LETTERS
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Influence of African dust on ocean–atmosphere variability in the tropical Atlantic

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The dominant source of coupled ocean–atmosphere variability in the tropical Atlantic is the so-called Atlantic Meridional Mode[1-3]. This mode of variability is characterized by an inter-hemispheric gradient in sea surface temperatures and by oscillations in the strength of surface winds that cross the Equator, thereby reinforcing sea surface temperature anomalies[1-4]. The Atlantic Meridional Mode is thermodynamically damped and must receive external forcing to persist as observed[3]. However, it is not known which external forcing factors have excited the Atlantic Meridional Mode in the historical record. Here we present simulations with an ocean general circulation model that is forced by a record of surface radiation from anomalous dust concentrations in the atmosphere, reconstructed from a coral proxy and satellite retrievals. We show that the Atlantic Meridional Mode is excited by variability in African dust outbreaks on interannual to decadal timescales. Our analysis indicates that sea surface temperature anomalies resulting from the aerosol direct effect persist in time through the positive ocean–atmosphere feedback[5] that defines the Atlantic Meridional Mode. We conclude that on interannual to decadal timescales, the state of the tropical Atlantic ocean is directly tied to dust emissions over West Africa, which in turn are linked to land-use change[6-8].

West Africa is the largest global source of atmospheric dust owing to an abundance of deflatable materials and strong low-level winds[9], and most dust generated in West Africa is advected over the tropical and subtropical North Atlantic[10]. Mineral aerosols have a high single-scatter albedo and over dark surfaces the scattering of sunlight dominates absorption of infrared radiation such that the net effect at the surface is a decrease in downwelling radiation[11]. To first order, such a decrease in the surface heat flux cools the ocean mixed layer[12–14], and since the mid 1980s a decrease in Atlantic dust aerosol optical depth[11,15] (DAOD; Fig. 1) has resulted in an increase in the amount of solar radiation absorbed at the ocean surface[14] and a small upward trend in tropical North Atlantic sea surface temperature[12] (SST). Between 1955 and 1985 there was a pronounced increase in DAOD over the tropical North Atlantic[7,11] (Fig. 1), which cooled SST over time[7].

To investigate the influence of dust on regional climate, we estimated the response of tropical North Atlantic SST to changes in monthly mean DAOD by forcing the Massachusetts Institute of Technology ocean general circulation model[16,17] with a dust radiative forcing climatology for the period 1955–2008 (ref. 11). The change in SST from anomalous DAOD is obtained by differencing model output from a 54-year run that is forced only by seasonally varying surface heat fluxes from reanalysis[18], and a separate run in which the monthly fluxes also include the historical contribution to

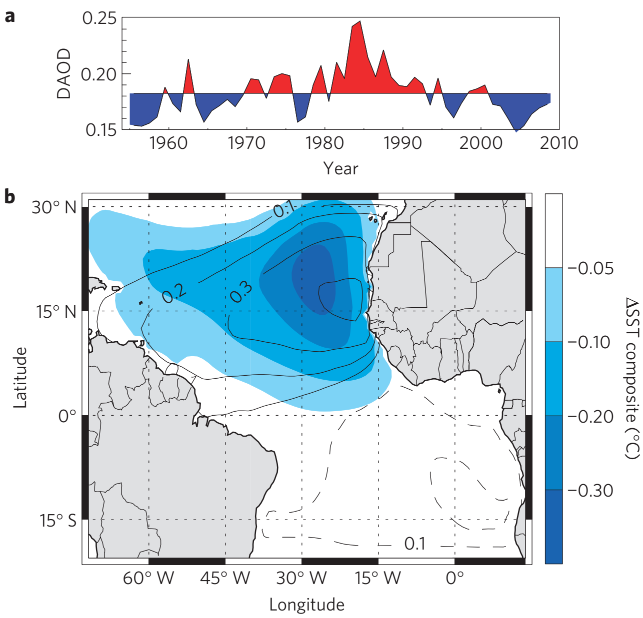

Figure 1 | Historical DAOD and the structure of the AMM and the SST response to dust variability. a, The annual time series of DAOD averaged over the region 10°–20° N and 20°–50° W (ref. 16). **b**, Contours of the spatial structure of the AMM (ref. 2), with composite differences of ΔSST for the 5 years of highest and lowest DAOD shaded, representing the structure of the sensitivity of SST to dust variability. Similarity between the structure of AMM and ΔSST indicates the projection of dust forcing onto the AMM.

the surface radiative flux by anomalous DAOD. We are estimating the effect of dust on Atlantic SST about the climatological mean state; thus, from the model, experimental periods of anomalously high dust force cool SST anomalies, whereas periods of anomalously low dust loading force warm SST anomalies (see Methods).

