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Key Points:
- The ICAS drives African dust change at decadal and longer time scales
- A unified framework supports the ICAS drive of African dust, and observations also support the ICAS-dust-ITCZ relationships
- Climate models suggest strong reduction in African dust due to increase in ICAS driven by global warming

Supporting Information:
- Supporting Information S1

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Anthropogenic Decline of African Dust: Insights From the Holocene Records and Beyond

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Abstract African dust exhibits strong variability on a range of time scales. Here we show that the interhemispheric contrast in Atlantic SST (ICAS) drives African dust variability at decadal to millennial timescales, and the strong anthropogenic increase of the ICAS in the future will decrease African dust loading to a level never seen during the Holocene. We provide a physical framework to understand the relationship between the ICAS and African dust activity: positive ICAS anomalies push the Intertropical Convergence Zone (ITCZ) northward and decrease surface wind speed over African dust source regions, which reduces dust emission and transport. It provides a unified framework for and is consistent with relationships in the literature. We find strong observational and proxy-record support for the ICAS-ITCZ-dust relationship during the past 160 and 17,000 years. Model-projected anthropogenic increase of the ICAS will reduce African dust by as much as 60%, which has broad consequences.

Plain Language Summary Interhemispheric contrast in Atlantic SST (ICAS) strongly affects African dust variability on decadal and longer time scales and modeled future ICAS points to a strong reduction in African dust due to global warming.

1. Introduction

African dust is an integral part of the Earth's climate and ecosystem. It contributes to maintain the energy balance of the climate (Evan et al., 2009; Jickells et al., 2005), modulates tropical Atlantic sea surface temperature (SST) (Evan et al., 2009), fertilizes terrestrial and marine ecosystems (Jickells et al., 2005; Yu et al., 2015), and modifies clouds and precipitation (Andreae & Rosenfeld, 2008; Zhao et al., 2011). African dust varies on a range of time scales, cascading that variability across the different subsystems. What causes the variability at decadal and longer timescales and what should be the expectations for African dust in a warming climate? Previous studies show close relationships between recent dust variability and a set of variables such as Sahel precipitation (Prospero & Lamb, 2003), the North Atlantic Oscillation (NAO; Moulin et al., 1997), and time series of a surface wind speed pattern over Northern Africa (Evan et al., 2016). However, these drivers are difficult to predict with high certainty using climate models and elude a systematic understanding of African dust variability at decadal and longer timescales. Here we propose a unified framework to understand observations of African dust variability in the historical past as well as in the paleo record of the last 17,000 years, making it possible to project its future long-term change.

The interhemispheric temperature contrast, averaged over a longitude span wide enough such as an ocean basin, emerges as an important variable in the atmospheric energy balance view and associated dynamics (Chiang & Friedman, 2012; Kang & Frierson, 2009; Schneider et al., 2014). Perturbation of the temperature contrast leads to an adjustment of the strength of Hadley cells in the two hemispheres to restore energy balance. The Hadley cell in the relatively warming hemisphere slows down while its counterpart in the other hemisphere speeds up in order to transport more energy toward the relatively cooling hemisphere and thus reduce the temperature contrast (Chiang & Friedman, 2012; Kang & Frierson, 2009; Schneider et al., 2014) (see Figure 1a for an illustration of a relative warming of the Northern Hemisphere). The lower branches of both Hadley cells, responsible for the trade winds, converge and give rise to the Intertropical

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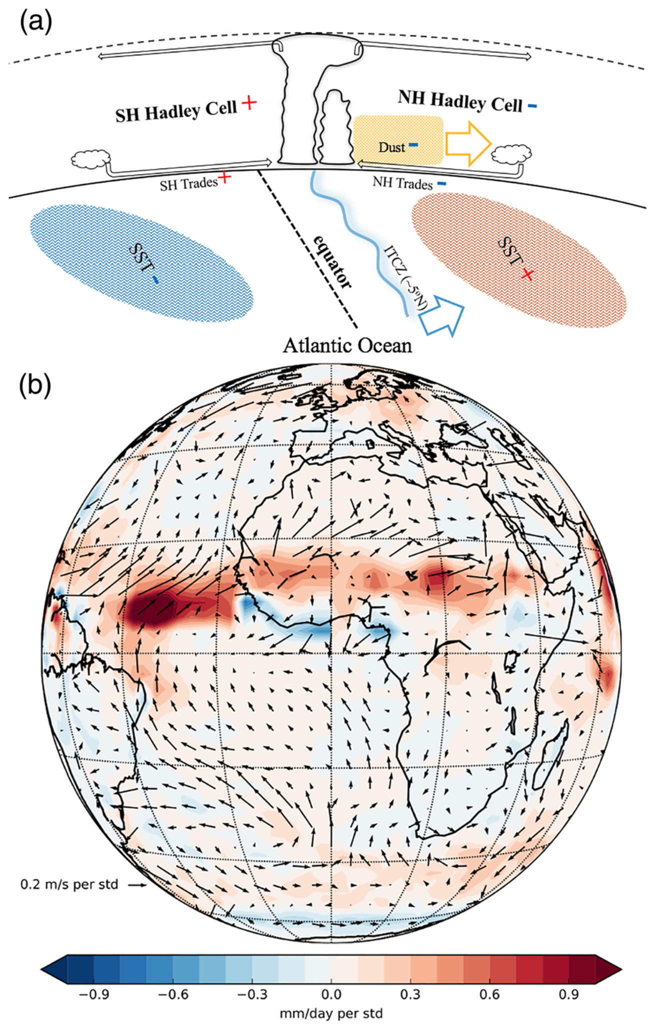

