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Interannual modulation of subtropical Atlantic boreal summer dust variability by ENSO

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Abstract Dust variability in the climate system has been studied for several decades, yet there remains an incomplete understanding of the dynamical mechanisms controlling interannual and decadal variations in dust transport. The sparseness of multi-year observational datasets has limited our understanding of the relationship between climate variations and atmospheric dust. We use available in situ and satellite observations of dust and a century-length fully coupled Community Earth System Model (CESM) simulation to show that the El Niño-Southern Oscillation (ENSO) exerts a control on North African dust transport during boreal summer. In CESM, this relationship is stronger over the dusty tropical North Atlantic than near Barbados, one of the few sites having a multidecadal observed record. During strong La Niña summers in CESM, a statistically significant increase in lower tropospheric easterly wind is associated with an increase in North African dust transport over the Atlantic. Barbados dust and Pacific SST variability are only weakly correlated in both observations and CESM, suggesting that other processes are controlling the cross-basin variability of dust. We also use our CESM simulation to show that the relationship between downstream North African dust transport and ENSO fluctuates on multidecadal timescales and is associated with a phase shift in the North Atlantic Oscillation. Our findings indicate that existing observations of dust over the tropical North Atlantic are not extensive enough to completely describe the variability of dust and dust transport, and demonstrate the importance of global models to supplement and interpret observational records.

Keywords Dust · ENSO · NAO · CESM · Teleconnections · Decadal variability

1 Introduction

The effects of aerosols on clouds, radiation, and atmospheric circulation operate locally on the order of days and weeks, yet can exert a global effect on climate over larger and longer spatiotemporal scales. In particular, mineral dust advected off the North African coast has been shown to modify stratocumulus cloud properties, fertilize minerals over the open ocean, and discourage the formation of North Atlantic tropical cyclones (DeFlorio et al. 2014; Doherty and Evan 2014; Mahowald et al. 2010; Evan et al. 2006a). Changes in local surface convergence impacting dust emission, wet and dry deposition removal rates and subsequent impacts on biogeochemistry, and Sahel desert precipitation are known to influence the variability of mineral dust in the atmosphere, both over the continent and the open ocean (Marticorena and Bergametti 1995; Doherty et al. 2014; Erickson et al. 2003; Prospero 1999; Prospero and Nees 1977).

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Recently, uncertainties in the parameters controlling dust emission have been reduced due to increased frequency of ground and aircraft based measurements, improved detection and retrieval of atmospheric dust particles through satellite measurements, and novel theoretical techniques resolving emitted dust size distributions (Washington et al. 2006; Heintzenberg 2009; Koffi et al. 2012; Evan et al. 2006a, b, c; Kok 2011). However, our understanding of large-scale controls on dust transport and variability remains incomplete. Previous studies examining the variability of North African dust on interannual and decadal timescales have been hindered by limited record length of observations, but have nevertheless yielded important insights. Mahowald et al. (2003) combined in situ and satellite observations with an implementation of the DEAD dust module (Zender et al. 2003) inside a chemical transport model to examine the global variation of column dust burden associated with two indices of large-scale climate fluctuations: the Niño 3.4 index (sea surface temperature anomalies averaged over 120W–170W, 5S–5N) and the Pacific Decadal Oscillation (PDO) index (the leading principal component of sea surface temperature anomalies in the region 110E–100W, 20N–65N; Mantua et al. 1997). They found only tenuous relationships between dust and these coupled climate modes, possibly because of the limited record length. Specific to North African dust, Evan et al. (2006b, c) correlated wintertime North African dust to various climate indices using the advanced very high resolution radiometer (AVHRR) satellite dust climatology. They showed that wintertime dust fraction over the tropical Atlantic between -30W and -10W was moderately correlated with the Niño 3.4 index, and that lag correlations between Niño 3.4 and dust fraction (ENSO leading dust events) were not as strong as the winter-to-winter correlation of these two variables. These results were generally consistent with the conclusions drawn from Prospero and Lamb (2003), who analyzed interannual variability of the Barbados dust dataset.

Other studies have suggested links between North African dust transport and other coupled climate modes, including the North Atlantic Oscillation (NAO) (Moulin et al. 1997; Ginoux et al. 2004) and the Atlantic Multidecadal Oscillation (AMO) (Evan et al. 2011). Chiapello et al. (2005) used the TOMS/Nimbus-7 and TOMS/Earth Probe satellite datasets to show that the influence of the NAO dominates winter export of dust to the eastern subtropical Atlantic. Riemer et al. (2006) implemented a “Centers of Action” approach to show that fluctuations in the strength of the Azores High, and not the NAO, explained the highest percentage of wintertime variance in tropical and subtropical North Atlantic atmospheric dust concentration. Doherty et al. (2008) found that the relationship between the NAO and mineral dust observed in winter is non-existent during the summer. Wang et al. (2012) used a proxy-derived dataset of dust aerosol optical depth over the tropical North Atlantic to suggest a feedback between the AMO and tropical North Atlantic dust that operates through variations in Sahel rainfall. Doherty et al. (2014) focused on boreal summer variations in North African dust concentration and showed that variations in the West African Convergence Zone (WACZ) partially control dust emission and transport westward towards the Caribbean.

Our work builds on these previous studies by characterizing variability of North African dust transport on interannual and decadal timescales using a fully-coupled GCM simulation with realistic ENSO variability (Deser et al. 2012) and a reasonable seasonal cycle of North African dust burden (DeFlorio et al. 2014). As noted in Wang et al. (2012), this type of CESM study would not have been possible using the previous generation of coupled climate models included in the Coupled Model Intercomparison Project 3 (CMIP3) because aerosol concentrations and emissions were prescribed (Ghan and Schwartz 2007). However, the new generation of CMIP5 models enables dynamical processes to influence dust concentrations and emissions. This greatly enhances the value of using such models to study aerosol–climate interactions, provided the relevant physical processes are represented realistically (and interactively) in the model of choice; Evan et al. (2014) showed that historical simulations of CMIP5 models (including CESM) tend to underestimate dust production over North Africa. However, DeFlorio et al. (2014) showed that CESM represented quite well the Atlantic dust seasonal cycle and its relative natural variability on monthly to interannual time scales. Improving our fundamental understanding of the physical relationships between climate modes and dust in coupled climate models should improve our interpretations of climate projections, and can also be used to inform seasonal predictions of tropical cyclones over the tropical North Atlantic, which are influenced by North African dust outbreaks (Evan et al. 2006a).

Instead of choosing a mode of climate variability a priori to relate to dust transport and variability, we first examine the relationship between dust anomalies over the tropical North Atlantic and global SST anomalies during boreal summer. We are interested in boreal summer because it is the season with the largest dust outbreaks over the tropical North Atlantic.

2 Data

2.1 Model and observational datasets

Our primary dataset in this study is a 150-year pre-industrial control global coupled climate model simulation. We ran this simulation using CESM 1.0.3 (http://www2.cesm.ucar.edu) with interactive dust emission and transport, which allows dust as well as other components of the aerosol to affect radiative budgets and cloud properties at each timestep (Hurrell et al. 2013). The treatment of aerosol size distribution is trimodal, as described in Liu et al. (2012). The simulation was run at a horizontal resolution of 2.5° (longitude (lon)) × 1.9° (latitude (lat)). The dust entrainment and deposition model (Zender et al. 2003) emits dust in both accumulation (0.1–1 μm) and coarse (1–10 μm) modes. Dust is assumed to be internally mixed with the other components in each mode (see Table 1 of DeFlorio et al. 2014 for a list of all aerosol species included in this CESM simulation, partitioned by mode). DeFlorio et al. (2014) explored natural variability of dust–climate interactions and evaluated the CESM simulation's representation of aerosol optical depth and size distribution near Cape Verde and aerosol optical depth and concentration near Barbados. They found realistic representations of the seasonal cycles and coherent fluctuations of these variables that were associated with regional monthly circulation anomalies extending from Africa into the subtropical North Atlantic.

