Aerosol interactions with African/Atlantic climate dynamics

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Abstract
Mechanistic relationships exist between variability of dust in the oceanic Saharan air layer (OSAL) and transient changes in the dynamics of Western Africa and the tropical Atlantic Ocean. This study provides evidence of possible interactions between dust in the OSAL region and African easterly jet–African easterly wave (AEJ–AEW) system in the climatology of boreal summer, when easterly wave activity peaks. Synoptic-scale changes in instability and precipitation in the African/Atlantic intertropical convergence zone are correlated with enhanced aerosol optical depth (AOD) in the OSAL region in response to anomalous 3D overturning circulations and upstream/downstream thermal anomalies at above and below the mean-AEJ level. Upstream and downstream anomalies are referred to the daily thermal/dynamical changes over the West African monsoon region and the Eastern Atlantic Ocean, respectively. Our hypothesis is that AOD in the OSAL is positively correlated with the downstream AEWs and negatively correlated with the upstream waves from climatological perspective. The similarity between the 3D pattern of thermal/dynamical anomalies correlated with dust outbreaks and those of AEWs provides a mechanism for dust radiative heating in the atmosphere to reinforce AEW activity. We proposed that the interactions of OSAL dust with regional climate mainly occur through coupling of dust with the AEWs.

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1. Introduction
Aerosols have the capability to alter regional-scale atmospheric and oceanic circulations (e.g. Ming and Ramaswamy 2011). This is due, in part, to their highly non-uniform distribution, which is in contrast to the well-mixed greenhouse gases. Nonlinear interactions between African dust aerosols and multi-scale atmospheric phenomena depend on many parameters such as the aerosol distribution, physical properties of the particles, regional climate dynamics and weather variability. There are several modeling experiments indicating that aerosols induce significant modifications in circulation patterns, precipitation, the hydrological cycle, cloud properties, and climate system in general (e.g. Lau et al 2009, Wilcox et al 2010, Kim et al 2010, Ming and Ramaswamy 2011). However, many of the physical and dynamical processes involved in these multi-scale interactions are still poorly understood and not well represented in global climate models (GCMs). GCM experiments suggest that the impacts of the radiative forcing by Saharan dust are not only limited to temperature perturbations where the dust is located, but also dust-induced dynamic responses at locations remote from the dust region (e.g. Miller and Tegen 1998).

Weather and dust transport variability in the Saharan outflow region is often related to African easterly waves (AEWs), which form as a result of hydrodynamic instability in the African easterly jet (AEJ). Using a dust transport model,
Jones et al (2003) showed that generation and transport of Saharan dust is modulated by AEWs. They conclude that about 10–20% of seasonal variability of dust over the ocean is related to the easterly wave activity. The Ma et al (2012) modeling simulations showed the possible role of African dust radiative forcing in intensifying of the AEWs. Understanding the relationships between African aerosols and climatic adjustments are crucial for efforts to evaluate climate predictions from the next generation of climate models, especially for the West Africa monsoon (WAM) region. The WAM region and its associated rainfall variability are tied to the evolution of the AEJ–AEW system, which plays a dominant role in generating rain in meso-scale convective systems (e.g. Cornforth et al 2009).

With regard to whether a cause and effect relationship exists between dust interactions with radiation and dynamics, several previous modeling studies (e.g. Reale et al 2011) have demonstrated that dust aerosols in the SAL induce local thermal/dynamical modifications.

We aim to gain further insight into mechanisms of interactions between African aerosol loading and regional variability of synoptic-scale to meso-scale climate dynamics. In particular we seek to understand from a climatological perspective how dust aerosol loading in the oceanic Saharan air layer (OSAL) region may interact with daily transient changes of AEJ–AEW system, convective circulations, and monsoonal precipitation in one of the most meteorologically sensitive areas of the world: the tropical Western African/Eastern Atlantic Ocean, and WAM region. In this study, we investigate the relationships between dust variability and the regional thermodynamics and dynamics through analyses of correlations between daily anomalies of dust offshore of Africa and meteorology over North Africa and the Eastern Atlantic Ocean. While observed correlations do not establish a causal relationship, we find mechanistic relationships that support hypothesis for dust–wave interactions suggested by modeling experiments in the existing literatures.

