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Influence of atmospheric circulation patterns on dust transport during Harmattan Period in West Africa

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ABSTRACT: This study has used TOMS AI as well as the reanalysis dataset of thirty-four years (1979-2012) to investigate the influence of atmospheric circulation on dust transport during the Harmattan period in West Africa, using Aerosol Index (AI) data, obtained from various satellite sensors. Changes in Inter-Tropical Discontinuity (ITD), Sea Surface Temperature (SST) over the Gulf of Guinea, and North Atlantic Oscillation (NAO) during Harmattan period (November-March) have been analyzed on daily basis with Harmattan dust mobilization as well as atmospheric circulation pattern being evaluated via a kernel density estimate that shows the relation between the two variables. The study has found out that strong north-easterly (NE) trade winds were over most of the Sahelian region of West Africa during the winter months with the maximum wind speed reaching 8.61 m/s in January. The strength of NE winds determines the extent of dust transport to the coast of Gulf of Guinea during winter. This study has also confirmed that the occurrence of the Harmattan chiefly depends on SST in Atlantic Ocean as well as ITD position, not to mention the strength of low level winds. However, it has been noted that NAO has limited effects on dust mobilization in West Africa, in shear contrast to North Africa where NAO is a strong factor in dust mobilization.

Keyword: dust, ITD, SST, TOMS, West Africa.

INTRODUCTION

The dust from deserts and arid regions is a major component of natural aerosols in the atmosphere, playing an important role in climate system by both changing radiation budget of the Earth-atmosphere system and modifying clouds (Kaufman et al., 2005). The dust radioactive effect can alter atmospheric circulation such as the monsoonal moisture transport, which in turn affects precipitation (Zhao et al., 2011). During the time between November and March, the West African region experiences prevailing north–easterly wind system, known as Harmattan (Falaiye et al., 2003), which is a ground level stream of dry desert air, part of the African continental trade wind system that blows far south from a consistent NE direction during the boreal winter (Hastenrath, 1988). This dry wind transports and deposits the Saharan dust over the entire region, extending as far as to the Gulf of Guinea. During the winter months the seasonally variable Harmattan current transports large amounts of dust at irregular intervals from Chad Basin to Sahel and Guinean coast, where it reduces visibility,

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causing relative humidity and temperatures (McTainsh & Walker, 1982; Adedokun et al., 1989; Breuning-Madsen & Awadzi, 2005). The dust plumes predominantly originate from the Bodélé Depression in Chad Basin (Bertrand et al., 1979) and accounts for the dust particles deposited over the region.

The Saharan dust haze is one of the many aerosols in the atmosphere and it is important to show the relation among various aerosols. The current understanding of Saharan dust transport has been achieved through various studies (Schutz & Jaenicke, 1974; D'Almeida & Schutz, 1983; Hamonou et al., 1999; Prospero, 1999) that have focused on climatology, frequency of occurrence, areal extent of impact, vertical distribution, total mass loadings, and origin of dust particle characteristics, to name a few.

Also, they have been derived from a limited number of discrete measurements, a limited number of ship haze observations, atmospheric optical thickness measurements, visibility studies, and remote sensing. Saharan aeolian aerosols have been measured in West Africa, over the Atlantic Ocean and its islands as well as the lands near the Gulf of Mexico, south-eastern North America, North Africa, and Europe (Chiapello et al., 2005; Kaufman et al., 2005). What is more, the data, related to Saharan dust are still being collected and relevant studies are still in progress, e.g. the Aerosol Robotic Network (AERONET) at the website, http://aeronet.gsfc.nasa.gov/ (Holben et al., 1998) which tries to provide a long-term analysis of the Saharan aeolian dust, during dry season, sufficient to yield a representative and accurate description of Harmattan phenomenon in West Africa together with large scale factors, influencing its mobilization and transport.

In order to understand the phenomenon of Saharan dust in the atmosphere, it is needed to get adequate information from the source areas, their location and strength along with their seasonal and long-term variations. Such information, abundant in print literature and the Internet, will enable more reliable estimations of the fluxes leaving the Sahara, as well as their fate in the atmosphere and composition elsewhere (Chiapello et al., 1995; Swap et al., 1996; Moulin et al., 1997b; Marticorena et al., 1997; Prospero, 1999; Hamonou et al., 1999; Chiapello &Moulin, 2002;Chiapello et al., 2005; Kaufman et al., 2005). However, changes in the source strength over long periods may also be significant. There have been some suggestions (Prospero & Nees, 1977) about a threefold increase in dust concentrations in Barbados between 1965 and 1976, which might be due to an increase in the source strength in the Sahel, possibly associated with the drought in this region.

Formation 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. Soil texture or aggregates which may be in the form of a surface crust, large clods, or small pellets of soil, largely determine the threshold velocity and intensity of deflation (Chepil, 1945; Gillette, 1980; Bagnold, 1971).

The packing and inter-particle cohesive forces of very small particles may make them difficult to entrain, whereas larger particles will be too heavy to be lifted by the erosive forces. Vegetation exerts an influence in various ways: through soil stabilization by roots, via absorption of some momentum flux to the soil surface, by alteration of the moisture, and by decay which adds organic material to the soil. Vegetative material protects the surface by covering the soil. Vegetation, rocks and boulders, being non erodible, absorb wind stress, reducing particle mobilization. Roughness of the soil traps sand grains and inhibits siltation. Soilmoisture and rainfall help stabilizing the soil and preventing erosion.

Dubief (1979) and Kalu (1977) compiled the occurrence of dust storms of different areas in the Sahara Desert. They established that there were different kinds of disturbances, affecting different parts of the Sahara during different seasons. In winter, dust storms are connected with the Mediterranean polar front with upper tropospheric troughs. In summer, they are related to easterly winds associated with Inter-Tropical Convergence Zone (ITCZ) and the North Atlantic Oscillation (NAO). The areas in the Sahara Desert, from which most of the air-borne particulate matter originate, are referred to as the source regions (D'Almeida, 1986; Prospero, 1999; Brooks & Legrand, 2000; Prospero et al., 2002), the identification of which has been done by different techniques including satellite observations, comparison of aerosol element composition, comparison of aerosol and soil sample color, monitoring of air mass trajectory, and visibility distribution analysis (Morales, 1979; Kaufman et al., 2005).

Thus some authors including McTainsh and Walker (1982), in Kano, Nigeria as well as Adedokun et al., (1989) in Ile Ife, Nigeria, inferred from element composition analysis of the settling Saharan dust particles to establish that Chad basin is the major source area of dust over most parts of West Africa. D'Almeida (1986), and Brooks and Legrand (2000) estimated the annual and monthly dust emissions from the Sahel and Sahara Desert of the northern Africa. The Saharan dust haze over West Africa turned out to originate from several dust sources, though a dominant source has been reported to come from FayaLargeau area in Chad basin (McTainsh, 1980; McTainsh and Walker, 1982). This is because the main transporting agent, the Northeast trade winds, blows from Sahara Desert in a Southwest direction across the West African region. In particular, it has been noted that dust sources around Chad basin, especially in the Bodélé depression, affect the countries around the Gulf of Guinea. Additional supplies of dust from fluvial and wind activity in Tibesti mountains, not dust sources by themselves though capable of providing dust material to be transported by water along wad is or temporary water courses to the Bodélé depression, have been recorded by Kalu (1977), Balogun (l974), and Adedokun et al. (1989).