One drawback of our CESM simulation is that dust emission parameterization is empirically tuned to reproduce observations (Ginoux et al. 2001; Zender et al. 2003). Dust emissions in our simulation do depend on wind speed and soil moisture, which provide mechanisms for feedbacks with meteorology. However, Kok et al. (2014a) showed that models that use this type of emission parameterization tend to underestimate the sensitivity of vertical dust flux to the soil's threshold friction velocity, and therefore underestimate the global dust cycle sensitivity. In their companion paper (Kok et al. 2014b), they implemented a new physically-based emission parameterization scheme which shifted emissions towards the world's most erodible regions and improved CESM's overall representation of dust emission. Consequently, dust emissions in our model simulation are not as realistic as those produced by a model with the newer physically-based dust emission parameterization.

We also use 44 years of monthly mean dust concentration recorded at Barbados from 1965 to 2008 (Prospero and Lamb 2003). This is the world's longest continuous record of in situ dust concentration.

To evaluate the model's simulation of dust over the tropical North Atlantic, we use a dataset derived from the Advanced Very High Resolution Radiometer (AVHRR) instrument, which provides estimates of dust Aerosol Optical Depth (dust AOD). This dataset is available over the tropical North Atlantic Ocean (−65W to −10W, 0N–30N) from January 1982 to May 2010 at 1° horizontal resolution. Evan et al. (2006b, c) calibrated this dataset to distinguish between optically thick dust and optically thick cloud over ocean surfaces. One limitation of using this dataset to examine interannual variability of dust is that it only spans 28 years, and therefore only contains approximately 7–8 ENSO events. The CESM model simulation has the advantage of spanning 150 years.

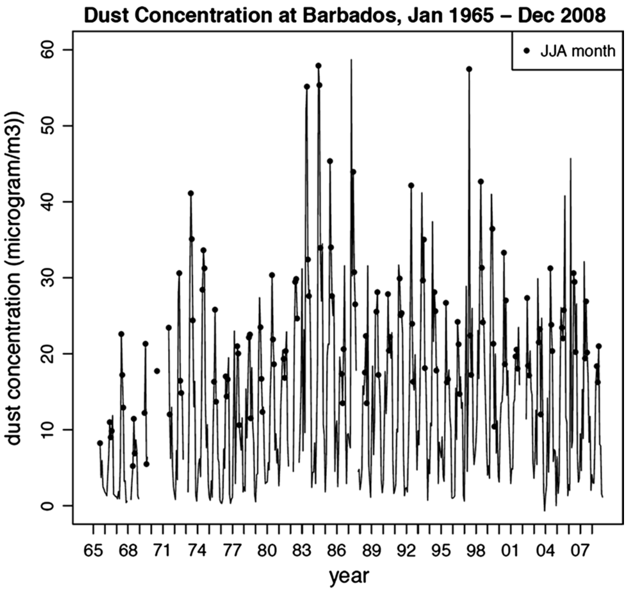


Fig. 1 Observed monthly dust concentration (μg/m^3) at Barbados, January 1965–December 2008. *Filled dots* denote June–July–August (JJA) months. Adapated from Prospero and Lamb (2003)

2.2 Dust variables used in this study

Three different dust variables are analyzed in this study: (a) atmospheric surface concentration (μg/m^3), (b) dust aerosol optical depth (dust AOD), and (c) total atmospheric dust burden (kg/m^2). Concentrations are used for model comparison to the Barbados dust dataset, since those observations measure dust concentration in the surface atmospheric layer. Dust AOD is used for model comparison to the tropical North Atlantic AVHRR dataset. Dust burden is defined as vertically integrated dust concentration and is used to examine the response of changes in atmospheric dust to changes in circulation associated with ENSO.

3 Observed dust concentration at Barbados

The time series of monthly mean dust concentration at Barbados (Fig. 1; adapted from Prospero and Lamb 2003) is perhaps the most widely used observational dataset of dust, and for good reason. It is one of only two in situ dust datasets extending more than 40 years (the other is located at Miami, and is also maintained by the University of Miami's Rosenstiel School of Marine and Atmospheric Science), and a high percentage of the record is continuous. There

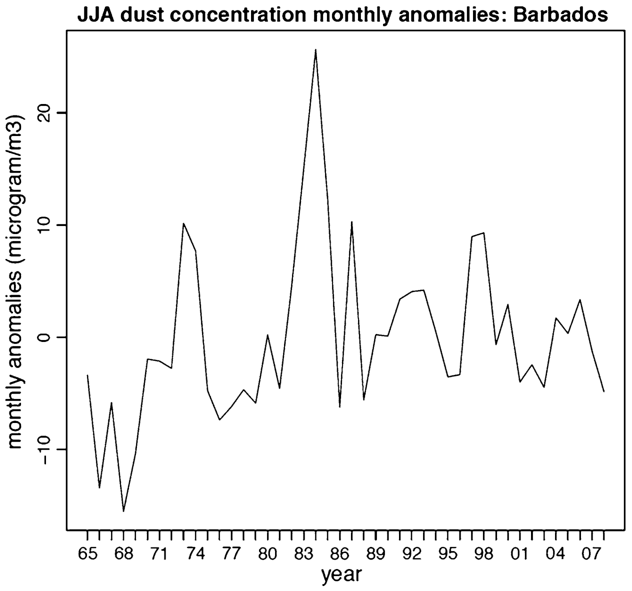


Fig. 2 Observed JJA monthly dust concentration anomalies (μg/m^3) at Barbados, January 1965–December 2008

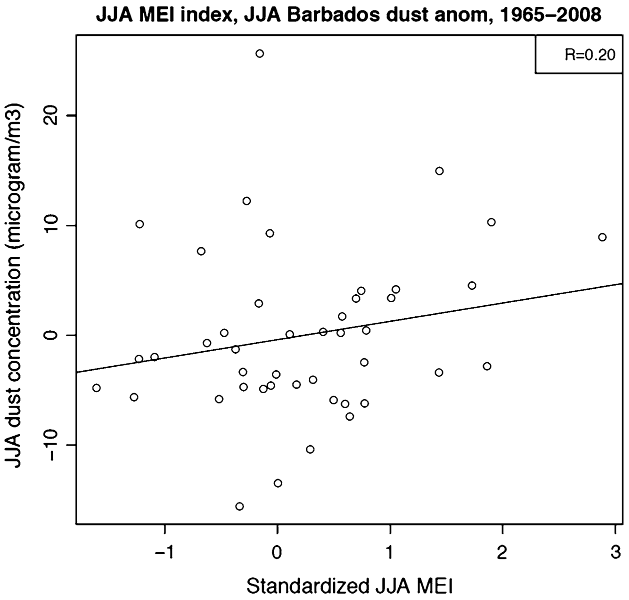


Fig. 3 Scatterplot of JJA standardized multivariate ENSO Index and JJA Barbados dust concentration anomalies, January 1965–December 2008

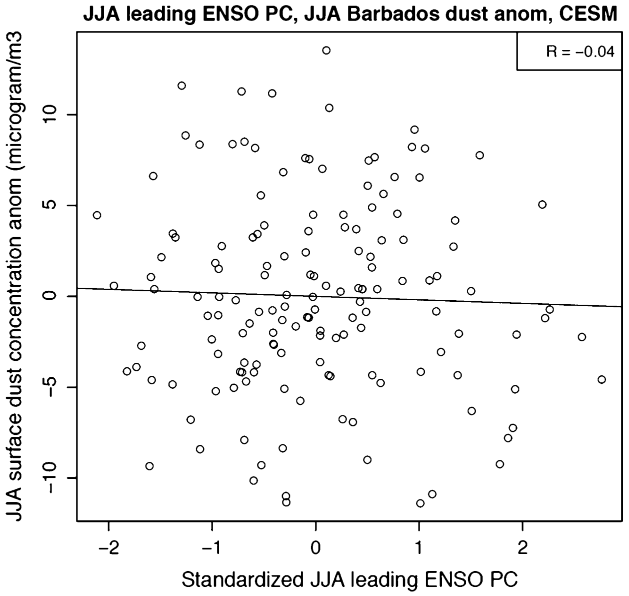


Fig. 4 Scatterplot of JJA standardized leading principal components of tropical Pacific SST variability and JJA Barbados dust concentration anomalies in 150-year CESM simulation

are very few other available observations that adequately record interannual and decadal changes in atmospheric dust (e.g. Evan and Mukhopadhyay 2010). Consequently, it is important to understand how the low frequency variability seen in the remote Barbados dataset relates to variability in dust transport originating upstream over North Africa.

