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Sensitivity of the Tropical Dust Cycle to Glacial Abrupt Climate Changes

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Key Points:

- Freshwater hosing forcing increases tropical dust loading in Earth System model simulations of the last glacial maximum
- Simulated response is non-linear with forcing in some regions, particularly North Africa
- Weaker events improve agreement with data and emitted dust produces a self-amplifying feedback

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract During abrupt climate changes of the last glacial period paleorecords show large amplitude changes in the dust cycle. We use Earth System model simulations to evaluate processes operating across these events. Idealized Heinrich stadial-like simulations show a southwards migration of tropical rainfall that dries the Sahel and reduces wet deposition causing a widespread enhancement of tropical dust loading. However, several discrepancies with marine core dust deposition reconstructions are evident. Simulations with a more limited freshwater forcing (0.4 Sv instead of 1.0 Sv) and weaker cooling over the North Atlantic (less than 3°C) show a switch in sign of the stadial dust deposition anomaly in several regions, improving agreement with paleorecords. The simulated dust cycle therefore displays in places a non-linear response to abrupt change. The global-mean stadial dust radiative forcing in the more realistic simulations is around −0.2 to −0.6 W m^{-2} and so could represent an amplifying feedback during these events.

Plain Language Summary Mineral dust in the atmosphere is mostly sourced from arid regions like the Sahara desert. The amount and geographical spread of this dust in the atmosphere is sensitive to environmental conditions such as drought. Paleoclimate records show that rapid cooling events centered on the North Atlantic during the last ice-age also saw large increases in the rate of dust deposited over the ocean. Earth System models are a computational tool that can be used to understand the links between climate and the dust cycle. Using a series of such simulations we found that abrupt cooling events in the North Atlantic can lead to a massive increase in dust over the equatorial (tropical) regions. However, the model's response is in many places non-linear, meaning that the change in dust is very sensitive to the magnitude of the climate changes occurring. This non-linearity is mostly due to interactions between changes in the water cycle and the dust. We show that a less severe cooling produces a more realistic dust response when evaluated against paleo-dust records. Since dust scatters incoming sunlight, increased atmospheric dust during these events may have amplified and even extended the cold phases.

1. Introduction

Abrupt climate change events of the last glacial period are among the most striking climate events in the geological record. Much focus has been on Greenland (Dansgaard et al., 1993), where recurrent warming events called Dansgaard-Oeschger (D-O) events of around 5°C–16.5°C occurred in a few decades or less (Kindler et al., 2014) and all major chemical records including dust show approximately synchronous abrupt changes (Wolff et al., 2010). The abrupt D-O warming phases are followed by a gradual cooling with a return to stadial conditions. Paleoclimate records from across the northern hemisphere show coincident abrupt events (Deplazes et al., 2013; Gibson & Peterson, 2014; Peterson et al., 2000; Y. Wang et al., 2001; X. Wang et al., 2017). Some of the stadials are characterized by the occurrence of massive ice-rafted debris layers in high- to mid-latitude Atlantic sediment. These are called Heinrich stadials (HS). Particularly large re-organizations of the hydrological cycle are associated with HS phases (Stager et al., 2011) including southward shifts in the tropical rainbelts (e.g., Deplazes et al., 2013; Peck et al., 2004; Schulz et al., 1998; Shanahan et al., 2015; Tierney & de Menocal, 2013; Y. Wang et al., 2001; X. Wang et al., 2017).

The iconic record of rapid dust fluctuations over Greenland shows variations of several orders of magnitude during D-O events (Fischer et al., 2007) but less so during HS. In the tropics dust deposited during the late-glacial

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also varied abruptly as recorded in marine sediment cores (e.g., J. Collins et al., 2013; Kienast et al., 2013; Kinsley et al., 2022; Loveley et al., 2017; Marcantonio et al., 2020; McGee et al., 2013; Middleton et al., 2018; Safaierad et al., 2020)—presumably in response to these rapid climate fluctuations. Although it is difficult to reconstruct dust fluxes this far back in time at sufficient temporal resolution to analyze abrupt changes, marine sediment records do show a relatively coherent signal of a dustier tropical Atlantic (Kinsley et al., 2022; McGee et al., 2013; Middleton et al., 2018), with up to doubling of dust deposition rates during HS 1 but with much smaller signals during D-O warming events (Kinsley et al., 2022; McGee et al., 2013). Elsewhere there are abrupt changes in the Eastern Pacific (Loveley et al., 2017; Marcantonio et al., 2020), the middle-East (Safaierad et al., 2020) and the Arabian Sea (Pourmand et al., 2007) associated with HS.

While some previous model simulations have focused on understanding the abrupt dust variations over Greenland (Tegen & Rind, 2000) or Europe (Sima et al., 2009, 2013), few modeling studies have examined the dust response to these events over the tropics (Murphy et al., 2014). Here we investigate the role of mineral dust aerosols in HS climate phases using a suite of Earth System (ES) model simulations. We focus on the tropics and North Africa because the Sahara is today the largest single source of atmospheric aerosols (e.g., Knippertz & Todd, 2012) and because it is known that the desert expanded significantly during glacial times and stadials (J. Collins et al., 2013). The Sahara is also adjacent to the Atlantic Ocean which is a critical region for understanding abrupt climate change (Clement & Peterson, 2008; Roberts & Hopcroft, 2020). We evaluate whether the model can reconstruct the processes that caused these rapid changes with a new compilation of HS1 dust deposition records. We also quantify dust radiative forcing (RF) and hence the potential for dust to act as a feedback.

2. Methods

We use an ES model to simulate the response of the mineral dust cycle during abrupt reductions in the Atlantic Meridional Overturning Circulation (AMOC) under a last glacial maximum (LGM) climate state (e.g., Kageyama et al., 2013). We focus on the onset of HS 1, a period of ice-rafted debris which occurred just after the LGM at 18.0 kyr BP (18 thousand years before present) and which is thought to have been characterized by a strong weakening to almost shutdown of the AMOC caused by an abrupt influx of meltwater to the North Atlantic Ocean (Clement & Peterson, 2008; Lynch-Stieglitz, 2017). We also present a compilation of marine sediment core records and compare them with the suite of model simulations to assess their quality.

2.1. Earth System Model Simulations

To simulate the global dust cycle we use the HadGEM2-ES model (W. Collins et al., 2011; HadGEM2 Development Team, 2011) in an atmosphere-only formulation. The atmosphere/land component of HadGEM2-ES has a resolution of $1.875° \times 1.25°$ (longitude-latitude) with 38 unequally spaced levels vertically in the atmosphere (HadGEM2 Development Team, 2011). HadGEM2-ES has been widely used for simulating past (Hopcroft & Valdes, 2019; Tindall & Haywood, 2020), historical (Booth et al., 2012) and future climate (Caesar et al., 2013). In HadGEM2-ES the mineral dust cycle is coupled with the atmosphere and interactive vegetation (Bellouin et al., 2011; Woodward, 2011). Emissions are calculated as a function of dynamically determined bare soil area, soil moisture and wind speed. Emissions and atmospheric transport are calculated for six size bins which have radii of 0.0316–31.6 μm, with bin boundaries at 0.1, 0.316, 1.0, 3.16, and 10.0 μm. Dry and wet deposition are considered separately but direct dust-cloud interactions are not represented. Both pre-industrial and present-day simulations of mineral dust with HadGEM2-ES have been evaluated in previous studies (Bellouin et al., 2011; Fiedler et al., 2016; Hopcroft et al., 2015).

The LGM simulation with HadGEM2-ES has been described before (Hopcroft et al., 2015, 2017). The boundary conditions appropriate for 21 kyr BP are ice-sheet area, topography and sea-level from ICE-5G (Peltier, 2004), greenhouse gas concentrations from ice-core records (Loulergue et al., 2008; Petit et al., 1999; Spahni et al., 2005) and Earth's orbital parameters as calculated by Berger (1978). The Coupled Model Intercomparison Project Phase 5 version of HadGEM2-ES produced an unrealistic dust-bowl climate state for LGM conditions. Therefore, here the model parameters in the land-surface are the tuned set that produces stable climate states for both the pre-industrial and the LGM (Hopcroft & Valdes, 2015). In this atmosphere-only configuration monthly sea-surface temperatures and sea-ice distribution are prescribed from atmosphere-ocean model simulations of the LGM performed using the older Hadley Centre model HadCM3 (Singarayer & Valdes, 2010; Valdes et al., 2017). The LGM simulation is 50 years long with the last 30 used to calculate climatologies.