Figure 1. (a) A schematic of the theoretical framework proposed to explain the relationships among the ICAS, the ITCZ position, and African dust. In current climate, the Atlantic ITCZ sits around 5°N in terms of annual mean with the main dust transport route to its north (about 12°N, see Figure S1). With increasing ICAS, the Northern Hemisphere (NH) Hadley cell weakens, and associated NH trade wind speed decreases, reducing dust emission and transport from Africa. Meanwhile, the ITCZ moves northward (light blue arrow) together with the dust transport route (light yellow arrow). (b) Regression of ICAS against precipitation and surface wind during JJA between 1979 and 2015. Color shaded areas and wind vectors depict, respectively, precipitation and surface wind anomalies associated with one standard deviation of ICAS. It indicates a northward displacement of the ITCZ and strengthening and weakening of the trade winds to the south and north of the ITCZ, respectively, because prevailing trade winds are northeasterly and southeasterly in the northern and southern hemispheres, respectively.

Convergence Zone (ITCZ). Slowing down of the Hadley cell in the relatively warming hemisphere reduces surface wind speed in the same hemisphere while increases surface wind speed in the other, effectively pushing the latitudinal position of the ITCZ toward the warming hemisphere (e.g., Figure 1b). The lower branch of the Hadley cell in the Northern Hemisphere covers most African dust source regions where surface wind speed is a controlling factor for dust variability (Chin et al., 2014; Knippertz & Todd, 2012; Ridley & Heald, 2014; Wang et al., 2012; Yuan et al., 2016). Therefore, African dust activities decrease with the relative warming of the Northern Hemisphere. The latitudinal movement of the ITCZ also affects the transport and removal of African dust through wet scavenging and determines transport route. In this study, we focus on the Atlantic Ocean and define the Interhemisphere Contrast in Atlantic SST, or ICAS, as the area-weighted SST difference between the North (−80–20°E, 0–70°N) and South Atlantic (−70–20°E, 70–0°S) Oceans.

The energy balance view offers the following testable predictions: Positive ICAS perturbations are associated with northward movement of the Atlantic ITCZ, reduced surface wind speed in the African dust source regions, and thus reduction in African dust (Figure 1a). We illustrate the interplay in a broad context by using surface wind from reanalysis data (Dee et al., 2011) and precipitation from the Global Precipitation Climatology Project (Huffman et al., 1997) in Figure 1b. Figure 1b shows regression maps between the ICAS and the anomalies of precipitation and surface wind vectors for the boreal summer of June–August (JJA) over a period of 1979–2015. Over the Saharan dust source regions, there is a clear shift of wind direction to be more southwesterly, which is an overland extension of a large-scale, systematic southwesterly surface wind anomaly covering the tropical North Atlantic (Figure 1b). The southwesterly surface wind anomaly is opposite in direction to that of the climatological northeasterly winds over the dust source regions. It therefore decreases the surface wind speed over much of the dust source regions (Figure S2) and reduces dust emission as well as westward transport to the tropical North Atlantic (Knippertz & Todd, 2012; Ridley & Heald, 2014; Wang et al., 2012). Associated with a positive ICAS is a zonal band of positive precipitation anomaly extending from the Sahel to the western tropical Atlantic Ocean, which is accompanied by a narrower and more meridionally confined band of negative precipitation anomaly along the northern coast of the Gulf of Guinea. Such alternating anomalies of precipitation suggest a northward movement of the ITCZ associated with a positive ICAS. The positive precipitation anomaly in the north may also contribute to suppress dust emission in this area. These observations are therefore consistent with theoretical predictions based on the energy balance view (see Figure 1a). In the following, we show observational evidence of ICAS control of African dust at decadal and longer time scales during the last 17,000 years.

2. Observational Evidence of ICAS Control of Dust Over the Past 160 Years

Empirical evidence of the past 160 years supports relationships between ICAS and African dust variability as well as the ITCZ latitudinal position. Figure 2 shows various time series of African dust activity (Figures 2a–2c and 2e) together with the ICAS (Figure 2f), Sahel precipitation (Figure 2d) (Becker et al., 2013), and the Atlantic Multidecadal Oscillation (AMO) index (Figure 2g) (Enfield & Nuñez, 2001).

