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Key Points:

- Dust deposition downwind of North Africa shows contrasting changes in the Atlantic and Mediterranean (Last Glacial Maximum to preindustrial)
- Simulations suggest control through shifted winds around Azores High under steepened meridional temperature gradients
- Shifts in wind direction should be considered when interpreting paleo-dust records

Supporting Information:

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

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Dipole in North African Dust Deposition at the Last Glacial Maximum Explained by Shifted Wind Direction Under Steepened Meridional Temperature Gradients

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Abstract Geological records strongly suggest that, globally, Earth's atmosphere was much dustier than present during the Last Glacial Maximum (LGM) but the explanation is debated, with greater aridity, stronger/gustier winds and less effective washout from a drier atmosphere all invoked. Yet dust deposition can be spatially complex. Both the North Atlantic Ocean and Mediterranean Sea receive dust from the world's main source, North Africa, but they suggest a dipole pattern of dust accumulation with increased and decreased LGM inputs respectively. Here we use pre-industrial and LGM simulations from two Earth System models to investigate this dipole. We show that African dust export westwards to the Atlantic Ocean is favored by steep meridional North Atlantic thermal gradients and a strengthened Azores High while transport northwards to the Mediterranean is favored when temperature gradients and the Azores High are weaker. Our results show that wind direction can strongly influence paleo-dust and -climate records.

Plain Language Summary Geological evidence shows that, compared to today, Earth's atmosphere contained much more dust during the last ice age, especially at its peak, the Last Glacial Maximum (LGM, about 21,000 years ago). These dusty conditions are usually attributed to drought and stronger winds. However, geological reconstructions of dust deposition depend not only on how much dust enters the atmosphere but also on where it is transported by winds. North Africa is the world's largest dust source, supplying both the North Atlantic Ocean and Mediterranean Sea. Yet geological records reveal a surprise for the LGM: dust inputs were higher than today in the North Atlantic but lower in the Mediterranean. We used Earth system models to examine how LGM climate influenced North African dust transport. We identify two main dust transport pathways from North Africa: a westward route toward the North Atlantic and a northward route toward the Mediterranean. Our results show that a stronger latitudinal gradient in surface ocean temperatures in the North Atlantic strengthened the subtropical high-pressure system, favoring the westward pathway while weakening the northward pathway. Our findings highlight the need to consider shifts in wind direction when reconstructing changes in Earth's climate.

1. Introduction

Mineral dust aerosols are an important component of the climate system with major radiative (Miller & Tegen, 1998; Sokolik & Toon, 1996; Woodward, 2001) and biogeochemical effects (Mahowald et al., 2017; Zan et al., 2025). Variations in their spatiotemporal distributions modulate climate feedbacks in both modern (Miller & Tegen, 1998; Yoshioka et al., 2007) and past climates (Albani & Mahowald, 2019; Hopcroft et al., 2015; Hopcroft & Valdes, 2019; Mahowald et al., 2006). Dust deposition in sedimentary archives provides crucial insights into past climate change with downcore dust flux variabilities commonly attributed to temporal changes in dust emissions mainly forced by a combination of changes in sediment availability (Mahowald et al., 2006; Rea, 1994) and the speed/gustiness (McGee et al., 2010) of the wind systems that prevail over dust source areas. More recent studies have linked changes in paleo-dust records to shifting dust transport pathways modulated by large-scale atmospheric circulation (Abell et al., 2021; Venugopal et al., 2023), in a manner analogous to the well accepted role these processes play in controlling dust distributions on intra-seasonal to decadal timescales (Moulin et al., 1997; Rodríguez et al., 2015; Schepanski et al., 2016, 2017). However, the regional atmospheric dynamics linking past circulation changes to dust transport and deposition patterns are far from well understood not least because these effects are yet to be studied with emissions constrained.

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Understanding the mechanisms driving past variability in dust cycling can help validate climate models (Pausata et al., 2016) and improve projections of future change under anthropogenic climate warming. The Last Glacial Maximum (LGM: ~21 thousand years ago, ka) provides a widely used benchmark testing ground for climate models (Braconnot et al., 2012; Harrison et al., 2015; Kageyama et al., 2021) because it involved a global radiative forcing change comparable in amplitude to the one projected for the end of this century (Friedrich et al., 2016) with climate boundary conditions (e.g., major Northern Hemisphere ice sheets; lower atmospheric CO₂ concentration) distinct from the preindustrial (PI) era (Clark et al., 2009; Petit et al., 1999). Paleoclimate reconstructions suggest a more active global dust cycle during the LGM than during the PI, especially in mid-to-high latitudes (Cosentino et al., 2024; Kohfeld & Harrison, 2001; Lambert et al., 2008; Maher et al., 2010). This result is commonly attributed to increased dust emissions associated with colder, drier, windier and less-vegetated conditions than today (Harrison et al., 2001). Yet, despite its significant contributions to global and regional radiative forcings (Albani & Mahowald, 2019; Hopcroft et al., 2015; Kageyama et al., 2017; Köhler et al., 2010; Mahowald et al., 2024), very few studies have attempted to properly represent and study dust in LGM simulations because only a handful of models are equipped with both the fully interactive dust cycle and dynamic vegetation modules required to simulate dust cycling (Albani et al., 2018).

