August and a decrease from September to February. This annual variability of the parameter *k* was correlated with the latitudinal location of the Inter Tropical Convergence Zone (ITCZ) in West Africa (not shown). This evolution is similar to the APW annual variability obtained in previous studies (Cadet and Houston, 1984; Faizoun et al., 1994) in the Sahelian zone. This Figure 4 shows that the value of the parameter k is influenced by the APW.

Figure 5 displays the relationship between the daily averages of α and APW, during the dry and wet seasons in Bidi in 1987. The slope of the linear regression between these two parameters is negative as are the correlation coefficients, meaning that an increase of the atmospheric water vapour content (or relative humidity) is associated with an increase in the particle sizes. Seasonal values of the correlation coefficients are about -0.32 for the dry period from January to April (Figure 5a) and -0.67 for the wet period from June to September (Figure 5b). Correlation coefficients between α and the APW is higher during the rainy season than in the dry season. In Figure 6, we track the origin of the different air masses which reach the measurements location and try to find where the aerosols over Bidi could be originated. In Figure 6, back trajectories at 500 and 1000 m show that air masses overpass respectively two main cities of Burkina Faso, Bobo Dioulasso and Ouagadougou at low altitudes (~1 km or less). It is therefore highly probable that mixing within the urban boundary layer over these cities may allow urban aerosols to load the transported air mass arriving at Bidi. The third trajectory overpassing Bidi at 3000 m and originating in the central southern Saharan border region (North of Niger), carries desert dust which reaches Bidi three days later.

Figure 7 shows the smoothed curves of the time evolution of daily values of the correlation coefficients obtained between α and the APW vapour in Bidi from October the 13th, 1986 to August the 31st, 1988. Daily values of the correlation coefficients are greater than the seasonal values in Figure 5. The parameters α and k are daily linked by the relation: $\alpha = 1.120 - 0.168\ k$.

Figure 7 confirms those correlation coefficients are higher in the wet season than in the dry season and that aerosol particles may grow in size by water vapour absor-

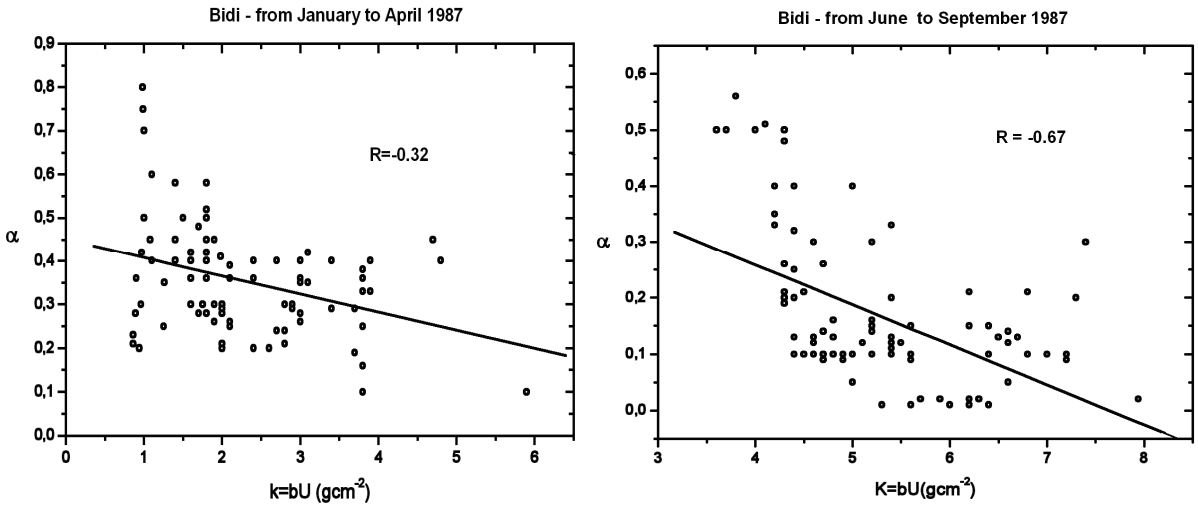

Figure 5. Relationship between the Angstrom exponent □ and the atmospheric precipitable water vapour at Bidi during the dry season (left) and the wet season (right) in 1987.