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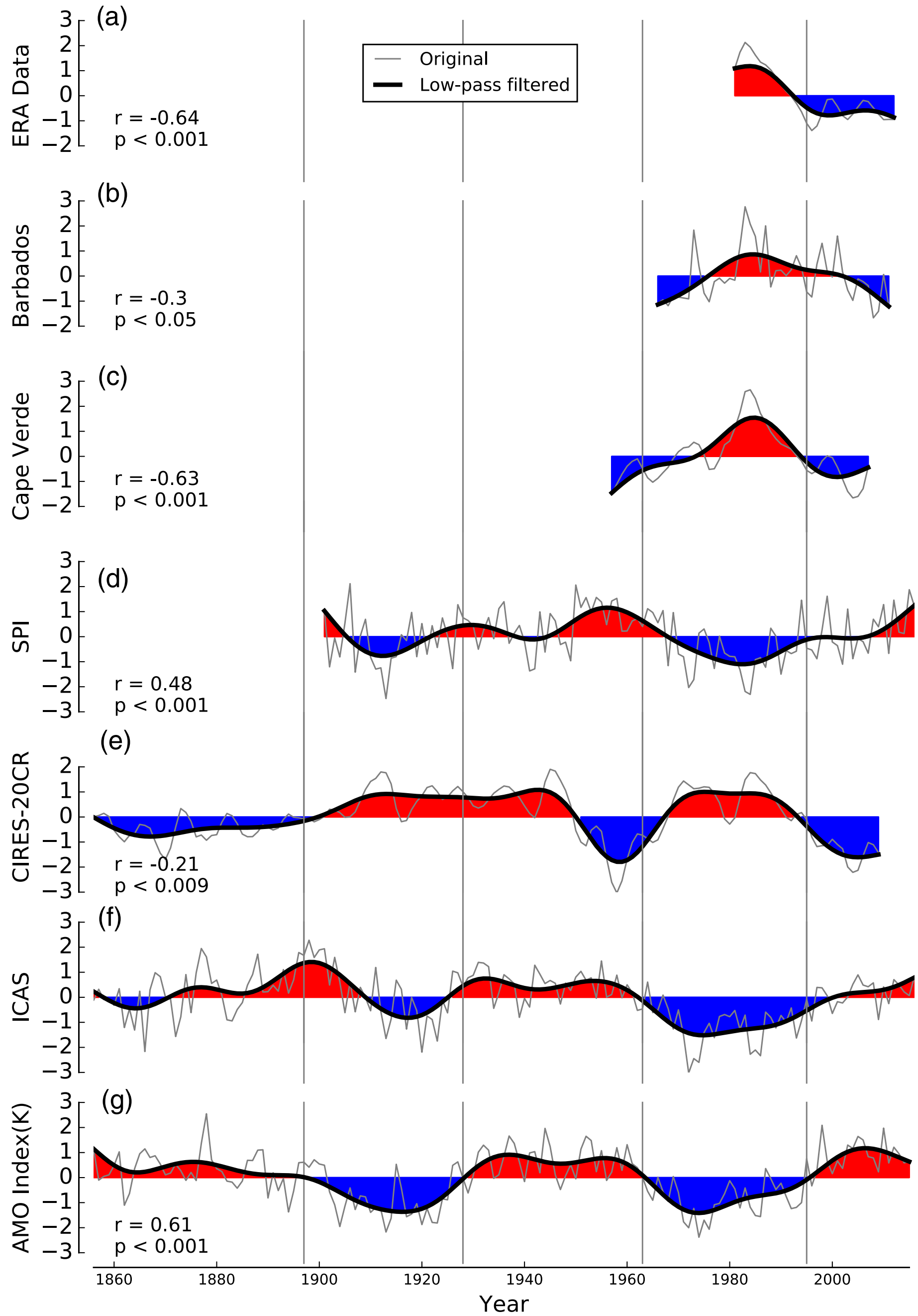

Figure 2. Time series of various dust activity proxies in the recent past, with vertical lines marking AMO phase changes. Both the original (gray lines) and low-pass (0.1 year^{-1} is the cutoff) filtered (bold solid) dust records are plotted. Each time series is detrended and then normalized by its standard deviation. Red (blue) shading indicates positive (negative) values. (a) Dust proxy based ERA-interim wind; (b) dust time series from Barbados record; (c) dust proxy based on Cape Verde record; (d) Sahel precipitation index; (e) dust proxy based on CIRES-20CR wind; (f) ICAS calculated based on the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) (Kennedy et al., 2011) data since 1850; and (g) AMO index since 1856. The correlation coefficients and associated *p* values are shown for each variable when regressed against the ICAS data using raw annual data.