Approximately half of the modern day total atmospheric dust load originates from North Africa (Kok et al., 2021) and the magnitude of dust export from this key source has waxed and waned for at least the last 11 million years in response to changes in insolation paced by the precession of Earth's axis and modulated by long-term changes in global climate state (Crocker et al., 2022). In addition to precession-paced low-latitude hydroclimate variability (Skonieczny et al., 2019), reconstructions of North African dust for the Quaternary suggest sensitivity to high latitude climate forcing associated with glacial-interglacial cycles (also a response to astronomically forced insolation change) (deMenocal, 1995; Trauth et al., 2009) and to abrupt cooling events in the North Atlantic Ocean associated with disruption to the Atlantic meridional overturning circulation (AMOC) (Kinsley et al., 2022; McGee et al., 2013; Mulitza et al., 2008). However, past records also reveal striking basin-to-basin variability in dust records. Off the coast of Northwest Africa and in the mid-latitude North Atlantic Ocean, dust fluxes for the LGM are higher than for the late Holocene (Kienast et al., 2016; McGee et al., 2013; Middleton et al., 2018) while dust records from the Mediterranean Sea, also downwind of North African dust sources, suggest significantly lower dust inputs during the LGM compared to the late Holocene (Ehrmann & Schmiedl, 2021). Decoupling between these two neighbouring regions downwind of the same overall source region raises questions about the way in which records of dust deposition are interpreted (e.g., Crocker et al., 2025; McGee et al., 2007; Rowland et al., 2021), implying a potential role of atmospheric dust transport processes. Here, we use the results from a suite of PI and LGM simulations from two Earth System models to evaluate mechanistic forcing of the North African dust cycle in response to a major shift in global and especially high northern latitudes, climate.

2. Methods

2.1. Models

We use the Hadley Centre Global Environment Model 2 (HadGEM2) and the Community Earth System Model 1 (CESM1), two global Earth system models that contribute to the Coupled Modeling Intercomparison Project (CMIP) and Paleoclimate Modeling Intercomparison Project (PMIP) (Braconnot et al., 2012; Brady et al., 2013; Jones et al., 2011). We performed a new LGM simulation using HadGEM2 and compared it with existing simulations from HadGEM2 and CESM1 (Albani et al., 2016; Hopcroft et al., 2015). The dust schemes in HadGEM2 (Bellouin, Rae, et al., 2011) and CESM1 (Mahowald et al., 2006; Zender et al., 2003) include broadly comparable representations of dust mobilization (emission), transport, and deposition, with the latter being the sum of wet and dry deposition.

For HadGEM2, we use its atmosphere, land surface and aerosol components (Bellouin, Collins, et al., 2011; Collins et al., 2011) in an atmosphere-only configuration (HadGEM2-A), with a dynamic vegetation scheme (Cox, 2001), land surface scheme (Collins et al., 2011), and a comprehensive representation of seven aerosol species (Bellouin, Rae, et al., 2011). Dust emissions are computed as a function of wind speed, soil moisture and bare soil area determined dynamically (Bellouin, Rae, et al., 2011; Woodward, 2011). Dust emissions and transport are calculated for six bins of particulates ranging in diameter from 0.0632 to 63.2 μm. The model parameters for land surface are tuned to prevent unrealistic bare soil expansion under LGM conditions (Hopcroft

& Valdes, 2015). The atmosphere-only configuration is prescribed with monthly sea surface temperature (SST) and sea-ice distributions derived from coupled simulations with the HadCM3 model (Singarayer & Valdes, 2010; Valdes et al., 2017). Because the focus of this study is North Africa, glaciogenic dust sources are not included in the LGM simulation. The globally integrated dust emission scheme was tuned using present day simulations for use in CMIP5 (Bellouin, Rae, et al., 2011; Collins et al., 2011) and this release version is used in this study and other related work (e.g., Hopcroft & Rousseau, 2026).

CESM1 (Gent et al., 2011) is used in fully coupled configuration with the dust Bulk Aerosol Model coupled to the Community Atmosphere Model 4 (Albani et al., 2014) to simulate the dust cycle response to the LGM boundary condition using PMIP3 equilibrium simulations as initial conditions following the PMIP3 protocol for greenhouse gases, land and ice sheets (Brady et al., 2013). Dust particles are represented in four bins spanning 0.1–10 μm diameter. Dust emissions vary in response to changes in vegetation area (Albani et al., 2014; Kaplan et al., 2003), with their magnitude and spatial patterns constrained separately for PI and LGM by quantitative reconstructions of dust mass accumulation rates and provenance fingerprints derived from radiogenic isotopes (Albani et al., 2014, 2016).

2.2. LGM Simulation Forced by Reconstruction-Based SST (LGM_reconSST)

There has been a long-running debate over the spatial distribution of SST cooling (and in some regions warming) at the LGM relative to the PI. This is true both among models (Kageyama et al., 2021) and between models and reconstructions (Jonkers et al., 2023; Paul et al., 2021; Tierney et al., 2020; Waelbroeck et al., 2009), particularly in the North Atlantic region. To test the extent to which representation of the LGM SST field can alter the response of the dust cycle, we performed an LGM simulation (LGM_reconSST) forced with reconstruction-based monthly SST and sea ice fields (Paul et al., 2021). Note that only HadGEM2 was used in the LGM_reconSST experiment and we compare it with the original HadCM3-based SST field (LGM_modelSST).