The spatial structure of the sensitivity of tropical Atlantic SST to changes in dust is obtained through a composite difference of modelled SST during the 5 most (1983–1988) and least (1956–1958, 2004 and 2005) dusty years (Fig. 1). The dust-forced SST (hereafter ΔSST) composite is a maximum of 0.3 °C over a broad region centred on 25° W and 20° N, decays to zero near the Equator and slightly north of 30° N, and decays along a weaker gradient to the west. The spatial structure of the ΔSST composite is very similar to that of the Atlantic Meridional Mode (AMM; Fig. 1). The AMM structure is estimated through

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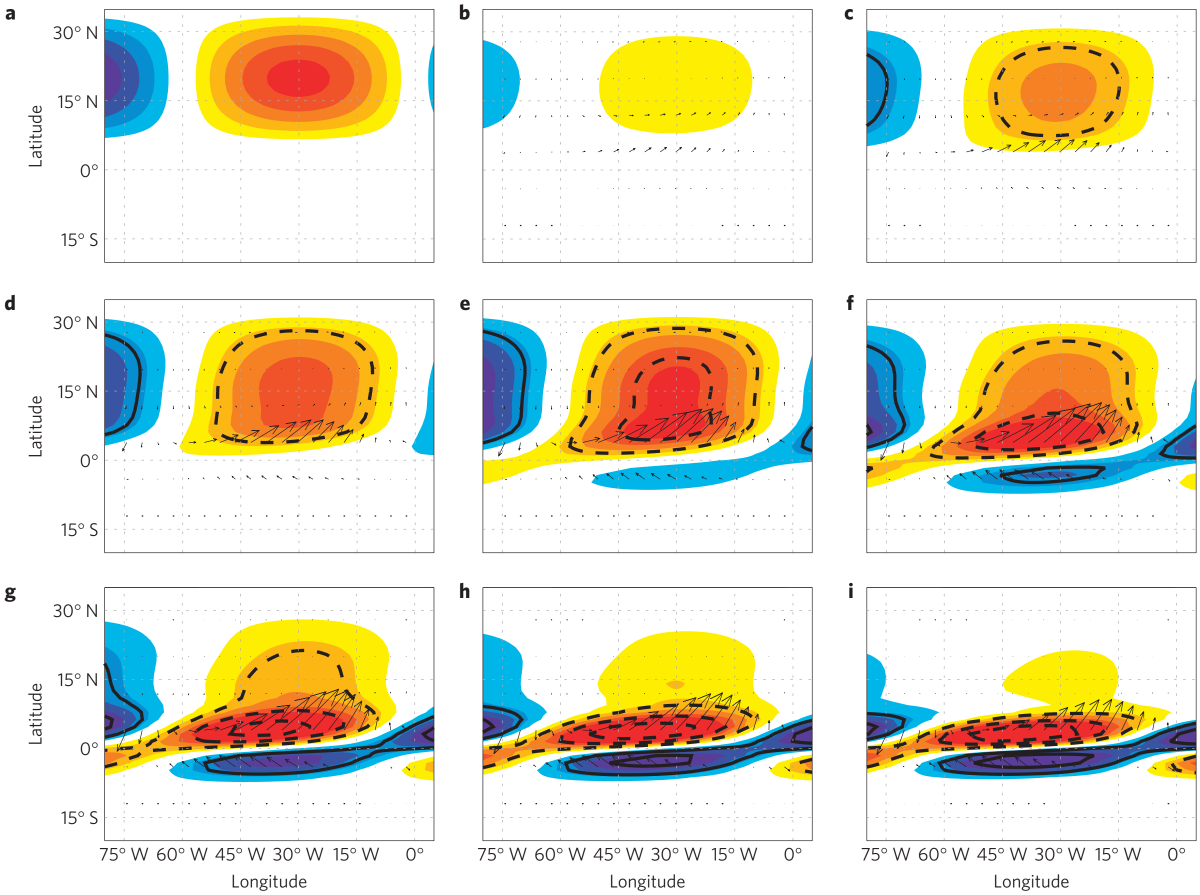

