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Gustiness: The driver of glacial dustiness?

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ABSTRACT

During glacial periods of the Late Quaternary, mineral dust emissions from Earth's dominant source areas were a factor of 2–4 higher than interglacial levels. The causes of these fluctuations are poorly understood, limiting interpretation of dust flux records and assessment of dust's role in past climate changes. Here we consider several possible drivers of glacial–interglacial dust flux changes in an effort to assess their relative importance. We demonstrate that a wide range of data supports wind gustiness as a primary driver of global dust levels, with steepened meridional temperature gradients during glacial periods causing increases in dust emissions through increases in the intensity and frequency of high-speed wind events in dust source areas. We also find that lake level records near dust source areas do not consistently support the hypothesis that aridity controls glacial–interglacial dust emission changes on a global scale, and we identify evidence negating atmospheric pCO_2 and sea level as dominant controls. Glaciogenic sediment supply, vegetation and aridity changes appear to be locally important factors but do not appear to explain the global nature of glacial–interglacial dust flux changes. We suggest that the gustiness hypothesis is aviable explanation for the close correspondence between dust emissions and high-latitude temperatures observed in paleorecords and is worthy of further testing.

1. Introduction

Records of mineral dust deposition in ice caps, ocean and lake sediments and loess deposits suggest that glacial climates of the Late Quaternary were accompanied by high dust emissions from each of the world's major source areas. Dust flux reconstructions reflecting emissions from North Africa, the Arabian Peninsula, East Asia, southern South America and Australia each show a factor of 2–4 increase in dust deposition during glacial periods (Hovan et al., 1989; Hesse, 1994; Rea, 1994; Tiedemann et al., 1994; Kohfeld and Harrison, 2001; Pourmand et al., 2004; Mahowald et al., 2006; Martínez-Garcia et al., 2009; Maher et al., 2010), while high-resolution records indicate that millennial-scale cold periods of the last glacial period and deglaciation were marked by abrupt dust flux increases (Mayewski et al., 1997; Fischer et al., 2007; Yancheva et al., 2007; Tjallingii et al., 2008). Major dust sources also developed in North America, Europe, central Asia and Siberia during glacial periods, forming thick loess deposits in each region (Mahowald et al., 2006; Maher et al., 2010 and references therein).

The remarkable consistency of dust flux changes from sources around the world, along with the strong coherence observed between high and low latitude dust records over multiple glacial cycles (Winckler et al., 2008), suggests that these variations reflect a global driver rather than local factors. At present there is no clear agreement on the dominant cause of glacial–interglacial changes in global dust emissions: high glacial dust levels have been variously attributed to source area aridity (Rea, 1994), wind strength (Werner et al., 2002), fine-grained sediment supply from glacial erosion (Reader et al., 1999; Sugden et al., 2009), exposure of continental shelves by sea level changes (De Angelis et al., 1997) and vegetation inhibition by low atmospheric CO_2 (Mahowald et al., 1999, 2006).

Our lack of understanding of the controls on global dustiness presents a barrier both to better modeling of dust's climate impacts and to accurate interpretation of dust flux records. Here we evaluate the importance of these proposed drivers in three major dust source areas – North Africa, East Asia and southern South America – drawing upon paleoclimate data, modern observations, and model results.

We specifically explore the hypothesis that winds – and in particular, high-speed wind events – are the primary driver of global dustiness on glacial–interglacial time scales. As described in