Table 1
Summary of HadGEM2-ES Dust-Climate Simulations

Simulation	Freshwater duration × flux	Hosing region[a]	ΔSST_{Atl} [K]	Δemi_{glob} [Tg year^{-1}] (%)	ΔdRF_{glob} [W m^{-2}]
LGM	-	-	-	-	-
LGMglac	-	-	-	-	-
LGM + fw1 (strong)	100 yr × 1.0 Sv	50–70 N	−3.3	1,498 (+13.6%)	−0.8
LGMglac + fw1	100 yr × 1.0 Sv	50–70 N	−3.3	2,619 (+15.4%)	−1.1
LGM + fw0.4a (strong)	300 yr × 0.4 Sv	60–80 N	−2.8	971 (+8.8%)	−0.7
LGM + fw0.4b	300 yr × 0.4 Sv	50–70 N:W	−2.1	1,755 (+15.9%)	−1.1
LGM + fw0.4c	100 yr × 0.4 Sv	50–70 N	−1.1	1,042 (+9.4%)	−0.5
LGM + fw0.4d (weak)	100 yr × 0.4 Sv	50–70 N:W	−0.8	692 (+6.3%)	−0.2
LGM + fw0.4e (weak)	100 yr × 0.4 Sv	60–80 N	−1.0	1,045 (+9.5%)	−0.6

Note. ΔSST_{Atl}: North Atlantic sea surface temperature anomaly averaged from 0 to 40°N. Δemi_{glob}: total dust emission anomaly averaged globally. ΔdRF_{glob}: globally-averaged net (short-wave plus long-wave) instantaneous dust top-of-the-atmosphere radiative forcing anomaly (strong/weak) indicates that the simulation is selected for the strong/weak stadial composites shown in Figures 2 and 3, Figures S3 and S4 in Supporting Information S1. LGM, last glacial maximum.
[a]Where marked with ":W" the freshwater is only applied west of 30°W.

The LGM HadGEM2-ES simulation was branched from year 25 and run for another 50 years with the inclusion of glaciogenic dust sources following the work of Mahowald et al. (2006) and Albani et al. (2014) as described in Figure S1, Table S1, and Text S1 in Supporting Information S1. This simulation is labeled LGMglac in Table 1 and includes seven additional source regions that represent areas where significant glacial erosion is thought to have generated fine-grained material that could be entrained into the atmosphere (see Mahowald et al., 2006, and references therein). The seven source regions are tuned so that the LGM glaciogenic simulation reproduces reconstructed fluxes of dust at a suite of marine, terrestrial and ice-core locations (Albani et al., 2014; Kohfeld et al., 2013) in a similar approach as Albani et al. (2014).

The LGM simulation was branched into a 50-year stadial simulation with HadGEM2-ES. HadGEM2-ES is forced with SSTs and sea-ice from the end of a 100 year simulation with HadCM3 in which 1.0 Sv (1 Sv = 1×10^6 m^3 s^{-1}) of freshwater was continuously added to the North Atlantic (between 50 and 70°N) (summarized in Table 1 as LGM+fw1 simulation). The unperturbed LGM AMOC in the HadCM3 simulations was 24 Sv but essentially collapses in response to the 1 Sv freshwater input (Singarayer & Valdes, 2010). This HadGEM2-ES run was then continued for 30 years in double-call mode (as used by Hopcroft et al., 2015) to calculate the instantaneous direct dust RF. This setup was then repeated but starting from the LGMglac setup described above to produce a stadial simulation that includes both glaciogenic dust sources and freshwater input which is labeled as LGMglac + fw1 (see Table 1).

In order to better understand the dust response we ran five additional stadial simulations with HadGEM2-ES (not including glaciogenic sources). The SSTs and sea-ice used are selected from an ensemble of 36 different freshwater hosing simulations performed with the coupled model HadCM3 under glacial model boundary conditions. This hosing ensemble samples the background conditions that are close in time to the LGM (i.e., with a similar configuration of ice-sheets) and the freshwater input location, flux and duration over the North Atlantic. Each HadCM3 simulation was initialized from the end of a 550 years simulation with appropriate background conditions (orbit, greenhouse gas levels and ice-sheets) described by Singarayer and Valdes (2010). Five contrasting members of this "hosing" ensemble were selected to provide SST and sea-ice boundary conditions for additional stadial simulations with HadGEM2-ES which were run for 30 years in each case and were then extended by 10 years for the RF diagnostics. These simulations all have a freshwater input of 0.4 Sv and are labeled LGM + fw0.4a-e.

2.2. Compilation of Marine Sediment Core Dust Flux Records

In marine sediment cores, the dust flux is mainly reconstructed using ^{230}Th normalized ^{232}Th flux, hereafter referred to as ^{232}Th-norm flux (Costa et al., 2020). ^{230}Th normalization is a constant vertical flux proxy which allows a correction for post-deposition sediment redistribution, that is, focusing or winnowing (see review by Costa et al., 2020, for details). ^{232}Th is highly enriched in continental crust compared to ocean basalts (Kienast et al., 2016) and so is mainly delivered to the oceans from the land areas. It is assumed that, far from the continents ^{232}Th is mainly brought by mineral dust aerosols. Alternatively, ^{3}He can also be used as constant vertical flux proxy and $^{4}He_{terr}$ as dust proxy (e.g., Middleton et al., 2018). We compiled the dust depositional fluxes from 15 published records covering the three tropical ocean basins (Table S2 in Supporting Information S1). Missiaen et al. (2018) have shown that the choice of the value of the ($^{232}Th/^{238}U$) detrital activity ratio (hereafter called R) used to calculate the $^{230}Th_{xs}$ could influence the relative amplitude of the flux between two time intervals (see Costa et al., 2020; Missiaen et al., 2018). For consistency in the comparison of dust flux variations in between the different locations within a given ocean basin we re-calculated the fluxes using a common R value for each ocean basin and employed the same value for the rate of production of ^{230}Th in the water column by decay of ^{234}U (usually referred to as β_{th}) (details of individual calculations are given in Text S2 in Supporting Information S1).

3. Results

3.1. Dust Response to Stadial Conditions

The most robust feature of the dust cycle response to stadial conditions is a large increase in dust emission in the Sahel region (Figure 1 left and right panels), in agreement with the reconstructed southward shift of the Sahel-Sahara boundary (J. Collins et al., 2013) during this time. Reduced rainfall as shown in Figure S2 in Supporting Information S1 supports an increase in dust whereas the windspeed is decreased over the Sahel in both JJA and DJF seasons. The dust deposition rates are the only way to validate the paleodust simulations. In both the LGM + fw1 and LGMglac + fw1 simulations there is an increase in deposition rates in stadial conditions. This is broadly driven by increased emissions. Over Greenland deposition increases by 50% which is smaller than the 80% increase measured during HS1 in the NGRIP ice-core, as calculated from the 500-year running mean of the record after splining to 20-year resolution (Ruth et al., 2007). The most prominent feature is an increase in dust in the southern tropical Atlantic, where a southward migration of the intertropical convergence zone (ITCZ) causes larger wet deposition fluxes. An increase in dust emissions from the Sahel is the dominant cause, and this can explain the increased dust deposition over northern South America and further afield. The dust aerosol optical depth (AOD) and top of the atmosphere (TOA) total direct RF show large changes centered on the equatorial Atlantic. In the stadial state relative to the LGM, the global-mean TOA RF is −0.8 and −1.1 W m^{-2} in the standard LGM and glaciogenic LGM setups respectively. Focusing on the Atlantic west of the Sahara, both the LGM + fw1 and LGMglac + fw1 stadial simulations show a similar reduced dust deposition flux (Figures 1g and 1h), in contradiction with several reconstructions from marine cores (McGee et al., 2013; Middleton et al., 2018).

The main difference with the inclusion of the glaciogenic sources (Figure 1, right panels) is an intensification of the dust cycle response in the Northern extra-tropics as would be expected with the additional source regions mostly being at high northern latitudes. Over Greenland the stadial anomaly is now +81% which is in excellent agreement with the NGRIP record demonstrating the importance of the glaciogenic sources at high latitudes. As in the LGM stadial anomaly (Figure 1, left panels) both the dust AOD and direct RF are elevated. This is caused by a larger loading of the finer particles, mostly emitted from the Sahel which have relatively little impact on the total depositional flux in the region off the west coast of North Africa. Murphy et al. (2014) have suggested that the model-data discrepancy for total deposition may be caused by the differences in particle size in the sediment core records and the model, where the records mostly consist of particles larger than simulated. However, McGee et al. (2013) reconstructed particle sizes in the range of 8–25 μm and HadGEM2-ES' largest bin covers similarly sized particles with a radius of 10–33 μm, yet this bin shows a very similar signal as the total across all size bins. Therefore other mechanisms should be explored.