2.3. Composite Analyses

To quantify the atmospheric dynamics and hence mechanistic controls on North African dust transport pathways, we performed composite analyses of monthly outputs from all simulations in both models. To account for seasonal variability, the monthly data were averaged for each season (DJF, MAM, JJA, SON) over 30 modeled years following a spin-up. For each simulation, we calculated the ratio of dust deposition between the subtropical Northeast Atlantic (16°W–40°W, 18°N–30°N) and the Mediterranean Sea (0°–30°E, 30°N–45°N). Model years with ratios above the 75th percentile (“high-ratio” years) and below the 25th percentile (“low-ratio” years) were composited and compared.

3. Results and Discussion

3.1. Distinct Dust Responses to Different SST Forcing Scenarios

The surface temperature anomaly for the LGM_modelSST—PI differs significantly from that for the LGM_reconSST—PI over the North Atlantic basin, with relatively small differences away from the North Atlantic (Figures 1a and 1b; Figure S1 in Supporting Information S1). The LGM_reconSST—PI shows a strong cooling pattern in mid-to-high latitudes (40–70°N) of the North Atlantic, with more intense cooling in the subpolar region (50–60°N; -13.2°C) and muted changes in subtropical North Atlantic (Figure 1b). These results are consistent with previous studies, in which a steeper meridional SST gradient in the North Atlantic is observed in reconstructions compared with coupled model simulations for the LGM (Jonkers et al., 2023; Paul et al., 2021; Waelbroeck et al., 2009), likely resulting from an inaccurate representation of the AMOC in the equilibrium simulations (Jonkers et al., 2023).

Forced with different SST fields, the LGM_modelSST and LGM_reconSST runs exhibit distinct responses in the dust cycle (Figure 1). Dust emissions are generally higher in North Africa in the LGM_modelSST simulation relative to the PI (+294 Tg/yr; Figure 1c), with higher emissions in both Northwest (20°W–7.5°E, 18°N–37.5°N; +58 Tg/yr) and Northeast Africa (7.5°E–35°E, 18°N–37.5°N; +236 Tg/yr). Dust emissions in the LGM_reconSST run are also higher than in the PI but the response (+80 Tg/yr; Figure 1d) is smaller than in the LGM_modelSST run. This is because, while LGM emissions are higher in Northeast Africa (+114 Tg/yr) than in the PI, they are lower in Northwest Africa (–34 Tg/yr). There are also significant differences in dust deposition