2. Data and methodology

Correlations of daily quantities are investigated for boreal summer (June–August (JJA)) from 2000 to 2012 using an ensemble of daily NASA satellite data sets. Daily correlations for the entire 13 years of data are shown in the figures, however correlations were also evaluated for individual years separately and are also discussed (examples are shown in the online supplementary material stacks.iop.org/ERL/0/000000/mmmedia). Daily anomalies of aerosol optical depth (AOD) over the OSAL region (the domain of OSAL region is represented by rectangle in figure 1(b)) were determined using Moderate Resolution Imaging Spectro-radiometer (MODIS) on the Terra satellite at 1° x 1° spatial resolution (Remer et al 2008). Temperature, wind, omega, and vorticity are obtained from the Modern-Era Retrospective Analysis for Research and Applications (MERRA, Rienecker et al 2011) reanalysis products. Precipitation data are obtained from the Tropical Rainfall Measuring Mission (TRMM) products at 0.25° x 0.25° spatial resolution (Huffman et al 2007), in addition to the MERRA precipitation. Long-term averages of climate variables (represented by contours in figures 1 and 2) are calculated over JJA using MODIS/Terra for AOD over the ocean from 2000 to 2012, MERRA products from 1979 to 2012, and TRMM from 1975 to 2012. Two long-term data sets were identified for AOD based on independent algorithms and well-calibrated sensors: the MODIS dataset and the Sea-viewing Wide Field-of-view Sensor deep blue dataset (Hsu et al 2012). Long-term mean of MODIS AOD (shaded in figure 1(b)) indicates the location of the SAL transporting dust aerosols from the Saharan desert across the Atlantic Ocean. We computed the correlations shown in the figures using both data sets for AOD in the OSAL region to confirm that the results were similar regardless of which data sets were used for AOD. Likewise, we investigated the correlation of precipitation with AOD using two different (though not wholly independent) datasets for precipitation: TRMM and MERRA.

In order to evaluate the correlation of meteorological variables with dust variability offshore of Africa, AOD is spatially averaged over the OSAL region for each calendar day of JJA, from 2000 to 2012, to provide the AOD time series in the OSAL region. Long-term means of AOD in the OSAL region are investigated for each calendar day, called day-to-day climatological means. The day-to-day climatological means of AOD are subtracted from the AOD time series in the OSAL region in order to compute the daily anomalies of AOD. Similarly, daily anomalies of meteorological variables (temperature, wind, vorticity, omega, and precipitation) are calculated with respect to their day-to-day climatological means at each location throughout the North Africa and tropical Atlantic Ocean region. In this fashion, seasonality is removed from daily data sets in order to investigate the correlations between the residual daily anomalies of climatic parameters and dust perturbations over the oceanic loading zone. Correlation analyses have also been investigated for each individual summer season (JJA) from 2000 to 2012 separately to gain insight into the inter-annual variability of correlations. The patterns are not shown in the figures, but the results are discussed in the following sections. Horizontal correlations, as well as vertical-longitudinal and vertical-latitude cross-section correlations were investigated to gain a 3D view of the correlation patterns over the two of the most meteorologically sensitive areas of the world: (1) Eastern Atlantic offshore, and (2) WAM region.

The MERRA data are based on the GEOS-5 global model and assimilation of available observations, including satellite data. In the model, the atmosphere is represented with 42 vertical pressure levels. Vertical cross-sections of the correlations of wind speed and precipitation with AOD are presented in the figures along with the horizontal patterns of correlation at selected pressure levels. The horizontal pattern of correlation between AOD and temperature at 850 hPa is presented, because this pressure level is almost near the middle of the 3D temperature anomalies that coincide with variability of the Saharan Air Layer (SAL) and the dust layer. Variability at this pressure level is used in many diagnostic studies of AEWs (e.g. Burpee 1972, Burpee 1974, Pytharoulis...
3. AEJ–AEW system: climatological background

The climatology of AEJ–AEW system over the tropical eastern Atlantic Ocean and the Western Africa have been investigated in many previous studies (e.g. Grist and Nicholson 2001, Hsieh and Cook 2005, Kiladis et al 2005). On average, the core of the AEJ is zonally oriented between ∼30°W–20°E represented by the core of high wind speeds in the contours in figure 2(b) and the jet axis is close to 15°N. Vertically, the core of the jet is located in the middle troposphere (∼500–700 hPa) during boreal summer (represented by the mid-level closed contours in figure 2(a)). Below 700 hPa and above 500 hPa the jet weakens and gives way to AEWs, which propagate Westward and have a deep vertical structure with significant perturbations extending up to tropopause (e.g. Kiladis et al 2005). AEWs are known as synoptic-scale disturbances affecting the tropical Eastern Atlantic and the Western African climate and their wave activity peaks during the boreal summer season (e.g. Frank 1969, Roundy and...
between the positive and negative regions of mean-vorticity shown in (e).