3.2. Sensitivity to the Magnitude of Stadial Climate Anomalies

To further understand the model response, we examine the suite of five simulations performed with different stadial states (LGM + fw0.4a-e) in comparison with the LGM simulation. We selected the four simulations from LGM + fw1 and LGM + fw0.4a-e with the largest and smallest changes over North Africa. From these we calculated the averages of the strongest pair and the weakest pair to produce one strong and one weak stadial

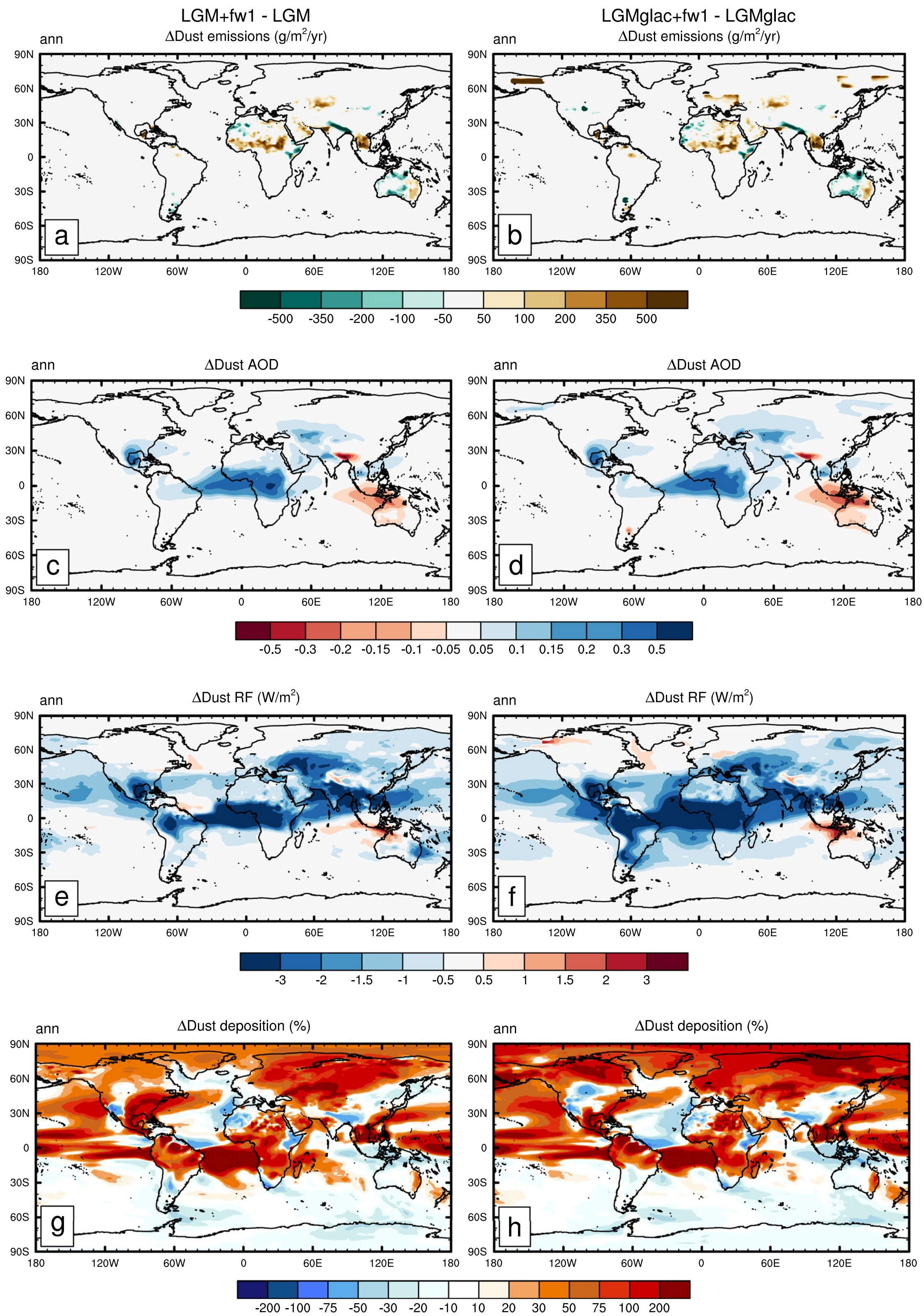

Figure 1. Dust cycle response to stadial conditions showing dust emissions, aerosol optical depth (AOD at 0.55 μm), radiative forcing (RF) and dust deposition (top to bottom). Left panels show the stadial simulation versus last glacial maximum (LGM) conditions and the right panels show the equivalent anomalies for the simulations that include glaciogenic dust source terms, that is, with respect to LGMglac.

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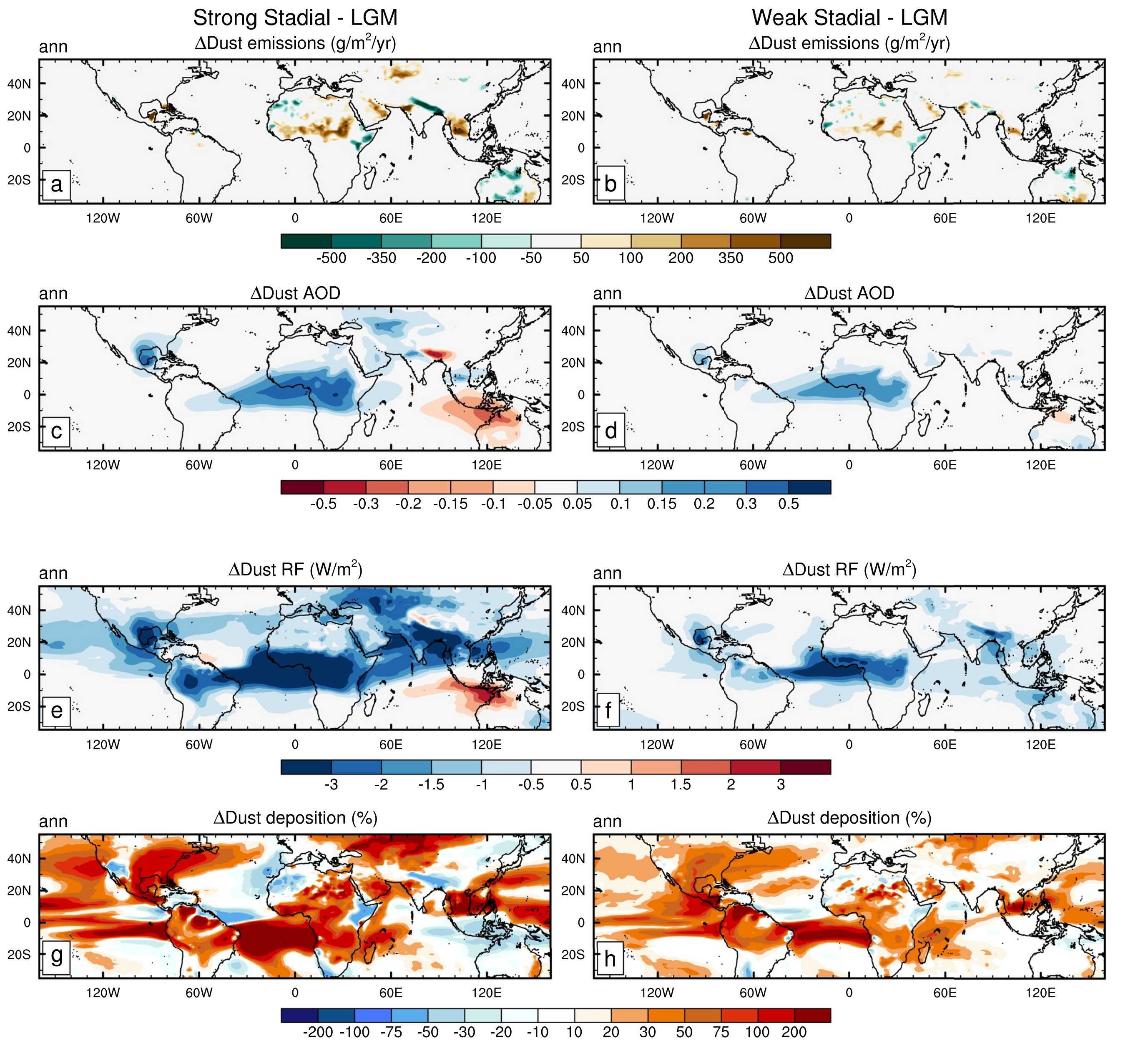

Figure 2. Stadial event dust cycle responses relative to the last glacial maximum (LGM) for the strong pair average (left) and the weak pair average (right), see text and Table 1 for details. Dust emissions, aerosol optical depth (AOD at 0.55 μm), radiative forcing (RF) and dust deposition.

composite. These are shown in Figure 2, left and right panels respectively. The simulations selected for these two composites are indicated in Table 1. In the tropical Atlantic and up to around 40°N, similar to the LGM stadial run (with 1 Sv freshwater), the strong stadial pair also predicts a decrease in dust flux, whereas the weak stadial simulations show a more realistic 29%–50% increase (Figure 2). This can be explained by examining the climate variables and the soil moisture changes in the Western Sahara. Figure S3 in Supporting Information S1 shows the annual mean climate anomalies for the strong and weak stadial-interstadial simulation pairs. Overall the results agree with previous modeling studies on the impacts of freshwater input on glacial climates (Armstrong et al., 2019; Hopcroft et al., 2014; Kageyama et al., 2013; Murphy et al., 2014), such as northern hemisphere cooling and decreased rainfall close to the Equator and across the Amazon basin (Deplazes et al., 2013).