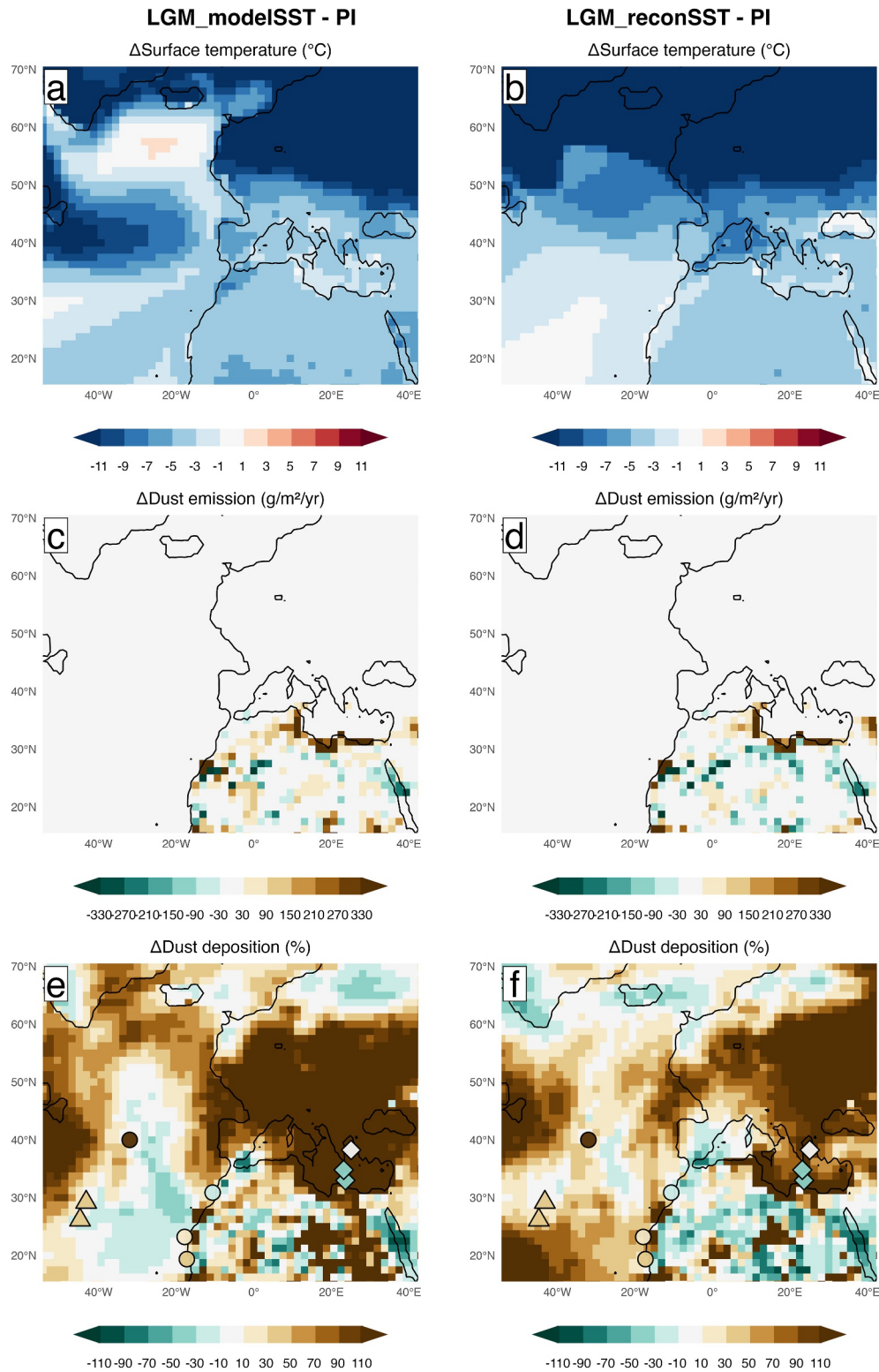


Figure 1. Simulated differences in the LGM_modelSST (left) and LGM_reconSST (right) relative to the PI in the HadGEM2 simulations. (a, b) Surface temperature anomalies (°C). (c, d) Modeled dust emission anomalies ($\text{g/m}^2/\text{yr}$). (e, f) Modeled dust deposition anomalies (colored shading) relative to PI (%). Also shown are reconstructed dust changes during the LGM (19–23 ka) relative to the late Holocene (0–4 ka) indicated by colored symbols: ^{230}Th -normalized dust flux (circles) (Lippold et al., 2012; McGee et al., 2013), $^3\text{He}_{\text{ET}}$ -normalized dust flux (triangles) (Middleton et al., 2018), and clay-sized Saharan dust influx as expressed by kaolinite/chlorite ratios (diamonds) (Ehrmann & Schmiedl, 2021). Coastlines are based on the ICE-5G LGM configuration (Peltier, 2004).

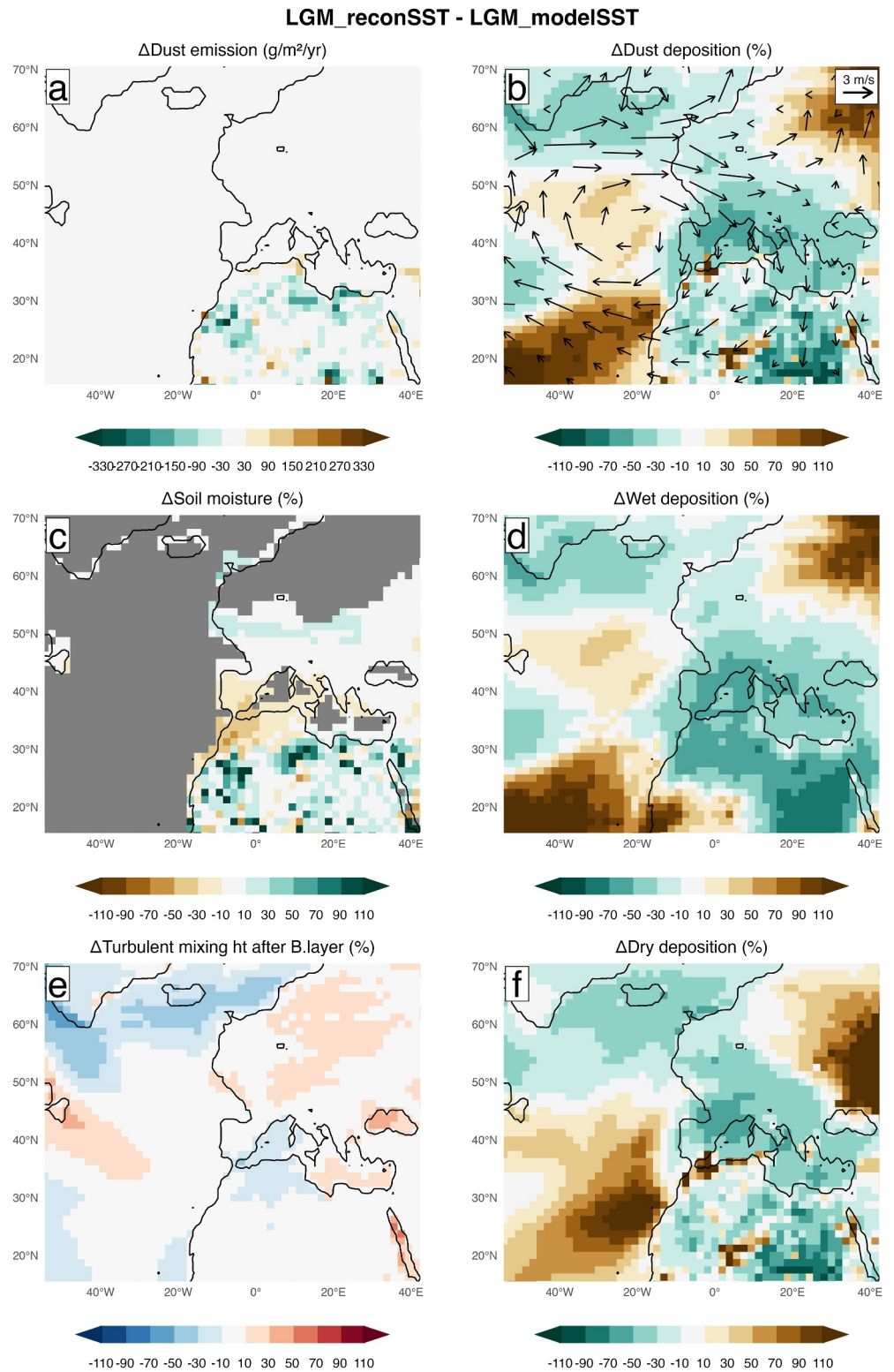
between the LGM_modelSST and LGM_reconSST runs (Figures 1e and 1f). When the LGM_modelSST field is prescribed, dust deposition in the subtropical Northeast Atlantic Ocean is lower (−15%) relative to the PI (Figure 1e) while dust deposition over the Mediterranean Sea is much higher (+367%) than during the PI. When the LGM_reconSST field is prescribed, dust deposition rates are higher in both the subtropical Northeast Atlantic (+47%) and over the Mediterranean Sea (+238%) compared to the PI (Figure 1f).