The fluvio-lacustrine (river-lake) transport systems within the desert are believed to be efficient to supply and replenish clay and silt components of the lake deposits in this source area. D'Almeida (1985) measured the source strength and deposition rate of the dust, emerging from the Sahara Desert, using turbidity results from sun photometers, installed at 11 stations in the Sahara Desert as well as its surrounding areas. Dust mass concentration was also measured at one of the stations for correlation with the turbidity and hence estimated the mass production of the Saharan dust to be between 630 x 10^6 and 710 x 10^6 tonnes per year for all suspended particulate matter and between 80 x 10^6 and 90 x 10^6 tonnes per year for aerosol particles smaller than 5 μm radius. Many authors have suggested that Meteorological factors, responsible for the influence of atmospheric circulation on dust transport, during the Harmattan period over West Africa may include Inter-tropical convergence zone (ITCZ), North Atlantic Oscillation (NAO) etc. However, the links between these large–scale atmospheric circulation systems, especially NAO and the variability of Harmattan dust emission and transport are still not well understood, hence the need for evaluating the influence of different large-scale systems including the Sea Surface Temperature (SST) on dust transport during winter in order to ascertain the major atmospheric circulation patterns affecting Harmattan dust transport in this region.

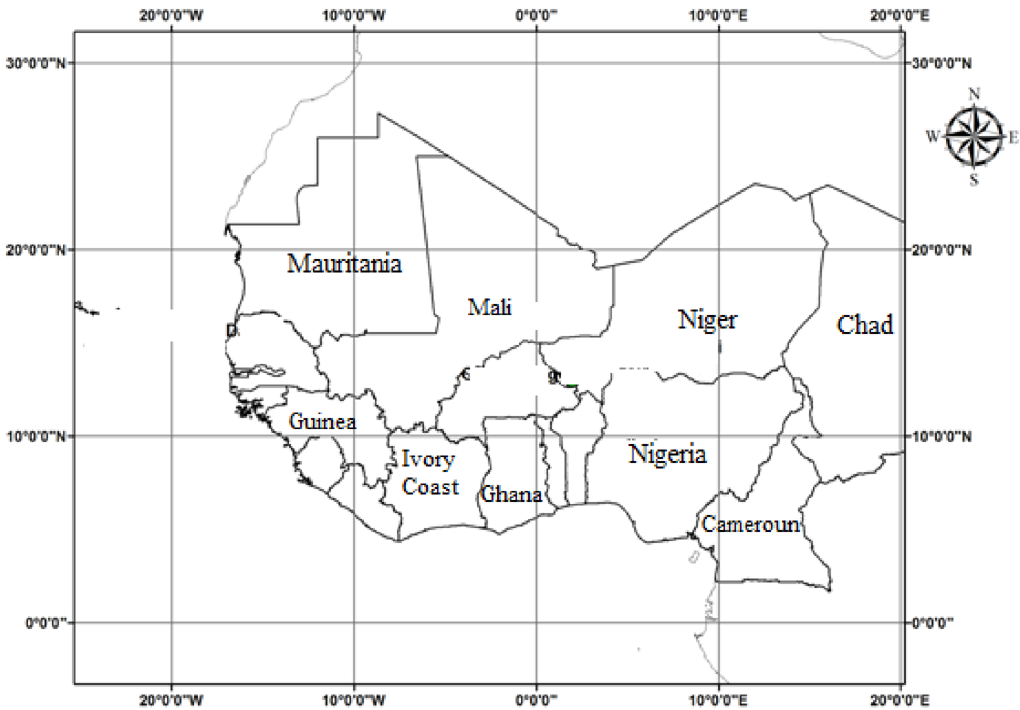

Fig. 1. Map of the study area, showing the Western boundaries

MATERIALS AND METHODS

Description of the study area

This study area involved the West Africa (0°S to 25°N) and (20°W to 20°E) (Fig.1), covering major sources in North Africa, Guinea Gulf in south, and a part of the Atlantic ocean. The region's climate is governed by north-south movement of ITD/ITCZ, i.e. the West Africa domain is divided into three climatic zones: Guinea coast (40 to 80°N), Savannah (8° to 11°N), and Sahel (11° to 16°N) (Omotosho & Abiodun, 2007; Abiodun et al. 2012). The Guinea coast represents the southern boundary to Atlantic Ocean, characterized by sub-humid climate with an average annual rainfall between 1250mm and 1500mm. The savannah zone is a semi-arid zone with an average annual rainfall between 750 mm and 1250 mm. The Sahel zone covers the northern boundary of Mauritania, Mali, and Niger, characterized by a single rainfall peak but short raining season (June to September) with an annual rainfall of about 750mm. Mean annual temperatures are usually above 18 °C. Areas within 10 °C of the equator have a mean annual temperature of about 26°C with a range of 1.7–2.8°C; the diurnal range is 5.6–8.3°C. Between latitudes 10°N and the southern part of the Sahara mean monthly temperatures can rise to 30°C, though the annual range is 9°C and diurnal range 14° to 17°C. In the central Sahara, mean annual temperature ranges between10° and 35°C (Food and Agriculture Organization, 2001).

Observational and remotely sensed data

Total Ozone Mapping Spectrometer (TOMS)

The Total Ozone Mapping Spectrometer (TOMS) data involved the primary long-term, continuous record of satellite-based observations, available for use in monitoring global and regional trends in total ozone over more than 25 years. TOMS also provides measurements of tropospheric aerosols, volcanic SO_2, ultraviolet irradiance, erythemal UV exposure, and effective reflectivity from the Earth's surface and clouds. The data were made available by the Laboratory for Atmospheres at NASA's Goddard Space Flight Center.

Four TOMS instruments were successfully flown in orbit – aboard Nimbus-7 (Nov. 1978-May 1993), Meteor-3 (Aug. 1991-Dec. 1994), ADEOS (Sep.1996-June, 1997), and Earth Probe (July 1996–Dec. 2006)satellites. Earth probe failed in December, 2006, and OMI took over its place since then. Version 8 TOMS data products were available from the Goddard Earth Sciences Distributed Information and Services Centre (GES DISC). They included level 3 gridded data (1.0° x 1.25°) as well as level 2 instrument resolution data (between 50x50 km and 26x26 km pixel at nadir). For this study, the data were from all the satellite sensors. It is understood that there are some differences among the data of each sensor due to different spectral range; hence there was some care to scale data from all sensors to enable comparison (Anuforom et al., 2007). The method of aerosol index retrieval from these sensors is described by Oluleye and Adeyewa (2011).

Era Interim reanalysis

Era Interim data are global reanalysis datasets, produced by European Centre for Medium-Range Weather Forecasts (ECMWF), covering the period from 1979 up to now. Data are gridded and made available at 2.50 x 2.50, 10 x 10, 1.1250 x 1.1250, and 0.750 x 0.750 with 37 vertical pressure levels. Compared to previous ERA-40 data, several problems concerning the humidity and hydrological cycle over the tropical region were improved for the ERA-interim to agree with the observations more (Dee et al., 2011; Uppala et al.,2008). Berrisford et al. (2009) provided a detailed description of the ERA-Interim product archive. The reanalysis datasets, used in this research, were the sea surface temperature over the North Atlantic, and daily mean zonal (u) and meridional (v) wind components at the surface and upper levels, gridded at 1.1250 x 1.1250 in space, and spanned for 30years (1983-2012) across the West Africa domain.