Figure 2 | Monthly mean output from idealized coupled model experiments. a, The idealized dust forcing (K d^{-1}) used to force the coupled model during the first 4 months. **b–i**, The equatorward and westward evolution of the model response in monthly mean SST (shaded), boundary layer pressure (contours) and boundary layer winds (vectors) for model months 1–8. Positive (negative) SST anomalies are shaded red (blue) and positive (negative) pressure anomalies have solid (dashed) contours, and the zero line has been omitted. Units are arbitrary but consistent throughout **b–i**.

a maximum covariance analysis of tropical Atlantic SST and 10 m winds from reanalysis over the domain 21° S–32° N and 74° W to the West African coastline[2]. The asymmetric structure of the AMM reflects the meridional gradient feature of the AMM, and the wind–evaporation–SST (WES) feedback, the destabilizing mechanism for transient growth of the AMM (refs 3,5,19). The WES feedback is the tendency of surface winds to blow from the cool to the warm hemisphere and decrease (increase) evaporation in the warm (cool) hemisphere through a net weakening (enhancement) of the climatological easterlies, thereby reinforcing the existing SST gradient[3,5].

Through the WES feedback the AMM is strongly influenced by the underlying SST. Therefore, the similarity in the spatial structures of the AMM and ΔSST indicates that dust radiative forcing may excite coupled variability of the equatorial Atlantic. To demonstrate the mechanics of such a process, we consider the coupled response to dust radiative forcing in an idealized coupled equatorial model[3]:

$$\frac{\partial}{\partial t}\begin{pmatrix} u \\ v \\ h \\ T \end{pmatrix} = \begin{pmatrix} -\epsilon_u & \beta y & -g'\partial/\partial x & \Gamma_{\mathrm{RG}}\partial/\partial x \\ -\beta y & -\epsilon_u & -g'\partial/\partial y & \Gamma_{\mathrm{RG}}\partial/\partial y \\ -H_{\mathrm{b}}\partial/\partial x & -H_{\mathrm{b}}\partial/\partial y & -\epsilon_M(y) & 0 \\ \alpha(y) & 0 & 0 & -\epsilon_T+\gamma\nabla^2 \end{pmatrix} \times \begin{pmatrix} u \\ v \\ h \\ T \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 0 \\ F_{\mathrm{dust}} \end{pmatrix} \quad (1)$$

where the left-hand side of (1) consists of the time tendencies of the zonal (u) and meridional (v) winds, perturbation boundary layer height (h) and SST (T). The right-hand side of (1) consists of the dynamical system matrix (4 × 4 matrix) and a forcing vector indicating possible SST forcing from dust (F_{dust}). The upper-left 3 × 3 matrix of the dynamical system matrix consists of the reduced gravity (g') shallow-water equations on an equatorial beta plane linearized about a state of rest[20], with linear dampening terms along the main diagonal; these represent a tropical atmospheric boundary layer of depth H_{b}. The atmospheric boundary layer is coupled to a slab ocean through SST-induced hydrostatic pressure perturbations ($\Gamma_{\mathrm{RG}}T$). The ocean is coupled to the atmosphere through the WES term (α) such that model growth occurs when u and T anomalies are in phase. T anomalies are damped through the linear and harmonic dampening term, in the lower right-hand corner of the 4 × 4 matrix. All coefficients have the same values as in ref. 3. Although it is a simplified version of the real atmosphere, the model in (1) provides a useful theoretical framework for understanding the response of the coupled tropical system to an idealized forcing.

From the unforced version of (1) the AMM emerges both as the structure exhibiting the maximum transient growth, and a steady response to 'optimal forcing' anomalies[3]. To examine the theoretical coupled response to dust-like forcing, we impose a forcing term F_{dust} in the SST tendency equation (1) with a spatial structure similar to that from our model experiment (ΔSST, Fig. 1), that is, zonal and meridional scales of 60° longitude and 30° latitude and centred at 20° N (Fig. 1); note that the model is harmonic in the zonal direction. The model is integrated forward for 1 year, forced with this idealized heating term for the first 4 months of the model integration, reflecting the typical timescale of anomalous forcing of SST by dust[11]. During the remaining 8 months, the model solution evolves through the internal coupled dynamics in the homogeneous version of (1).