Dust activity measurements and proxies include (Figure 2c) a synergy of satellite and coral dust proxy data (Evan & Mukhopadhyay, 2010), which is referred to as "the Cape Verde data," (Figure 2a) proxies based on time variations of a surface wind speed pattern (8) from the European Center for Medium-Range Weather Forecasts Interim reanalysis (ERA-I) (Dee et al., 2011) (Figure 2e), NOAA-CIRES 20th Century Reanalysis

(Compo & Whitaker, 2011) (CIRES-20CR), and (Figure 2b) the long-term Barbados surface dust concentration measurements (Prospero & Lamb, 2003), "the Barbados data." Both the raw annual and low-pass filtered (with a cut-off frequency of 0.1 year^{-1}) data are used to probe interannual and decadal variability.

The ERA-I data (Figure 2a) indicates that dust activity experienced an overall decreasing trend since the beginning of the 1980s and it is well correlated with the ICAS time series ($r = -0.64$, $p < 0.001$). The Cape Verde data (Figure 2c) extends Atlantic dust activity measurements back to 1955. It shows an increasing trend between the1950s and the end of the1970s and a decreasing trend afterward, with the latter half agreeing with the ERA-I data. The Barbados record (Figure 2b) has a similar trend since the 1950s, but its minimum in the 1960s dips lower than the Cape Verde data. Correlations between dust data sets and the ICAS are statistically significant at 99.9% ($r = -0.63$, $p < 0.001$) and 95% level ($r = -0.3$, $p < 0.05$) for the Cape Verde and the Barbados data, respectively. For the Barbados record, the correlation coefficient increases to −0.58 if the raw annual data are low-pass filtered, which may suggest that point measurements at Barbados have a strong interannual variability component that is not directly related to the ICAS.

The CIRES-20CR data (Figure 2e) spans 162 years from 1851 to 2012. During this period, the African dust activity experiences roughly two oscillation cycles. After a brief period of slightly decreasing trend, dust activity increases from the 1870s to the 1910s, persists until a quick drop at the beginning of 1950s, and then follows a similar trajectory as the Cape Verde data and the Barbados data. The ICAS also undergoes two cycles during this period, but with opposite phase (Figure 2f). The correlation coefficient between the ICAS and the CIRES-20CR data is −0.21 ($P < 0.01$). Prior to about 1900 SST, measurements over the South Atlantic Ocean are sparse (Rayner et al., 2003), which may affect the reliability of calculated ICAS during this period. The AMO index, which is based on North Atlantic SST measurements, can be used as a proxy for the ICAS (Folland et al., 1986; Zhang & Delworth, 2006) before the 1900s if we assume the high correlation between them after 1900 ($r = 0.72$, $p < 0.001$) holds. Using the AMO index as proxy, the correlation coefficient between ICAS and the CIRES-20CR data increases to −0.4 ($p < 0.001$). Positive ICAS is also strongly correlated with the Sahel precipitation index (SPI) ($r = 0.48$, $p < 0.001$) as shown in Figure 2d. This is consistent with a northward movement of ITCZ associated with the positive ICAS (Figure 1) because northward displacement of ITCZ brings more precipitation into the Sahel region (Figure 1b).

Low-pass filtered time series (thick black lines in each panel) show that dust activity and the ICAS undergo phase changes (indicated by vertical lines in Figure 2) at a similar time, further clarifying the ICAS-dust connection. The low-pass filtering generally increases the correlation between ICAS and dust or its proxies (r values in parenthesis of Figure 2), which highlights the dominant role of ICAS in determining dust variability at decadal and longer timescales. See the supporting information for correlation coefficients and corresponding p values if the autocorrelation is removed from the correlation calculations.

3. Evidence of the ICAS-Dust-ITCZ Connections in the Holocene and Beyond

The ICAS-ITCZ-dust relationships in Figures 1 and 2 find further support from paleo-records over the past 16,800 years, especially in the Holocene (Figures 3 and 4). See Data and Method in the supporting information for details on the data and proxies. The ICAS (Figure 3e) during this period is approximated by the hemispheric temperature difference based on temperature reconstructions (Marcott et al., 2013; Shakun et al., 2012), M13 and S12, respectively. The Atlantic ITCZ latitudinal position has been shown to positively correlate with the Titanium concentration record (Figure 3a) from the Cariaco Basin (Haug, 2001). African dust activity is measured by records of dust and terrigenous fluxes at several sites, including the GCC103 and GGC100 cores around the Bahamas (26°N, 78°W) (Figure 3a), the Ocean Drilling Program Site 658C (ODP658C, 20.75°N, 18.58°W) (Figure 3b) and the OCE437-7 GC68 (GC68, 19.36°N,17.28°W) (Figure 3c) off the Mauritania coast, and the VM20-234 (5.33°N, 33.03°W) (Figure 3d) over the tropical Atlantic Ocean site. The ICAS undergoes a general upward trend between approximately 20,000 and 6,000 BP, punctuated by two abrupt events: the Younger Dryas (12,900–11,700 BP) and the Bolling-Allerod warming (14,700–12,700 BP), and a gradual downward trend since 6,000 BP (Figure 3e). The gradual trends and abrupt events are used to test the ICAS-dust-ITCZ connections.

