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Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability

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Systematic climate shifts have been linked to multidecadal variability in observed sea surface temperatures in the North Atlantic Ocean[1]. These links are extensive, influencing a range of climate processes such as hurricane activity[2] and African Sahel[3–5] and Amazonian[5] droughts. The variability is distinct from historical global-mean temperature changes and is commonly attributed to natural ocean oscillations[6–10]. A number of studies have provided evidence that aerosols can influence long-term changes in sea surface temperatures[11,12], but climate models have so far failed to reproduce these interactions[6,9] and the role of aerosols in decadal variability remains unclear. Here we use a state-of-the-art Earth system climate model to show that aerosol emissions and periods of volcanic activity explain 76 per cent of the simulated multidecadal variance in detrended 1860–2005 North Atlantic sea surface temperatures. After 1950, simulated variability is within observational estimates; our estimates for 1910–1940 capture twice the warming of previous generation models but do not explain the entire observed trend. Other processes, such as ocean circulation, may also have contributed to variability in the early twentieth century. Mechanistically, we find that inclusion of aerosol–cloud microphysical effects, which were included in few previous multimodel ensembles, dominates the magnitude (80 per cent) and the spatial pattern of the total surface aerosol forcing in the North Atlantic. Our findings suggest that anthropogenic aerosol emissions influenced a range of societally important historical climate events such as peaks in hurricane activity and Sahel drought. Decadal-scale model predictions of regional Atlantic climate will probably be improved by incorporating aerosol–cloud microphysical interactions and estimates of future concentrations of aerosols, emissions of which are directly addressable by policy actions.

An understanding of North Atlantic sea surface temperature (NASST) variability is critical to society because historical Atlantic temperature changes are strongly linked to the climate, and its impacts, in neighbouring continental regions. For example, strong links between NASST variability and periods of African Sahel drought are found in observations[4,13] and physical climate models[3,5,14]. Similar covariation between NASSTs and rainfall in eastern South America has been found[5], as have links to changes in both mean rainfall[15] and rainfall extremes[16], Atlantic hurricane activity[2,10,14] and European summer climate[8]. These changes are not solely limited to the regions bordering the Atlantic, but also have links to Indian monsoon rainfall[14], Arctic and Antarctic temperatures[17], Hadley circulation[1], El Niño/Southern Oscillation[18] and relationships between El Niño/Southern Oscillation and the Asian monsoon[19].

A link between multidecadal variability in NASST and circulation changes internal to the ocean was first proposed in 1964 (ref. 20) and later named the Atlantic Multidecadal Oscillation[21]. This variability is often characterized as the detrended NASST between the equator and latitude 60° N (longitude 7.5–75° W; ref. 8). Although it has recently been questioned[22], the present consensus remains that most of the observed Atlantic temperature variations occur in response to the ocean's internal variability. This picture emerged from general circulation models, a number of which inherently produce multidecadal Atlantic variability in the absence of external climate forcing[7] and, when considered together as a multimodel mean, have shown little evidence of forced changes projecting onto the NASSTs[6,9]. Observationally, this interpretation has been accepted because the Atlantic temperature changes seem to be oscillatory, both around any secular long-term trend and when calculated as anomalies from the global-mean change.

Motivated by the recent identification of the importance of aerosol process complexity in interhemispheric Atlantic temperature changes[23], apparent aerosol correlation[1,11] and volcanic modulation of Atlantic variability[22], we use new general circulation model simulations to question whether the CMIP3 (Climate Model Intercomparison Project phase 3) models contained the complexity necessary to represent a forced Atlantic Multidecadal Oscillation[7,9]. We use HadGEM2-ES (the Hadley Centre Global Environmental Model version 2 Earth System configuration[24]), a next-generation CMIP5 (Climate Model Intercomparison Project phase 5) model, which represents a wider range of Earth system processes (in particular aerosol interactions[25]) than do CMIP3 models.

To separate internal variability from forced changes, we present climate model ensemble-mean NASSTs, averaged over parallel model simulations started from different initial conditions[26]. If external forcing dominates the NASST evolution then ensemble members will evolve in phase and thus combine to produce a robust ensemble-mean response. If internal ocean dynamics dominate then each member will evolve separately and the resulting ensemble mean will show little residual variation around the underlying warming trend. This approach allows identification of physical mechanisms linking forced changes to Atlantic temperatures and was used in previous CMIP3 studies[6,9].