To evaluate the modeled dust deposition anomalies in the two LGM simulations relative to PI, these results are compared with a suite of dust reconstructions from marine cores located downwind of North Africa (Figures 1e and 1f; Table S1 in Supporting Information S1). ^{230}Th - and $^3\text{He}_{\text{ET}}$ -normalized dust flux records from marine sediment cores lying to the west of North African dust sources off Northwest Africa (McGee et al., 2013) and in the mid-latitude North Atlantic Ocean (Lippold et al., 2012; Middleton et al., 2018) indicate higher dust fluxes during the LGM than in the late Holocene. In contrast, a suite of sediment cores lying to the north of North Africa, including one at 31°N in the North Atlantic (McGee et al., 2013) and clay mineral-based reconstructions (kaolinite/chlorite ratios track inputs from lateritic North African soils (Scheuven et al., 2013)) from the Mediterranean Sea (Ehrmann & Schmiedl, 2021) indicate lower dust inputs during the LGM than during the late Holocene. Although both the LGM_modelSST and LGM_reconSST fail to simulate the observed lower dust deposition in the Mediterranean relative to the PI (Figures 1e and 1f), the overprediction is significantly reduced when the colder subpolar LGM SSTs (LGM_reconSST) are prescribed. Therefore, the dust deposition patterns that we simulate in HadGEM2 using the colder subpolar SSTs show better agreement with the downcore records from the North Atlantic and Mediterranean Sea (Figure 1f) than those simulated using the LGM_modelSST field (Figure 1e).

3.2. Decoupling Between Dust Emission and Deposition

Figure 2 shows anomalies for the LGM_reconSST minus LGM_modelSST simulations. Dust emissions across North Africa are substantially lower in the colder subpolar LGM SST simulation (by −212 Tg/yr, Figure 2a). We attribute this result to the lower aridity across the North Africa indicated by higher surface soil moisture content (Figure 2c), and very slightly by reduced gustiness in the Northwest Africa (indicated by a lower turbulent mixing height, Figure 2e) in LGM_reconSST.

In the LGM_reconSST run with more realistic SSTs, where the prescribed subpolar SST field is colder, our simulations show markedly higher dust deposition rates over most of the North Atlantic Ocean and noticeably lower deposition rates over the Mediterranean Sea (Figure 2b) relative to LGM_modelSST. The subtropical Northeast Atlantic and Mediterranean Sea receive aeolian dust primarily from North Africa in both the modern climate (Kok et al., 2021; Mahowald et al., 2006) and during the LGM based on deposited sediment provenance reconstructions (Blanchet et al., 2021; Crocker et al., 2025; Grousset et al., 1998; Rodrigo-Gámiz et al., 2015; Sarnthein et al., 1981). Our results, in which higher rates of deposition (+75%) are achieved in the subtropical Northeast Atlantic despite lower emissions over North Africa in the LGM_reconSST run relative to the LGM_modelSST run, show that changes in emissions do not necessarily translate directly into changes in deposition and, regionally, they may even yield change of opposing sign (Figures 2a and 2b). Such behavior can be accounted for by either transport or depositional processes. Changes in wet deposition can exert strong control on total deposition rate, particularly in regions where rainfall is highly seasonal (Mahowald et al., 2011; Rowland et al., 2021; van der Does et al., 2020, 2021). However, in LGM_reconSST—LGM_modelSST anomalies, both wet and dry deposition patterns are very similar to total dust deposition patterns (compare Figures 2b, 2d, and 2f). Similar patterns are also evident across all seasons and size bins (Figures S2, S3 and S4 in Supporting Information S1). Therefore, changes in dust deposition processes are unlikely to be the primary driver of the large-scale decoupled behavior identified between emission and deposition. This leaves changes in dust transport as the most viable explanation for the decoupling of dust deposition from emissions. This hypothesis is supported by the 850 hPa wind anomalies for LGM_reconSST—LGM_modelSST (Figure 2b), which show an anticyclonic anomaly centered west of Iberia, facilitating a northerly wind field anomaly over the Mediterranean Sea and an easterly wind field anomaly over North Africa. This feature, together with the strong spatial correspondence between the dust deposition and wind anomalies, strongly suggests that changes in tropospheric wind flow drive the switch in North African dust transport from a more northward pathway (in LGM_modelSST) to a more westward pathway in LGM_reconSST (Figure 2b).