Data analysis

The daily mean wind components and TOMS AI, obtained for this study, were analyzed in order tounderst and the spatial and temporal characteristics of Harmattan dust in terms of deposition, emission, and distribution. The flow pattern of the near surface wind vector was plotted to see the strength and major atmospheric circulation features, driving Harmattan dust emission over West Africa. Moreover, the relation between Harmattan dust mobilization over West Africa and atmospheric circulation pattern was evaluated, using a kernel density estimate that showed the areas where most of points were concentrated between the variables.

The evolution of ITD, SST, and NAO, during Harmattan period (November-March) was analyzed and temporal averages ITD positions, SST, and the NAO were plotted on daily basis. The wind vector flow and point of convergence were obtained from the meeting points of the two major wind systems over the region where the winds slowed down, weakening.

DISCUSSION AND RESULTS

Distribution and emission of Harmattan dust over West Africa in the winter months were analyzed, using remote sensing products i.e. TOMS AI. Moreover, to understand the role of atmospheric circulation systems in occurrence of dust haze in this region, near surface wind speed, the long term mean daily surface position of the Inter-Tropical Discontinuity (ITD), and monthly mean North Atlantic Oscillation (NAO) index were assessed with respect to TOMS AI during Harmattan season. The Inter-Tropical Discontinuity (ITD) over land, the Sea Surface Temperature (SST) over the Atlantic Ocean, and the North Atlantic Oscillation (NAO) are the large-scale atmospheric systems, known to affect the weather in the northern hemisphere. Qualitatively, the link between ITD and dust transport from the Sahara desert in most parts of West Africa, during the months of November to March, has been reported (Resch et al., 2002; D'Almeida, 1986; Kalu, 1977). Foltz and McPhaden (2008) used a multi decadal aerosol optical thickness time series from TOMS to show a strong correlation between AOT on one hand and changes in northern tropical Atlantic SST on the other, suggesting that 35% of the inter-annual variability in SST was related to the changes in dust cover.

The link with NAO has not been extensively explored. However, Chiapello et al. (2005) studied the impact of the NAO on Sahara dust aerosol in southern Mauritania, the tropical Atlantic, and the Bodélé depression in the central Chad. In the past, (Hurrel, 1995) the relation between NAO and Sahara dust transport had been inferred from the influence of NAO on the Northern Hemisphere in general.

Harmattan dust emission, ITD, and wind distribution

Harmattan emission

Due to wind blows, dust emissions only occur on several types of surfaces such as desert and arid lands. This section of the present paper explains dust emission and spatial distribution as a function of wind speed over West Africa. Figure 2 shows the long-term monthly mean of TOMS AI for entire West Africa during winter months from November to March. There was a significant build-up of dust particles with the hot spot of TOMS AI, observed in Bodélé Depression in central Chad (15^{o}N-17^{o}N and 15^{o}E and 20^{o}E) throughout the winter period, identified as one of the most intense and persistent dust sources in the world (Prospero et al., 2002; Barkan et al., 2004; Washington et al., 2003; 2006a; b;c).

Although according to TOMS AI data, the Bodélé Depression reaches its peak in March, Washington and Todd (2005) showed that, despite some differences among the datasets (TOMS AOT, TOMS AI, and dust plume frequency), dust emissions in Bodélé Depression were strongest at the beginning of the year (January-March). The offset in the TOMS AImay be explained by the potential height bias of the datasets. Also observable from December was the transportation of dust particles by northeasterly trade winds from the Sahara desert towards the Gulf of Guinea (between 4^{o}N and 10^{o}N), where the dust are mixed with pollutants from biomass burning, resulting in a relatively strong TOMS AI signal near the Guinea coast in January. The high concentration of dust aerosols, experienced in the Guinea coast, originated from this Bodélé depression. Moreover, this result is consistent with the findings by Herman et al. (1997). However, the TOMS AI progressively became weaker due to the fact that the dust particles were washed out by moisture as the south-westerly winds intensified in March, beginning from the coast of West Africa.

The time-latitude cross section of TOMS AI (Fig. 3) shows that there were large variations in daily TOMS AI signal, observed in West Africa. It was found that TOMS AI signal was strong in early November, predominantly over the Guinea coast (2^{o}N-8^{o}N). This period, perhaps represents an "informant" to dust episode occurrence as the north easterly wind makes its first annual appearance at the upper level over Guinea Coast. It then retreats, later come back force fully with much dust to occupy the whole area of Guinea Coast in the months to follow. Moreover, the extent and strength of TOMS AI signal spread from early December, and throughout January. The month of February also showed daily variations with the highest magnitude of TOMS AI signal, found around mid-February over the Guinea coast. However, a significant TOMS AI feature was observed in March spreading from Guinea coast to the Sahara (2^{o}N-18^{o}N). The hot spot of the TOMS AI showed the highest magnitude indicated the occurrence of aerosol particles in the atmosphere in West African region.

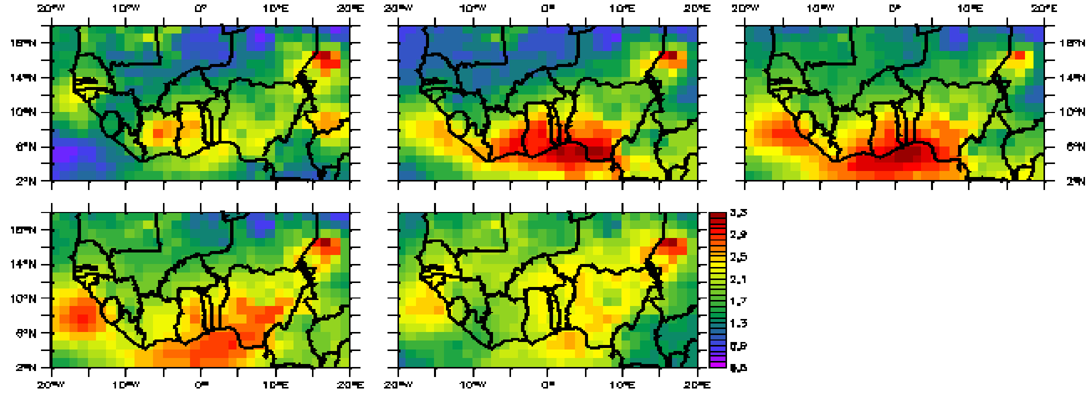

Fig. 2. Mean monthly TOMS AI for November, December, and January (The top three panel from the left); as well as February and March (lower panel from the left) from 1979-2015