Figure 2. (a) Vertical-longitudinal cross-section correlation (shaded) between variability of MODIS AOD in the OSAL domain and anomalies of wind speed (ms$^{-1}$) and contours represent long-term mean of wind speed (ms$^{-1}$), latitudinally averaged over the AOD domain. (b) Horizontal correlation (shaded) between anomalies of wind speed (ms$^{-1}$) at 600 hPa and MODIS AOD in the domain; contours and vectors represent long-term mean of magnitude and direction of wind speed at 600 hPa. (c) The same as (b) but for wind speed at 950 hPa, and contours represent long-term mean of precipitation (mm per day), and vectors represent wind speed at 950 hPa. Horizontal correlation (shaded) between anomalies of (d) omega at 500 hPa (e) vorticity (s$^{-1}$) at 600 hPa and MODIS AOD in the domain; the contours represent long-term time-average of (d) omega at 500 hPa (e) vorticity (s$^{-1}$) at 600 hPa (f) TRMM precipitation (mm per day). Correlations and time averages are for climatology of JJA. White hatches and white cross-hatches show the correlations are statistically significant at the 95% and 99% confidence level, respectively, using a standard T-Test. The location of the climatological-mean AEJ is approximately indicated in (a) by the elongated local maximum in wind speed contours (∼12 ms$^{-1}$) over the Western Africa and the Eastern Atlantic Ocean that lies between the positive and negative regions of mean-vorticity shown in (e).

The initiation and the growth of AEWs are supported by extracting kinetic energy from the AEJ (e.g. Burpee 1972). The strength of the AEJ and the instability that gives rise to the AEWs is associated with horizontal shear related to deep convection (contours in figure 2(d)) south of the AEJ and vertical wind shear related to the differences between the low-level South-westerlies and the mid-level easterlies and the jet (vertical shear can be observed by contours in figure 2(a)) accompanied by convection and temperature gradients. The instability structure and the energetic properties of AEWs are obtained by examining various dynamical parameters in previous studies (e.g. Charney and Stern 1962, Chang 1993, Pyharoulis and Thorncroft 1999, Kiladis et al 2005, Diaz and Aiyer 2013). AEWs serves as seed energetics for Atlantic hurricanes and their wave activity impacts on regional instability as well as changes in precipitation variability over African/Atlantic intertropical convergence zone (ITCZ) (e.g. Frank 1969, Landsea et al 1998, Thorncroft and Hodges 2001). Jones et al (2004) showed that dust loading in the SAL precedes the maximum geopotential height at 700 hPa by about 1–2 days and that dust may enhance the magnitude of AEWs. Kiladis et al (2005) showed that the convection within AEWs is initiated by dynamical forcing, which induced vertical motion at low levels and then couples the wave to deeper convection when it matures. The Thorncroft et al (2008) modeling study also showed that localized forcing of mid-to lower-troposphere heating generates vortices and establishes the circulations at the vicinity of the AEJ core, which is the genesis of the simulated AEW growth further downstream. In the following sections, we document the observed correlations of dust and meteorology in the context of the AEJ and AEW features described above, and explores the possibility that dust may influence them.

4. Does OSAL contribute in wave activity? thermodynamic perspective

The regional thermal changes associated with dust outbreaks result primarily from warm advection and radiative interactions (e.g. Prospero and Carlson 1981). The Ma et al (2012) modeling experiments showed that the local thermal anomalies induced by dust loading may tend to intensify the AEWs. In this section, we provide a 3D view of the correlations between daily fluctuations of dust aerosols in the OSAL region and temperature. Figure 1(a) shows the vertical-longitudinal cross-section of the 13-year climatological correlation between AOD in the OSAL region and vertical profile of temperature during boreal summer (JJA), meridionally averaged over the OSAL domain (10°–20°N). The horizontal pattern of the correlation of AOD and temperature at 850 hPa is shown in figure 1(c). These patterns along with the vertical-latitude cross-section of correlation (not shown here) give us a 3D view of the thermal anomalies associated with variations of dust AOD in the OSAL domain. A significant positive correlation (R ≅ 0.5) over the Eastern Atlantic Ocean (∼5°–35°W and 10°–30°N) along with a negative correlation (R ≅ −0.4) over the tropical Western Africa, particularly the WAM region (∼10°E–5°W and 10°–30°N) indicates that enhanced dust aerosols over the OSAL region are associated with warming over the offshore and cooling over the west coast of Africa. The locations of the warming and cooling dipole cores are opposite during the days that AOD is suppressed in the OSAL region. Examination of the correlations for each individual years (JJA, 2000–2012) indicates that the correlation coefficient is greater than 0.6 and statistically significant (up to R ≅ 0.7), and the warming/cooling cores of the correlation pattern are zonally expanded (not shown).