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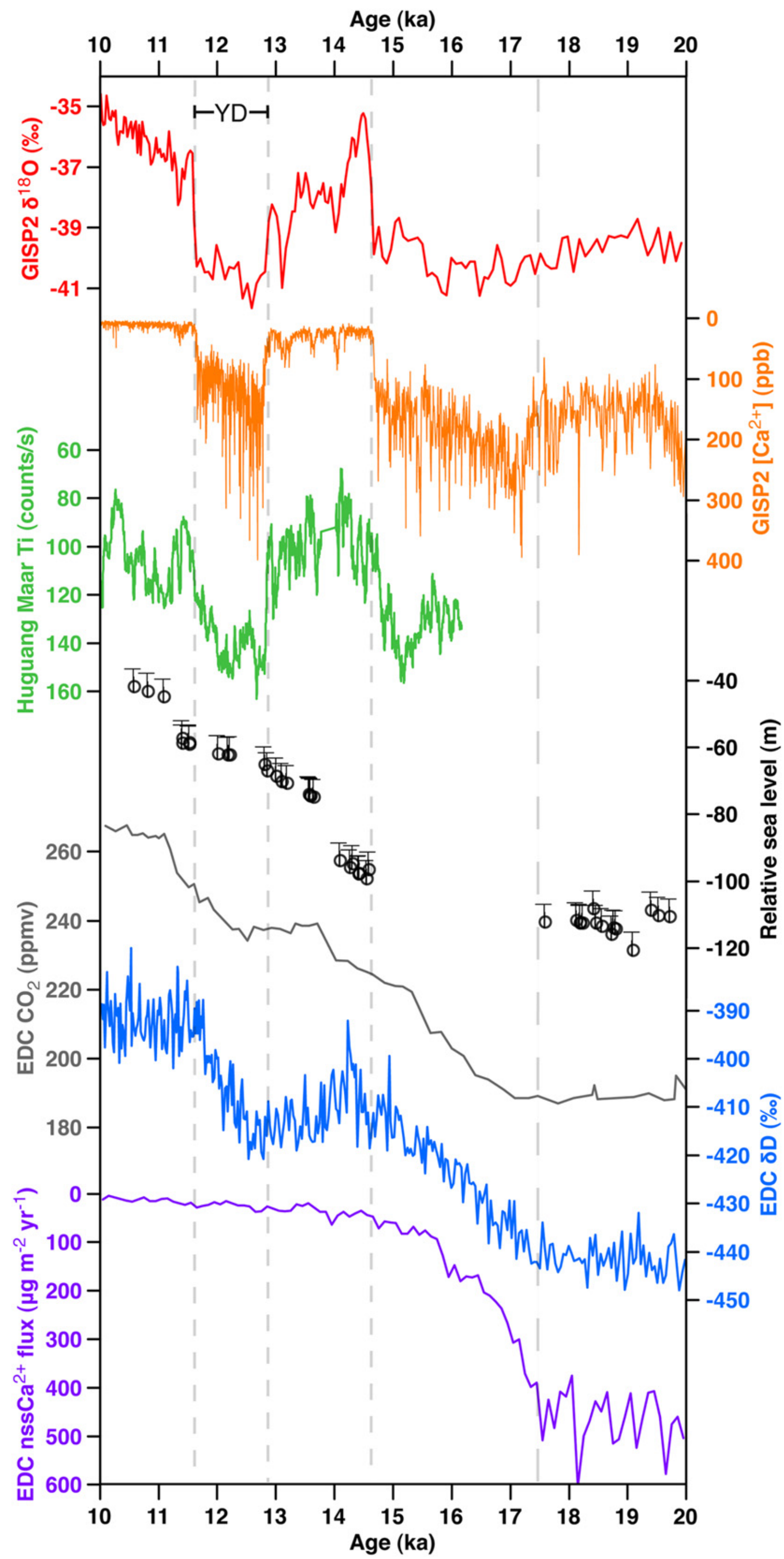

Fig. 1. Dust fluxes and related climate proxy data during the last deglaciation. Proxy records of high-latitude temperature and dust flux (with reversed scale) demonstrate tight links in each hemisphere, while dust fluxes do not appear to follow pCO_2 and sea level changes. Dashed lines indicate onsets of temperature changes in Antarctica or Greenland for comparison with dust records. From top: $\delta^{18}O$ (Grootes et al., 1993) and $[Ca^{2+}]$ (Mayewski et al., 1997) from Greenland's GISP2; Ti counts, representing dust deposition, from Huguang Maar lake in Southern China (Yancheva et al., 2007); sea level data from Barbados (Peltier and Fairbanks, 2006); pCO_2 (Monnin et al., 2001), δD (Augustin et al., 2004) and non-sea salt Ca^{2+} fluxes (Röthlisberger et al., 2008) from EPICA Dome C in Antarctica. YD: Younger Dryas. Data from GISP2 are plotted on the Blunier and Brook (2001) age model. EPICA Dome C data are shown on the EDC3 time scale (Parrenin et al., 2007).

Section 2, the importance of gustiness in dust emissions has been previously explored both in modern observations and models of modern dust emissions; separate studies have suggested that increased gustiness may have played a role in increased dust emissions during glacial periods (Fuhrer et al., 1999; Reader et al., 1999; Fischer et al., 2007; Röthlisberger et al., 2008), but these studies have not sought to test this proposition, nor have they considered gustiness as a primary driver. We do not offer new data; instead, the novel contribution of this study is to provide a more complete assessment of the role of gustiness in glacial–interglacial dust flux changes by 1) integrating paleoclimate data, modern observations and model results to explore relationships between high-latitude temperatures, gustiness and dust emissions, and 2) using paleoclimate data to assess other potential controls on global dust levels.

2. Dust, gustiness and high-latitude temperatures

Dust flux records from both ice caps and more proximal deposits show tight coupling with high-latitude temperatures (Figs. 1 and 2). High-resolution data from EPICA Dome C in Antarctica show synchronous changes in proxies for local temperature (δD) and dust