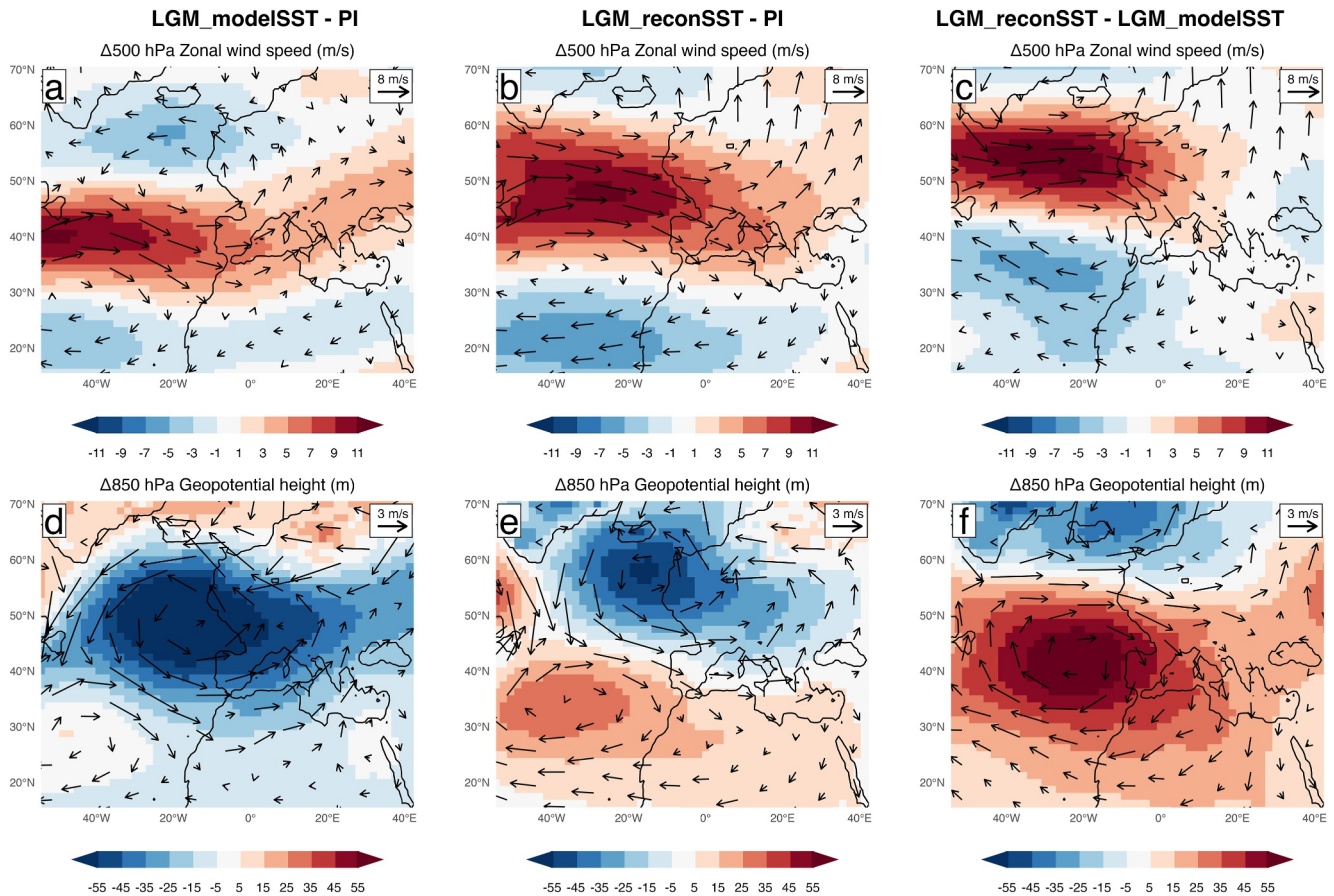


Figure 3. Simulated differences in the LGM_modelSST—PI (left), LGM_reconSST—PI (middle) and LGM_reconSST—LGM_modelSST (right) in HadGEM2 simulations. (a–c) 500 hPa zonal wind speed (m/s, colored shading) and wind vector anomalies (m/s, arrows). (d–f) 850 hPa geopotential height (m, colored shading) and wind vector anomalies (m/s, arrows).

3.3. North African Dust Deposition Patterns Driven by Atmospheric Circulation

To investigate the mechanistic links between North Atlantic Ocean temperatures, 850 hPa wind flow and dust transportation pathways, we examined the response of atmospheric pressure and large-scale circulation to different SST fields (Figure 3).

Forced with distinct SST inputs (Figures 1a and 1b), the LGM_modelSST and LGM_reconSST show markedly different atmospheric circulation patterns (Figure 3), with the mid-latitude Jet Stream shifted poleward in LGM_reconSST relative to LGM_modelSST (Figures 3a–3c). This is dynamically consistent with the steeper meridional SST gradient between 40°N and 60°N over the North Atlantic (Figure S5 in Supporting Information S1) as implied by thermal wind balance. We also identify a stronger and more poleward-extending Northern Hemisphere subtropical overturning circulation in LGM_reconSST (Figure S6 in Supporting Information S1), consistent with a strengthened Azores High anticyclonic system (Figures 3d–3f). This enhanced overturning may be linked to enhanced mid-latitude eddy activity which is ultimately driven by a steeper North Atlantic SST gradient in LGM_reconSST (e.g., Caballero, 2007; Walker & Schneider, 2006).