There is strong year-to-year variability in boreal summer (JJA) dust concentration anomalies (μg/m^3; long term monthly mean subtracted, then seasonally averaged) at the Barbados site (Fig. 2). Maximum negative values occurred in the late 1960's, and maximum positive values occurred in the early 1980's.

Prospero and Lamb (2003) qualitatively suggested that many of the large dust outbreaks seen in the Barbados dataset might be related to the same-season or previous-season ENSO phase. Figure 3 explores this suggestion by regressing the JJA Multivariate ENSO Index (MEI) onto JJA dust concentration anomalies at Barbados. The MEI is defined as the leading principal component of the combined fields of sea level pressure, horizontal surface wind, sea surface temperature, surface air temperature, and cloud fraction. Positive MEI values are associated with El Niño-like conditions in the eastern tropical Pacific (weakened westerly winds, increased sea surface temperature, and increased cloud fraction) and negative MEI values are associated with La Niña-like conditions in this region (strengthened westerly winds, decreased sea surface temperature, and decreased cloud fraction) (Wolter and Timlin 1998).

The correlation between the two time series is 0.20, and no physically meaningful relationship is evident in this plot. A similarly weak correlation is seen in various lag-correlations of the two time series, and in the regression of the PDO index (Mantua et al. 1997) onto JJA Barbados dust burden anomalies (not shown). Doherty et al. (2014) found similarly weak correlations ranging from −0.02 to 0.24 between Barbados dust concentration and various indices of ENSO.

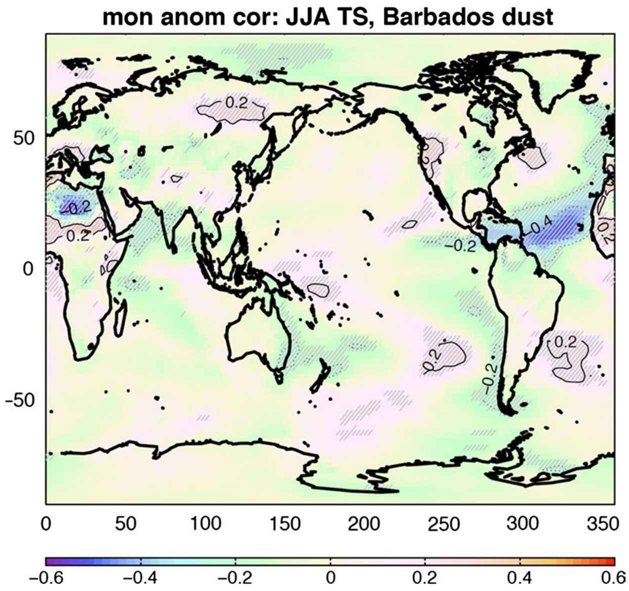


Fig. 5 Pearson correlation of JJA Barbados dust concentration anomalies and global surface temperature anomalies in 150-year CESM simulation. *Grey hatches* indicate regions where there is 95 % confidence that the true correlation is not equal to zero, using a two-sample *t* test

4 Relating boreal summer tropical SST variability to North African dust

4.1 Interannual variability of atmospheric dust at Barbados

Figure 3 suggests that observed boreal summer dust concentration anomalies at Barbados are only weakly related to anomalous tropical Pacific SST variability. However, long-term observations of dust are essentially limited to this point-station dataset. Using our CESM simulation, which contains realistic ENSO variability (Deser et al. 2012) and a correctly timed seasonal cycle of atmospheric dust at Barbados (DeFlorio et al. 2014), what can we learn about the relationship of atmospheric dust anomalies to the major coupled-ocean atmosphere modes that drive interannual to decadal climate variability of many atmospheric variables?

The leading principal component of JJA tropical Pacific SST anomalies ("leading ENSO PC") is uncorrelated to JJA Barbados surface dust concentration anomalies ($\mu g/m^3$) in CESM (Fig. 4; $R = -0.04$). The weak relationship found here is consistent with section 3 in Doherty et al. (2014) (Table 3), finding that the correlation of observed Barbados dust with ENSO can vary from weakly positive ($R_{max} = 0.24$) to weakly negative ($R_{min} = -0.02$) depending on the ENSO index used. In Fig. 5 we examine the spatial structure of the relationship between CESM dust burden anomalies near Barbados and SST anomalies around the globe, which shows the point-by-point correlation of global JJA SST anomalies (3D) with JJA Barbados surface dust concentration anomalies over the entire 150-year simulation. There are only weakly negative correlation values over the central and eastern tropical Pacific, reinforcing other analyses indicating that tropical Pacific SST variability is not related to fluctuations in atmospheric dust at Barbados (see Figs. 3, 4). Moderate negative correlations are found with SST anomalies upstream of Barbados over the central tropical North Atlantic. This is likely due to a combined effect of cooling of SSTs associated with large dust outbreaks (radiative effect) and increased ocean-to-atmosphere latent and sensible heat fluxes associated with increased trade winds in the southern easterly branch of the Azores High, which is prevalent during boreal summer over this region (Doherty et al. 2012).

Dust plumes that originate over North Africa must travel across the entire tropical Atlantic basin before reaching Barbados. Consequently, atmospheric processes such as wet and dry deposition, vertical ascent into the upper troposphere, and cloud seeding can change the signature of dust as it travels westward across the ocean, away from its continental source in the Sahara–Sahel desert region. Different atmospheric circulation patterns far from emission sources can also change the spatial structure of dust anomalies. Because of these processes, concentrations measured at Barbados are not always indicative of source region characteristics (Prospero and Mayol-Bracero 2013; Engelstaedter et al. 2009). Given this and our goal of understanding low frequency variability of North African dust in the climate system, it is useful to characterize the low frequency variability of atmospheric dust anomalies closer to the source of emission. To do so, we will use AVHRR satellite-derived observations in conjunction with the model simulation to try to learn more about the relationship of interannual and decadal variability of North African dust anomalies to the major modes of global climate.

4.2 Interannual variability of atmospheric dust close to North African source regions

The raw and detrended time series of JJA dust AOD monthly anomalies from AVHRR downstream of North Africa (−40W to −20W, 15N–25N) are shown in Fig. 6. Interannual variations of dust AOD are present over this region, and a downward trend of dust AOD anomalies has been observed since 1982. Figure 7 shows the regression of the JJA MEI onto detrended JJA dust AOD anomalies over downstream North Africa. The correlation between the two time series is −0.23, suggesting a weak association between anomalously dusty summers and cool tropical Pacific SST anomalies over this region.

We now compare the observed interannual variability of dust anomalies over the tropical North Atlantic to our CESM simulation. Several interesting features exist in the