In the Holocene, from the start of the Holocene (around 11,700 years BP), ICAS increases relatively fast, and the ITCZ moves northward accordingly. Dust activities at all four sites also generally decrease. They reach a global minimum during the African Humid Period (de Menocal et al., 2000), roughly 10,000 to 5,000

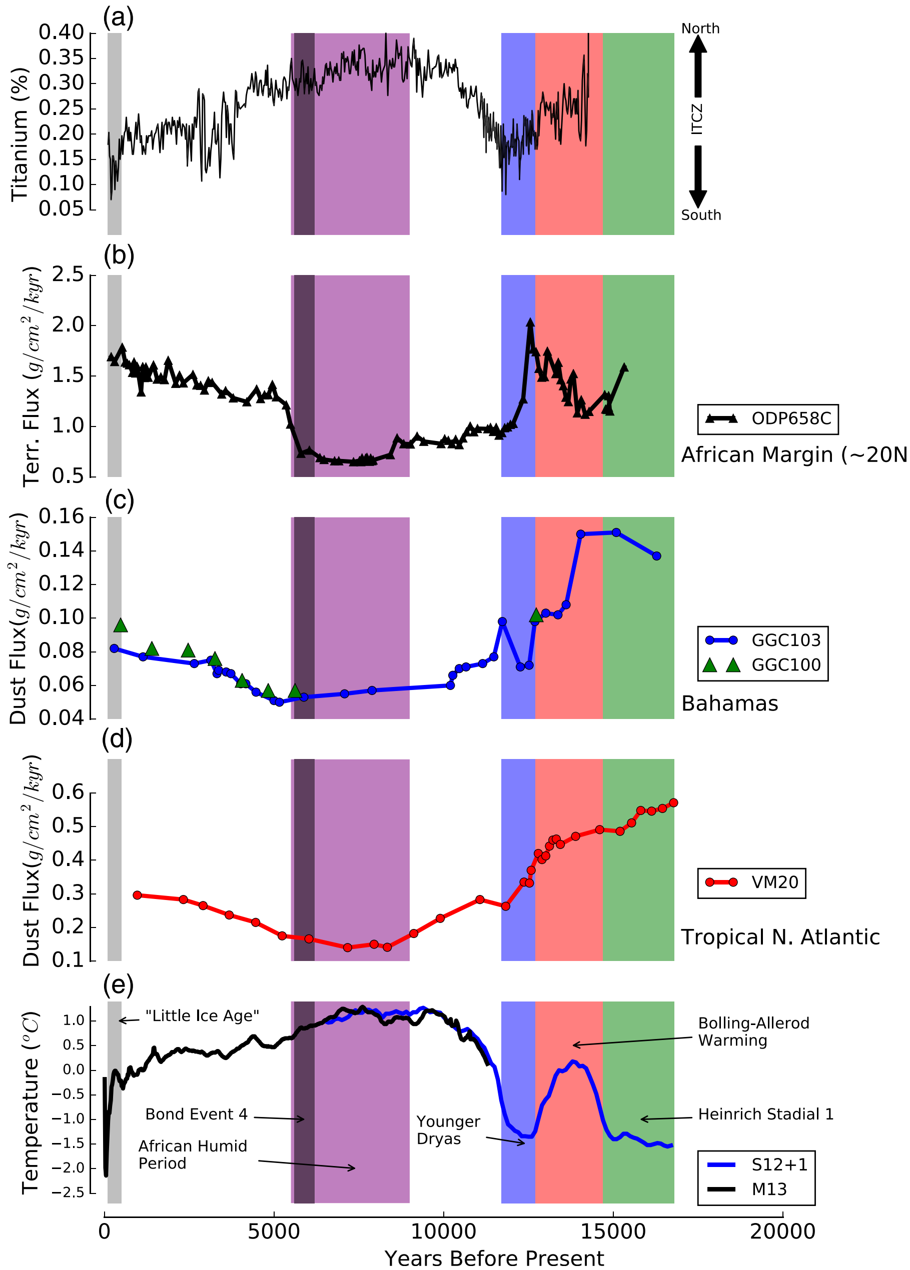

Figure 3. (a) Titanium concentration from the Cariaco Basin, a proxy for ITCZ meridional position, for the last 14,000 years. Higher values indicate more northward position of the ITCZ. (b) Terrigenous flux at the Ocean Drilling Program Site 658C (20.75°N, 18.58°W), a proxy for dust deposition, for the last 17,000 years. (c) Dust fluxes at the two sites near the Bahamas, OCE205-2 100GGC (26.0612°N, 78.0277°W) and 103GGC (26.0703°N, 78.05617°W), for the last 22,000 years. (d) Dust flux measured at the VM20 site (5.33°N, 33.03°W) for the last 20,000 years. (e) The Northern-Southern Hemisphere temperature difference for the last 17,000 years. The M13[22] uses temperature difference between the extratropics (90 and 30) of two hemispheres, and the S12[23] uses full hemisphere averages.