In Fig. 1a, we reproduce the multimodel-mean NASST response of the six CMIP3 models used in ref. 9 (ENS1, blue) and the eleven models used in ref. 6 (ENS2, green) (Supplementary Table 2). The observations (Fig. 1) show marked multidecadal variations. The multimodel-mean responses in both ENS1 and ENS2 do capture the underlying trend through the century; they capture only weak multidecadal variability. For example, the ensembles' 1950–1975 cooling is only a small fraction of the observed value (Fig. 1a and Supplementary Fig. 4). Therefore, the unexplained multidecadal signal was previously attributed to internal ocean variability[6,9].

By contrast, HadGEM2-ES (Fig. 1b) reproduces much more of the observed NASST variability (correlation, 0.65; 75% of detrended standard deviation (smoothed over 10-yr intervals to highlight multidecadal component)). The post-1950s cooling and subsequent warming now falls within the observed trends (Supplementary Table 1). Observed warming in the earlier period (1910–1940) is larger than simulated by HadGEM2-ES (Fig. 1b and Supplementary Table 1); however, these new simulations capture roughly twice the early-twentieth-century warming of previous CMIP3 generation models.

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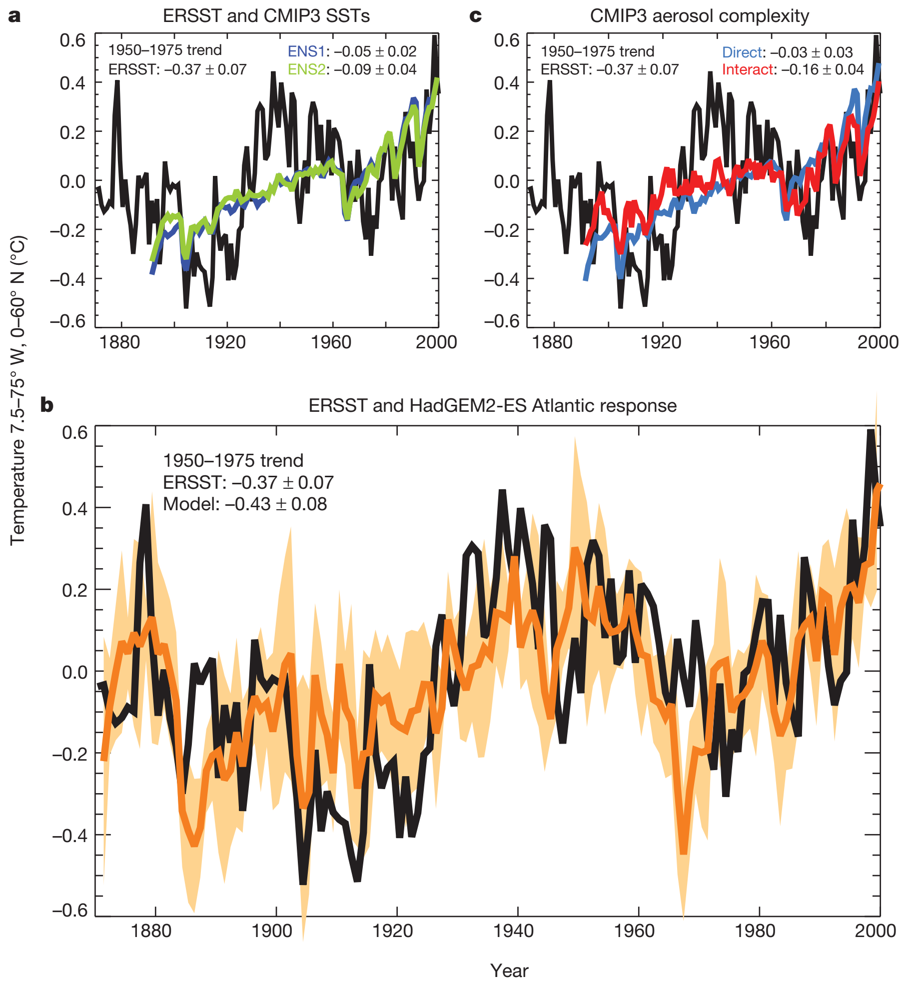