The strengthened Azores High in LGM_reconSST, in turn, enhances westward flow from North Africa toward the North Atlantic while weakening northward flow toward the Mediterranean (Figure 3f). Critically, the pattern of 850 hPa wind anomalies switches sign over North Africa when we compare LGM_modelSST—PI and LGM_reconSST—PI (Figures 3d and 3e), matching the dust deposition anomalies surrounding North Africa (Figures 1e and 1f). This is dynamically consistent with both the modeled and reconstructed dust deposition anomalies surrounding North Africa (Figure 1f, and discussed above).

The large-scale atmospheric circulation pattern produced in LGM_reconSST—PI, wherein a strengthened Azores High during the LGM facilitates a westerly wind anomaly north of the subtropical gyre and an easterly wind anomaly to the south (Figure 3e), is consistent with the stronger wind stress curl and deepened North Atlantic subtropical ocean gyre inferred for the LGM (Wharton et al., 2024) (Figure S7 in Supporting Information S1). The atmospheric circulation pattern produced in LGM_modelSST—PI, on the other hand, is not supported in this way and we do not use it in our subsequent analyses.

To further test the inferred causal link between atmospheric circulation and dust deposition patterns, we used composite analysis to identify the atmospheric conditions associated with preferential Saharan dust flux to the North Atlantic in two Earth System models (Figure 4). In both models the modeled years that favor dust deposition in the North Atlantic are associated with an enhanced westward and a weakened northward dust export from North Africa (Figures 4a and 4b). Both models show strikingly similar atmospheric circulation patterns favoring the westward North African dust transport pathway, with a northward shifted North Atlantic Jet Stream (Figures 4c and 4d) and a strengthened Azores High anticyclonic system (Figures 4e and 4f). The atmospheric circulation patterns favoring enhanced westward and reduced northward dust transport are also robust across different seasons, dust deposition mechanisms (wet vs. dry) and grain size bins (Figures S8–S16 in Supporting Information S1), with all anomalies resembling those of the HadGEM2 LGM_reconSST—LGM_modelSST (Figures 3c and 3f). We therefore conclude that changes in large-scale atmospheric circulation are responsible for both the modeled and reconstructed dust deposition patterns, wherein a stronger anticyclonic system over the Azores under steeper meridional SST gradients favors westward transport of North African dust and suppresses northward transport, creating a dipole pattern of deposition between the western Mediterranean Sea and subtropical North Atlantic Ocean (Figure 2b).

The mechanistic link we propose to explain LGM North African dust transport is rooted in a large-scale atmospheric circulation adjustment to SST field and supported by modern observations. The North African dipole, a measure of low-level geopotential height gradient between tropical and subtropical North Africa (Rodríguez et al., 2015), is known to be modulated by the regional atmospheric circulation associated with the Azores High system and exerts a critical control on summer-time North African dust transport pathways on intra-annual to interannual timescales (Rodríguez et al., 2015; Schepanski et al., 2016, 2017). Our work strongly suggests that similar mechanisms can operate on paleo-timescales and may influence dust deposition patterns and fluxes recorded by sedimentary archives (Figures 1e and 1f).

3.4. Implications for Paleo-Dust Reconstructions

Our results suggest that spatial and temporal variations in dust deposition are not solely determined by emission strength but can also be strongly modulated by atmospheric transport. Specifically, our simulations suggest that the higher dust fluxes observed in the subtropical Northeast Atlantic during the LGM can be accounted for by a strengthened Azores High anticyclonic system associated with a steeper meridional SST gradient in the North Atlantic Ocean without necessarily requiring increased dust emissions from North Africa.

Our main finding is that geological records of past variability in dust accumulation are sensitive to changes in wind direction as well as wind strength and aridity as shown for past latitudinal shifts in the westerlies winds (Abell et al., 2021; Venugopal et al., 2023). Shifts in the direction of dust-transporting winds over Africa can be mechanistically linked to adjustments in large-scale atmospheric circulation driven by changes in high latitude climate (such as glaciation). Because the atmospheric circulation patterns governing dust transport from North Africa are controlled by latitudinal temperature gradients, we posit that this mechanism likely contributed to the elevated dust fluxes recorded at distal sites in the subtropical mid-Atlantic Ocean during the millennially paced cold events of the last glacial (Middleton et al., 2018). Variability in wind direction may also help explain why the dust flux response to North Atlantic cooling is not uniform at more proximal sites along the Northwest African margin, for example, the different magnitudes of response observed north and south of 20°N during the Younger Dryas and Heinrich Stadial 1 cold events (Kinsley et al., 2022; McGee et al., 2018). Further model-data integration studies will help test the roles of atmospheric circulation versus dust emissions in driving dust deposition in sedimentary archives across the globe.