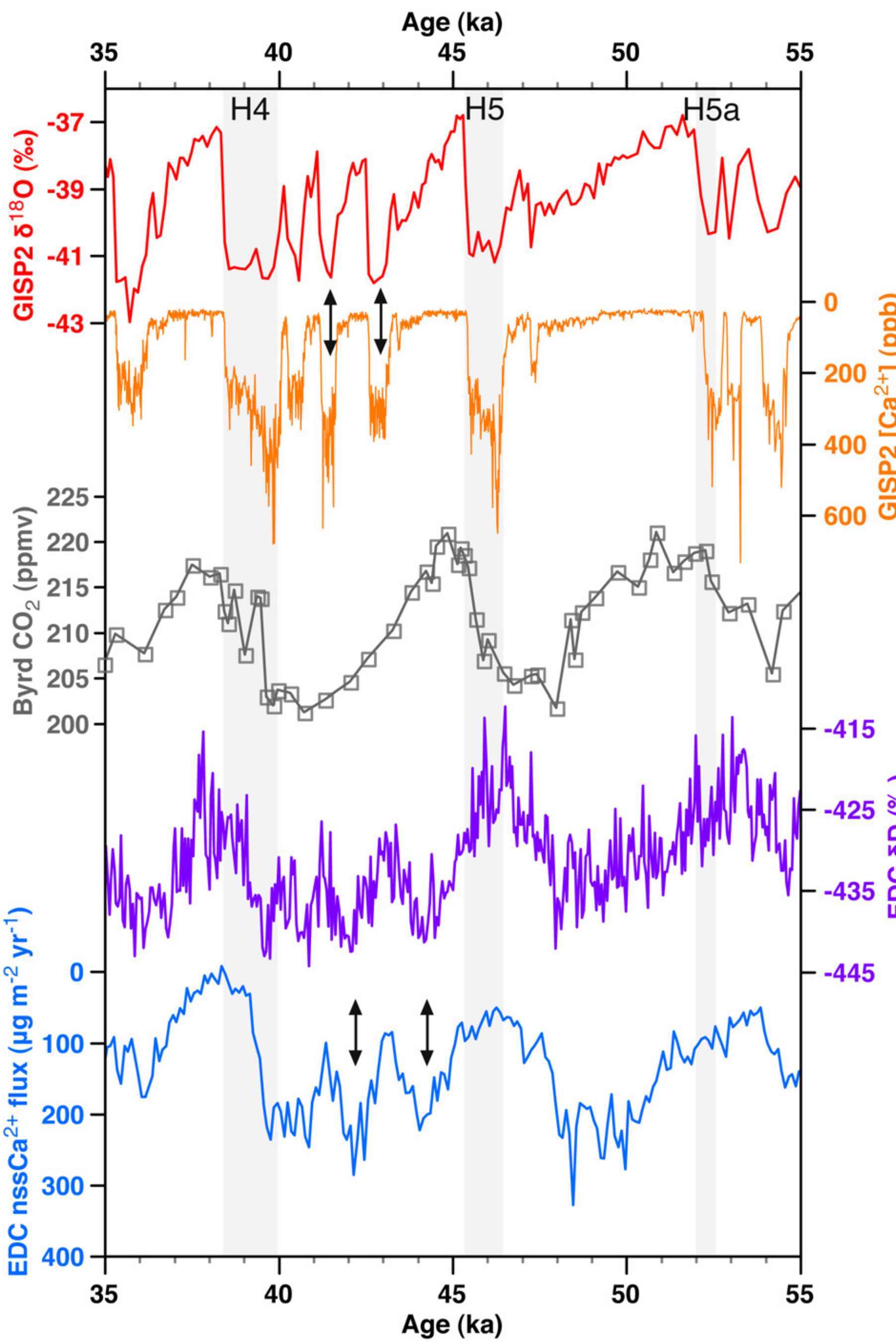

Fig. 2. Ice core records from 55 to 35 ka. GISP2 and EDC records as in Fig. 1; pCO_2 from the Byrd ice core (Ahn and Brook, 2008). Heinrich events H4, H5, and H5a show high dust in Greenland during periods of rising atmospheric pCO_2, in opposition to the relationship expected if pCO_2 controlled source area extent. Arrows indicate examples of millennial-scale changes in both hemispheres showing tight links between dust and local temperature proxies and no correspondence with pCO_2 changes. Data from GISP2 and Byrd ice cores are plotted on age models synchronized using CH_4 data (Blunier and Brook, 2001), while the EDC data are plotted using the EDC3 time scale (Parrenin et al., 2007).

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flux (non-sea salt Ca^{2+}) at the onsets of the past eight glacial terminations (Röthlisberger et al., 2008). In Greenland, records with sub-decadal resolution from the NGRIP ice core demonstrate that abrupt changes in both Ca^{2+} and the temperature proxy $\delta^{18}O$ occur with no consistent leads or lags (Fischer et al., 2007; Steffensen et al., 2008). Closer to dust source regions, a high-resolution record from Huguang Maar lake in southern China shows dramatic changes in dust flux coinciding with deglacial temperature changes in Greenland (Yancheva et al., 2007) (Fig. 1), and records from the North African margin show increases in dust deposition during Heinrich events (Tjallingii et al., 2008), periods of enhanced winter cooling in high northern latitudes. The ice core and Huguang Maar records also demonstrate that large-amplitude dust flux changes – approaching the full range of glacial–interglacial changes – can occur extremely quickly; in NGRIP these changes occur over periods of a few years to decades (Fischer et al., 2007; Steffensen et al., 2008).

These observations pose a key test for any hypothesized driver of the global dust system: it must explain both the close correlations and near-zero lag between changes in high-latitude temperatures and dust emissions in remote source areas. As explained in Sections 3 and 4, we suggest that wind gustiness could provide a robust means of linking high-latitude temperatures to dust emissions.