The vertical cross-section of the correlation between AOD variability in the OSAL domain and temperature (figure 1(a)) shows that the layer between about 750- and 950 hPa is where dust and its associated thermal anomaly have their strongest impact. The Kiladis et al (2005) modeling experiments also indicated that over the coastal regions the AEWs have maximum temperature anomalies between 750–950 hPa.

Neither the AEWs, nor the dust related thermal anomalies, are confined to the lower troposphere. The pattern of vertical correlation of AOD-temperature in figure 1(a) shows that the middle to upper-tropospheric temperature is anti-correlated with AOD in OSAL region, such that increasing AOD coincides with a cool anomaly below the jet level and a cool anomaly above. The low-to mid-level warming and mid-to upper-level cooling during high AOD days leads to ascent of the air mass and destabilization of the mid-to-upper troposphere and stabilization of the low-to-middle troposphere. The variations in instability associated with fluctuations in high dust loading may also affect clouds and top of the atmosphere radiative flux

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changes. Using sounding data for moist non-SAL and dry SAL outbreak cases, Dunion and Marron (2008) hypothesized that mid- to upper-level cooling is related to the Saharan dust due to the relatively drier air found to exist in mid- to upper-layer above the SAL. The modeling study of Spyrou et al (2013) suggested that the local cooling at high altitude is due to the reflection from the dust clouds below. This pattern of warm and cool anomalies described above as correlated with high dust AOD strongly resembles the thermal anomalies over the western Africa and the WAM region related to features of AEWs in figure 11 from Kiladis et al (2005). As a climatological impact of dust on easterly waves, our hypothesis is that the thermal anomalies coinciding with variability in AOD in the OSAL region may positively reinforce the pattern of thermal anomalies inherent in AEWs downstream over the offshore region and negatively reinforce the upstream waves over the west coast, particularly the WAM region.

Surface cooling is not observed in our patterns of correlations with OSAL in agreement with the Randles and Ramaswamy (2010) modeling experiments. Strong reductions in downwelling solar flux at the surface owing to scattering and absorption by dust do not register as a negative correlation between daily temperature and AOD anomalies because of the high heat capacity of the ocean, which leads to a lagged ocean response to surface radiative forcing. In contrast with analyses for the AOD in OSAL region, a low-level negative correlation between temperature and AOD is observed for dust loading over the continent (not shown), which is due to the small thermal capacity and fast response of land.

Previous modeling experiments showed that since the AEJ and the low-level monsoon flow are strongly controlled by temperature gradients, a change in the thermal structure due to the interactive-dust signals must induce substantial modification in the AEJ, the low-level monsoonal flow, and in general on circulations (e.g. Kim et al 2010, Lau et al 2009, Reale et al 2011, Wilcox et al 2010). Ming and Ramaswamy (2011), simulations showed that the vertical wind shear is tied to changes in the local meridional temperature gradient induced by aerosols. The following section provides a climatological view of 3D modifications in wind profile over the offshore and land regions correlated with dust aerosols in OSAL, which propose a mechanism for how transient changes in background mean-flow may coincide with variability of the oceanic dust loading from climatological perspective.

5. Transients in AEJ–AEW system and the OSAL variability

This section provides a 3D view of transient changes of wind flow in AEW-AEJ system and their association with AOD perturbations. The vertical-longitudinal cross-section of the 13-year daily correlation between AOD in the OSAL region and wind speed is shown in figure 2(a), and the 13-year horizontal correlations of AOD with wind speed at 600 hPa and 950 hPa are shown in figures 2(b) and (c), respectively. A significant core of positive correlation \( R \approx 0.5 \) over the Western Atlantic indicates that enhanced AOD in the OSAL region coincides with positive wind anomaly at ~400–900 hPa over the offshore region (~40–90°W) downstream of the mean-AEJ. Comparing this with the mid-level long-term mean flow (contours and vectors in figure 2(b)) indicates that increasing dust AOD in the OSAL region is accompanied by a strengthening of the low-to mid-level easterlies at ~400–900 hPa over ~40–90°W downstream and particularly at the exit region of the mean-AEJ core. The correlation pattern is similar when evaluated for individual years, and the coefficient is larger, up to 0.6.