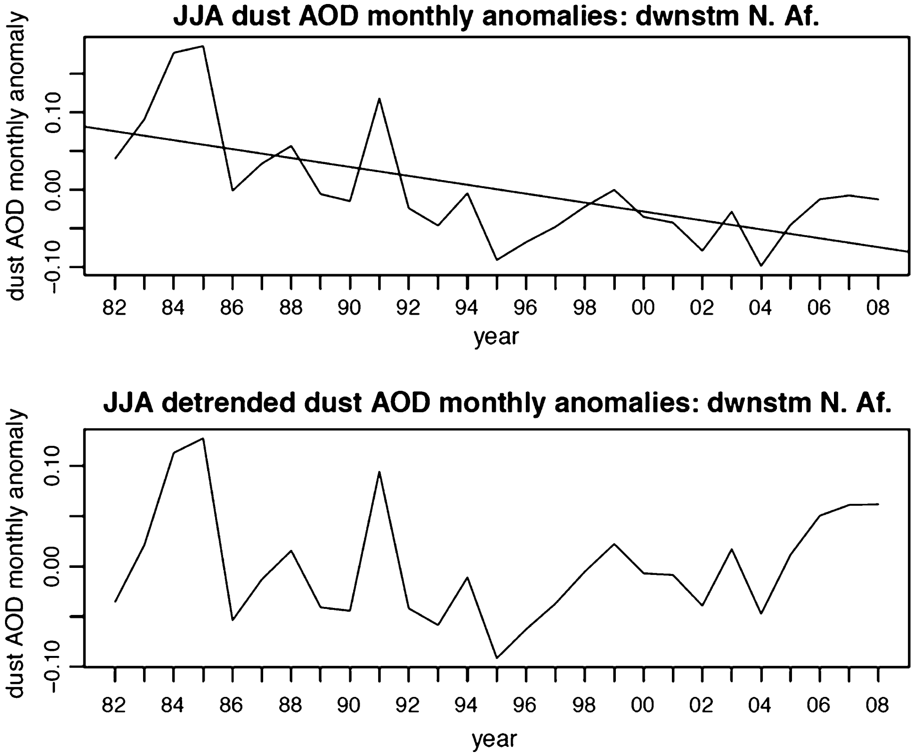


Fig. 6 JJA downstream North Africa (−40W to −20W, 15N–25N) dust aerosol optical depth (AOD) anomalies (*top*) and detrended dust AOD anomalies (*bottom*), January 1982–December 2008. Data were derived from satellite estimates described in Evan et al. (2006a, b)

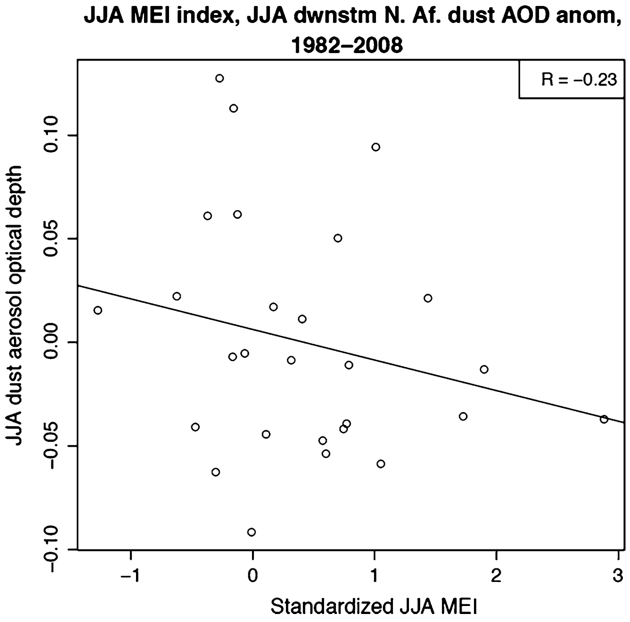


Fig. 7 Scatterplot of JJA standardized multivariate ENSO Index and JJA detrended downstream North Africa dust AOD anomalies, January 1982–December 2008

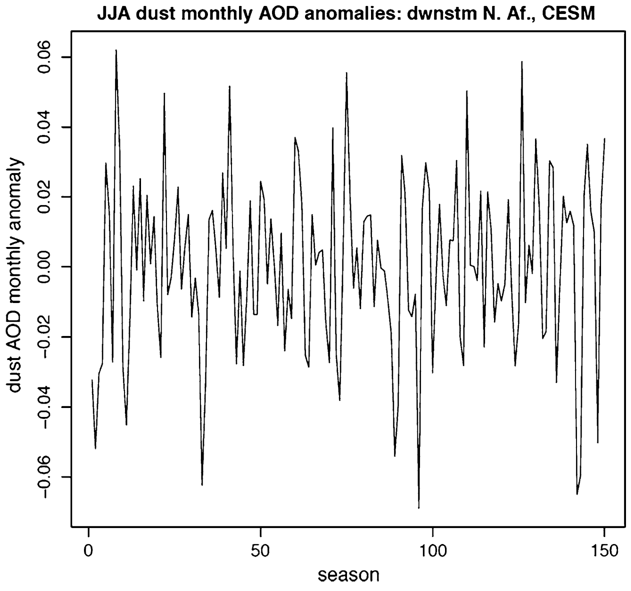


Fig. 8 JJA downstream North Africa dust AOD anomalies in CESM, normalized by the downstream mean value of raw dust burden over this area

150-year model time series of area-averaged JJA downstream North Africa dust AOD anomalies, which is shown in Fig. 8. Most importantly, strong interannual variations in dust AOD anomalies in this region exist. Discernable interannual variability can also be seen in observed dust concentration anomalies at Barbados (Fig. 2), but Fig. 3 and previous work both show that those summertime fluctuations are not strongly correlated to ENSO. In addition, the magnitude of boreal summer dust AOD anomalies in

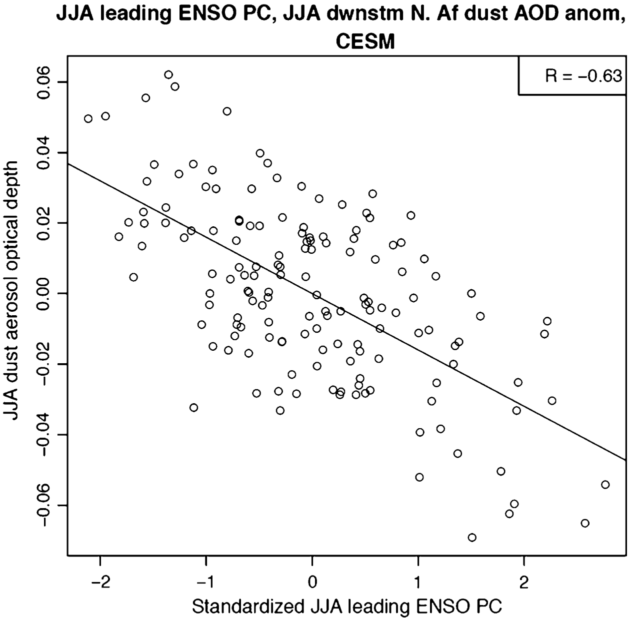


Fig. 9 Scatterplot of JJA standardized leading principal components of tropical Pacific SST variability and JJA downstream North Africa dust AOD anomalies in 150-year CESM simulation

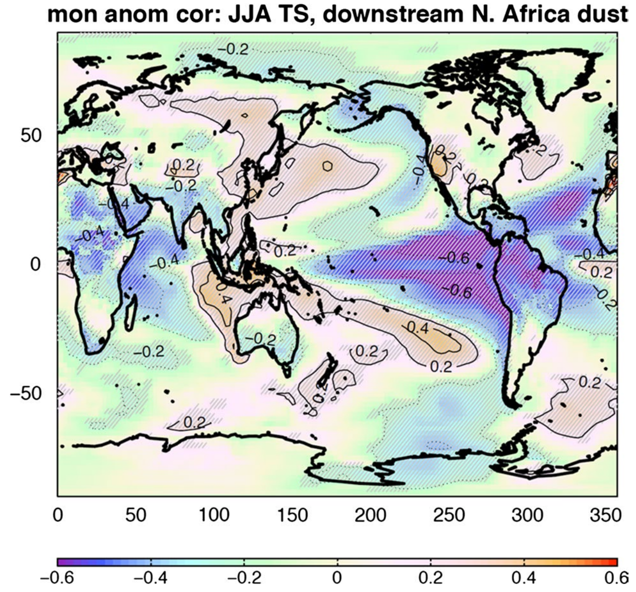


Fig. 10 Pearson correlation of JJA downstream North Africa (320E–340E, 15N–25N) dust burden anomalies and global surface temperature anomalies in 150-year CESM simulation. *Grey hatches* indicate regions where there is 95 % confidence that the true correlation is not equal to zero, using a two-sample *t* test

CESM is similar to observations (Fig. 6). The correlation between the JJA leading ENSO principal component and JJA dust AOD anomalies over downstream North Africa is −0.63 (Fig. 9), which considerably higher than observed. However, the CESM simulation (150 years) is over five times as long as the AVHRR dataset (28 years).