We focus on the strength and prevalence of strong winds, referred to hereafter as "gustiness", rather than mean wind speed due to the non-linear relationship between wind speed and dust entrainment (Gillette, 1974). Dust emissions typically scale with the cube of wind speed, as stronger winds have more energy available for particle entrainment and create additional fine particles by breaking up soil aggregates (Alfaro and Gomes, 2001).

The sensitivity of dust emissions to gustiness is well established by both modern observations and models. Measures of wind gustiness taken from reanalysis datasets (i.e., datasets of atmospheric variables based on observations and model output) correlate 70% better with dust storm activity than does mean wind speed (Engelstaedter and Washington, 2007b). Gustiness appears to be the dominant factor in determining modern dust emissions both from East Asian sources (Sun et al., 2001; Laurent et al., 2005) and from the Bodélé Depression, the dominant dust source in North Africa (Washington and Todd, 2005). In dust models, small changes in the wind speed distribution can have dramatic effects. Timmreck and Schulz (2004) found a 2-fold difference in simulated dust fluxes using versions of an atmospheric model that produced slight differences in the prevalence of high-speed winds, and Tegen et al. (2002) were able to produce a doubling of simulated annual dust fluxes by doubling wind speeds in only three 6-hourly time steps over the course of a year. Recognizing the significance of gusts, one model of glacial dust emissions attempted to account for the tendency of modeled winds to underestimate wind speed variance, but the model assumed that this variance (i.e., gustiness) was the same in modern and glacial climates (Werner et al., 2002).

To further illustrate the importance of wind gusts, in Fig. 3 we plot wind speed data from a North African meteorological station recording maximum wind speeds in each 1-minute interval. In this month-long dataset, winds greater than the average regional threshold wind speed of 8 m s^{-1} (Chomette et al., 1999) occurred only 2.3% of the time. Using a cubic relationship between wind speed and dust emissions (Gillette, 1974; Tegen and Rind, 2000), the top 0.1% of this wind speed distribution accounts for more than 50% of modeled dust emissions. The prevalence of dust-generating winds increases to 10% with a lower threshold wind speed of 6 m s^{-1}, but 50% of emissions are still driven by only the top 0.3% of winds.

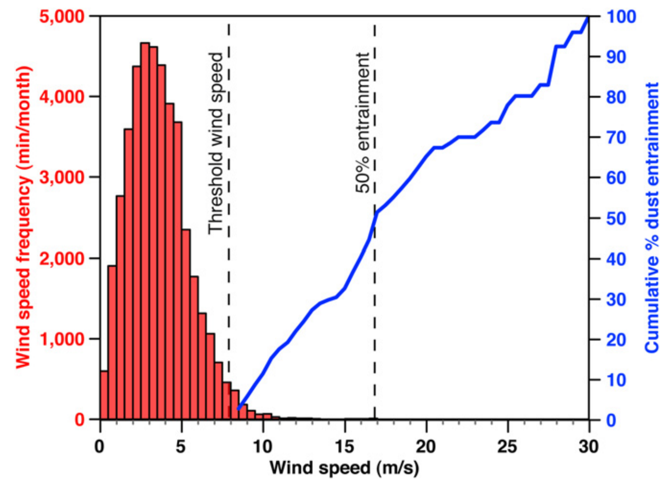

Fig. 3. Wind speed data and modeled dust entrainment from Niamey, Niger, in the northern Sahel. Wind data record the maximum wind speed in each 1-min period for the month of June, 2006. The distribution of wind speeds is shown in red, and the cumulative percentage of modeled dust entrainment assuming a threshold wind speed of 8 m s^{-1} is shown in blue. The top 0.1% of the wind speed distribution drives more than 50% of the predicted dust emissions.

3. Glacial–interglacial changes in gustiness: theoretical and model perspectives

Strong winds can result from a wide variety of atmospheric conditions, but some useful generalizations can be made to assist in predicting glacial–interglacial changes in gustiness. In East Asia and Patagonia, gustiness peaks in spring and is most often related to cyclonic storms accompanying cold fronts (Labraga, 1994; Roe, 2008). In North Africa, the relative importance of various gust-(and dust-) generating wind systems is poorly constrained, but strong winds in winter/spring are generally related to northeasterly trades (Engelstaedter and Washington, 2007a) and cold fronts (Knippertz et al., 2009), while summer gusts primarily accompany convection and maximize as the intertropical convergence zone (ITCZ) approaches from the south (Engelstaedter and Washington, 2007a).