Comparing figures 1 and 2 shows that positive wind anomalies downstream of the mean-AEJ above and below the altitude of the core of the jet coincides with warming below the jet level and to some extent the cooling above of the jet level. Furthermore, these downstream anomalies are accompanied by negative wind anomaly and cooling at about 850–1000 hPa over the WAM. All the above features coincide with increasing of the AOD in OSAL domain. The signs of anomalies are opposite when AOD is suppressed. The pattern of correlation between the wind profile and AOD resembles the anomalous wind pattern for the passage of AEWs displayed in figure 6 by Kiladis et al (2005).

The correlation between AOD in the OSAL region and the 950 hPa wind speed (figure 2(c)) shows enhanced dust AOD is also accompanied by a strengthening the north-easterly winds \( R \approx 0.5 \) north of the ITCZ, and also the weak southerly winds about the ITCZ near the coast. The correlation coefficient is increases up to \( R \approx 0.6 \) and is statistically significant in correlation patterns for individual years, especially for the easterlies on the Northern side of Atlantic ITCZ. The following section shows aspects of correlation between vertical motions and dust loading in the OSAL region.

6. Convective overturning and the OSAL variability

Several studies have shown how variability of cumulus convection is an important factor in determining the structure and propagation of AEWs (e.g. Hsieh and Cook 2005). The results of this section provide evidence for the presence of synoptic-scale anomalies in the vertical motion coincident with aerosol fluctuations in the OSAL region. These anomalies suggest where the vertical motions of synoptic-scale convective systems fit into the relationship between dust and AEWs over the offshore region. The 13-year daily correlation between daily mid-troposphere vertical motions and AOD in the OSAL region (figure 2(d)) indicates that increasing AOD is accompanied by anomalies of the mid-troposphere upward motions located to the West (ahead) of the OSAL region along with anomalous downward motions located to the east of this aerosol loading domain. The pattern of anomalous vertical motion is opposite during days of reduced AOD in the OSAL region. Although the correlation coefficient seems to be weak in the pattern of climatological correlation between daily AOD and omega in the 13-year data set, it is statistically significant at the 99% confidence level (shown with white cross-hatches). The correlation coefficient is
greater than 0.5 and statistically significant (up to $R \geq 0.6$) when the correlation pattern is evaluated for individual years (not shown). The spatial patterns of correlation between AOD and vertical motion are similar from year-to-year but vary in detail owing to inter-seasonal variability of the waves proposed by several previous studies (e.g. Hall et al 2006, Diaz and Aiyyer 2012). This may evidently act to reduce the magnitude of the correlations when all 13 years of data are evaluated.

Comparing these features with results of previous sections suggests that these correlations and anti-correlations of increasing AOD with the anomalous overturning vertical motions are accompanied by strengthening of the mid-level easterlies downstream of the mean-jet, and strengthening of the low-level North-easterlies at the Northern side of Atlantic ITCZ. This is in agreement with Kiladis et al (2005) showing that convection occurs in northerly flow as the AEWs propagate offshore into the Atlantic ITCZ, and that the AEWs has environmental synoptic-scale and meso-scale impacts as they propagate, which is favoring new convection downstream as they propagate along the zonally varying AEJ between the continent and the Atlantic Ocean. Zuluaga et al (2012) also found anomalous upward motion in the lower to middle troposphere between 12°–22°N during dust outbreaks over the Atlantic Ocean.

Our study indicates that enhanced AOD coincides with anomalous vertical motions over the offshore which are accompanied by: (1) local warming below the AEJ level with strengthening of the low- to mid-level easterlies, and (2) local cooling above the AEJ level with weakening of the mid- to upper-level wind flow (upper-level negative correlation in figure 2(a)). These indicate that over the offshore region, the anomalous vertical motions associated with high AOD are confined between the upper level westerly anomaly and the low-to mid-level easterly anomaly along with warming below the AEJ level. All these are the signatures of correlation between dust loading and a mid-level synoptic-scale anomalous overturning cell, which is zonally elongated across the Eastern Atlantic and located within the mean-subsidence zone in the northern branch of the climatological-mean Hadley circulation (contours in figure 2(d)). In agreement with our data analyses results, the Ma et al (2012) modeling experiments showed that dust heating is converted to the kinetic energy of the AEWs through the convection overturning. The Lau et al (2009) modeling study also showed the signatures of the dust-induced Walker-type anomaly in convective circulation across the tropical Atlantic.