Soil moisture changes reflect changes in rainfall and evaporation. The enhanced cooling in the strong stadial simulation reduces evaporation rates in North Africa, increasing soil moisture in some regions and so inhibiting

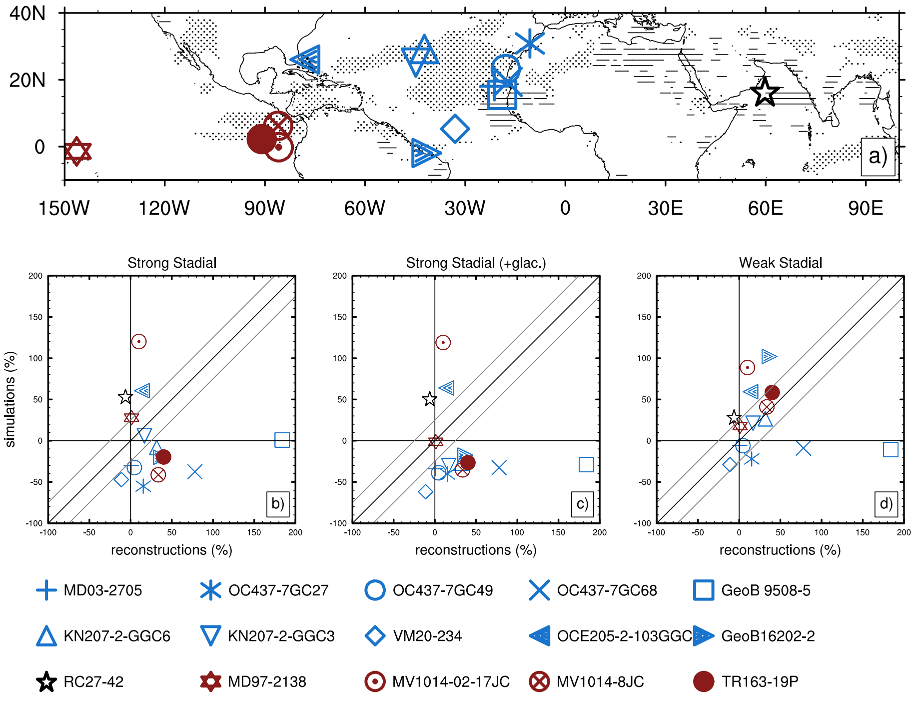

Figure 3. Simulated versus reconstructed changes in dust deposition (%) during Heinrich stadial 1 compared to the last glacial maximum (LGM). (a) Marine sediment core locations. Stippling shows regions where the simulated deposition anomaly (stadial minus LGM) changes sign from a decrease to an increase when reducing the magnitude of the stadial climate forcing from the strong to weak stadial. Hatching shows the regions with the opposite response (i.e., a change from an increase to a decrease). Regions without stippling of hatching show the same sign of change in the weak and strong stadial anomalies. Scatter plots comparing (b) strong stadial pair average, (c) strong stadial with glaciogenic dust (single simulation), and (d) weak stadial pair average compared with the reconstructions. The scatter plots show the 1:1 line with an arbitrary ±25% error. The dust deposition records are summarized in Table S2 in Supporting Information S1.

dust emissions. Conversely, in the weak stadial simulations there is a similar rainfall reduction in the western Sahara, but there is a much more muted cooling signal, and hence less of an impact on evaporation and soil moisture. The interplay between temperature and hydrological change are therefore crucial for understanding the dust cycle response in Sahara-Sahel.

Thus, contrary to the strong or the LGMglac + fw1 stadial simulations, the weak stadial shows increased dust deposition compared to the LGM in the 15–30°N band in the Atlantic. Apart from close to the Atlantic coast of North Africa, there is an increase in dust deposition during HS, which is in closer agreement with marine sediment records (Kinsley et al., 2022; McGee et al., 2013; Middleton et al., 2018). The smaller cooling of 2°C–3°C (see Figure S3 in Supporting Information S1) over the Atlantic in the weak stadial pair is also in better agreement with reconstructed sea surface temperature anomalies during HS1 (Kinsley et al., 2022).

3.3. Model-Data Comparison for Stadial Dust Changes

We further evaluate the simulated stadial minus LGM changes in dust deposition with a new compilation of dust deposition fluxes anomalies during HS1 which we have assembled from available high-resolution marine sediment cores. The data sources are listed in Table S2 in Supporting Information S1 with a full description of our compilation procedure in Text S2 in Supporting Information S1. This comparison is shown in Figure 3 for the relative change and the absolute fluxes are shown in Figure S4 in Supporting Information S1.

For the strong stadial minus LGM three major discrepancies are evident in Figure 3b. As already discussed there is a simulated reduction in dust deposition over most of the northern tropical Atlantic, where the records show an increase (McGee et al., 2013; Middleton et al., 2018). At two of three sites in the Eastern Equatorial Pacific (EEP) the model simulates a decreased flux whereas records show the opposite. Over the Southern tropical Atlantic the model overestimates changes and a simulated increase in dust over the Arabian Sea again contradicts the data. The inclusion of glaciogenic sources does not appreciably alter the comparison (Figure 3c).

The model-data comparison shows a systematic improvement across three ocean basins in the weak stadial simulations compared to the strong stadial or LGM simulations (Figure 3d). This improvement is not evident in the comparison of absolute dust fluxes shown in Figure S4 in Supporting Information S1 probably because the comparison in Figure S4 in Supporting Information S1 spans several orders of magnitude. The improvement in Figure 3 in several regions is caused by a switch in sign of the simulated dust deposition (i.e., from an increase to a decrease or vice-versa) when considering the weak or strong stadial anomaly with respect to the LGM. This is shown in Figure 3 by the stippling where the strong simulation shows a decrease but the weak simulations shows an increase, and hatching for the reverse situation. Areas with neither stippling or hatching show the same sign of change in response to both weak and strong stadials (e.g., both increase or both decrease). The switch in the sign of the response in the modeled dust cycle therefore shows potentially important non-linearity in response to abrupt climate change forcing.

In the weak stadial simulations, 8 of 15 sites are within the 25% bounds around the reconstructions, compared to 2 or 1 of 15 for the strong or LGMglac + fw1 runs, respectively. Whilst soil moisture change is important over North Africa, over the EEP the changes are caused by a much weaker wet-deposition signal because in the weak stadial simulation the precipitation anomalies are much more muted (Figure S3d in Supporting Information S1). The more muted precipitation anomalies also improve the model comparison at sites in the equatorial Atlantic, again because wet-deposition anomalies are not so strong and because of a smaller latitudinal shift in the rainbelts. A similar picture emerges over the Arabian Sea where the model is again much closer to the reconstructed signal.

3.4. Radiative Forcing Changes

A dust-climate feedback during past abrupt changes has been studied before but with conflicting findings (Murphy et al., 2017; Overpeck et al., 1996). The global mean RF values in our HadGEM2-ES simulations are given in Table 1. The mean RF in the strong events is -0.9 W m^{-2}, versus -0.4 W m^{-2} for the weak stadial pair. Even the smaller forcing represents a potentially significant perturbation to the tropical energy balance whereby additional dust loading further cools the cold stadial states and thereby acts as an amplifying feedback that could also extend the duration of these events. Dust feedbacks could conceivably have had a major impact but this requires further coupled model simulations for a robust evaluation of the potential impacts on the evolution of abrupt events.

4. Discussion

Overall we find that the weaker stadial simulations with a smaller ocean circulation perturbation (0.4 Sv instead of 1 Sv) provide a better, though still imperfect, simulation of HS1 dust change. Possible reasons for this are because the simulation does not include changes in ice-sheet topography which are important for stadial simulations (Roberts et al., 2014b), and because the prescribed sea-surface conditions mean that the ocean does not respond to the dust radiative effects described above. At three different sites, the tropical north Atlantic, the East Equatorial Pacific and to a lesser extent the Arabian Sea, the weak stadial simulations shows the opposite sign of change in dust flux compared to the strong stadial simulation (see Figure 3a). This is explained either by changes in land surface and soil moisture (North Africa) or through differences in wet deposition (elsewhere). If this is applicable to other models, it strongly suggests that the 1 Sv type model simulations for HS are unrealistic and much smaller perturbations should be used, consistent with climate-ice-sheet modeling (e.g., Roberts et al., 2014a). Observational constraints on the freshwater input during these events are subject to wide uncertainties (Carlson & Clark, 2012) and so do not provide strong constraints on the fluxes.