A range of evidence suggests that glacial periods and millennial-scale cold events were likely to have been marked by increased gustiness in dust source areas. Meridional temperature gradients became steeper in glacials, as annual average temperatures were 21–23 °C lower in Greenland (Dahl-Jensen et al., 1998) and 8–10 °C lower in Antarctica (Jouzel et al., 2007) during the Last Glacial Maximum (LGM) while the tropics experienced only a 1–5 °C cooling (Ballantyne et al., 2005). Temperature gradients would have been especially great during winter and spring in each hemisphere due to increased seasonality at mid and high latitudes (Denton et al., 2005). In East Asia and Patagonia, relict cryogenic forms indicate mean annual temperatures 10 °C or more colder than at present at the LGM (Trombotto, 2002; Yang et al., 2004), while glacial moraines indicate summers only 6 °C or less colder (Hulton et al., 2002; Yang et al., 2004). Together these records indicate stronger LGM seasonality in both dust source regions, suggesting that steep local temperature gradients would have existed in local spring as poleward regions remained cold while equatorward regions warmed.

Increased seasonal and annual-mean meridional temperature gradients during glacial periods could reasonably have impacted each of the causes of gustiness mentioned above, providing a means of linking high-latitude temperatures to dust generation. In the mid-latitudes, the thermal wind relationship predicts strengthened jets as temperature – and thus pressure – gradients increase. Simplified climate models suggest that stronger jets would be accompanied by enhanced synoptic eddy wind variance, strengthening gust-generating cold fronts in mid-latitude source areas such as China and southern South America (Rind, 1998). In a similar idealized model, O'Gorman and Schneider (2008) find a monotonic increase in near-surface eddy kinetic energy with increasing pole-to-equator temperature difference, though their results also indicate a decrease in the same parameter at mean global temperatures lower than at present.

In addition to an overall increase in the energy of mid-latitude frontal systems, some models indicate that jets may have been displaced equatorward in glacial climates, bringing their mean annual position closer to dust source regions (Braconnot et al., 2007; Yanase and Abe-Ouchi, 2007). There is considerable disagreement among models regarding glacial–interglacial changes in the position and strength of the Southern Hemisphere westerlies (Rojas et al., 2009), but paleoclimate studies generally support equatorward displacements of mid-latitude jets in both hemispheres. Hesse (1994) and Kawahata (2002) find a modest northward shift in the westerlies-driven Australian dust plume during the LGM, while a variety of evidence for wetter LGM conditions in southern South America has been interpreted as reflecting a northerly position for the Southern Hemisphere westerlies (Lamy et al. 1998, 1999; Moreno et al., 1999; Valero-Garcés et al., 2005). In the Northern Hemisphere, higher lake levels in the western U.S. (Benson et al., 1990), loess grain size records in central Asia (Machalett et al., 2008), terrestrial records from Japan (Ono and Irino, 2004), and stable isotope records from the North Pacific Subarctic front (Oba et al., 2006) are all consistent with southward displacements of the westerlies in glacial periods.

In low latitudes, steepened temperature gradients should intensify Hadley circulation, strengthening trade winds responsible for winter dust emissions (Rind, 1998; Broccoli et al., 2006). Additionally, an intensification of Hadley circulation should increase vertical velocities near the ITCZ, potentially strengthening convective updrafts that drive summer dust emissions in North Africa (Rind, 1998).

Though these generalizations indicate that glacial increases in source area gustiness are plausible, we cannot be assured that changes in zonal-average conditions in the troposphere would result in changes in surface gustiness in specific dust source areas. Even in the presence of strengthened mid-latitude jets, increased vertical stability of the atmosphere may limit the transfer of energy to surface winds in some regions (Li and Battisti, 2008), and local temperature gradients may not follow the overall hemispheric temperature gradient (Roe, 2008). In North Africa, the linking of the overall Hadley cell to surface winds depends strongly on boundary layer dynamics that are poorly constrained for glacial climates.

As an initial test of glacial–interglacial changes in gustiness in dust source areas, we explored the prevalence of wind gusts (here defined as wind speeds $\geq 16\ \mathrm{m\,s^{-1}}$) in recent atmosphere-only simulations of LGM and preindustrial (PI) climates. We analyzed instantaneous surface winds in dust source regions in the Community Atmospheric Model, version 3 (CAM3), the atmospheric component of the fully coupled Community Climate System Model (CCSM3) developed by the National Center for Atmospheric Research (Li and Battisti, 2008). Instantaneous surface winds at $\sim 2.8^{\circ}$ (T42) horizontal resolution were sampled each 12 h in 50-year runs forced by sea surface temperatures from CCSM3 simulations of LGM and PI climates (Otto-Bliesner et al., 2006).

This model is capable of resolving mesoscale features such as mid-latitude eddies and has been used to investigate LGM–PI differences in storminess in the North Atlantic (Li and Battisti, 2008). The resolution is certainly quite coarse compared to the fine-scale dynamics often involved in dust generation, but the results allow a first-order evaluation of glacial–interglacial changes in gustiness.

To determine the significance of LGM–PI differences in the occurrence of strong instantaneous winds, we used a bootstrap method. Annual and seasonal wind fields were randomly sampled with replacement to produce 1000 realizations of 50-year datasets. The standard deviations of strong wind occurrences were then calculated for these realizations and used as an estimate of 1-sigma confidence intervals. All LGM–PI differences in the occurrence of winds $\geq 16\ \mathrm{m\,s^{-1}}$ were significant at the 2-sigma level.