The correlation between JJA downstream North Africa dust burden anomalies and simultaneous global SST anomalies shows a robust signature of tropical Pacific influences (Fig. 10). Similar to the results obtained for Barbados dust in Fig. 5, the correlation map for dust anomalies west of Africa is strongly negative over the tropical North Atlantic, meaning that surface temperature anomalies are negative when dust concentrations are higher, indicating that under these conditions, more dust is blown off the African continent. However, a much different spatial structure from the Barbados map is found over the Pacific basin. For the anomalies west of Africa, large negative values are present in the central and tropical Pacific, very similar to the anomalous SST structure associated with strong ENSO events. Negative values in this region in Fig. 10 indicate that anomalously strong JJA dust outbreaks downstream of North Africa over the tropical North Atlantic occur during anomalously cool SST summers over the central and eastern tropical Pacific. There is also structure of the correlation map over the North Pacific basin that is reminiscent of the Pacific Decadal Oscillation. These results suggest a relationship in CESM between anomalous Pacific SST variability and North African dust transport during boreal summer that is stronger than observed, particularly at Barbados, over the late twentieth century.

It is important to more precisely quantify the associated timescale of variability of North African dust anomalies over the tropical North Atlantic. This is a region of great interest for seasonal forecasting, as it is the genesis region of many Atlantic hurricanes that form as a result of easterly waves propagating from continental Africa. Because dust outbreaks discourage tropical cyclone formation due to cooling of underlying SST (Evan et al. 2006a), associating anomalously dusty seasons with a more predictable component of the climate system (e.g. ENSO) has the potential to increase predictability of these related phenomena on shorter timescales.

We compute a time-evolving metric that encompasses the relationship between the downstream dust burden anomalies and global surface temperature anomalies by calculating the pseudo-principal component of boreal summer dust-surface temperature variability. Here, we define the pseudo-principal component of boreal summer dust-surface temperature variability as

$$Pseudo\,PC = \frac{1}{n}\sum_{i=1,j=1}^{n}\sum_{k=1}^{K} Cor_{i,j} \cdot TS_{i,j,k}$$

where n = total number of grid cells, K = number of model years, Cor = spatial pattern of correlations of boreal summer global surface temperature anomalies and downstream North African dust burden anomalies (e.g., Fig. 10), and TS = anomaly field of global surface temperature

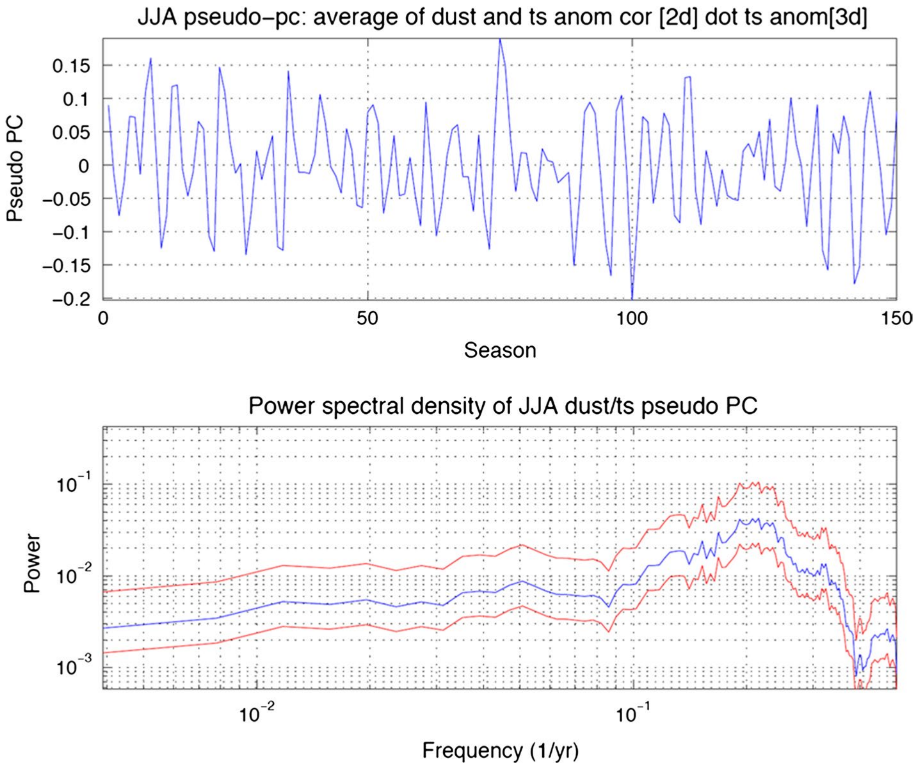


Fig. 11 Pseudo principal component of JJA global surface temperature and downstream North African dust anomalies in CESM (*top*) and associated power spectrum (*bottom*, *blue*), computed using a Thomson multitaper power spectral estimate. The spectrum is bounded by 95 % confidence limits (*red*)

anomalies for each summer, k. The pseudo-PC shows how strongly global surface temperature anomalies project onto the pattern in Fig. 10 over time.

Figure 11 shows the boreal summer pseudo principal component time series (top panel) and its associated power spectrum (bottom panel) with 95 % confidence bounds. The power spectrum was computed using a Thomson multitaper power spectral estimate (Percival and Walden 1993). There is a peak in the pseudo principal component spectrum around 5 years, with appreciable power in the decadal and multidecadal bands. This spectral estimate shows that the pseudo-PC, which mathematically encompasses the relationship between JJA downstream North African dust burden anomalies and global surface temperature anomalies, is varying most strongly on interannual timescales. This result is not surprising given the spatial structure of the correlations over the Pacific basin (Fig. 10), but is interesting in that it is consistent with the hypothesis that surface temperature variability in the Pacific basin could be remotely driving changes in dust burden anomalies over North Africa on interannual timescales.

4.3 Composites of mineral dust and circulation on strong ENSO seasons

Composites of raw values of dust burden, surface zonal wind, and 700 hPa zonal wind, averaged on the top 10 % La Niña seasons (top panels) and the top 10 % El Niño seasons (middle panels) are shown in Figs. 12, 13 and 14. The percentiles were defined using the leading principal component time series of tropical Pacific SST anomalies (Supplementary Figures S1-S2). The bottom panel is the top panel minus the middle panel. DeFlorio et al. (2014) showed that maximum boreal summer dust concentration over the open ocean is simulated around 700 hPa in CESM, which is why we calculate zonal wind at the 700 hPa level here. These three figures show that on strong La Niña seasons, downstream North African dust burden values in CESM increase due to statistically significant increases in lower tropospheric easterly wind. A similar qualitative picture emerges for decadal variability of dust transport, but the magnitude of the effect is smaller than for interannual variability (Supplementary Figures S5-S7).

5 Modulation of ENSO–North African dust relationship on decadal timescales

The importance of the differing record lengths for observations and CESM is explored in Fig. 15, which shows a 28-year sliding correlation of the JJA leading ENSO principal component and JJA dust AOD anomalies over downstream North Africa. The window length is chosen to be 28 years in order to match the length of the AVHRR dataset. The correlation coefficients range from −0.34 to −0.77, which demonstrates the sensitivity of the ENSO-dust

Fig. 12 Composite of JJA dust burden (kg/m^2) on *top* 10 % La Niña seasons (*top*) and top 10 % El Niño seasons (*middle*) in CESM. The *bottom panel* is the top panel minus the middle panel. *Grey hatches* in the *bottom panel* indicate regions where there is 95 % confidence that the true difference between the two samples is not zero, using a two-sample *t* test