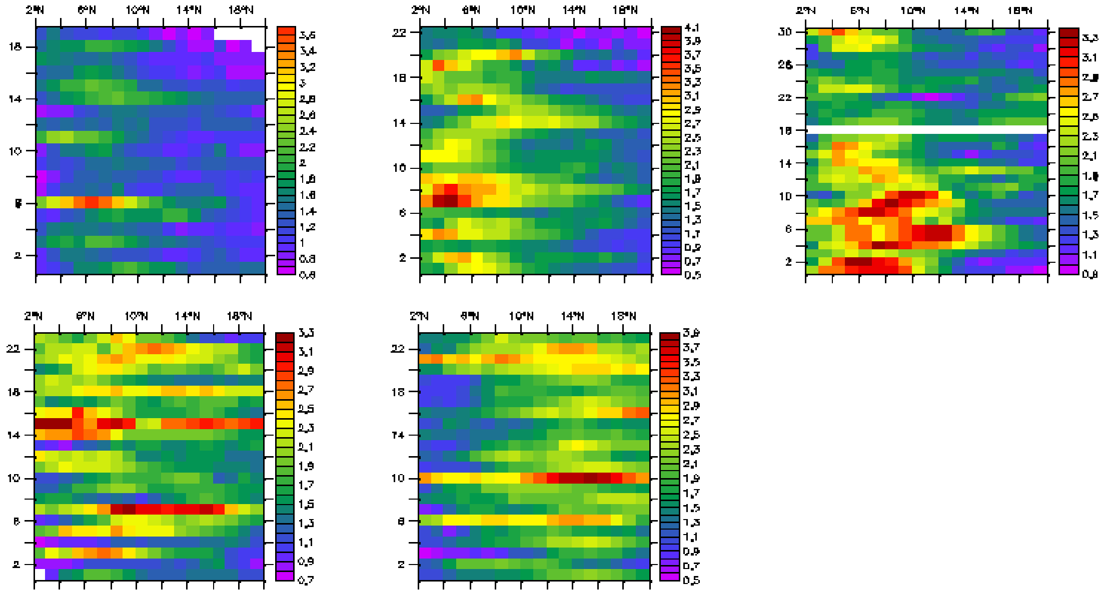

Fig. 3. Time-Latitude cross section of mean daily TOMS AI for November, December, and January (the top three panels from the left); as well as February and March (lower panels from the left) from 1979-2015

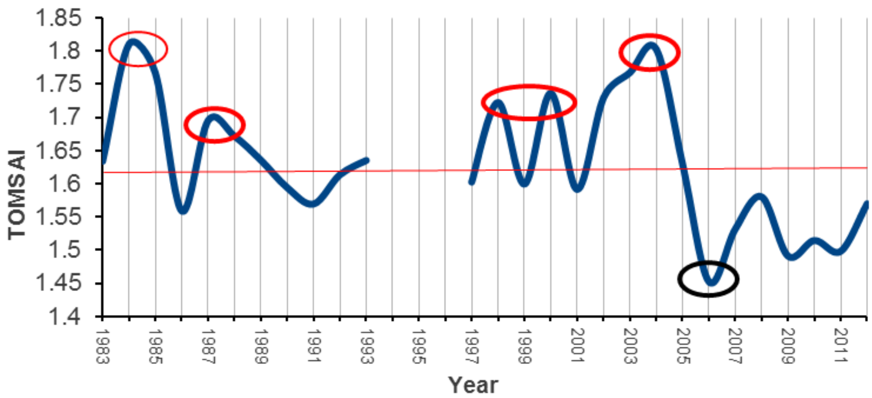

Fig. 4. Inter-annual variations of dust occurrence captured by TOMS AI signal in West Africa

Figure 4 shows the inter-annual and long-term mean variability of dust occurrence during winter months. The red and black circles show the high- and low-dust years, respectively. The discontinuity in the trend of TOMS AI values occurred between 1993 and 1996 due to absence of observational data. Moreover, TOMS AI signal showed weak occurrence of dust aerosols in November and December in all the years. However, strong TOMS AI signal were observed from January to March with its maximum rate, occurring in later months (February and early March). The inter-annual variability of TOMS AI revealed that, the high dust years were between 1984-1985,1987-1988, 1997-1998, 1999-2000, and 2002-2004. Significantly, the low dust year occurred between2005 and 2006 in all periods. The high dust, observed during these years, might be attributed to the extension of occurrences days as well as the intensity of dust particles in the air. In addition, the years of strong surface winds usually have high dust loads (Ridley et al., 2014).

Inter-Tropical Discontinuity (ITD)

The Inter-Tropical Discontinuity over land is an area of low pressure, formed where the northeast trade winds meet the southwest monsoon ones near the Earth’s equator in West Africa. It is important to realize that ITD, as the name implies, is indeed a zone rather than a line of demarcation; however, a line is defined as the Inter-Tropical Front (ITF), which is the same as the northern most limit of the ITD. ITF always stayed at 3^{o}-5^{o}N of the ITD during winter season (Adeyefa et al., 1995). Since ITF is a line limit of ITD, we shall adopt ITD which is generally used to represent the boundary between the dry north winds and the warm humid winds to the south (Griffiths & Soliman, 1972; Kalu, 1977; Dubief, 1979; Adeyefa et al., 1995). The ITD band moves seasonally, first towards the southern Hemisphere from September through February and then in reverse direction during the northern Hemisphere's summer, occurring in the middle of the calendar year.

Thus, ITD is an average feature and highly variable, giving rise to greater variability in daily temperatures than normal. As ITD moves in association with the zone of maximum seasonal temperature (or the thermal equator), it reaches the farthest northward position at about latitude 25^{o}N in summer, moving to the most southward position at about latitude 4^{o}N in winter. The seasonal extremes of ITD have a definite effect on the climate of the areas over which it moves.

Areas north of the ITD are normally under the northeast trade winds system and are dry, while the southern ones are under the Southwest monsoon winds and are wet. Normally, within the region, affected by Harmattan, the farther north a location is from ITD, the more severe the Harmattan condition will be and the more pronounced the Saharan dust concentration will become (Adeyefa et al., 1995; Moulin et al., 1997). Therefore, ITD position has a strong influence over the Saharan dust transport. The relative position of ITD is a major determinant of the steadiness of the Saharan dust transport, towards the Gulf of Guinea. The latitudinal position of ITD is the strongest factor that determines the severity and level of concentration of the Saharan dust at a particular location near the Gulf of Guinea. Therefore, the long-term daily average latitudinal positions of the ITD, used in this research, were obtained by plotting the streamlines of both zonal and meridional wind vector flow, and extracting the corresponding latitudinal boundaries between the dry northeasterly trade winds from the Saharan regions and the warm moist southwesterly winds from the Atlantic Ocean, covering the winter months (November-March) over the study domain.

The presence of Harmattan strongly depends on ITD surface position over land in West Africa. Therefore, ITD position and movement during the Harmattan season were carefully examined.