These simulations show significant increases in strong wind gusts under LGM conditions in each of the three source regions considered here both in the annual mean and in each season (Fig. 4). Maximum LGM increases in gustiness occur in winter and spring in East Asia and southern South America and in winter and summer in North Africa, the seasons of peak gustiness and dust export in each region (Labraga, 1994; Engelstaedter and Washington, 2007a; Roe, 2008). We emphasize that given the coarse resolution of GCMs relative to dust emission processes, these results do not comprise a sufficient test of the gustiness hypothesis; nevertheless, they demonstrate that the increases in gustiness predicted for dust source areas by simple climate models appear to hold in state-of-the-art GCM simulations, setting the stage for higher-resolution regional modeling of LGM gustiness for each source area.

4. Glacial–interglacial changes in gustiness: empirical evidence

Empirical evidence provides further support for the gustiness hypothesis. Maximum quartz diameters in Chinese loess deposits are ~50% higher in glacials than in interglacials (Xiao et al., 1995), indicating winds capable of transporting grains with a factor of three greater mass. The mean grain size of terrigenous sediment deposited near Cape Verde, dominantly reflecting eolian dust from North Africa, is ~50% higher during the last glacial period than in the Late Holocene (Zhao et al., 2000). Grain size maxima in eolian sediments from both East Asian (Porter and An, 1995) and North African (Tjallingii et al., 2008) sources correlate with Heinrich events, periods of maximum meridional temperature gradients in the Northern Hemisphere.

We interpret these grain size data as recording stronger wind gusts in North Africa and East Asia during periods of steepened meridional temperature gradients. We focus on grain size records from locations near dust source areas, as with increasing distance dust grain size may reflect high-level transporting winds rather than surface winds. Grain sizes in dust deposits can be also be influenced by changes in the distance to the source area, but provenance data suggest that sources have remained constant from the LGM to the late Holocene in North Africa (Grousset et al., 1998; Cole et al., 2009) and have either remained constant or moved closer to the loess plateau over this period in East Asia (Sun et al., 2008). It has also been suggested that strong winds lead to increased production of fine-grained material (Alfaro and Gomes, 2001), causing median grain sizes measured at distal sites to have an inconsistent relationship with wind speed; however, the close correspondence of maximum and median grain size records in Chinese loess (Porter and An, 1995) and records from the North African margin (Zhao et al., 2000; Tjallingii et al., 2008) suggests that production of fine-grained material by strong winds does not bias proximal grain size records.

Corroborating evidence of a relationship between high-latitude cooling and strengthened seasonal winds in East Asia comes from Huguang Maar lake (Yancheva et al., 2007). Its sediments show evidence of an abrupt breakdown of wintertime stratification at the onset of the Younger Dryas cold period, consistent with an increase in the strength and/or duration of autumn-to-spring wind events.