Figure 1 | Atlantic surface temperatures. Comparison of the area-averaged North Atlantic SSTs (defined as 7.5–75° W and 0–60° N), relative to the 1901–1999 average, of an observational estimate (the US National Oceanic and Atmospheric Administration's Extended Reconstructed SST[27] (ERSST), black) and two published[6,9] CMIP3 model composites (ENS1, blue; ENS2, green; **a**); the HadGEM2-ES model (orange; shading represents 1 s.d. of the model ensemble spread; **b**); and two recomposites from CMIP3, the first with models that represent only direct aerosol (mean of five contributing models, red) and the second with models representing both indirect effects interactively (three models, blue) (**c**). In all panels, trends between 1950–1975 (K per decade) are shown. The error estimates are based on the s.d. of the 25 trends between a 5-yr period (1948–1952) at the start of this interval and a 5-yr period (1973–1977) at the end. All data have been latitude-weighted when calculating area averages.

This points to a larger forced role in this period. Other processes not represented by our ensemble-mean response (such as ocean dynamical changes) may also contribute to this early trend.

In examining why the HadGEM2-ES ensemble reproduces the observed NASST variability better than previous multimodel studies have done[6,9] (Fig. 1a, b), we can discount the possibility that the HadGEM2-ES variability is predetermined, because the initial conditions were selected to sample different phases of Atlantic variability[26]. Furthermore, an additional HadGEM2-ES ensemble that omits changes in aerosol emissions neither has the same multidecadal variability as the all-forcings ensemble nor reproduces the observed NASSTs (Fig. 2a).

Replication of a large fraction of the observed NASST variability by HadGEM2-ES allows us to identify forcings and mechanisms, consistent with the observed variability, within the model framework. Variability of ensemble-mean NASST from historical simulations including time-varying aerosol emissions is strongly correlated with variability in simulated net surface shortwave radiation (Fig. 2b), which in turn has the same temporal structure as variability in aerosol optical depth changes (Fig. 2c) and periods of volcanic activity (Fig. 2d). Other terms in the surface heat budget (Supplementary Fig. 2) have a role in the simulated NASST change. However, it is the surface shortwave component that produces the dominant multidecadal variations. Volcanoes and aerosols respectively explain 23 and 66% of the temporal (10-yr-smoothed) multidecadal variability of the detrended NASST (Supplementary Fig. 5). Combining both contributions explains 76% (80% after inclusion of mineral dust aerosols) of the simulated variance. Inclusion of mineral dust processes may potentially be important because emissions are known to respond to North-Atlantic-driven changes in Sahel rainfall, and thus represent an important positive feedback on NASSTs in the real world[12]. The lack of a multidecadal dust signal (Supplementary Information) in HadGEM2-ES simulations suggests that we are likely to be underestimating the magnitude of the forced Atlantic response.

The volcanic influence on Atlantic variability has been demonstrated previously[12,22]. We focus on the anthropogenic aerosol component of the shortwave changes identified here as driving the model's multidecadal NASST variability. Aerosol concentration changes influence the spatial response (Fig. 3) of NASST as well as its temporal evolution. Prevailing winds advect aerosols emitted in industrial North America in a band across the North Atlantic that mixes with polluted air masses over Europe before being transported by trade winds south and west. The large-scale pattern of shortwave change is explained by the effect of cloud microphysical response to these changes in aerosol concentration. The shortwave variability largely occurs where aerosol changes coincide with large-scale cloud distribution. On a regional