BP, when the ICAS reaches the global maximum and the ITCZ reaches the northernmost position in the records examined here. In addition to dynamics effect discussed here, the greening of the Sahara (de Menocal et al., 2000) during this period may have also contributed to the African dust minimum. Toward the end of the African Humid Period, the ICAS continues to decrease, and the ITCZ moves southward slightly while dust activity at the ODP658C and GC68 sites increases relatively abruptly. Increase of dust flux is more gradual over other sites. This geographical dependence of dust sensitivity to

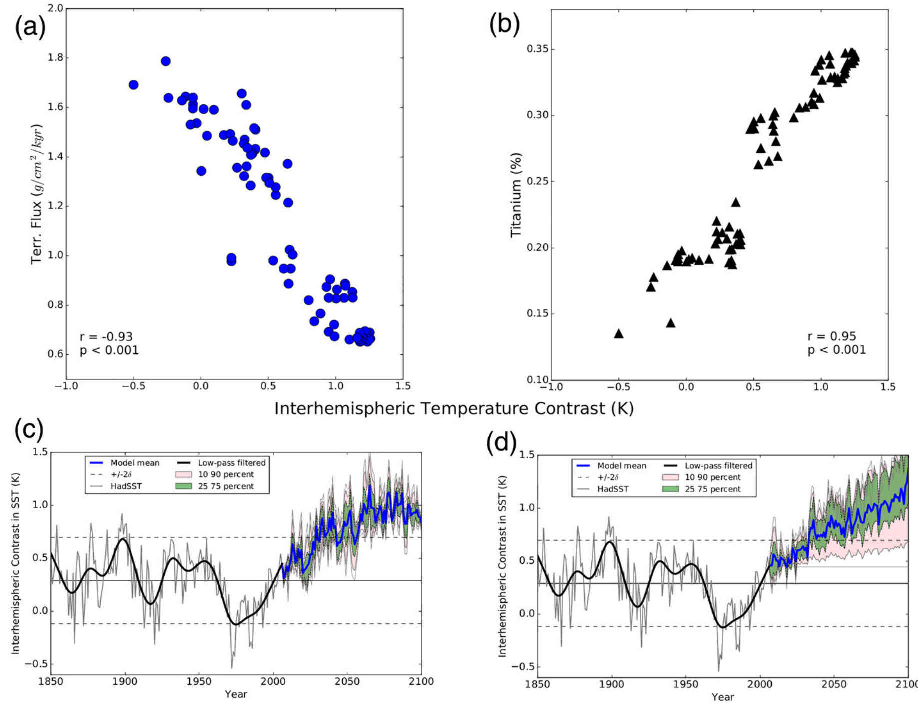

Figure 4. Scatter plot between ICAS proxy and (a) terrigenous flux at ODP658C and (b) the ITCZ position proxy for the last 11,300 years. Both correlations are statistically significant and suggest robust relationships for the last 11,300 years. Each point represents a terrigenous flux measurement and corresponding ICAS and Titanium records averaged over the same period that the dust record covers. Similar evidence is found for the period between 6,000 and 17,000 BP (SOM) (see Figure S3 for more discussions). The HadISST based ICAS splined with model simulated ICAS. The horizontal solid lines mark the mean ICAS during the last 167 years. The dashed lines are two standard deviations from the mean. Multimodel means for RCP4.5 (c) and RCP8.5 (d) are plotted using the solid blue lines. In c and d, only "good" models are used. The criteria for "good" models are given in Data and Method. The green shading marks the 25% to 75% range of the distribution among models and the pink the 10% to 90% range. Individual model results are plotted using solid gray lines.

the ICAS will be further discussed later. After this period, the ICAS gradually decreases, and the ITCZ moves southward gradually, while dust activities from all sites generally increase. During the relatively brief "Little Ice Age," the decreased ICAS and southward ITCZ shift are accompanied by an increase of dust activity at the ODP658C site and one site at the Bahamas.

Regression analyses further clarify these interpretations using two records at the African margin because they better represent African dust activities given their locations (Figure 4). During the Holocene, the ICAS proxy highly correlates with dust activities and the ITCZ position. Both the ICAS proxy and the ITCZ position proxy data are averaged to match the time resolution of ODP658C and GC68 dust records. The time resolution of the ODP658C and GC68 records varies but is on the order of a few hundred years. The ICAS proxy is strongly anticorrelated with the dust activity ($r = -0.93$, $p < 0.001$) and positively correlated with the Titanium concentration, thus the ITCZ position ($r = 0.95$, $p < 0.001$). The ICAS can explain more than 90% of the variance in African dust time series at centennial timescales. It is worth noting that there is a clear increase in the correlation coefficient values with timescale between the ICAS and dust activity (see Figures 2 and 4), reflecting the dominant role of the ICAS when high-frequency signals are averaged out. Both the ITCZ position and dust activity proxy data appear to have two regimes during the Holocene, with a separation mark at around 5,000 BP, which is most clearly indicated by a dust activity jump in Figures 3b and 3c. However, the slopes between the ICAS and the ITCZ and between the ICAS and dust activity are very similar for the two regimes, which indicates robust sensitivity of dust activity and the ITCZ position to the ICAS during the Holocene.