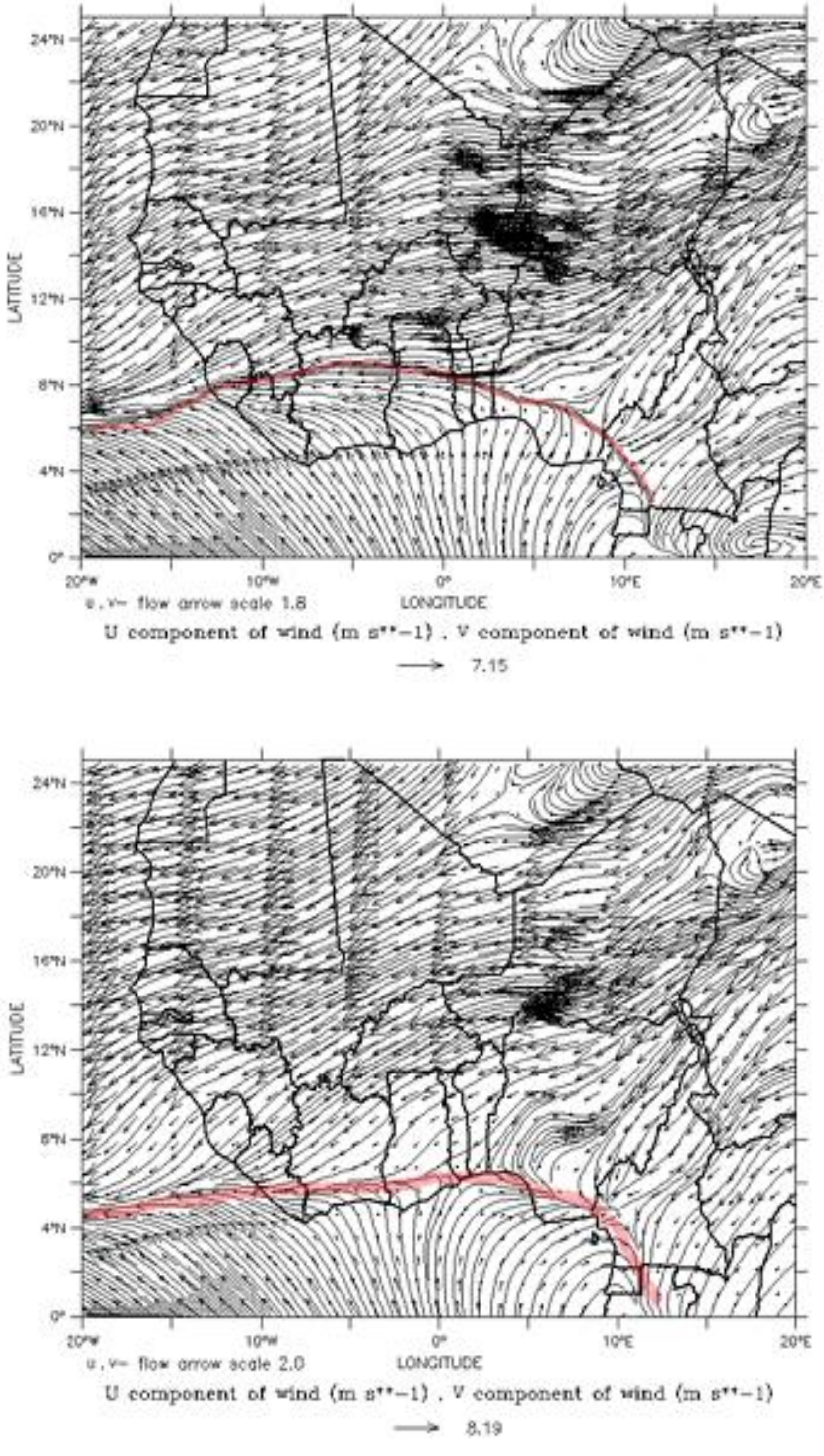

Fig. 5. The near surface winds tream lines, showing the long-term daily surface positions of ITD for (a) November, (b) December, (c) January, (d) February, and (e) March; over land in West Africa

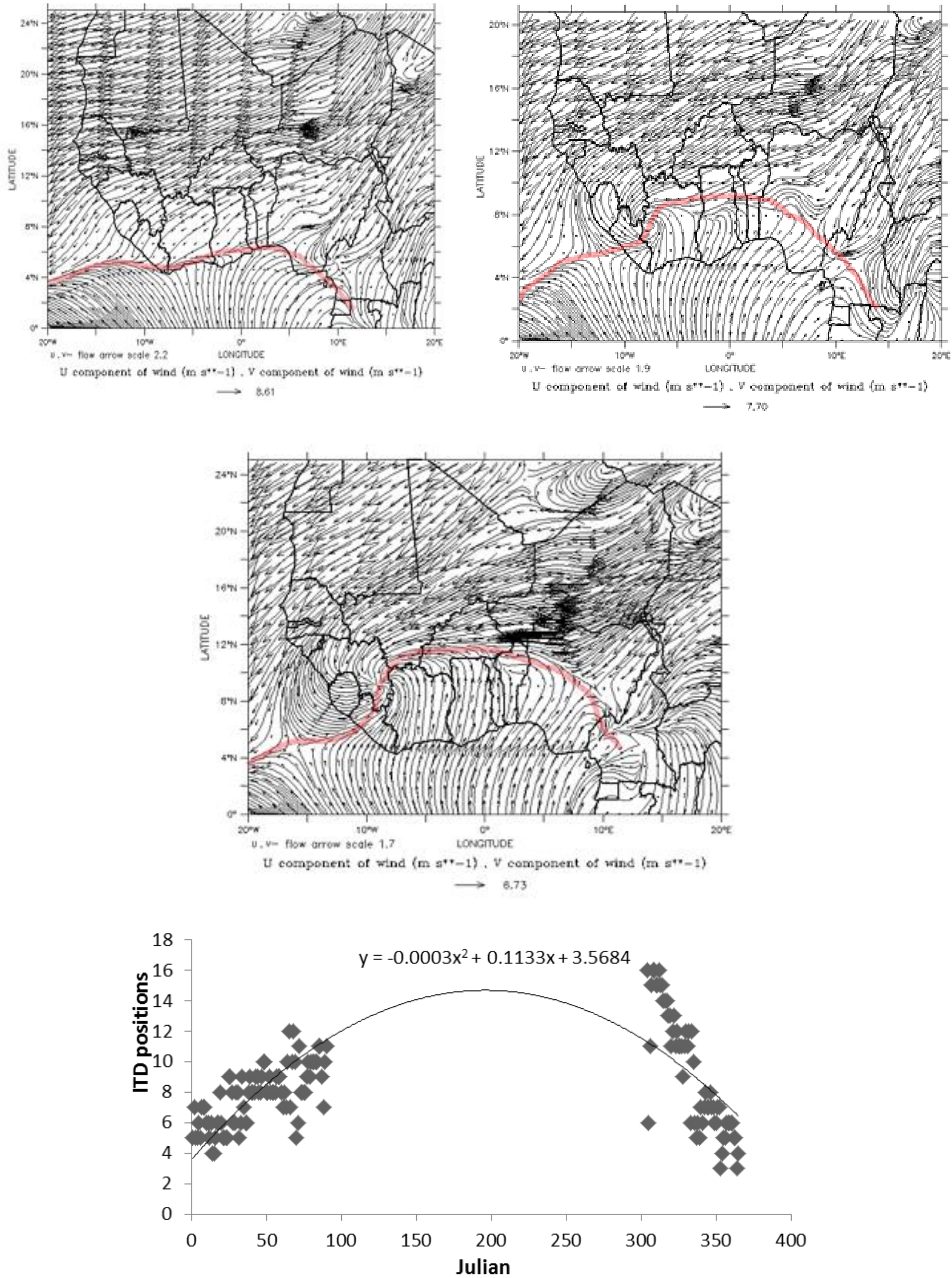

Fig. 6. Long-term daily surface positions of ITD over land in West Africa, obtained by taking daily average position from plot of zonal and meridional components of winds during the period of study

The long-term daily ITD surface positions (indicated by red lines), derived from the wind vector flow (u and v winds), from a standard height of 10m above ground level in West Africa during the Harmattan period, were analyzed as shown in Figure 5, which demonstrates the streamlines of the surface winds system and the obtained ITD positions, too. The convergence point of the northeast and the southwest wind streamlines was considered to be the average surface position of the ITD over the region on daily basis. The ITD is located around latitude 6^oN in early December, progressively moved out of the land and found over the Atlantic Ocean at latitude 4^oN late in December. On these occasions the Harmattan winds have fully overcome the entire West African severe Harmattan events. The ending of the Harmattan period was indicated by the ITD position, which was found receding to higher latitudes where the ITD was located around latitude 2^oN early in January, 6^oN early in February, and 10^oN early in March.