Although we evaluated the effects of adding glaciogenic dust sources, we chose not to focus on these because the additional high-latitude sources do not fundamentally alter the model-data comparison at marine sediment core locations, that is, within the intertropical area. They are important at mid- to high latitudes and future work could re-examine the glaciogenic aspect in more detail.

The sensitivity of dust deposition to the strength of the stadial suggests that the equatorial dust response during Heinrich events is very variable. This is consistent with Middleton et al. (2018) who see varying magnitude of changes during the last 70 kyr, and little change in dust flux during HS events 5 and 6. The results also suggest that other locations in the Atlantic basin would be likely to have experienced stronger dust deposition changes, for example, in the Gulf of Guinea and the south west equatorial Atlantic. In those regions the simulated rainfall changes are a dominant control on the dust flux because of large changes in wet deposition. It would be helpful to validate this model prediction with new dust and/or salinity reconstructions.

The model-data comparison highlights discrepancies between the model and records (see Figure 3). There is some uncertainty in these records because fluvial inputs cannot be distinguished from the dust only using ^{230}Th-normalized ^{232}Th flux. One way to circumvent the problem is to conduct grain-size analyses (e.g., McGee et al., 2013). For example, HadGEM2-ES overestimates the abrupt change in dust flux over the western tropical north Atlantic (see Figure 3). For core OCE205-2-103GGC in the Bahamas, the smaller increase in dust flux can be explained by the effect of bioturbation. A model of the resultant smoothing effect on the dust flux record (Williams et al., 2016) shows that during HS1 the dust change may have been twice as high. Correcting for bioturbation would put the model-data comparison near the 1:1 line (Figure 3).

Core GeoB16202-2 lies at the transition between LGM-stadial increased and decreased precipitation areas in the simulation (Figure S3 in Supporting Information S1) with the area of increased precipitation located slightly more to the south in the LGM-weak stadial simulation. δD measured in plant wax n-alkanes in this core show a greater tree-cover during HS1 than during the LGM (Mulitza et al., 2017). This was interpreted as reflecting increased rainfall which would be in better agreement with the LGM-strong stadial simulations for which the data-model agreement is better. This subtle difference shows the sensitivity of the dust cycle to the modeled distribution of positive and negative precipitation anomalies which are likely resolution- and model-dependent.

There are also model-data discrepancies along the north African margin for cores GeoB9508 and OC437-7GC68 for which the simulations underestimate the dust flux. The high amplitude dust flux increase for core OC437-7GC68 has been ascribed to gustier conditions (McGee et al., 2013) which the model may fail to resolve (Garcia-Carreras et al., 2021). For core GeoB9508 the HS1 flux increase was attributed to Sahel mega-drought and increased dust in the Sahara Air Layer (Mulitza et al., 2008). In our simulations the Bodélé depression receives more precipitation during HS1 than during the LGM. As one of the main dust emitters in North Africa, fueling dust to the Saharan Air Layer (Flamant et al., 2009), a simulated wetter Bodélé depression may explain why the model fails to reconstruct the increased HS1 dust flux recorded in core GeoB9508.

Finally, the discrepancies in dust flux variations observed in the EEP can be explained by the latitudinal positions of the cores. The simulations overestimate the LGM-fw1 dust flux variation compared to data for the southernmost one MV1014-02-17JC. The ITCZ behavior over the EEP is known to be complex and difficult to reproduce in models (Rincón-Martínez et al., 2010; Schneider et al., 2014). It is thus possible that over the area where the three cores are located, the actual southward shift of the ITCZ is smaller than modeled. Hence, MV1014-02-17JC would mostly receive dust from the southern hemisphere where dust load variations are smaller than that of the northern hemisphere as recorded in the two other EEP cores.

The ocean conditions in this study are prescribed from HadCM3. The LGM HadCM3 simulation captures the main features of the LGM climate but remains too warm over Greenland (Singarayer & Valdes, 2010). It seems likely that additional cooling due to vegetation feedbacks (Davies-Barnard et al., 2017) and possibly from dust (Hopcroft et al., 2015) could resolve this. HadGEM2-ES, the model used here to simulate dust, is also colder at the LGM than HadCM3 and is thus closer to these reconstructions. Paleoceanographic evidence suggests a shallower AMOC (Lippold et al., 2012; Skinner et al., 2017) but HadCM3 does not reproduce this. It is unclear how this may impact the simulated dust response. This, and the actual timing of HS1 at 3 kyr after the LGM should be evaluated in future work.

Some coupled climate models integrated under glacial conditions have shown spontaneous oscillations that resemble D-O events (Peltier & Vettoretti, 2014). However, HS events probably involve additional interactions with dynamic ice-sheets. Questions remain because if as commonly assumed, both D-O and HS events hinge on abrupt variations in the strength of the AMOC it is unclear why Greenland ice-core records show small signals during HS events but very large changes during D-O events. Roberts and Hopcroft (2020) showed that D-O events must be associated with large changes in Atlantic sea-ice area rather than in the AMOC. It is unclear how this would engender such large changes in dust over Greenland. A European source region that accounts for the dustier stadials seems a promising explanation (Rousseau et al., 2017, 2021; Újvári et al., 2015). Future work with longer climate-dust simulations may help address these interrelated questions.

The representation of dust aerosols in ES Models is subject to caveats. The generation of intense dust storms in convective downdraughts (Garcia-Carreras et al., 2021) is not represented in many models, including

HadGEM2-ES. Additionally, it is still not fully understood how coarse aerosol particles are transported so far from source regions (Ryder et al., 2018) and these particles are therefore not well simulated (Evan et al., 2014). Changing dust source regions such as due to dried lake beds—which are known to be important dust contributors (e.g., Goudie, 2018) are also not fully accounted for in paleoclimate simulations including with HadGEM2-ES. Dust particles are also an important source of ice nuclei in mixed phase clouds (e.g., Nenes et al., 2014; Sagoo & Storelvmo, 2017) but this is also not included in HadGEM2-ES.

5. Conclusions

We present ES model simulations of abrupt climate change and dust for the last glacial. Colder, dryer conditions across much of the tropics but especially equatorial Africa contribute to a surge in atmospheric dust and increased depositional fluxes in agreement with paleoclimate records. However, simulations with more extreme cooling show decreased dust fluxes over the Atlantic in contradiction with reconstructions. The simulated change in dust switches sign in when the cooling over the tropical Atlantic (and Africa) is more limited at around 2°C–3°C or less. This non-linear dust response may explain why other model simulations also simulate an incorrect signal (Murphy et al., 2014). The more realistic simulations with less pronounced cooling have a smaller RF from dust. Nevertheless, this smaller forcing of -0.2 to -0.6 W m^{-2} still represents a potentially important perturbation that should be included in future modeling of abrupt climate change. In future studies of abrupt change, the inclusion of other tracers such as methane (Rhodes et al., 2015; Ringeval et al., 2013) and nitrous oxide (Joos et al., 2020; Schmittner & Galbraith, 2008) may bring complementary constraints on the mechanisms at play, as could a more detailed representation of the dust cycle.

Data Availability Statement

All HadGEM2-ES model output is available for further analysis from https://www.paleo.bristol.ac.uk/ummodel/scripts/papers or directly from www.paleo.bristol.ac.uk/ummodel/users/Hopcroft_et_al_2022/new2.