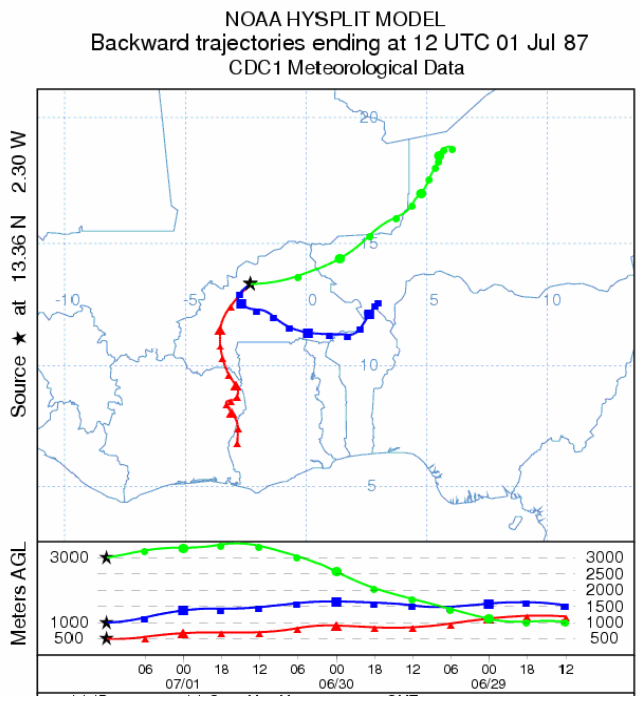

Figure 6. Back trajectories ending at Bidi location, for three different altitudes, 500 m (circle), 1000 m (square) and 3000 m (triangle) and for July, 1st 1987 at 12 h.

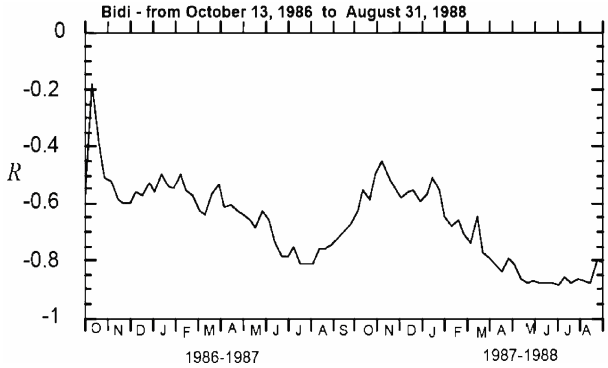

Figure 7. Smoothed curve of the temporal evolution of the linear correlation coefficients R between the Angstrom exponent and the atmospheric precipitable water vapour from October 13, 1986 to August 31, 1988.

ption. The effect of air humidity on aerosol particle size is more important in the wet season than in the dry season. This may be due to the fact that in the rainy season the relative humidity of the air is relative humidity is frequently over 70%, the minimum value required for hygroscopic growth of dry particles (Hanël, 1976).

DISCUSSION

We have used sunphotometric measurements performed for three years at Bidi (13.36°N; 2.30°W) in Burkina Faso from October 1986 to January 1989 to estimate atmospheric precipitable water vapour (APW) and the Angstrom Negative linear correlation coefficients were obtainned between these two parameters, showing that any increase in water vapour corresponds to decrease of α. For daily values, the average correlation coefficient varies from - 0.32 in dry seasons (November-May) to - 0.67 in wet season (June-September), emphasing the hygroscopic properties of aerosol particles in the Sahel.

However, average daily values of the correlation coefficients between α and the precipitable water vapour could be negative or positive (not shown here). Positive correla-

tion between α and APW may correspond to the cases where the presence or absence of large aerosol particles in the atmosphere is unrelated to precipitable water vapour contents. This may be linked to the advection of small particles or to washout by rain, and/or the fallout of larger particles. Negative correlations between α and the water vapour may correspond to the cases where the increase in the water vapour content is associated with decrease of α, meaning an increase in particle size. The distinction between positive and negative values of the linear correlation coefficient is an indicator about variations in aerosol optical depth caused by changes in aerosol loading (in terms of number and size distributions) from those due to changes in relative humidity.

A study by Levin and Lindberg (1979) at Tel Aviv (Israel) showed that desert soil dust particles are not hygroscopic. They concluded that the hygroscopic behaviour is due to the presence of urban anthropogenic aerosols. This is similar to the case over Bidi where water uptake of atmospheric aerosol particles at large relative humidity (low level monsoon flow) is possible regarding the chemical composition of the urban aerosols at Ouagadougou and Bobo Dioulasso (sulphates, black and organic carbon).

Prospero et al. (1981) and Faizoun et al. (1994) showed that the Sahelian area is affected mainly by desert aerosol particles from the Sahara. We have also noticed from Figure 6 that this desert aerosol reach Bidi at high levels after 3 days, thus, the question of change with time of Sahelian aerosols optical and hygroscopic characteristics needs to be further investigated though at altitude of 3000 m relative humidities are quite low (Kohler theory). For these reasons, one assumes that the hygroscopic behavior of aerosols in summer time at Bidi most probably originate from the polluted aerosols from Bobodioulasso and Ouagadougou advected over Bidi at low level and in a humid air. Studying the dust-water vapor interactions over north western Israel, Yakerson (1996) reported an increase in particle sizes, by a minimum of 10 - 15% from its "dry" sizes, when humidity grows up to 60 - 80%, similarly to our results. However, correlations between α parameter and wind direction (not shown here) are weak during the dry period because the wind direction is mainly from the East-Northeast whereas, during the wet period, since the wind blows from all directions, the contribution of aerosols particles transported in the monsoon flow (Southwest-Southeast) could be not negligible. Further investigations are needed which requires measurements as will be the case in the LOP-AMMA (Long Observing Period of AMMA International Program - African Monsoon Multidisciplinary Analysis

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