Figure 6 shows the average daily surface ITD positions in West Africa, during the Harmattan, over a 30-year period, from 1983 to 2012. The locus of the ITD positions can be described by polynomial functions, showing that the average position of ITD moves from high latitudes, around 14^oN, in the middle of the year to a lower latitude, of about 6^oN, around the6th January (6th Julian day) then to recede to higher latitudes, beyond 11^oN after the Harmattan period. It is worth noting the large intra- and inter-annual variability of these positions.

The mean positions show daily oscillations, varying from about $1\text{-}2^o$in latitude. Apart from these oscillations, the graph shows a general gradual migration of ITD from low latitudes of about 5^oNaround Julian day 6 (6th January), to a maximum of about latitude 14^oN around Julian day 200 (19^{th} July). From the maximum position, ITD then recedes gradually to lower latitudes (<12°N), while maintaining the daily oscillation movements until the end of the Harmattan period, around Julian day 90 and beyond. These results are in reasonable agreement, when compared with the range of $5\text{-}10^oN$ for ITD position during the Harmattan at longitude 3^oE, reported by Adeyefa et al. (1995) as well as the ones, reported by Swap et al. (1996) who observed a minimum range of $0\text{-}5^oN$ over the AtlanticOcean in January and the maximum position of $5\text{-}10^oN$ in December. The observation of Moulin et al. (1997) who found the minimum position over the North Atlantic Ocean to be at latitude 5^oN is also consistent.

Wind field near surface (925hpa) wind field

Figure 5 depicts the average wind speed and flow pattern for each month over a period of 30 years period. Strong north-easterly trade winds were found over most of the Sahelian region of West Africa during the winter months with a maximum wind speed of 8.61m/s in January. However, the winds became progressively weaker as they moved towards the Guinea coast, reaching their lowest at the region of ITD over West Africa. Furthermore, significantly observed from the analysis, was an extension of winds, associated with sub-tropical anticyclone from the mid-latitude towards the Sahara region (20^oN-24^oN). The extension of the trough leads to a steep pressure gradient that brings about strong winds, responsible for high dust emission, captured by TOMS AI in the Sahara during these periods (Kalu, 1977).

A cyclonic feature was also observed in Guinea-Ivory Coast border (about 8^oN and 9^oW) in February which might be responsible for the gradual washing out of the dust aerosols in the atmosphere in the Guinea coast. Besides, the strength of the north-easterly winds was pronounced in December and January, manifested in the surface position of ITD retreating southwards to 4^oN. The strong northeasterly trade winds, predominant in the whole West Africa during these periods, transported the Harmattan dusts from the source region towards the Gulf of Guinea where it mixed with black carbon from biomass burning as captured by the strong TOMS AI signal. This observation is in line with the results of Washington et al. (2006c) who noticed high dust load over the Gulf of Guinea. Vertical cross section of the mean zonal wind was further analyzed in West Africa. The result, as shown in Figure 7, illustrates the main mechanisms driving the large scale features associated with Harmattan dust dynamics and turbulent activity in the winter season over West Africa. The output exhibits a stratified structure of atmospheric circulation locating the Harmattan fluxes (between 10 and 18°N) at low level between the surface and 900hpa.

The African Easterly Jet (AEJ) is located in the mid-level at about (600-700hpa) centered between 2 and 8°N. The AEJ appeared in West Africa during the winter as a result of strong temperature gradients between the hot Sahara and the Atlantic Ocean, characterized by moist convection to the south and dry convection to the north (Thorncroft & Blackburn, 1999; Cook, 1999). The AEJ intensified the wind speeds at lower levels, thus transporting the dust far into the Guinea Coast and beyond.

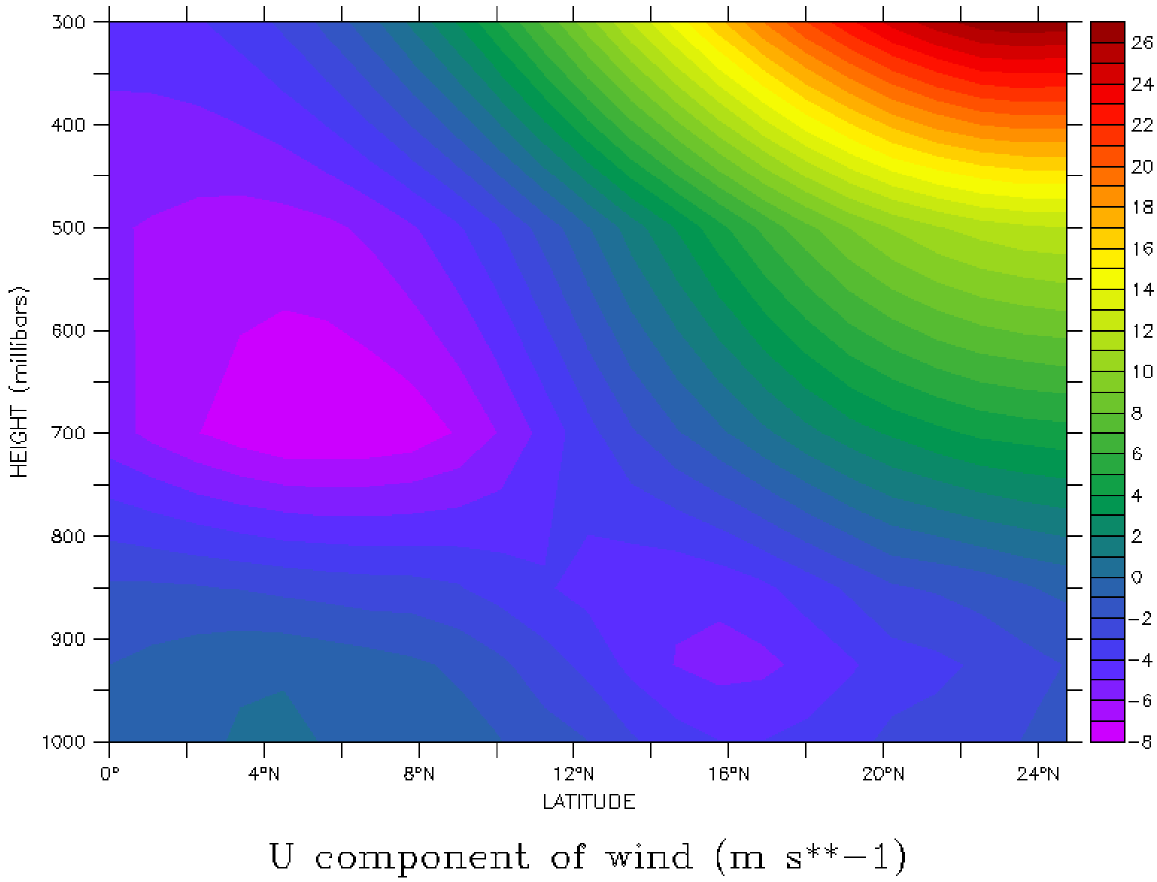

Fig. 7. The vertical cross section of mean zonal wind for winter (November – March). The AEJ is located around 600–750 hpa and the core is centered around 650–700hpa around Latitude 4°N. Low level Jet (LLJ) is also observed at 900 hpa at Latitude 16°N