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References

Albani, S., Mahowald, N., Perry, A., Scanza, R., Zender, C., Heavens, N., et al. (2014). Improved dust representation in the Community Atmosphere Model. *Journal of Advances in Modeling Earth Systems*, *6*(3), 541–570. https://doi.org/10.1002/2013MS000279

Armstrong, E., Hopcroft, P., & Valdes, P. (2019). A simulated Northern Hemisphere terrestrial climate dataset for the past 60,000 years. *Scientific Data*, *6*(1), 265. https://doi.org/10.1038/s41597-019-0277-1

Bellouin, N., Rae, J., Jones, A., Johnson, C., Haywood, J., & Boucher, O. (2011). Aerosol forcing in the CMIP5 simulations by HadGEM2-ES and the role of ammonium nitrate. *Journal of Geophysical Research*, *116*(D20), D20206. https://doi.org/10.1029/2011JD016074

Berger, A. (1978). Long-term variations of daily insolation and quaternary climatic changes. *Journal of the Atmospheric Sciences*, *35*(12), 2362–2367. https://doi.org/10.1175/1520-0469(1978)035⟨2362:LTVODI⟩2.0.CO;2

Booth, B., Dunstone, N., Halloran, P., Andrews, T., & Bellouin, N. (2012). Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nature*, *484*(7393), 228–232. https://doi.org/10.1038/nature10946

Caesar, J., Palin, E., Liddicoat, S., Lowe, J., Burke, E., Pardaens, A., et al. (2013). Response of the HadGEM2 Earth System model to future greenhouse gas emissions pathways to the year 2300. *Journal of Climate*, *26*(10), 3275–3284. https://doi.org/10.1175/jcli-d-12-00577.1

Carlson, A., & Clark, P. (2012). Ice sheet sources of sea level rise and freshwater discharge during the last deglaciation. *Reviews of Geophysics*, *50*(4), RG4007. https://doi.org/10.1029/2011RG000371

Clement, A., & Peterson, L. (2008). Mechanisms of abrupt climate change of the last glacial period. *Reviews of Geophysics*, *46*, RG4002. https://doi.org/10.1029/2006rg000204

Collins, J., Govin, A., Mulitza, S., Heslop, D., Zabel, M., Hartmann, J., et al. (2013). Abrupt shifts of the Sahara–Sahel boundary during Heinrich stadials. *Climate of the Past*, *9*(3), 1181–1191. https://doi.org/10.5194/cp-9-1181-2013

Collins, W., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., et al. (2011). Development and evaluation of an Earth-System model—HadGEM2. *Geoscientific Model Development*, *4*, 1051–1075. https://doi.org/10.5194/gmd-4-1051-2011

Costa, K., Hayes, C., Anderson, R., Pavia, F., Bausch, A., Deng, F., et al. (2020). ^{230}Th normalization: New insights on an essential tool for quantifying sedimentary fluxes in the modern and quaternary ocean. *Paleoceanography and Paleoclimatology*, *35*(2), e2019PA003820. https://doi.org/10.1029/2019PA003820

Dansgaard, W., Johnsen, S., Clausen, H., Dahl-Jensen, D., Gundestrup, N., Hammer, C., et al. (1993). Evidence for general instability of past climate from a 250 kyr ice-core record. *Nature*, *364*(6434), 218–220. https://doi.org/10.1038/364218a0

Davies-Barnard, T., Ridgwell, A., Singarayer, J., & Valdes, P. (2017). Quantifying the influence of the terrestrial biosphere on glacial–interglacial climate dynamics. *Climate of the Past*, *13*(10), 1381–1401. https://doi.org/10.5194/cp-13-1381-2017

Deplazes, G., Luckge, A., Peterson, L. C., Timmermann, A., Hamann, Y., Hughen, K. A., et al. (2013). Links between tropical rainfall and North Atlantic climate during the last glacial period. *Nature Geoscience*, *6*(3), 213–217. https://doi.org/10.1038/ngeo1712

Evan, A., Flamant, C., Fiedler, S., & Doherty, O. (2014). An analysis of aeolian dust in climate models. *Geophysical Research Letters*, *41*(16), 5996–6001. https://doi.org/10.1002/2014GL060545

Fiedler, S., Knippertz, P., Woodward, S., Martin, G. M., Bellouin, N., Ross, A. N., et al. (2016). A process-based evaluation of dust-emitting winds in the CMIP5 simulation of HadGEM2-ES. *Climate Dynamics*, *46*(3–4), 1107–1130. https://doi.org/10.1007/s00382-015-2635-9

Fischer, H., Siggaard-Andersen, M. L., Ruth, U., Rothlisberger, R., & Wolff, E. (2007). Glacial/interglacial changes in mineral dust and sea-salt records in polar ice cores: Sources, transport, and deposition. *Reviews of Geophysics*, *45*, RG1002. https://doi.org/10.1029/2005RG000192

Flamant, C., Lavaysse, C., Todd, M., Chaboureau, J.-P., & Pelon, J. (2009). Multi-platform observations of a springtime case of Bodélé and Sudan dust emission, transport and scavenging over West Africa. *The Quarterly Journal of the Royal Meteorological Society*, *135*(639), 413–430. https://doi.org/10.1002/qj.376

Garcia-Carreras, L., Marsham, J., Stratton, R., & Tucker, S. (2021). Capturing convection essential for projections of climate change in African dust emission. *npj Climate and Atmospheric Science*, *4*(44), 44. https://doi.org/10.1038/s41612-021-00201-x

Gibson, K., & Peterson, L. (2014). A 0.6-million year record of millennial-scale climate variability in the tropics. *Geophysical Research Letters*, *41*(3), 969–975. https://doi.org/10.1002/2013GL058846

Goudie, A. (2018). Dust storms and ephemeral lakes. *Desert*, *23*, 153–164. https://doi.org/10.22059/JDESERT.2018.66370

HadGEM2 Development Team, Bellouin, N., Collins, W. J., Culverwell, I. D., Halloran, P. R., Hardiman, S. C., et al. (2011). The HadGEM2 family of met office unified model climate configurations. *Geoscientific Model Development*, *4*(3), 723–757. https://doi.org/10.5194/gmd-4-723-2011

Hopcroft, P., & Valdes, P. (2015). Last glacial maximum constraints on the Earth System model HadGEM2-ES. *Climate Dynamics*, *45*(5), 1657–1672. https://doi.org/10.1007/s00382-014-2421-0

Hopcroft, P., & Valdes, P. (2019). On the role of dust-climate feedbacks during the mid-Holocene. *Geophysical Research Letters*, *46*(3), 1612–1621. https://doi.org/10.1029/2018GL080483

Hopcroft, P., Valdes, P., O'Connor, F., Kaplan, J., & Beerling, D. (2017). Understanding the glacial methane cycle. *Nature Communications*, *8*, 14383. https://doi.org/10.1038/ncomms14383

Hopcroft, P., Valdes, P., Wania, R., & Beerling, D. (2014). Limited response of peatland CH_4 emissions to abrupt changes in Atlantic Ocean circulation in glacial states. *Climate of the Past*, *10*(1), 137–154. https://doi.org/10.5194/cp-10-137-2014

Hopcroft, P., Valdes, P., Woodward, S., & Joshi, M. (2015). Last glacial maximum radiative forcing from mineral dust aerosols in an Earth System model. *Journal of Geophysical Research*, *120*(16), 8186–8205. https://doi.org/10.1002/2015JD023742

Joos, F., Spahni, R., Stocker, B. D., Lienert, S., Muller, J., Fischer, H., et al. (2020). N_2O changes from the last glacial maximum to the preindustrial—Part 2: Terrestrial N_2O emissions and carbon–nitrogen cycle interactions. *Biogeosciences*, *17*(13), 351–3543. https://doi.org/10.5194/bg-17-3511-2020

Kageyama, M., Merkel, U., Otto-Bliesner, B., Prange, M., Abe-Ouchi, A., Lohmann, G., et al. (2013). Climatic impacts of fresh water hosing under last glacial maximum conditions: A multi-model study. *Climate of the Past*, *9*(2), 935–953. https://doi.org/10.5194/cp-9-935-2013

Kienast, S., Friedrich, T., Dubois, N., Hill, P., Timmermann, A., Mix, A., & Kienast, M. (2013). Near collapse of the meridional SST gradient in the eastern equatorial Pacific during Heinrich Stadial 1. *Paleoceanography*, *28*, 4–674. https://doi.org/10.1002/2013pa002499

Kienast, S., Winckler, G., Lippold, J., Albani, S., & Mahowald, N. M. (2016). Tracing dust input to the global ocean using thorium isotopes in marine sediments: ThoroMap. *Global Biogeochemical Cycles*, *30*(10), 1526–1541. https://doi.org/10.1002/2016GB005408

Kindler, P., Guillevic, M., Baumgartner, M., Schwander, J., Landais, A., & Leuenberger, M. (2014). Temperature reconstruction from 10 to 120 kyr b2k from the NGRIP ice core. *Climate of the Past*, *10*(2), 887–902. https://doi.org/10.5194/cp-10-887-2014

Kinsley, C., Bradtmiller, L., McGee, D., Galgay, M., Stuut, J., Tjallingii, R., et al. (2022). Orbital- and millennial-scale variability in Northwest African dust emissions over the past 67,000 years. *Paleoceanography and Paleoclimatology*, *37*(1), e2020PA004137. https://doi.org/10.1029/2020pa004137

Knippertz, P., & Todd, M. (2012). Mineral dust aerosols over the Sahara: Meteorological controls on emission and transport and implications for modeling. *Reviews of Geophysics*, *50*(1), RG1007. https://doi.org/10.1029/2011rg000362