While correlations from observations of a system of highly coupled variables cannot establish cause-and-effect relationships among the variables, these results suggest that oceanic dust plumes correlate with the AEWs which in-turn interact with Hadley cell through anomalous convection. While it is possible that the dust is merely a passive tracer modulated by the easterly wave variability, note that the temperature anomaly associated with dust outbreaks coincides with the temperature anomalies typical of AEWs (Kiladis et al 2005). Thus, if dust interactions with radiation are contributing to the thermal anomaly of dust outbreak events, these interactions could strengthen the wave variability as suggested by Jones et al (2004). Although the relationship between dust variability in the OSAL region and the suggested relationship to vertical motion is relatively weak, the patterns are statistically significant at the 99% confidence level.

7. Transient changes in vorticity dipoles and the OSAL variability

The results of this section show that mid-level vortices may contribute in dust interactions with climate dynamics, particularly downstream of the mean-AEJ core. In this section we focused on the relationships of AOD and vorticity mainly over the offshore region. Karyampudi et al (1999) showed that the SAL near the west coast contributes with African/Atlantic dynamics through two separate plumes, particularly with exaggerated features at the northern branch. In agreement with their modeling result, this study shows that AOD in the OSAL domain is anti-correlated/correlated with the mid-level vorticity (shaded in figure 2(e)), particularly at the northern and to some extent Southern of the mean-AEJ over the Eastern Atlantic Ocean. The anti-correlative/correlative cores indicate that northern negative and Southern positive anomalies of vorticity coincide with enhanced AOD in the OSAL region. The correlation pattern is similar when evaluated for individual years, and the coefficient is up to 0.61 (not shown). The locations of these negative and positive features of the correlation pattern coincide respectively with the long-term means of anti-cyclonic and cyclonic vorticity at northern and southern sides of the jet axis in the offshore region (vorticity cores represented by closed contours in figure 2(e)). This tends to strengthen both vortices in the mean-vorticity field, particularly the northern anti-cyclonic vorticity, when AOD is enhanced in the OSAL domain. Because the mean-AEJ resides between the mean northern anticyclonic and Southern cyclonic vortices, the anomalous vortex dipoles lead to easterly acceleration onto the mean-jet and the downstream easterly flow when the AOD is enhanced in the OSAL region. This results in a strengthening of the mid-level easterlies downstream of the mean-jet core. We propose that enhanced AOD in the OSAL domain coincides with the easterly anomalous flow accelerated by the anomalies of vorticity dipoles. This coincides with the anomalous convective Walker-type overturning circulation over the eastern tropical Atlantic and the thermal anomalies which may enhance wave activity. This condition favors TC formation downstream of the jet in the offshore region. Jury and Santiago (2010) proposed that African dust plumes may inhibit Atlantic tropical cyclogenesis during the hurricane seasons. However, in agreement with our results, Tyner et al (2012) also showed that TC formation is associated with the evolution of AEWs, which are irreversibly deformed within the developing vortex. The Thorncroft et al (2008) modeling study also showed that forcing of the mid- to lower-level heating generates vortices near the jet core, which tends to grow easterly waves downstream over the offshore region.
The relationships between AOD variability and the meteorological anomalies related to the AEWs upstream over the WAM region are presented in the following section.

8. Mechanistic relationships between OSAL variability and the WAM

Previous studies have shown the WAM results from complex multi-scale ocean-land-atmosphere interactions involving mechanisms that are difficult to isolate (e.g. Thorncroft et al. 2003, Sander and Jones 2008). This challenge contributes to poor representations of the WAM physical processes and multi-scale interactions in GCM simulations including the AEJ, AEWs and the location of the ITCZ. The WAM region, in particular the Gulf of Guinea coast, is upstream of the OSAL region with respect to the direction of easterly jet-wave system. Since the anomalies related to the downstream transients are correlated with dust variability in the OSAL region, a weaker correlation of conditions consistent with the upstream transients is apparent in the WAM region during dust outbreaks over the OSAL region.