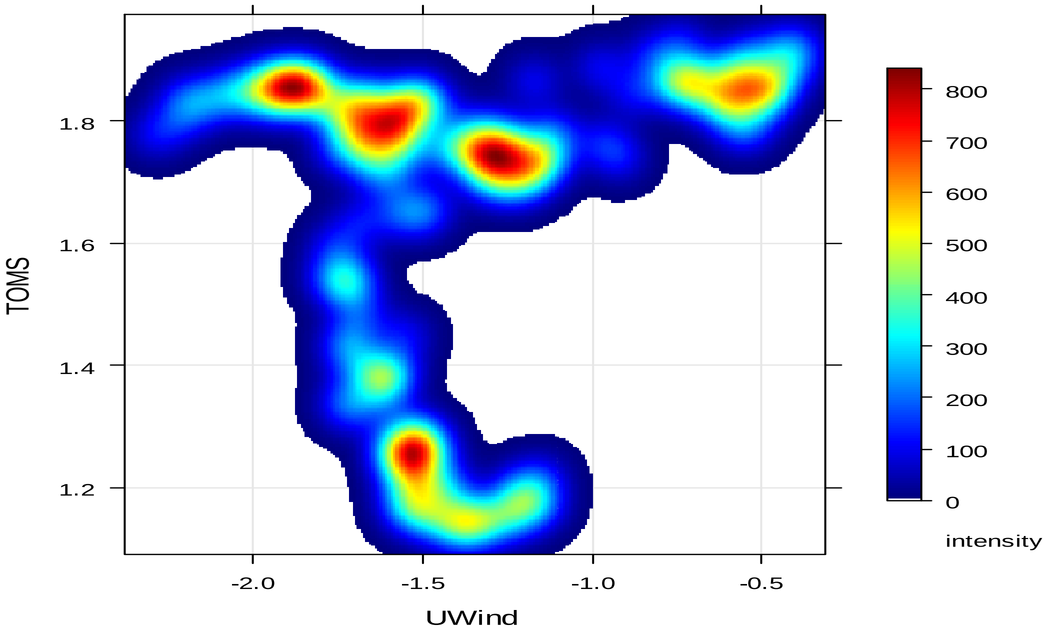

Fig. 8. Kernel density plot of long-term daily zonal wind speed averaged over West Africa. U wind is the zonal wind over the study area.

As noted earlier, the major dust source (Bodélé depression) is located between 15-18^{o}N in arid regions of Saharan Desert, where there is little or no vegetation. Given the assumption that erodibility factors that can limit dust emissions (such as the availability of deflatable sediments or vegetation cover) do not change significantly in this region over the course of the year, dust production is, to a large extent, a function of the surface wind speed. Thanks to this understanding, a positive relation is expected between dust and wind speed over the long term mean in winter days, an increase in surface wind speed enhances dust production. In order to establish this, we analyzed the intensity of dust occurrence with respect to the zonal wind speed as in Figure 8.The long-term daily mean of TOMS AI also showed that the density had risen from 1.7 to 2.0, having a peak at 1.8. This indicates that the highest density of zonal winds corresponded with those of TOMS AI**,** i.e. as the easterly winds got stronger, the extent and magnitude of dust load also increased over West Africa during winter.

Evolution and influence of NAO

The climate variability over the North Atlantic Ocean basin is associated to a large extent with NAO, which is a dominant pattern of atmospheric circulation variability. Over this North Atlantic Ocean basin, the atmospheric circulation normally displays a strong meridional (north-south)contrast, with low sea-level pressure in the northern edge of the basin, centered close to Iceland, and high pressure in the subtropics, centered near the Azores. Such a pressure contrast drives the mean surface winds and the winter-time mid-latitude storms from west to east across the north Atlantic, bringing warm moist air to Europe. It has long been observed that the monthly and seasonal (particularly winter time) average sea level pressure in stations in Iceland and the Azores display an out-of-phase relation with one another. TO be more precise, there is at endency for sea level pressure to be less normal in the Icelandic low pressure center when it is higher than normal near the Azores and vice versa. This fluctuation is referred to as the NAO (Hurrel, 1995). One of the most famous

NAO features is the NAO index, obtained from the difference between the Azores sea level pressure and the Icelandic low sea-level pressure, normalized by their mean and standard deviation. The North Atlantic Oscillation (NAO) index data sets, used in this work, were obtained from the archive of National Aeronautics and Safety Administration (NASA).

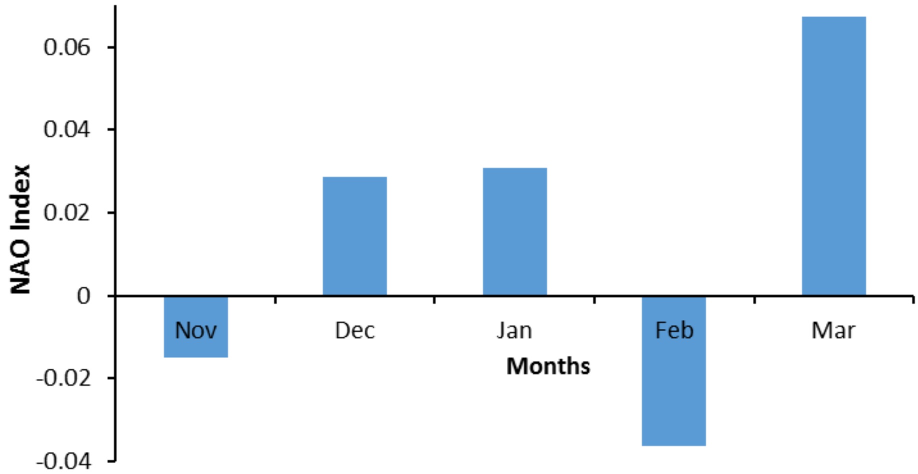

Fig. 9. Long term averages of NAO index in winter months, from November to March. Positive anomaly is associated with high pressure over the Saharan region

The sea level pressure was measured at a station, Ponta Delgada (37°44'N, 25°40'W) on the Azores and another at Reykjavik (64°8'N, 21°56'W) in Iceland spanning the central latitudes of the North Atlantic. Figure 9 illustrates the plot of long-term monthly NAO index as a function of winter months. It appears to reach a maximum value in March. The positive NAO index phase (NAO index > 0) in December, January, and March shows a stronger subtropical high-pressure center than the usual rate as well as a deeper than normal Icelandic low average sea-level pressure.