During months 1–4, when the dust heating term is applied, the monthly mean maps of the coupled model SST, surface wind and boundary layer pressure fields show an equatorward and westward migration of SST anomalies outside the original forcing region, which are forced by the anomalous westerlies (easterlies) on the equatorward side of the negative (positive) geopotential anomaly that overlies the warm (cool) SST anomaly (Fig. 2). Starting in month 4 there is an SST anomaly in the Southern Hemisphere that is opposite in sign to the imposed forcing. This SST signal is the response to the anomalous cross-equatorial flow, and it continues to amplify through coupled dynamical processes for several months after the imposed forcing is turned off. At model month 8, 4 months after the imposed heating is turned off, there still exists a meridionally asymmetric SST anomaly accompanying the cross-equatorial winds, and this pattern persists through the model integration (Supplementary Fig. S5).

The similarity between the spatial structure of the AMM and ΔSST (Fig. 1) and the result from our idealized model experiments (Fig. 2) indicate that there may be a coupled equatorial response to Atlantic dust outbreaks in nature. The relative importance of such dust-forced variability on interannual to decadal timescales is ascertained by comparing the time series of the observed AMM with the component we estimate to be directly forced by dust. We recover the observed AMM time series (AMM_{obs}) by projecting maps of observed SST anomalies[21] onto the stationary spatial pattern of the AMM (Fig. 1; $AMM_{x,y}$), and normalizing to a mean of zero and standard deviation of one,

$$AMM_{obs}(t=t_0)=\frac{SST'(t=t_0)\times AMM_{x,y}}{\sigma_{AMM(t)}} \quad (2)$$

The left-hand side of (2) indicates the value of AMM_{obs} at time t_0, the prime indicates monthly anomalies of SST also at time t_0 and $\sigma_{AMM(t)}$ is the standard deviation of the product in the numerator for all t. We note that SST anomalies have been detrended and SST variability associated with the El Niño/Southern Oscillation (ENSO) has been removed by regressing out the monthly Niño 3.4 index at each point (although excluding the ENSO regression step gives a similar result). We estimate the dust-forced component of the AMM (AMM_{dust}) by calculating the magnitude of the projection of monthly mean ΔSST onto $AMM_{x,y}$,

$$AMM_{dust}(t=t_0)=\frac{\Delta SST(t=t_0)\times AMM_{x,y}}{\sigma_{AMM(t)}} \quad (3)$$

where the left-hand side of (3) indicates the value of AMM_{dust} at time t_0 and ΔSST is used in place of SST′ in (2). The normalization coefficients are the same for AMM_{obs} and AMM_{dust}; thus, the magnitudes of the two time series are comparable.

AMM_{obs} exhibits both interannual and decadal-scale variability[1,2,19], with coherent periods of positive and negative values during each decade (Fig. 3a). AMM_{dust} exhibits mostly positive values during the beginning and end of the record, and mostly negative values in the middle of the time series, consistent with historical estimates of regional dustiness[7,11,15] (Fig. 3b). AMM_{dust} anomalies are of a similar magnitude to AMM_{obs}. The range of annual mean AMM_{obs} and AMM_{dust} is 5.32 and 3.02 units of standard deviation, respectively, and the standard deviation of AMM_{dust} is 0.67 (that of AMM_{obs} is by definition unity). The

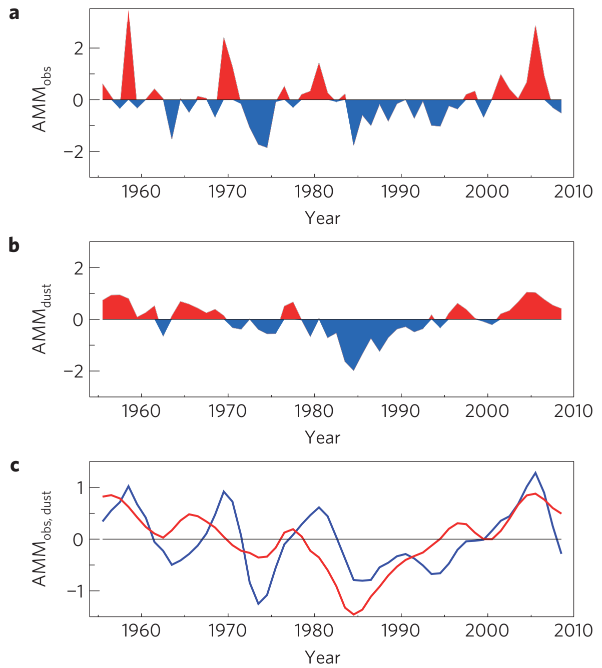

Figure 3 | Observed and dust-forced component of the AMM time series. **a–c**, The annually averaged observed AMM time series (**a**), the dust-forced component of the AMM (**b**) and the 5-year low-pass-filtered observed (blue) and dust-forced component (red) of the AMM (**c**). Both time series have the same normalization so that similarity between the observed and dust-forced AMM indicates direct forcing of the AMM by African dust outbreaks.

magnitude and standard deviation of 5-year low-pass-filtered AMM_{obs} and AMM_{dust} anomalies (Fig. 3c) are nearly equal, indicating that dust forcing is an important component of observed coupled variability on decadal timescales.