As it is discussed in the following, enhanced AOD in the OSAL region is accompanied by weakening of the low- to mid-level wind profile over the WAM region. Cold shaded colors in figures 2(a)–(c) shows that the wind speeds of the low-level westerlies as well as the mid-level easterlies in the WAM region are negatively correlated with AOD in the OSAL region. Furthermore, the WAM is characterized by low-level westerly flow in the 850–1000 hPa layer (vectors in figure 2(c)) and the mid-level easterly flow in about 400–700 hPa layer (vectors in figure 2(b)). These indicate that direction of the horizontal anomalies of the low- to mid-level wind over the WAM region is opposed to the direction of background horizontal mean- flow when the AOD is enhanced in the OSAL region. The coefficient of this negative correlation is greater (up to $R \cong 0.5$) and statistically significant for individual years. A weakening of the mid-level mean easterlies over the WAM region requires an anomalous westerly acceleration onto the easterly mean flow. Such acceleration onto the flow exists when anomalous changes occur in the direction of circulation of the mid-level vortices elongated at the northern and southern side of the easterly flow.

Dust outbreaks in OSAL are negatively correlated with the mid-level vorticity over the Southern WAM coastal region and positively correlated with the mid-level vorticity over the Northern WAM region (figure 2(e)). This pattern shows that increasing of the AOD in OSAL region is accompanied by a cyclonic vorticity anomaly in the Northern WAM region and anti-cyclonic vorticity anomaly in the Southern WAM region. Furthermore, the location of this cyclonic vorticity anomaly coincides with the climatological-mean anti-cyclonic vorticity core over the Northern WAM region and the location of anti-cyclonic vorticity anomaly coincides with the climatological-mean cyclonic vorticity core over the Southern WAM region (climatological-mean vorticity dipole over the land is represented by negative/positive closed contours over the northern and southern of the WAM region, respectively, in figure 2(e)). Thus increasing dust in the OSAL region coincides with weakening of the climatological-mean vortices over the land and contributes westerly acceleration onto the mid-level easterly mean-flow over the WAM region. This tends to weaken the mid-level easterlies at the southern edge of the AEJ over the WAM region. The statistically significant anti-correlation between AOD over the OSAL region and wind over the WAM region is consistent with the pattern of correlation between AOD and vorticity, in spite of the weaker magnitude of the coefficient of correlation in the vorticity pattern.

Furthermore, the pattern of the 13-year climatological correlation of dust in the OSAL region with vorticity is opposite but weaker in the WAM region compared to the climatological correlation with vorticity offshore. Hence, the direction of vorticity forcing and the impact on the mid-level mean flow is simultaneously opposite over WAM region compared to the vorticity forcing onto the mid-level easterlies over the eastern Atlantic offshore region. This is in agreement with the correlation of the AOD loading with the mid-level wind over the offshore and the anti-correlation over the WAM region regions with regard to changes in magnitude and direction of the wind speed. Although the correlation coefficient of vorticity over the WAM region is lower than 0.3 for individual years in the figure, the spatial pattern is statistically significant at the 99% confidence level (white cross-hatches in figure 2(e)). Furthermore, the correlation coefficient over the WAM region for individual years is as high as 0.5 for some summer seasons such as JJA 2000, 2003, 2004, 2007 (not shown).

Fluctuations of dust in the OSAL region is not only associated with a synoptic-scale walker-type anomaly in the circulation of the eastern Atlantic offshore region, but is also accompanied by a meso-scale Hadley-type overturning anomaly in the upstream circulations. The patterns of correlation between dust outbreaks and omega for each individual year ($R \cong 0.4$; not shown) indicate that enhanced AOD coincides with regional anomalous vertical motions in convective circulations over the WAM region. These features are not well captured in the pattern of climatological daily correlations (figure 2(d)). However, this correlation pattern is in agreement with the Lau et al. (2009) modeling experiments, which showed evidence of a Hadley-type shallow vertical overturning cell generated by radiative interactions with loading of dust aerosols.

Patterns of rainfall in the African/Atlantic ITCZ exhibit significant year-to-year variability (figure 2(f)). However, there is a corresponding statistically significant but weak negative climatological correlation observed between dust AOD in OSAL region and TRMM precipitation over the WAM region. Furthermore, the correlation with MERRA precipitation yields higher magnitudes of the correlation coefficient in region of ITCZ precipitation with a larger region of coherent correlation. Correlations between AOD in the OSAL region and TRMM precipitation for each individual year (not shown) are greater ($R \cong 0.4$) than shown here for the full 13-year daily dataset. This could be related to the inter-seasonal variability of the waves (e.g. Diaz and...
Aiyyer 2013) which may act to weaken correlation coefficient and the spatial variability of precipitation in the correlation pattern. These results are in agreement with the Solmon et al. (2012), model simulations showing that the mean effect of dust is to reduce precipitation over most of the Sahel regions during boreal summer as a result of strong surface cooling. The Konare et al. (2008) modeling results also showed that Saharan aerosols tend to induce a circulation anomaly opposite to the monsoon flow. Furthermore, Mahowald and Kiehl (2003) find that total clouds and high cirrus clouds are reduced when mineral dust is high, and that an increase in low cloud may result from suppression of precipitation owing to increasing concentrations of cloud condensation nuclei during dust outbreaks.