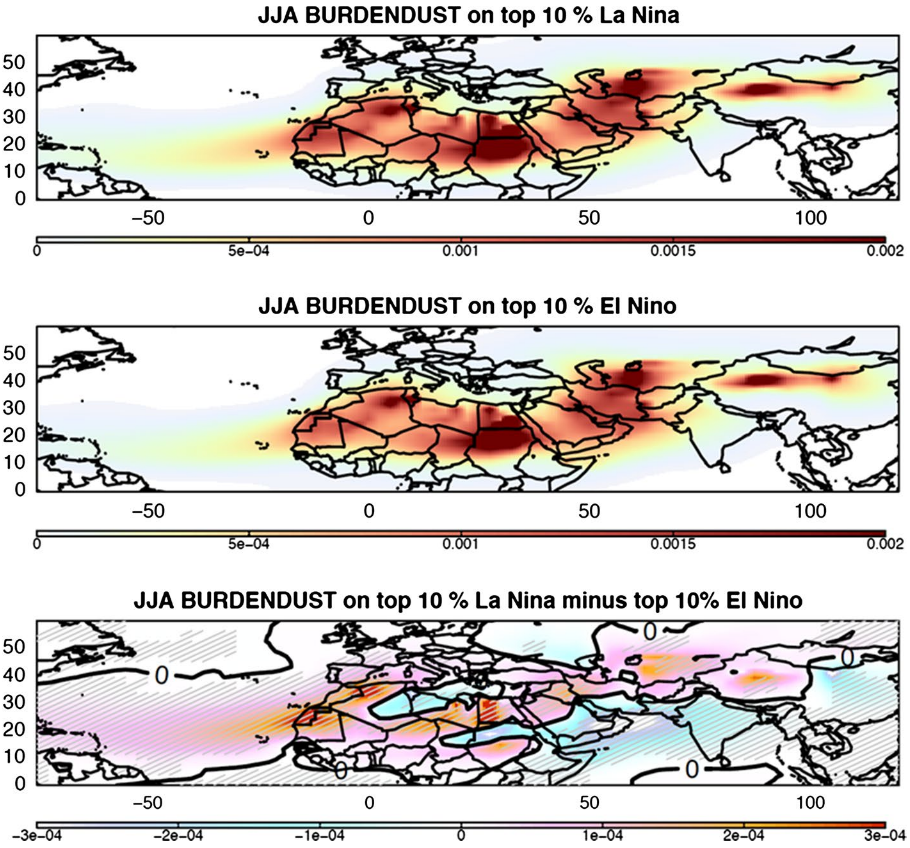
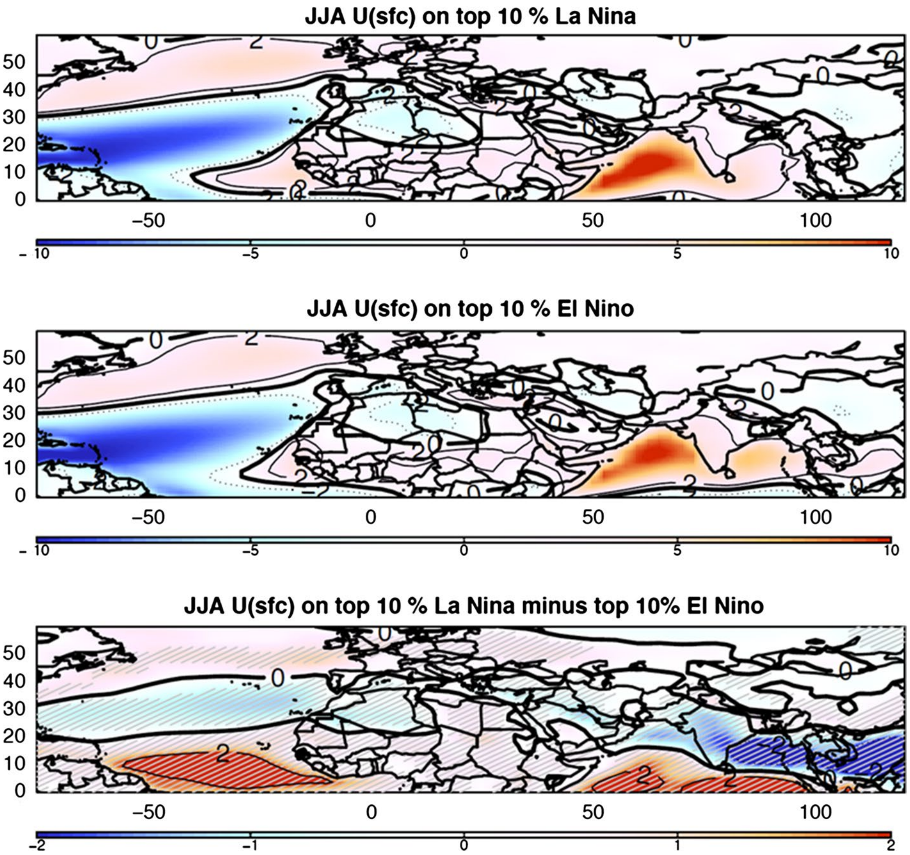