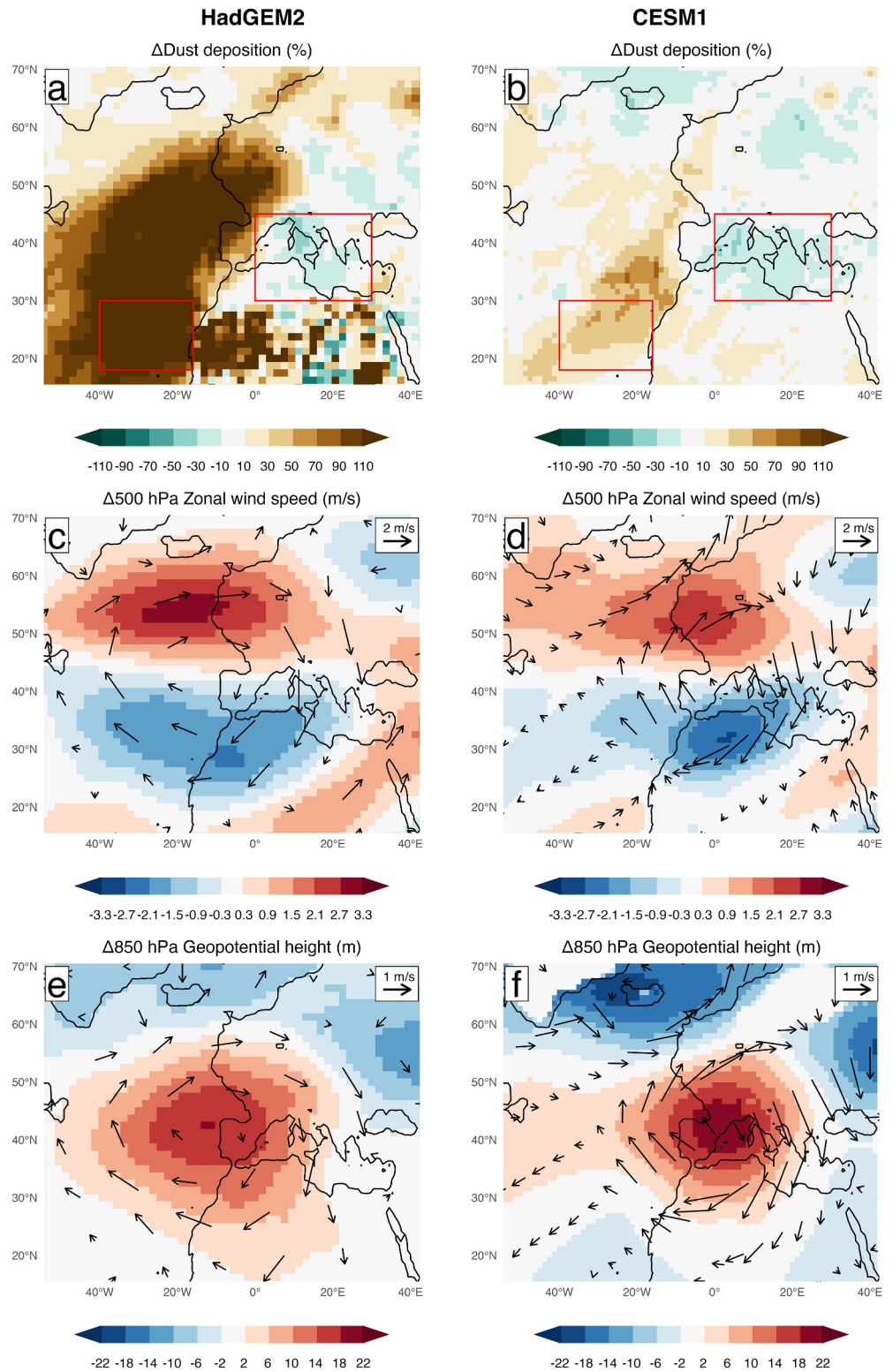


Figure 4. Composite analyses for the differences between the modeled years with high (>75th percentile) and low (<25th percentile) ratios in dust deposition between the subtropical Northeast Atlantic and Mediterranean Sea regions (marked by red boxes) in the LGM_reconSST run of HadGEM2 (left) and LGM simulation of CESM1 (right). (a, b) Dust deposition anomalies (%). (c, d) 500 hPa zonal wind speed (m/s, colored shading) and wind (m/s, arrows) anomalies. (e, f) 850 hPa geopotential height (m, colored shading) and wind (m/s, arrows) anomalies.

4. Conclusions

We used a suite of Earth System model simulations to reveal how atmospheric dynamics influence spatial patterns of North African dust deposition during the LGM. Simulations forced with a reconstruction-based (cold subpolar) North Atlantic SST field for the LGM yield dust deposition patterns that better align with downcore paleo-dust records than those forced by a model-derived SST field. Our results reveal a decoupling between dust emissions and deposition surrounding North Africa, with a dipole pattern in modeled dust deposition between the subtropical North Atlantic and western Mediterranean revealing the importance of atmospheric circulation in controlling dust transport pathways. The cold subpolar North Atlantic Ocean of the LGM steepens latitudinal temperature gradients and strengthens anticyclonic flow around an intensified Azores High pressure cell favoring westward- and suppressing northward-transport of dust from North Africa. Our study implies that shifts in wind direction contribute to the elevated dust fluxes recorded for millennially paced cold events in the North Atlantic Ocean. Shifts in wind direction must be considered when interpreting geological records of past change in dust cycling. Our results show that the impact of shifting wind direction can be large. So large in fact that, temporal changes in rates of dust deposition cannot automatically be assumed to faithfully record even the sign of change in emissions at source.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

All HadGEM2 and CESM1 model outputs are available for further analysis from Zhu (2025): <https://doi.org/10.5281/zenodo.18017718>.

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Erratum

Since original publication of this article the following sponsor has been removed from the funding information: Birmingham Environment for Academic Research. This may be considered the authoritative version of record.