On the basis of our idealized coupled model experiments (Fig. 2) and given timescales of the WES feedback[3,5], we expect growth of a dust (radiatively)-forced AMM anomaly over a finite period. SST forcing by dust should excite a zonal wind anomaly that reinforces and grows the initial radiatively forced anomaly. The cross-correlation function of the unfiltered and 5-year low-pass-filtered AMM_{obs} and AMM_{dust} is a maximum (0.34 and 0.57, respectively) when the dust-forced component leads the AMM by 2 years, both statistically significant at the 95% level on the basis of a 1,000-sample permutation test (Supplementary Fig. S6). The positive correlation when AMM_{dust} leads AMM_{obs} indicates that the integrated effects of anomalous dust surface radiative forcing and the WES feedback conspire to amplify the response of the coupled mode to anomalous DAOD.

Historical variability of the AMM may have been externally forced by the North Atlantic Oscillation and ENSO (ref. 22), and the Atlantic Multidecadal Oscillation[23], or it may have emerged from random variability[1]. Historical dust emission is a function of surface processes and local to synoptic-scale meteorological conditions[7,9,10,15], and transport is related to the phase of the North Atlantic Oscillation[24] and ENSO (ref. 25). We suggest that dust variability contributes to observed AMM variability through the coupled mechanisms described here. Our finding that solar radiation forces a significant portion of the observed tropical Atlantic SST variability is consistent with a tropical Atlantic surface heat budget analysis[26] and additional model experiments examining the relative contributions of latent heat and solar radiation fluxes to long-term variability of the AMM (see Supplementary Information).

As tropical Atlantic environmental conditions are more favourable for hurricane genesis and intensification when the AMM is in a positive phase[23,27], the negative correlation between Atlantic dustiness and hurricane activity[28,29] may be the result of forcing of the AMM by anomalous dust outbreaks. In addition, anthropogenic land use has played a role in augmenting African dust emissions, although by what amount is uncertain[6–8]. Thus, human activity is already altering regional climate through the dust–ocean–atmosphere interactions shown here. Furthermore, in the future, carbon dioxide fertilization may lead to shrinking desert areas and a decrease in African dust outbreaks[6], and therefore more favourable conditions for hurricanes to form and intensify through anomalous dust forcing of the AMM.

Methods

The dust climatology[11] is based on a reconstructed time series of DAOD over Cape Verde that uses a coral proxy record (1955–1994) and satellite retrievals (1982–2008). African dust outbreaks are advected over the Atlantic at the latitude of Cape Verde throughout the year[10], and therefore DAOD over the tropical North Atlantic is well correlated to dust at Cape Verde[11]. In addition, a comparison of the dust time series used here with a slightly shorter series made from *in situ* measurements at Barbados[15] shows good agreement on interannual to decadal timescales (Supplementary Fig. S1). Further details regarding the forcing and DAOD climatology are given in ref. 11. A global version of the Massachusetts Institute of Technology Ocean general circulation model[16,17] is spun up to a steady state with climatological monthly surface horizontal momentum fluxes and surface heat fluxes calculated offline using the National Centers for Environmental Protection Reanalysis[18]. We carried out two separate model runs, each initialized from a 150-year spinup. For the control run, we continue forward the climatology forcing for an additional 54 years; for the perturbation run, we subtract from the surface heat flux climatology the monthly mean contribution from anomalous dust variability. The dust contribution to the surface heat flux is defined as the monthly dust aerosol direct effect at the surface minus the annual cycle. The difference between the control and perturbation runs is considered to be the effect of departures in dustiness from the seasonal mean. Further details on the model configuration are given in the Supplementary Information.

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Author contributions

A.T.E. and D.J.V. designed and carried out the model experiments; A.T.E., G.R.F., D.J.V. and D.Z. analysed and interpreted the model output and co-wrote the paper.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.T.E.