Fig. 13 As in Fig. 12, but for surface zonal wind



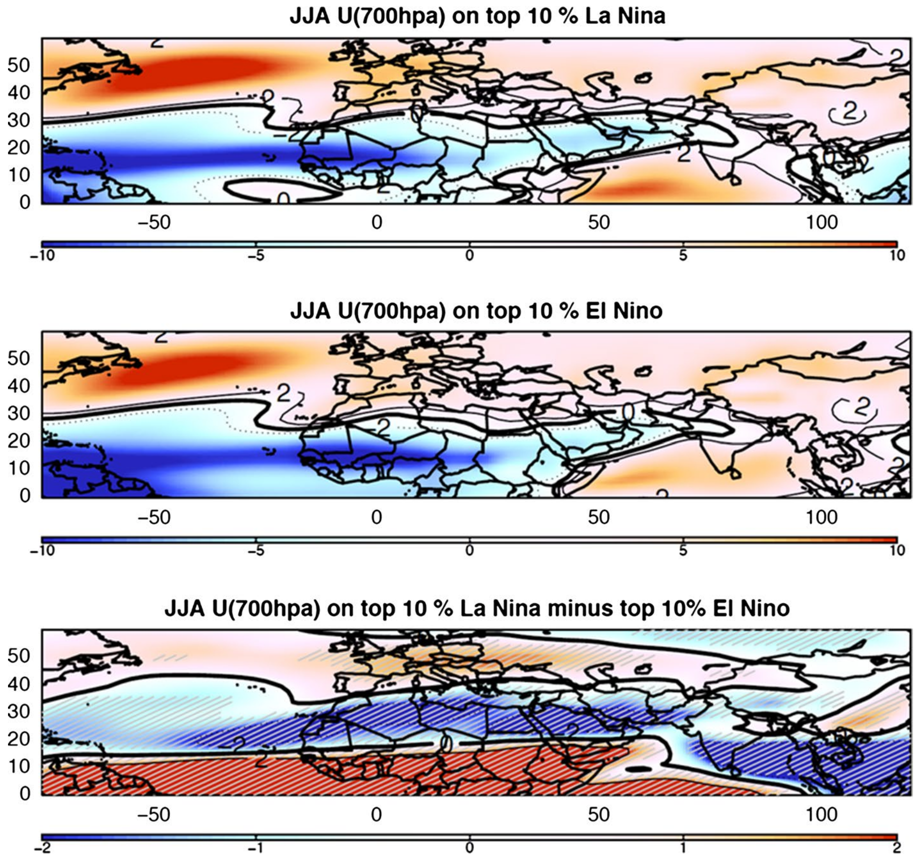


Fig. 14 As in Fig. 12, but for 700 hPa zonal wind

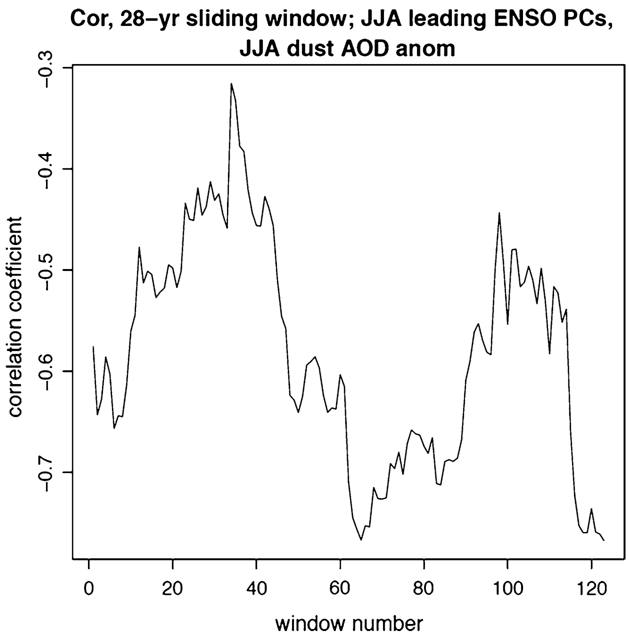
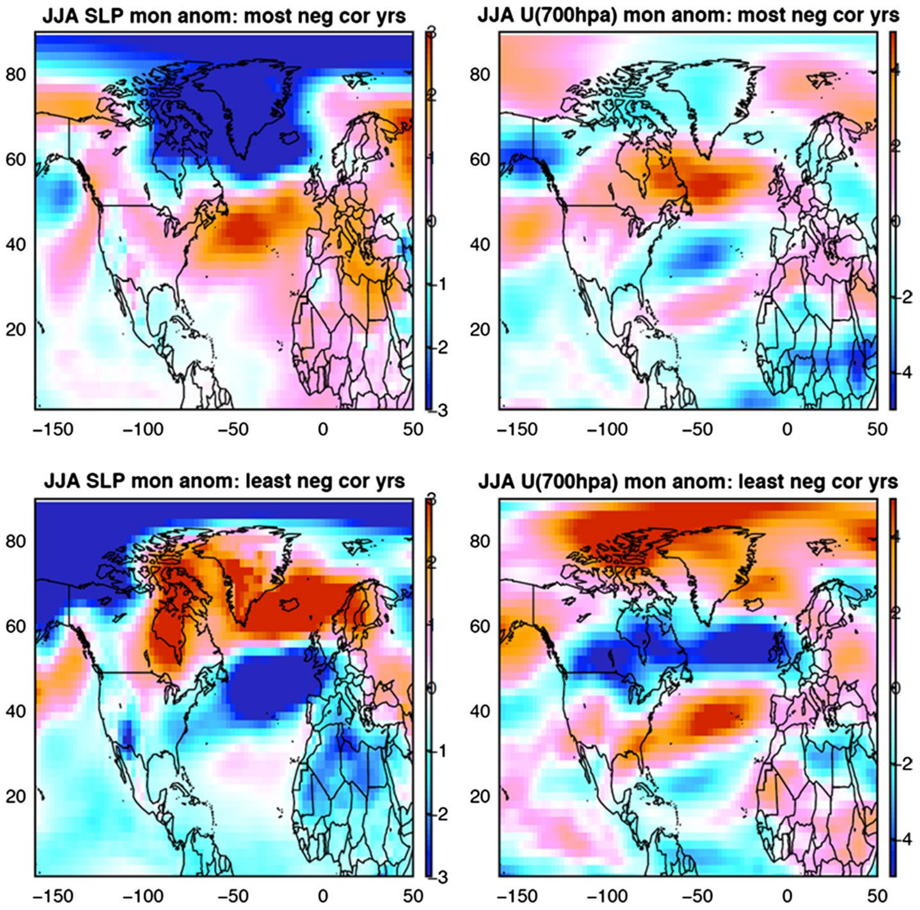


Fig. 15 28-year sliding correlation of JJA standardized leading principal components of tropical Pacific SST variability and JJA downstream North Africa dust AOD anomalies in CESM

regression to record length. This figure suggests that existing observations over the tropical North Atlantic are not extensive enough to characterize the varying relationship between tropical Pacific SST variability and North African dust.

Sea level pressure (SLP) and 700 hPa zonal wind composites on the most and least negative ENSO-dust sliding correlation periods are shown in Fig. 16. The composites are calculated as an average of top 10 % most negative and top 10 % least negative sliding correlation periods from Fig. 15 (<−0.730 and >−0.435, respectively). The spatial structure of both SLP and lower tropospheric zonal wind anomalies are distinctly reminiscent of variability associated with the North Atlantic Oscillation (NAO). In addition, the 28-year sliding correlation of ENSO and downstream North African dust appears to be roughly out of phase with the 28-year running mean of the NAO index in CESM (Fig. 18; R ~ 0.54). Previous studies (e.g. Riemer et al. 2006) have found no relationship between the NAO and North African dust variability during boreal summer, and the relationship between the JJA NAO index (which we define as the difference between monthly anomaly SLP values near Azores and Iceland)

Fig. 16 Composite of JJA sea level pressure monthly anomalies (*left column*) and 700 hPa zonal wind anomalies (*right column*) on the most negative (*top row*) and least negative (*bottom row*) sliding correlation periods in CESM, determined from Fig. 15



and downstream North Africa dust anomalies is weak in CESM (R ~ 0.16). However, Figs. 16 and 17 provide evidence in our model simulation that the NAO may be destructing the Pacific SST–North African dust relationship on decadal timescales.

The boreal summer NAO index is more strongly correlated to downstream North Africa dust AOD anomalies during the least negative ENSO-dust sliding correlation periods (Fig. 18, top panel), but the relationship between the NAO index and lower tropospheric zonal wind during these periods is quite weak (Fig. 18, bottom panel). We conclude that the NAO modulation of North African dust variability manifests itself via other atmospheric processes in the North African region. In addition, ENSO variability is larger during the most negative sliding correlation periods (Fig. 19), suggesting that fluctuations in the strength of ENSO on decadal timescales may also be modulating the relationship between Pacific SST variability and North African dust. However, the regression shown in the top right panel of Fig. 19 is very similar even after removing the anomalously strong ENSO events (not shown), which weakens this hypothesis.

6 Conclusions and discussion

In this study, we used a 150-year preindustrial control CESM 1.0 simulation, which complements existing observations of mineral dust at Barbados and over the tropical North Atlantic, to show that boreal summer dust variability over the eastern tropical North Atlantic may be strongly influenced by Pacific SST variability. This influence manifests itself through changes in lower tropospheric atmospheric circulation patterns over the North African continent (Figs. 12, 13, 14) that are reminiscent of a Walker Cell teleconnection. The relationship between Pacific SST variability and North African dust fluctuates on decadal to multidecadal timescales in CESM, and we show that this fluctuation is strongly associated with North Atlantic SST variability. We also show that observations of dust at Barbados are weakly correlated with observations of Pacific basin SST variability, and that the correlation is of opposite sign as observed dust AOD anomalies and Pacific basin SST variability over the tropical North Atlantic, downstream of North Africa. This suggests that other atmospheric processes and/or coupled–ocean atmosphere

Fig. 17 As in Fig. 15, but with JJA NAO index 28-year running mean (*black line*)