The increased pressure difference resulted in stronger winter storms crossing the Atlantic Ocean, on a more northerly track, experienced in drier weather during these months over West Africa due to enhanced Saharan dust transport and severe Harmattan condition. However, the negative NAO index phase (NAO index < 0) in November and February shows a weak subtropical high and a weak Icelandic low. The reduced pressure gradient resulted in fewer and weaker winter storms crossing on a more west-east pathway. Consequently, West Africa may experience a wet winter, decreased Saharan dust transport, and mild Harmattan condition during these months. Although the positive phase of NAO was associated with drier Saharan condition, it did not mean more dust mobilization until the surface wind became strengthened. This statement is further confirmed when a low (0.22) coefficient of correlation was obtained between NOA and AI indices. The overall effect of NAO on West Africa dust mobilization seems to be unclear; however, the resulting high pressure over the Sahara due to positive phase of NAO would contribute to lower atmospheric instability and tendency for dust mobilization.

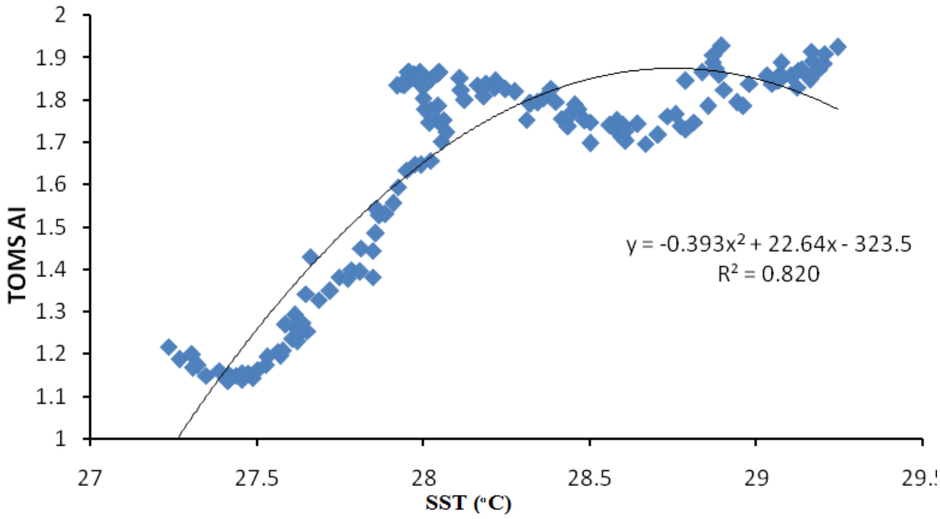

Fig. 10. Relation between long-term SST and TOMS AI over West Africa

Evolution and influence of Sea Surface Temperature (SST)

Characteristics of long term Sea Surface Temperature (SST) for each winter month in the Atlantic Ocean, covering areas between 0-5N and 20W-5E (i.e. the Gulf of Guinea at the southern boundary of the study area), and its role in Harmattan dust distribution was examined. It was observed that the Ocean temperature varied from one month to another with values, ranging between 298 and 303K in winter (Figure not shown). The hotspots of the Atlantic Ocean was found close to the Guinea Coast from November-January, which gradually retreated southwards away from the coast in February. The hotspots, found between November and January, tended to weaken the westerly winds, in turn strengthening the easterly ones in West Africa. This process tended to draw the surface position of the ITD southward, consequently bringing Harmattan dust aerosols towards the Guinea Coast. However, as the hotspots shifted away from the previous areas in late March, the westerly winds intensified, bringing about the ITD position advancing towards the north, and washing out of the dust aerosols over the Guinea coast.

From the long-term mean daily and inter-annual trends of Harmattan dust occurrence and that of the Atlantic Ocean temperature(Figure not shown) it can be deduced that an increase in dust particles, as quantified by TOMS AI, coincided with decreasing SST over Atlantic Ocean near the coast. The inter-annual trend of SST with respect to TOMS AI also showed large variability with the warmest ocean surface, occurring between 1998 and 1999, with the coolest SST between 1986 and 1987. The SST and TOMS AI further showed a polynomial positive relation with high correlation coefficient of 0.89 (Fig. 10).

The polynomial function showed that the average SST relative to the Harmattan dust distribution moved from the cool region of (27°C) and low (1.0) TOMS AI at the beginning of Harmattan period to warm (29°C) and high (1.85) TOMS AI signal, then to recede to its original state. The non-linear relation, observed on daily basis, was climatologically consistent because, warmer SST led to reduced dust load in West Africa, in the sense that both AI and SST rose at the beginning of winter to reach a critical value (equilibrium) after which warmer SST led to reduced dust load. Warmer SST implies more evaporation from the sea surface and more moisture in the atmosphere, enhancing convection leading to the formation of clouds that scavenge the dust as rain out.

CONCLUSIONS

This study conducted a comprehensive analysis of the link between large-scale atmospheric circulation systems and West African dust export on the basis of long-term satellite dust records available. It was able to identify Bodélé Depression in central Chad (15°N-17°N and 15°E and 20°E) as the major, most intense, and persistent dust source throughout the winter period. The hotspot of the TOMS AI showed the highest magnitude/ intensity, indicating the occurrence of dust aerosol particles in the atmosphere over West Africa region. The inter-annual variability of TOMS AI revealed that the high dust years were between 1984-1985, 1987-1988, 1997-1998, 1999-2000, and 2002-2004.Significantly, low dust year was found between 2005 and 2006 in all periods.

The research found that strong north-easterly trade winds were over most of the Sahelian region of West Africa during the winter months with the maximum jet speed at 8.61m/s in January. The vertical structure of wind fields exhibited a stratified structure of atmospheric circulation, locating the Harmattan fluxes (around 10 and 18˚N) at low level between the surface and 900hpa. The African Easterly Jet (AEJ) was located in the mid-level at about (600-700 hpa) centered between 2 and 8˚N. This study confirmed that the presence of Harmattan strongly depended on the wind structure and dynamics over West Africa. The wind regime was directly related to ITD positions over the region, and the relation between ITD and dust was also significant.

The North Atlantic Oscillation is often characterized by NAO index. Here, this index showed inverse relation in some years (1985-1986 and 1998-1999) and direct ones in others (such as 2000-2001 and 2005-2006). A poor positive relation between NAO and TOMS AI was observed, implying that NAO was not a major factor of dust outbreak over the region of study. Temporal relation between the Saharan dust transport and the NAO revealed that the NAO index reached a maximum value in March. An NAO peak contradicts a peak of maximum dust concentrations. The lag between NAO occurrence and peak of the dust could be the subject for further works.

Dust particles, as quantified by TOMS AI, also responded to SST signals in Atlantic Ocean. The inter-annual trend of SST with respect to TOMS AI also showed large variability with the warmest ocean surface, occurring between 1998 and 1999, and coolest SST between 1986 and 1987 over the 30 years of study duration. The SST and TOMS AI showed polynomial positive relation with a high correlation coefficient of 0.89. The non-linear relation, observed on daily basis, was significant because, warmer SST over the ocean close to the coast led to reduced dust load in West Africa.

Finally, the study concluded that the evolution of near surface wind field at 925 hpa, and the variations of SST and ITD positions were the major large scale atmospheric circulation systems, driving the emission, distribution, and transport of Harmattan dust aerosols throughout West Africa. However, the influence of NAO was shown to have less significance on Harmattan dust transport in the region, unlike northern Africa where the correlation between dust load and NAO was observed to be very strong.

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