During the late Pleistocene, Betweenb14,700 and 17,000 years BP, the Northern Hemisphere differentially cools as the thermohaline circulation slows down (Heinrich, 1988; McManus et al., 2004), and the ICAS is

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at its minimum in our data (Figure 3f). Concurrently, three dust records are at global maxima, while the incomplete coverage during this period by the ODP658C record only shows a local maximum. Between 12,700 and 14,700 BP, the ICAS first strongly increases and then decreases before entering the Younger Dryas (Clark et al., 2012). Compared to the period between 14,700 and 17,000 years BP, dust activity generally decreases with the increasing ICAS. However, the timing and the magnitude of the decrease and recover are different among records. The record of ITCZ position starts from 14,800 BP, and it catches the decreasing period of the ICAS. The ITCZ moves southward as indicated by the decreasing Titanium concentration (Figure 3e). The general trends of ITCZ position and dust activity agree with the ICAS changes, but the timing does not agree perfectly for all records, which might be due to data timing uncertainty as discussed later and in the supporting information. The abrupt initial cooling during the Younger Dryas, around 12,700 B, in the Northern Hemisphere decreases the ICAS sharply.

While the ITCZ moves significantly southward and remains to the south during the Younger Dryas as expected (Figure 3e), the strong decrease of the ICAS is only accompanied by strong initial dust increase at the African coast sites ODP658C and GC68. At Bahamas sites that are further north (~26°N) and away from the West African Coast, dust activity decreases. We propose that the differing responses at the ODP658C and the Bahamas sites may be explained if the southward shift of the ITCZ (Figure 3e) pushes the main dust transport route southward by an extent that is large enough to cut off the dust transport to the Bahamas sites given the Bahamas sites are at the northern edge of the transported African dust plume in current climate with relatively higher ICAS (Figure S1).

Regression analysis for the period between 6,000 and 16,800 BP finds qualitatively similar relationship using the S12 ICAS proxy data, and the correlations are statistically significant (see Figure S3). However, a subset of the ICAS values has two significantly different dust activity and ITCZ position values during the Younger Dryas and Bolling-Allerod warming that are marked by abrupt changes. This creates "loop"-like features in the scatter plots (see Figure S4). We argue that slight mismatches in age determinations of dust (see discussion of dating uncertainty in the supporting information), the Titanium concentration, and temperature records during abrupt events may create the loop-like plots (Figure S5). Indeed, the loop-like features can be effectively removed by shifting the time series by 300 years (Figures S4), which is within the uncertainty of age determinations of these paleo-records (McGee et al., 2013) (also see the supporting information). With the realigning of different records, the correlations between the ICAS and dust activity and the ITCZ position are as good as those during the Holocene.

4. A Framework for Understanding and Projecting African Dust Activity

Supported by observations from both recent and distant past, our hypothesis on the interplay among the ICAS, dust activity, and the ITCZ position provides a unified large-scale framework to understand African dust variability on decadal and longer timescales. This framework provides a systematic and consistent way to understand previous studies that deal with African dust variability. For example, the reported correlation between Sahel precipitation and dust variability (Prospero & Lamb, 2003) can be understood as a direct result of the ICAS simultaneously driving changes in Sahel precipitation and dust activity (Figure 1–4). The Sahel sits on the northern edge of the ITCZ over the continent and receives its precipitation from the ITCZ excursions. Positive (negative) ICAS anomalies pull the ITCZ northward (southward) and increase (decrease) precipitation in the Sahel region (Figures 1–4). Meanwhile, positive ICAS anomalies reduce dust emission by slowing down surface wind speed (Figure 1–4), thus creating an anticorrelation between the Sahel precipitation and dust activity. This interpretation is also in accordance with multiple studies that show surface wind speed in dust source regions as the dominant factor for African dust variability in recent decades and distant past (Chin et al., 2014; McGee et al., 2010; Ridley & Heald, 2014). Our framework is also consistent with the relationship between the wintertime NAO and wintertime African dust because the NAO is closely related to the AMO and ICAS (Peings & Magnusdottir, 2014). The close relationship between the ICAS and the position of ITCZ also agree with the role of ITCZ in affecting African dust transport. It is worth noting that this framework is most applicable to decadal and longer time scales while other higher-frequency processes such as the El Nino Southern Oscillation (DeFlorio et al., 2016) may be important at interannual time scales.