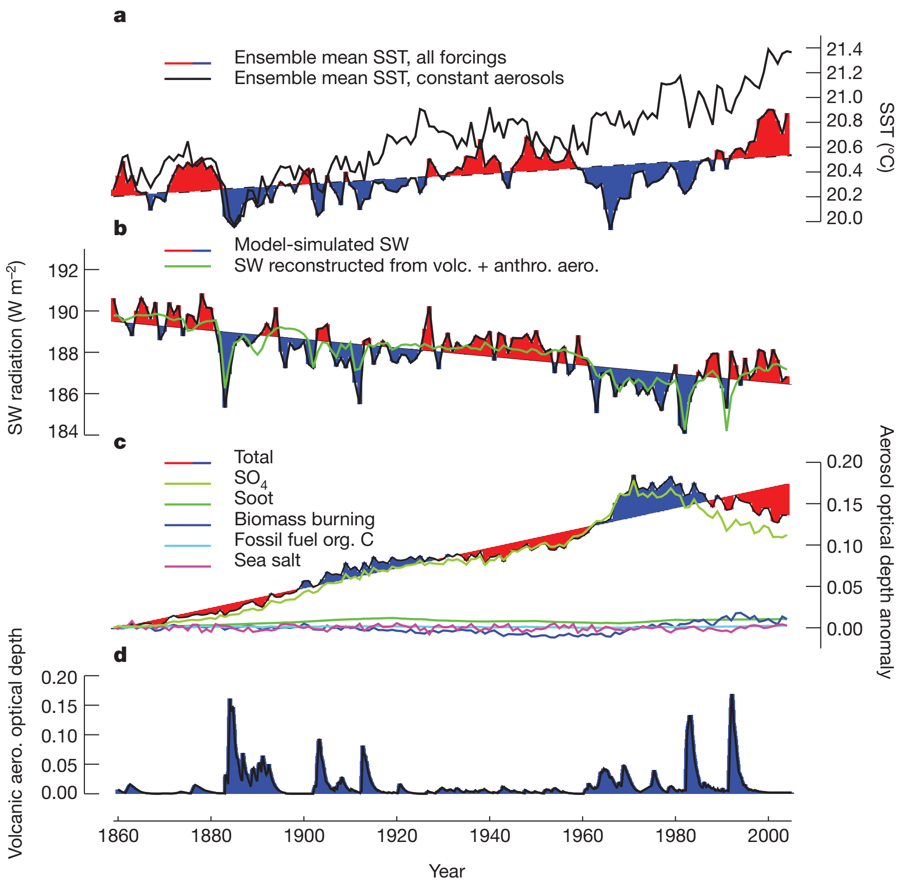

Figure 2 | External forcing of surface temperature and surface shortwave radiation linked to aerosol and volcanic changes. **a**, Ensemble-mean NASST (7.5–75° W and 0–60° N) simulated by the HadGEM2-ES model considering all available external climate forcings (red/blue), and all forcings except anthropogenic aerosol emissions (black). **b**, Ensemble-mean shortwave (SW) radiation entering ocean (red/blue) alongside reconstruction of this shortwave radiation based on a linear relationship with total anthropogenic aerosol and volcanic optical depth changes (green). The linear model explains 79% of the simulated variance. **c**, Change in total (red/blue shading) and individual species (coloured lines) of anthropogenic aerosol optical depth (degree of absorption/scattering) over the North Atlantic. **d**, Volcanic optical depth from ref. 30 as implemented in HadGEM2-ES simulations. In **a**–**c**, red and blue shading represents values above or below (or vice versa) a least-squares linear fit to the data.

scale, coupled processes, such as temperature feedbacks, can lead to an enhanced local response (Supplementary Information). The same horseshoe-shaped signature is seen in shortwave and NASST variability (Fig. 3). The map of NASST change between warm and cold phases of multidecadal variability is consistent with the observed variations in SSTs (Fig. 3).

So far consistent spatial and temporal changes between aerosol burden, shortwave and NASST have been presented. It is not clear, however, whether these changes are externally forced by aerosols or are mediated by ocean circulation. Here we present a parallel simulation of the historical period, driven by identical emission and concentration changes, but with the SSTs explicitly fixed at their 1860 climatological values. The shortwave changes arising in this parallel experiment share the temporal structure and magnitude of the shortwave changes from our standard historical simulations (Fig. 4a). By explicitly removing any feedback from SST change on shortwave, we demonstrate that simulated historical shortwave variability arises directly from aerosol and volcanic forcing of the surface radiation and is not mediated by ocean circulation change.

One of the reasons why the role of aerosols in driving multidecadal variability has not previously been identified is the level of aerosol physics represented in climate models at the time of the CMIP3 multi-model comparison project (Supplementary Table 2). Although all the CMIP3 models represented the direct effect of aerosols on shortwave radiation, most omitted or only partly represented the indirect aerosol effects[23].

Recently, albedo differences in CMIP3 aerosol representation have been shown to be important for simulating SST changes[23]: models that represent indirect aerosol effects capture more of the observed Atlantic interhemispheric change than those that do not. Recompositing the models used in Fig. 1a into those with only direct aerosols effects, and those that also include the first indirect effect interactively, shows some evidence of multidecadal variability (Fig. 1c), illustrating that aerosol–cloud microphysical processes have a role even in previous-generation models. These models do not, however, reproduce the magnitude of the multidecadal NASST of HadGEM2-ES.