Kohfeld, K., Graham, R., de Boer, A., Sime, L., Wolff, E., Le Quere, C., & Bopp, L. (2013). Southern hemisphere westerly wind changes during the last glacial maximum: Paleo-data synthesis. *Quaternary Science Reviews*, *68*, 76–95. https://doi.org/10.1016/j.quascirev.2013.01.017

Lippold, J., Luo, Y., Francois, R., Allen, S. E., Gherardi, J., Pichat, S., et al. (2012). Radiocarbon constraints on the glacial ocean circulation and its impact on atmospheric CO_2. *Nature Geoscience*, *5*(11), 813–816. https://doi.org/10.1038/ngeo1608

Loulergue, L., Schilt, A., Spahni, R., Masson-Delmotte, V., Blunier, T., Lemieux, B., et al. (2008). Orbital and millennial-scale features of atmospheric CH_4 over the past 800,000 years. *Nature*, *453*(7193), 383–386. https://doi.org/10.1038/nature06950

Loveley, M., Marcantonio, F., Wisler, M., Hertzberg, J. E., Schmidt, M., & Lyle, M. (2017). Millennial-scale iron fertilization of the eastern equatorial Pacific over the past 100,000 years. *Nature Geoscience*, *10*, 760–766. https://doi.org/10.1038/NGEO3024

Lynch-Stieglitz, J. (2017). The Atlantic meridional overturning circulation and abrupt climate change. *Annual Review of Marine Science*, *9*(1), 83–104. https://doi.org/10.1146/annurev-marine-010816-060415

Mahowald, N. M., Muhs, D., Levis, S., Rasch, P., Yoshioka, M., Zender, C., & Luo, C. (2006). Change in atmospheric mineral aerosols in response to climate: Last glacial period, preindustrial, modern, and doubled carbon dioxide climates. *Journal of Geophysical Research*, *111*, D10202. https://doi.org/10.1029/2005JD006653

Marcantonio, F., Hostak, R., Hertzberg, J., & Schmidt, M. (2020). Deep Equatorial Pacific Ocean Oxygenation and atmospheric CO_2 over the last ice age. *Scientific Reports*, *10*(1), 6606. https://doi.org/10.1038/s41598-020-63628-x

McGee, D., de Menocal, P., Winckler, G., Stuut, J., & Bradtmiller, L. (2013). The magnitude, timing and abruptness of changes in North African dust deposition over the last 20,000 yr. *Earth and Planetary Science Letters*, *371–372*, 163–176. https://doi.org/10.1016/j.epsl.2013.03.054

Middleton, J., Mukhopadhyay, S., Langmuir, C., McManus, J. F., & Huybers, P. J. (2018). Millennial-scale variations in dustiness recorded in Mid-Atlantic sediments from 0 to 70 ka. *Earth and Planetary Science Letters*, *482*, 1–20. https://doi.org/10.1016/j.epsl.2017.10.034

Missiaen, L., Pichat, S., Waelbroeck, C., Douville, E., Bordier, L., Dapoigny, A., et al. (2018). Downcore variations of sedimentary detrital ($^{238}U/^{232}Th$) ratio: Implications on the use of $^{230}Th_{xs}$ and $^{231}Pa_{xs}$ to reconstruct sediment flux and ocean circulation. *Geochemistry, Geophysics, Geosystems*, *19*(8), 2560–2573. https://doi.org/10.1029/2017GC007410

Mulitza, S., Chiessi, C., SchefuB, E., Lippold, J., Wichmann, D., Antz, B., et al. (2017). Synchronous and proportional deglacial changes in Atlantic meridional overturning and northeast Brazilian precipitation. *Paleoceanography*, *32*(6), 622–633. https://doi.org/10.1002/2017PA003084

Mulitza, S., Prange, M., Stuut, J.-B., Zabel, M., von Dobeneck, T., Itambi, A. C., et al. (2008). Sahel megadroughts triggered by glacial slowdowns of Atlantic meridional overturning. *Paleoceanography*, *23*(4), PA4206. https://doi.org/10.1029/2008PA001637

Murphy, L., Clement, A. C., Albani, S., Mahowald, N. M., Swart, P., & Arienzo, M. M. (2014). Simulated changes in atmospheric dust in response to a Heinrich stadial. *Palaeocenaography*, *29*, 1–14. https://doi.org/10.1002/2013PA002550

Murphy, L., Goes, M., & Clement, A. (2017). The role of African dust in Atlantic climate during Heinrich events. *Paleoceanography*, *32*(11), 1291–1308. https://doi.org/10.1002/2017PA003150

Nenes, A., Murray, B., & Bougiatioti, A. (2014). Mineral dust and its microphysical interactions with clouds. In P. Knippertz & J.-B. Stuut (Eds.), *Mineral dust: A key player in the Earth System* (pp. 287–325). Springer Science+Business Media. https://doi.org/10.1007/978-94-017-8978-3_12

Overpeck, J., Rind, D., Lacis, A., & Healy, R. (1996). Possible role of dust-induced regional warming in abrupt climate change during the last glacial period. *Nature*, *384*(6608), 447–449. https://doi.org/10.1038/384447a0

Peck, J., Green, R., Shanahan, T. O., King, J., Overpeck, J., & Scholz, C. (2004). A magnetic mineral record of Late Quaternary tropical climate variability from Lake Bosumtwi, Ghana. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *215*(1–2), 37–57. https://doi.org/10.1016/s0031-0182(04)00438-9

Peltier, W. (2004). Global glacial isostasy and the surface of the ice age Earth: The ICE-5G (VM2) model and GRACE. *Annual Review of Earth and Planetary Sciences*, *32*(1), 111–149. https://doi.org/10.1146/annurev.earth.32.082503.144359

Peltier, W., & Vettoretti, G. (2014). Dansgaard-oeschger oscillations predicted in a comprehensive model of glacial climate: A "kicked" salt oscillator in the Atlantic. *Geophysical Research Letters*, *41*(20), 7306–7313. https://doi.org/10.1002/2014GL061413

Peterson, L. C., Haug, G. H., Hughen, K. A., & Rohl, U. (2000). Rapid changes in the hydrologic cycle of the tropical Atlantic during the last glacial. *Science*, *290*(5498), 1947–1951. https://doi.org/10.1126/science.290.5498.1947

Petit, J., Jouzel, J., Raynaud, D., Barkov, N., Barnola, J.-M., Basile, I., et al. (1999). Climate and atmospheric history of the past 420, 000 years from the Vostok ice core, Antarctica. *Nature*, *399*(6735), 429–436. https://doi.org/10.1038/20859

Pourmand, A., Marcantonio, F., Bianchi, T., Canuel, E. A., & Waterson, E. J. (2007). A 28-ka history of sea surface temperature, primary productivity and planktonic community variability in the western Arabian Sea. *Paleoceanography*, *22*(4), PA4208. https://doi.org/10.1029/2007pa001502

Rhodes, R., Brook, E., Chiang, J., Blunier, T., Maselli, O., McConnell, J., et al. (2015). Enhanced tropical methane production in response to iceberg discharge in the North Atlantic. *Science*, *348*(6238), 1016–1019. https://doi.org/10.1126/science.1262005

Rincón-Martínez, D., Lamy, F., Contreras, S., Leduc, G., Bard, E., Saukel, C., et al. (2010). More humid interglacials in Ecuador during the past 500 kyr linked to latitudinal shifts of the equatorial front and the Intertropical Convergence Zone in the eastern tropical Pacific. *Paleoceanography*, *25*(2), PA2210. https://doi.org/10.1029/2009PA001868

Ringeval, B., Hopcroft, P., Valdes, P., Ciais, P., Ramstein, G., Dolman, A., & Kageyama, M. (2013). Response of methane emissions from wetlands to the Last Glacial Maximum and an idealised Dansgaard-Oeschger event: Insights from two models of different complexity. *Climate of the Past*, *9*(1), 149–171. https://doi.org/10.5194/cp-0-149-2013

Roberts, W., & Hopcroft, P. (2020). Controls on the tropical response to abrupt climate changes. *Geophysical Research Letters*, *47*(6), e2020GL087518. https://doi.org/10.1029/2020GL087518

Roberts, W., Valdes, P., & Payne, A. (2014a). A new constraint on the size of Heinrich events from an iceberg/sediment model. *Earth and Planetary Science Letters*, *386*, 1–9. https://doi.org/10.1016/j.epsl.2013.10.020

Roberts, W., Valdes, P., & Payne, A. (2014b). Topography's crucial role in Heinrich events. *Proceedings of the National Academy of Sciences*, *111*(47), 16688–16693. https://doi.org/10.1073/pnas.1414882111

Rousseau, D.-D., Antoine, P., & Sun, Y. (2021). How dusty was the last glacial maximum over Europe? *Quaternary Science Reviews*, *254*, 106775. https://doi.org/10.1016/j.quascirev.2020.106775