That the correlation coefficients are a little weaker and the regions of statistical significance are a little smaller over the WAM region compared to the offshore region may be a result of time lags that may exist between the daily transient changes in dynamics/thermodynamics over WAM with the daily anomalies of dust in the oceanic domain. Since the dust transport and meteorological variability are both impacted by AEW activity as shown above, a time lag may be related to the propagation of wave from the continent to the ocean. Consideration of lag-correlations between dust aerosols offshore and meteorology upstream in the context of AEW variability, as well as correlations with dust variability over the Sahara, are topics for a subsequent study.

9. Summary

This study provides evidence of mechanistic relationships between the aerosol concentration in the OSAL region and the transient changes in AEJ–AEW system, tropical convective circulations, and monsoonal signatures over the Eastern Atlantic Ocean and the Western Africa during Northern hemisphere summer. Patterns of climatological correlations between variations of dust loading in the OSAL domain and changes in dynamics/thermodynamics tend to be opposite over land in the region of the WAM compared to downstream over the offshore region:

(1) We propose that anomalous transients correlated with variability of AOD in the OSAL region is associated with enhanced AEW activity downstream over the offshore region, which is expressed as follows:

- Strengthening of the mean-flow over the offshore region accelerated by the mid-level anti-cyclonic and cyclonic transient vortices respectively at the northern and Southern side of the mean-AEJ axis is correlated with enhanced AOD in the OSAL domain.
- Low-to middle troposphere warming below the mean-AEJ and middle to upper troposphere cooling above of the jet-level coincides with enhanced dust outflow through the OSAL region. These significant dipole thermal anomalies tend to change the instability of the column of troposphere over the offshore region.

- Such changes in regional instability are accompanied by an anomalous synoptic-scale Walker-type overturning circulation correlated with the AOD variability.
- This may tend to amplify AEWs, which favors TC formation downstream of the jet in the offshore region.

(2) We suggest that the aerosol loading in the OSAL region is negatively correlated with the wave activity upstream over the west coast, particularly the WAM region, which is expressed as follows:

- Increasing AOD in the OSAL region coincides with the upstream low- to mid-level cooling, which increases stability and weakens the low-level monsoonal westerlies and the mid-level easterlies over the WAM region.
- Upstream features suggest that enhanced dust loading in OSAL region coincides with opposite anomalous conditions over the land compared to thermal/dynamical disturbances over the offshore region, which may contribute to unfavorable conditions for upstream wave activity in the WAM region.

The results presented here cannot establish a cause and effect relationship. Nevertheless, we found statistically significant correlations between aerosol variability in the OSAL and opposite transient changes in regional climate of the Western Africa with respect to the Eastern Atlantic Ocean. Furthermore, the similarity between the pattern of thermal/dynamical anomalies associated with dust outbreaks and those of AEWs provides a mechanism for dust radiative heating in the atmosphere to reinforce AEW activity. These mechanisms will be evaluated in subsequent observational analysis and model sensitivity studies.

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References

Burpee R W 1972 The origin and structure of easterly waves in the lower troposphere of North Africa J. Atmos. Sci. 29 77–90
Burpee R W 1974 Characteristics of North African easterly waves during the summers of 1968 and 1969 J. Atmos. Sci. 31 1556–70
Chang E K M 1993 Downstream development of baroclinic waves as inferred from regression analysis J. Atmos. Sci. 50 2038–53
Charney J G and Stern M E 1962 On the stability of internal baroclinic jets in a rotating atmosphere J. Atmos. Sci. 19 159–72
Corinna R J, Hoskins B J and Thorncroft C D 2009 The impact of moist processes on the African easterly jet–African easterly wave system Q. J. R. Meteorol. Soc. 135 894–913
Diaz M and Aiyyer A 2012 Energy dispersion in African easterly waves J. Atmos. Sci. 70 130–45