In HadGEM2-ES, the aerosol indirect effects account for 80% or more of the total aerosol forcing in the North Atlantic region (Fig. 4b and Supplementary Fig. 1). Although there is some discussion of the magnitude of the indirect effects[28,29], omission of these processes will lead to an underestimation of the modelled aerosol impact on the NASST. Looking at the relative roles of the first and second indirect effects (using changes in optical depth and cloud effective radius as respective metrics for these effects; Fig. 4c), we see a more pronounced response to early-twentieth-century variations for the indirect effect (effective radius) due to higher sensitivity of cloud albedo changes to changes in aerosol number in cleaner conditions[3]. In all, the inclusion of aerosol indirect effects in HadGEM2-ES magnifies the shortwave and, hence, the NASST response to aerosols, as well as influencing the spatial and temporal character of the historical multidecadal variability. We also note that although some climate models (such as HadGEM2-ES) reproduce the observed sensitivity of cloud albedo to changes in

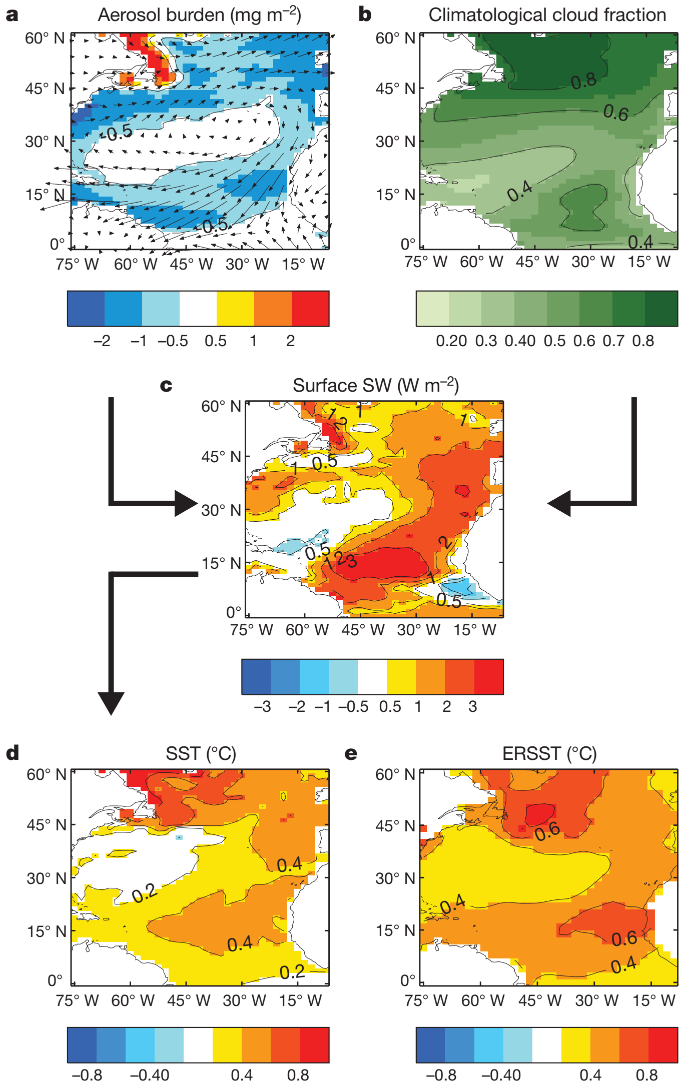

Figure 3 | Differences in spatial response between warm and cold Atlantic phases. Differences between the average of warm years (warmest third of the data) and the average of cold years (coldest third of the data), after the data has been detrended, show how patterns of multidecadal variability in aerosol burden (**a**) interact with the climatological cloud field (**b**) to influence the pattern of net surface shortwave radiation change (**c**) and, hence, NASSTs (**d**). The pattern of aerosol burden changes is linked to emissions in industrial North America and Europe by the climatological wind field (the direction and magnitude of which is indicated by the arrows). The exception is the localized increase in aerosol burden (Canadian coast) driven by increases in sea salt aerosols (warm years reduce sea ice extent in this area). The warm phase/cold phase SST pattern simulated by the model (**d**) agrees well with the observed change (**e**). Vertical axes show latitude; horizontal axes show longitude.