Rousseau, D.-D., Boers, N., Sima, A., Svensson, A., Bigler, M., Lagroix, F., et al. (2017). (MIS3 2) millennial oscillations in Greenland dust and Eurasian Aeolian records: A paleosol perspective. *Quaternary Science Reviews*, *69*, 99–113. https://doi.org/10.1016/j.quascirev.2017.05.020

Ruth, U., Bigler, M., Rothlisberger, R., Siggaard-Andersen, M. L., Kipfstuhl, S., Goto-Azuma, K., et al. (2007). Ice core evidence for a very tight link between North Atlantic and east Asian glacial climate. *Geophysical Research Letters*, *34*(3), L03706. https://doi.org/10.1029/2006GL027876

Ryder, C., Marenco, F., Brooke, J., Estelles, V., Cotton, R., Formenti, P., et al. (2018). Coarse-mode mineral dust size distributions, composition and optical properties from AER-D aircraft measurements over the tropical eastern Atlantic. *Atmospheric Chemistry and Physics*, *18*(23), 17225–17257. https://doi.org/10.5194/acp-17-17225-2018

Safaierad, R., Mohtadi, M., Zolitschka, B., Yokoyama, Y., Vogt, C., & SchefuB, E. (2020). Elevated dust depositions in West Asia linked to ocean-atmosphere shifts during North Atlantic cold events. *Proceedings of the National Academy of Sciences*, *117*(31), 18272–18277. https://doi.org/10.1073/pnas.2004071117

Sagoo, N., & Storelvmo, T. (2017). Testing the sensitivity of past climates to the indirect effects of dust. *Geophysical Research Letters*, *44*(11), 5807–5817. https://doi.org/10.1002/2017GL072584

Schmittner, A. E., & Galbraith, E. D. (2008). Glacial greenhouse gas fluctuations controlled by ocean circulation changes. *Nature*, *456*(7220), 373–376. https://doi.org/10.1038/nature07531

Schneider, T., Bischoff, T., & Haug, G. (2014). Migrations and dynamics of the intertropical convergence zone. *Nature*, *513*(7516), 45–53. https://doi.org/10.1038/nature13636

Schulz, H., von Rad, U., Erlenkeuser, H., & von Rad, U. (1998). Correlation between Arabian Sea and Greenland climate oscillations of the past 110,000 years. *Nature*, *393*(6680), 54–57. https://doi.org/10.1038/31750

Shanahan, T., McKay, N., Hughen, K., Overpeck, J., Otto-Bliesner, B., Heil, C., et al. (2015). The time-transgressive termination of the African humid period. *Nature Geoscience*, *8*(2), 140–144. https://doi.org/10.1038/NGEO2329

Sima, A., Kageyama, M., Rousseau, D.-D., Ramstein, G., Balkanski, Y., Antoine, P., & Hatte, C. (2013). Modeling dust emission response to North Atlantic millennial-scale climate variations from the perspective of East European MIS 3 loess deposits. *Climate of the Past*, *9*(4), 1385–1402. https://doi.org/10.5194/cp-9-1385-2013

Sima, A., Rousseau, D. D., Kageyama, M., Ramstein, G., Schulz, M., Balkanski, Y., et al. (2009). Imprint of North-Atlantic abrupt climate changes on western European loess deposits as viewed in a dust emission model. *Quaternary Science Reviews*, *28*(25–26), 2851–2866. https://doi.org/10.1016/j.quascirev.2009.07.016

Singarayer, J., & Valdes, P. (2010). High-latitude climate sensitivity to ice-sheet forcing over the last 120 kyr. *Quaternary Science Reviews*, *29*(1–2), 43–55. https://doi.org/10.1016/j.quascirev.2009.10.011

Skinner, L. C., Primeau, F., Freeman, E., de la Fuente, M., Goodwin, P. A., Gottschalk, J., et al. (2017). Radiocarbon constraints on the glacial ocean circulation and its impact on atmospheric CO_2. *Nature Communications*, *8*(1), 16010. https://doi.org/10.1038/ncomms16010

Spahni, R., Chappellaz, J., Stocker, T., Loulergue, L., Hausammann, G., Kawamura, K., et al. (2005). Atmospheric methane and nitrous oxide of the late Pleistocene from Antarctic ice cores. *Science*, *310*(5752), 1317–1321. https://doi.org/10.1126/science.1120132

Stager, J., Ryves, D. B., Chase, B. M., & Pausata, F. S. R. (2011). Catastrophic drought in the Afro-Asian monsoon during Heinrich event 1. *Science*, *331*(6022), 1299–1302. https://doi.org/10.1126/science.1198322

Tegen, I., & Rind, D. (2000). Influence of the latitudinal temperature gradient on soil dust concentration and deposition in Greenland. *Journal of Geophysical Research*, *105*(D6), 7199–7212. https://doi.org/10.1029/1999jd901094

Tierney, J., & de Menocal, P. (2013). Abrupt shifts in Horn of Africa hydroclimate since the Last Glacial Maximum. *Science*, *342*(6160), 843–846. https://doi.org/10.1126/science.1240411

Tindall, J., & Haywood, A. (2020). Modelling the mid-Pliocene warm period using HadGEM2. *Global and Planetary Change*, *186*, 103110. https://doi.org/10.1016/j.gloplacha.2019.103110

Újvári, G., Stevens, T., Svensson, A., Klotzli, U. S., Manning, C., Nemeth, T., et al. (2015). Two possible source regions for central Greenland last glacial dust. *Geophysical Research Letters*, *42*(23), 10399–10408. https://doi.org/10.1002/2015gl066153

Valdes, P., Armstrong, E., Badger, M., Bradshaw, C., Bragg, F., Crucifix, M., et al. (2017). The BRIDGE HadCM3 family of climate models: HadCM3@Bristol v1.0. *Geoscientific Model Development*, *10*, 3715–3743. https://doi.org/10.5194/gmd-10-3715-2017

Wang, X., Edwards, R. L., Auler, A. S., Cheng, H., Kong, X., Wang, Y., et al. (2017). Hydroclimate changes across the Amazon lowlands over the past 45,000 years. *Nature*, *541*(7636), 204–207. https://doi.org/10.1038/nature20787

Wang, Y., Cheng, H., Edwards, R., An, Z., Wu, J., Shen, C.-C., & Dorale, J. (2001). A high-resolution absolute-dated late Pleistocene monsoon record from Hulu Cave, China. *Science*, *24*(5550), 2345–2348. https://doi.org/10.1126/science.1064618

Williams, R., McGee, D., Kinsley, C., Ridley, D., Hu, S., Fedorov, A., et al. (2016). Glacial to Holocene changes in trans-Atlantic Saharan dust transport and dust-climate feedbacks. *Science Advances*, *2*(11), e1600445. https://doi.org/10.1126/sciadv.1600445

Wolff, E. W., Chappellaz, J., Blunier, T., Rasmussen, S. O., & Svensson, A. (2010). Millennial-scale variability during the last glacial: The ice core record. *Quaternary Science Reviews*, *29*(21–22), 2828–2838. https://doi.org/10.1016/j.quascirev.2009.10.013

Woodward, S. (2011). *Mineral dust in HadGEM2* (Vol. 87). Hadley Centre Technical Note.

References From the Supporting Information

Kienast, S., Kienast, M., Mix, A., Calvert, S., & Francoise, R. (2007). Thorium-230 normalized particle flux and sediment focusing in the Panama Basin region during the last 30,000 years. *Paleoceanography*, *22*(2), 4. https://doi.org/10.1029/2006PA001357

Marshall, B. (2015). *Proxy development and application for reconstructing the surface ocean carbonate System* (unpublished doctoral dissertation). University of South Carolina. Retrieved from https://scholarcommons.sc.edu/etd/3181

Pichat, S., Sims, K., Francois, R., McManus, J. F., Brown Leger, S., & Albarede, F. (2004). Lower export production during glacial periods in the equatorial Pacific derived from $(^{231}Pa/^{230}Th)_{xs,0}$ measurements in deep-sea sediments. *Paleoceanography*, *19*(4), PA4023. https://doi.org/10.1029/2003pa000994

Skonieczny, C., McGee, D., Winckler, G., Bory, A., Bradtmiller, L. I., Kinsley, C. W., et al. (2019). Monsoon-driven Saharan dust variability over the past 240,000 years. *Science Advances*, *5*(1), eaav1887. https://doi.org/10.1126/sciadv.aav1887

Waelbroeck, C., Lougheed, B., Vazquez Riveiros, N., Missiaen, L., Pedro, J., Dokken, T., et al. (2019). Consistently dated Atlantic sediment cores over the last 40 thousand years. *Scientific Data*, *6*(165), 165. https://doi.org/10.1038/s41597-019-0173-8