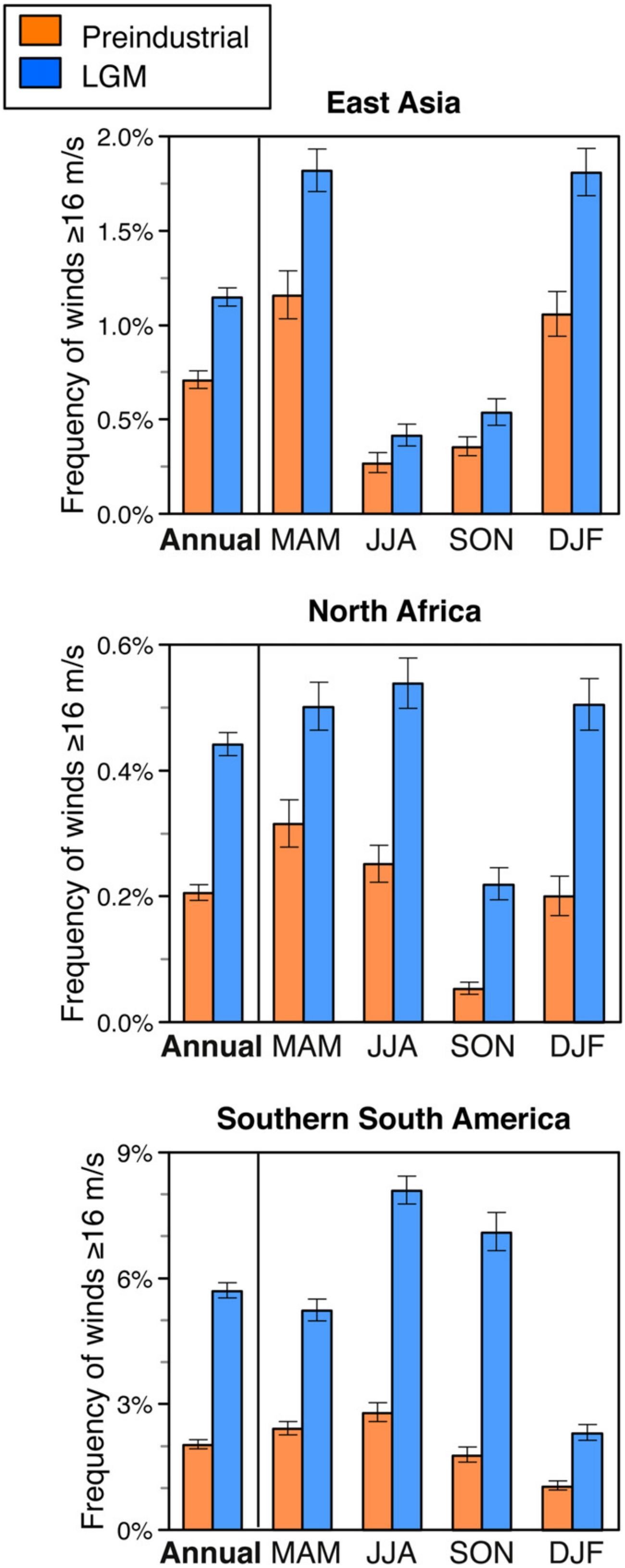

Fig. 4. Frequency of strong surface winds ($\geq$16 m s^{-1}) in dust source areas in preindustrial (orange) and LGM (blue) simulations using the NCAR CAM3 (Li and Battisti, 2008). Instantaneous winds were sampled twice daily in 50-year simulations of each climate state. Error bars indicate 2-sigma confidence intervals. Significant increases in strong wind gusts are observed in each dust source area during the LGM both annually and seasonally, with maximum LGM–PI differences in the winter and spring in East Asia and southern South America and in winter and summer in North Africa.

This transition is accompanied by a similarly abrupt increase in the accumulation of terrigenous matter, interpreted as dust, in lake sediments (Fig. 1). Modern observational data support these ties, showing strong correlations between winter temperature gradients, spring cyclonic activity and dust storm frequency in China (Qian et al., 2002).

Together, these results indicate that steeper meridional temperature gradients during glacial periods would have been accompanied by enhanced gustiness in dust source areas, contributing to and plausibly driving increases in global dust emissions. The question then becomes, how important were other potential drivers in contributing to high dust fluxes during glacial periods?

5. Other potential drivers of glacial–interglacial dust flux changes

5.1. Source area aridity

Source area expansion due to aridity is perhaps the most widely cited potential driver of dust flux increases (Rea, 1994). In order to test the aridity hypothesis, we examine lake-level records from closed-basin lakes near dust source areas, which reflect effective precipitation in the lake's drainage basin, to determine whether low lake levels occurred during periods of high dust emissions. If aridity is a potential control on glacial–interglacial dust flux changes, closed-basin lake records should indicate higher lake levels during interglacials and lower levels during glacials.

Provenance data (Bory et al., 2003; Sun et al., 2008), observations of modern dust storms (Qian et al., 2002) and satellite data (Prospero et al., 2002) point to two dominant dust source regions in East Asia: the Taklimakan desert in the Tarim Basin of northwestern China, and the deserts of northern China and southern Mongolia, which include the Badain Jaran, Tengger and Mu Us deserts (Fig. 5a). The latter are the dominant source represented in the Chinese Loess Plateau (Sun et al., 2008), while dust from the Tarim Basin is more likely to be lifted to high levels and transported to distant sites, including Greenland (Pye and Zhou, 1989; Bory et al., 2003).

Closed-basin lakes near both East Asian dust source areas appear to have been larger during the last glacial period, inconsistent with the aridity hypothesis. Near the Tarim Basin, cores from Lake Balikun – currently a shallow, hypersaline lake – contain deep-lake clays with aquatic pollen and ostracodes that have been dated to the LGM by both ^{14}C and U–Th methods (Yu et al., 2003; Ma et al., 2004). U–Th isochron dates indicate that similar facies were deposited in Marine Isotope Stages (MIS) 4 and 6, while saline mudflat deposits and evaporites date to MIS 1, 3, and 5 (Ma et al., 2004). Deep-lake facies radiocarbon-dated to the last glacial period are also found in cores from Aydingkol Lake (Wünnemann et al., 2007) and the currently dry Lop Nur Basin (Yu et al., 2003; Yang et al., 2004; Wünnemann et al., 2007). Sedimentary evidence also indicates that Lakes Aqigejkule and Tianshuihai at the southern margin of the Tarim Basin were significantly larger in the last glacial (Yu et al., 2003).

There is also evidence for increased moisture availability during the last glacial period near the deserts of northern China and southern Mongolia. In the Tengger Desert, radiocarbon dating of shorelines deposits indicate that a single large lake or several small lakes occupied the region from ~35 to 22^{14}C ka (>~26 cal ka) (Zhang et al., 2004). Though this region's highest lake levels predate the LGM, the highstand extends into MIS 2 and overlaps with the highest observed dust fluxes in Greenland (Mayewski et al., 1997). In the Qaidam Basin to the south of these deserts, U–Th dating of sediment cores indicates that transitions from lake sediments to evaporites occurred during the last two glacial terminations