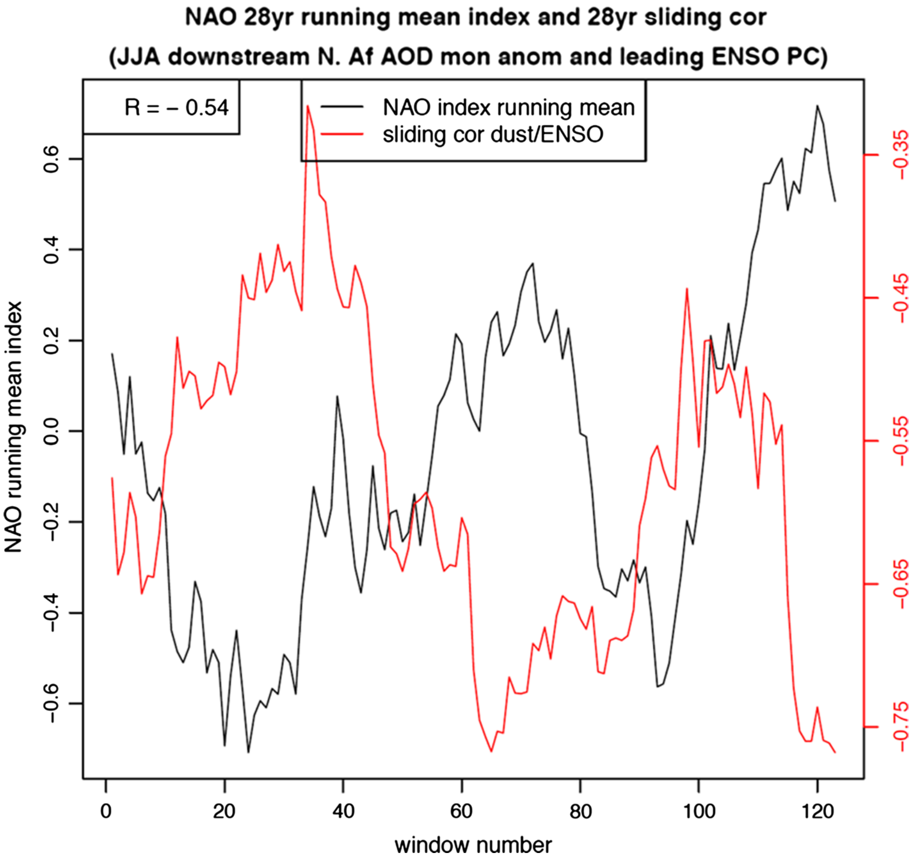
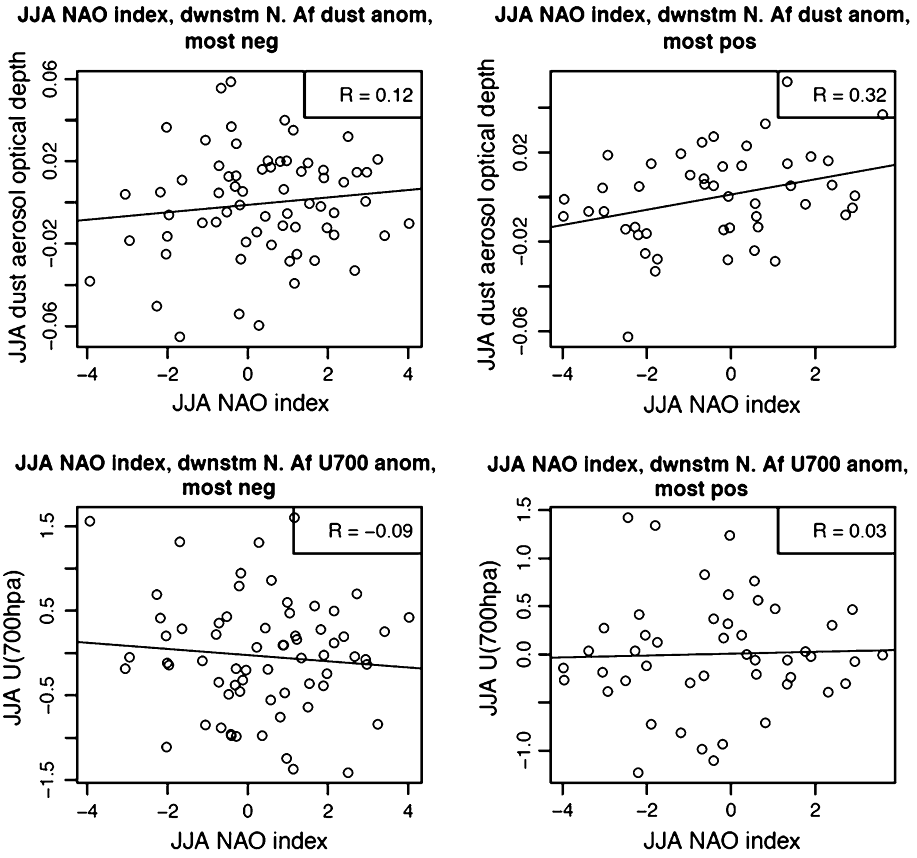


Fig. 18 Scatterplot of JJA NAO index and JJA downstream North Africa dust AOD anomalies (*top row*) and 700 hPa zonal wind anomalies (*bottom row*) on the most negative (*left column*) and least negative (*right column*) sliding correlation periods in CESM



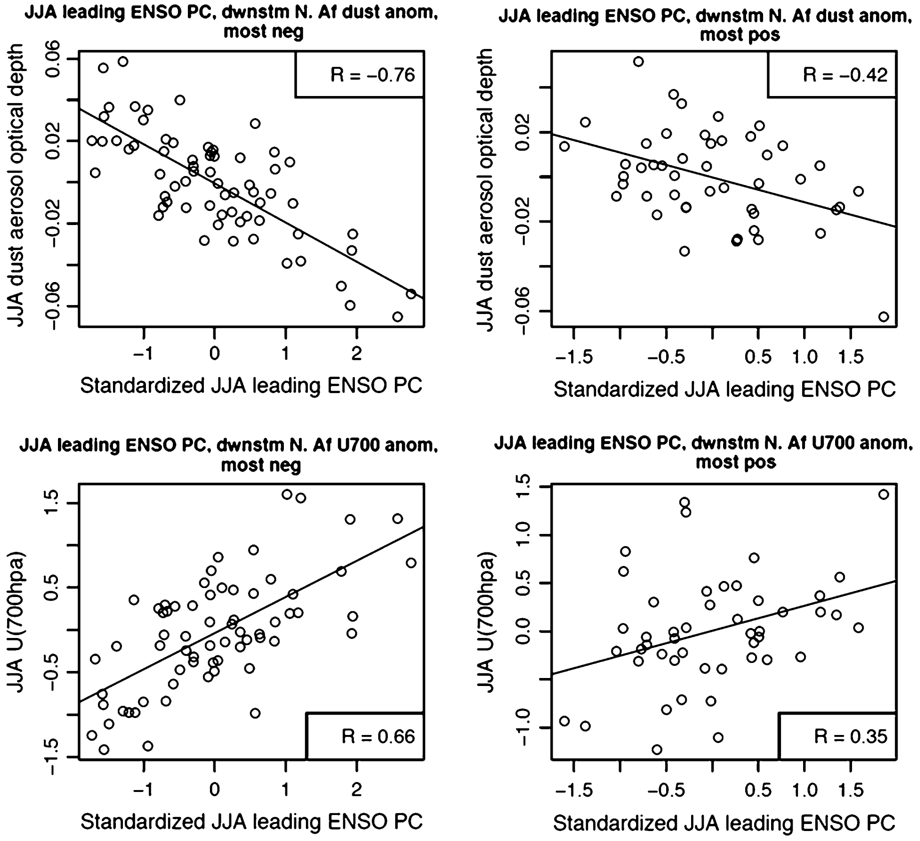


Fig. 19 Scatterplot of JJA standardized leading principal components of tropical Pacific SST variability and JJA downstream North Africa dust AOD anomalies (*top row*) and 700 hPa zonal wind anomalies (*bottom row*) on the most negative (*left column*) and least negative (*right column*) sliding correlation periods in CESM

interactions are dominant in characterizing the cross-basin variability of dust.

This work adds to previous studies that have demonstrated the complex response of atmospheric dust to perturbations in the climate system. It is important for future studies to better understand the relationship of the results here to recently published work which shows that a statistically significant portion of variability in dust concentrations at Barbados can be explained by fluctuations in the West African Convergence Zone (Doherty et al. 2014).

One caveat of our work is that we use a CESM preindustrial control simulation, but observations of dust at Barbados and over the tropical North Atlantic could reflect anthropogenic contributions to dust variability such as agricultural practices. Ginoux et al. (2012) estimate that up to 8 % of North African dust emissions are anthropogenic, mostly due to land use changes in the Sahel region. In addition, late twentieth century historical CMIP5 simulations have elucidated errors in the representation of dust emissions and interannual variability (Evan et al. 2014).

Future studies are needed to explore the implications for seasonal predictability implied by the relationships found here between North African dust transport and tropical Pacific SST variability. ENSO is the dominant coupled-ocean atmosphere energetic component of the climate system, and because statistical and dynamical models have demonstrated some skill in predicting tropical Pacific SST interannual variability some months ahead (e.g. Barnston et al. 2011), there may be potential to improve predictability of North African dust transport on similar timescales. This could subsequently lead to more skillful forecasts of the initiation of tropical cyclones over the eastern tropical Atlantic on seasonal timescales. Our work also suggests that we may learn more about the interaction of climate modes and North African dust variability in the coming decades, when our existing network of observations from both in situ measurements and satellite products become more extensive.

North African dust varies on timescales of seconds to millennia, and the characteristics of this variability depend critically on season, local conditions, and remote ocean–atmosphere teleconnection patterns. Because of sparsely available observations, the hybrid observational-modeling approach employed in this study is a useful and necessary tool for increasing our understanding of dust variability on long timescales.

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