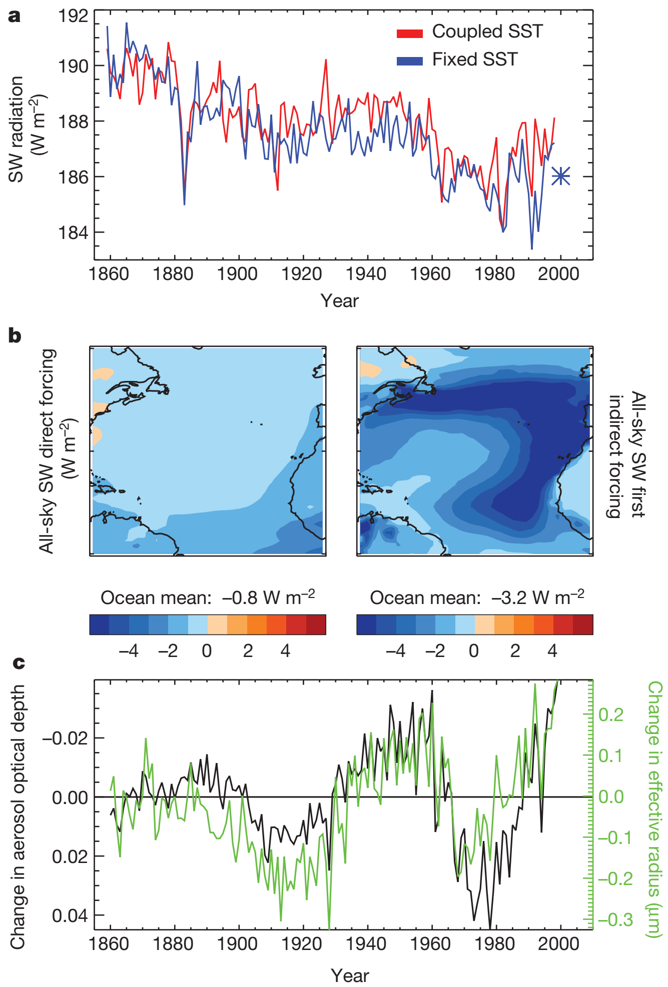

Figure 4 | Magnitude and origin of forced changes in net surface shortwave radiation. **a**, Ensemble-mean time evolution of surface shortwave in the North Atlantic region (red; see also Fig. 2b) and the surface shortwave from a parallel simulation in which the SSTs were held fixed at climatological values from 1860 (blue). The comparison shows that these shortwave changes are externally forced. These long-term trends in surface shortwave match the changes observed in a snapshot experiment (2000 aerosol emissions, 1860 SSTs; blue asterisk), indicating that the underlying trend is consistent with that expected from aerosol changes alone. **b**, Spatial patterns of surface shortwave forcing arising from the 2000 direct effect (left) and the first indirect effect (right) of aerosols (Supplementary Information), which illustrate the dominant role of indirect effects in the total forcing and the spatial distribution. **c**, Detrended time series of aerosol optical depth (black) and cloud-top effective radius (green) from the coupled simulations, which are indicators of the temporal evolution of direct and, respectively, indirect effects. Although the variations in effective radius are largely in phase with those in optical depth, there is greater divergence (implying a larger role for indirect effects) in the early historical period.

aerosol optical depth in maritime regions, not all parameterizations of aerosol indirect effects do so (Fig. 2e in ref. 29).

We have shown that volcanic and aerosol processes can drive pronounced multidecadal variability in historical NASST, which leads to improved (for the early twentieth century) or reproduces (for the later period) the observed historical trends. In these simulations, it is the inclusion of aerosol indirect effects that allows us to capture the magnitude and the temporal and spatial structure of SST variability. Our results show that volcanoes and, crucially (from a policy and climate impact perspective), anthropogenic emissions of aerosols can drive NASST variability resembling that which is observed. This work suggests that we need to reassess the current attribution to natural ocean variability of a number of prominent past climate impacts linked to NASSTs, such as Sahel drought.