The robust relationship between the ICAS and dust variability makes it a useful predictor to project long-term future of African dust in the context of anthropogenic climate change. Adopting the ICAS as a predictor has advantages over previously used variables such as the Sahel precipitation (Prospero & Lamb, 2003), the NAO (Moulin et al., 1997), and surface wind speed pattern (Evan et al., 2016). This is because simulated regional changes of these variables in general circulation models (GCMs) are highly uncertain. For example, even under similar boundary conditions and forcing, surface wind speed in the dust source region shows strikingly different changes in current GCMs (Yuan et al., 2016). Large-scale mean temperature and ICAS on the other hand can be more reliably predicted based on forcing scenarios. Assuming that the same relationship between the ICAS and dust activity operates in the future, the future of African dust may be more reliably predicted using model generated SST fields. We calculate the ICAS for a set of models participating in Phase 5 of the Coupled Model Intercomparison Project Phase 5 (CMIP5) under two forcing scenarios: Representative Concentration Pathway (RCP) 8.5 and RCP 4.5. In both scenarios, the multimodel mean of the ICAS is projected to increase significantly, pointing to a substantial reduction in African dust activity in the future (Figures 4 and S5). In particular, the multimodel mean ICAS trend predicts that the African dust activity will be two standard deviations below the mean of the past 160 years in about three and five decades for RCP 8.5 and RCP4.5 scenarios, respectively, which would cut the current dust loading over the tropical Atlantic by more than 30%. This is qualitatively consistent with future decline of African dust reported in another study (Evan et al., 2016), but with much larger magnitude. In the RCP8.5 scenario, dust activity will decrease to this level by 2050 and continue to decline as the ICAS increases due to continued preferential anthropogenic warming of the Northern Hemisphere.

Dust activity is projected to decrease to that level sooner if only models that better simulate past AMO (Martin et al., 2014) are included (see Table S1 for models). The projected reduction in African dust by the end of this century using this set of models is about twice of the all model mean (Figures 4 and S5), and African dust loading over the Tropical Atlantic will only be at 40% of its current level, about 20% of the level in the 1980s. In fact, for this set of models the multimodel mean ICAS will approach and even surpass the African Humid Period peak by the end of this century, which would imply a new global minimum of African dust activity for the last 20,000 years.

5. Discussion and Conclusion

Our results focus on understanding observed low-frequency variability of African dust on decadal or longer timescales. The ICAS appears to be increasingly important at longer timescales as suggested by the higher correlation coefficients with coarser time resolutions (Figures 2 and 4). Several separate but related questions remain open for further research. For example, what are the other factors that determine dust interannual variability since the ICAS explains only a small portion of its variance at interannual timescales (Prospero & Lamb, 2003)? How are the large-scale dynamics discussed here connected to smaller scale and short-term processes such as African easterly waves and individual dust storms (Cowie et al., 2015)? Do finer-scale spatial patterns of SST (Giannini et al., 2003) matter in addition to the areal mean used here? Other factors such as vegetation and soil properties may also play a role in determining dust variability. Modeling African dust climatology and, particularly, its variability remains challenging and highly uncertain for current climate models. Improvements to the models, especially the key surface wind speed response to the ICAS (Murphy et al., 2014; Yuan et al., 2016), are critical before they can be useful as tools to elucidate the mechanisms discussed here. In the historical period, radiative forcing induced by human activities and natural events in the past may have already affected the ICAS and thus dust activity (Murphy et al., 2017). Decadal to multidecadal natural variability such as the AMO could have affected and will continue to influence dust activity depending on its strength and phase (Yuan et al., 2016). More work is also needed to address the causes for preferential future warming of the North Atlantic SST in model projections. Finally, for the Younger Dryas and Bolling-Allerod warming periods, cross-validation effort of the age determination of different proxy records is much needed to synchronize them during abrupt changes.

Our results here also have several important implications. The strong decline of African dust due to future ICAS increase will improve air quality in downwind areas. The strong decline in African dust over the tropical North Atlantic due to future ICAS increase may constitute a positive dust feedback to the anthropogenic warming of the ICAS since dust differentially cools the tropical North Atlantic SST (Evan et al., 2009) and has minimum impact on the South Atlantic, which may further reduce the African dust loading (Yuan et al., 2016). The tropical North Atlantic SST will experience a unique additional warming due to the strong decline in dust compared to other tropical oceans, which has implications for zonal overturning circulation. The tropical Atlantic warming can have wide range of effects such as accelerating Antarctic sea ice loss (Li et al., 2014) and inducing more hurricane activity in the Atlantic basin (Zhang & Delworth, 2006). Reduced African dust emission and transport will decrease the supply of nutrients such as iron and phosphorus to ecosystems in the Atlantic Ocean and Amazon forests (Yu et al., 2015), affecting the biogeochemical cycles. Lastly, our results underscore that continued monitoring of dust activity from space for the next 30 years will be critical for detailed understanding of the African dust variability in a warming world.

Data Availability Statement

Data are available through references in the Data and Method section of the supporting information. The reanalysis data are also openly available in data producing centers.

Acknowledgments

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