METHODS SUMMARY

The climate model used in this study is HadGEM2-ES[24]. This model is notable for the number of climate–biogeochemical interactions that are interactively calculated rather than specified in advance. Of relevance to this work, HadGEM2-ES models the supply of oxidants, an important component for aerosol formation, and mineral dust aerosols interactively, and yields improved predictions of biomass and carboniferous aerosol properties. Source terms for natural aerosols (or precursors) and mineral dust are also modelled interactively. Each simulation in the ensemble is forced with driving data (greenhouse gases, aerosols, volcanoes, land use and solar changes) based on historical data sets compiled for CMIP5 simulations. These data sets and their implementation within this model are extensively documented in ref. 26. Volcanic forcing is prescribed in latitudinal bands. Over the North Atlantic, the magnitude of optical depth changes are prescribed individually for the bands spanning 0–30° N and 30–90° N, capturing the differences between tropical and extratropical volcanoes. Individual members of the ensemble were initiated from a control simulation using start points located 50 yr apart[26].

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions B.B.B.B., N.J.D. and P.R.H. jointly led the analysis, produced figures and wrote the paper. T.A. and N.B. contributed additional experiments to diagnose different aspects of the aerosol forcing, provided technical and scientific insight and commented on the manuscript.

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METHODS

The central finding of this paper (that changes in volcanic and aerosol forcing are capable of driving variability in NASSTs much like that observed) is based on an ensemble of four HadGEM2-ES historical simulations (Methods Summary). The following parallel simulations were also used.

- An ensemble of three HadGEM2-ES simulations (parallel to the first three members of the all-forcings ensemble) with no changes in aerosol emissions. Results of this experiment are shown in Fig. 2 and Supplementary Fig. 2. These simulations used identical driving data to the standard historical ensemble, prescribing changes in emissions and concentrations based on the CMIP5 historical data sets. The exception is the anthropogenic aerosol emissions, which (along with the surface chemistry and consequent contribution to aerosol oxidation) were kept constant at their 1860 values. This ensemble provides a comparison with historical NASSTs where the historical changes in aerosol emissions did not take place.
- A parallel historical simulation of HadGEM2-ES in which the annual cycle of global SSTs are held at 1860 values, as calculated from the pre-industrial control simulation. Results of this experiment are shown in Fig. 4. This simulation used identical driving data to the standard historical ensemble and is designed to characterize the evolving nature of the historical forcings. Radiative forcing is the impact on the radiative balance resulting from a change or changes in the atmospheric constituents, or other external change (such as solar), before any SST-driven feedback on that change. This parallel run with fixed SSTs provides information on the shortwave changes (or the changes in any other radiative component) due directly to changes in atmospheric concentrations, explicitly removing any contribution arising from SST-driven feedbacks.
- As a companion experiment to the fixed-SST historical simulation (described above), snapshot experiments were carried out to assess the impact of aerosol changes alone between the beginning and end of this simulation. This set-up used SSTs, and all forcings other than anthropogenic aerosol emissions, held at their 1860 values. Anthropogenic aerosol emissions were set to either their 2000 or 1860 values. The comparison of the two allows an estimate to be made of the radiative changes (including shortwave) between 1860 and 2000, rather than, for example, as a feedback to the warming SSTs. The result of this experiment is shown in Fig. 4 alongside the fixed-SST historical simulation (in which other atmospheric consistent also varied).
- Three snapshot experiments in which the model code calculating the instantaneous radiation balance was run twice at each forward step of the model—once with the relevant aerosol process included and one without—to quantify separately the radiative impact of the direct and the first indirect effects of aerosols. The three snapshot experiments used aerosol emissions from 1950, 1980 and 2000 and calculated the surface shortwave radiative impact (forcing) of aerosols in those three years. These are presented in Supplementary Fig. 1 and the 2000 snapshot is included in Fig. 4. The value of these runs is that they allow the radiative impacts of these two aerosol effects to be compared

The HadGEM2-ES model, like others before it[9], captures SST variability in simulations unforced by external factors (fig. 20 in ref. 25), which, in unforced pre-industrial simulations, are strongly correlated with variability in Atlantic meridional overturning circulation (0.65, using 10-yr smoothing). However, variations in circulation are less important in the ensemble-mean variability of the historical simulations, where shortwave forcing dominates. This is discussed further in the section on shortwave changes and the surface heat budget in Supplementary Information.

ERRATUM

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The accepted date should read 08 February 2012, rather than 2011. This error has been corrected in the PDF and HTML versions online.