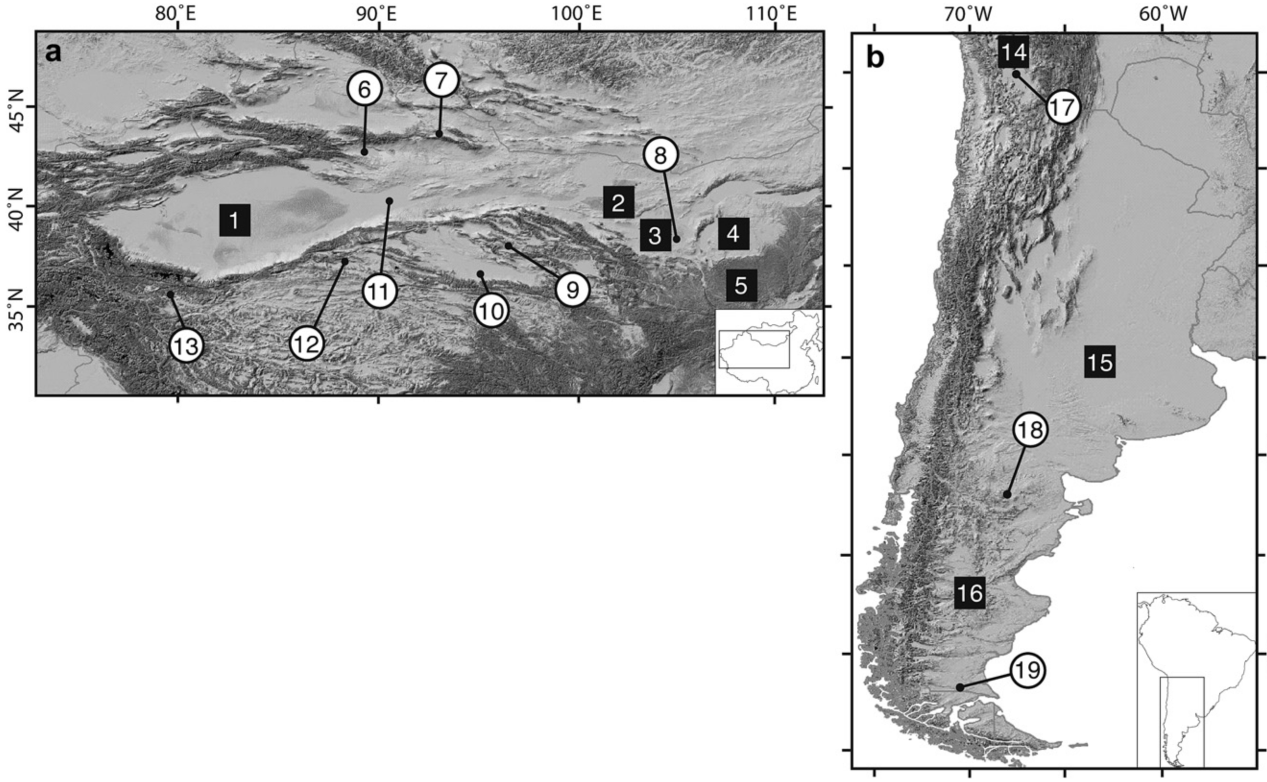

Fig. 5. Dust sources and depositional sites (black squares) and sites indicating greater moisture availability at the LGM (white circles). a. Sites in East Asia: 1. Taklimakan Desert; 2. Badain Jaran Desert; 3. Tengger Desert; 4. Mu Us Desert; 5. Central Loess Plateau; 6. Aydingkol Lake; 7. Lake Balikun; 8. Tengger Desert lake or lakes; 9. Dunde Ice Cap; 10. Qaidam Basin; 11. Lop Nur Basin; 12. Lake Aqigejkule; 13. Lake Tianshuihai. b. Sites in southern South America: 14. Altiplano plateau; 15. Pampas region; 16. Patagonia; 17. Salar de Uyuni; 18. Lake Cari-Laufquen; 19. Lake Potrok Aike.

(Phillips, 1993). Additionally, concentrations of chloride and sulfate in nearby Dunde ice cap, reflecting exposure of playa evaporites in the Qaidam Basin, are anticorrelated with dust concentrations (Thompson et al., 1989). Both these findings indicate high lake levels in the Qaidam Basin during glacial periods and low levels during interglacial periods, contrary to the predictions of the aridity hypothesis.

Southern South America's primary dust sources are located in the Altiplano plateau, the Pampas region of northern Argentina, and Patagonia to the south (Prospero et al., 2002); all three regions may have contributed dust to Antarctica during the last glacial period (Gaiero, 2007). Higher glacial dust fluxes from sources in southern South America are recorded in Antarctic ice cores (Petit et al., 1999; Wolff et al., 2006), South Atlantic sediments (Kumar et al., 1995; Martínez-Garcia et al., 2009), and loess deposits in northern Argentina (Zárate, 2003). In the Altiplano, the dry Salar de Uyuni supported a shallow lake during the LGM, reflecting overall expansion of lake area in the Poopo–Coipasa–Uyuni system by a factor of 2 relative to the present (Fig. 5b) (Placzek et al., 2006). To the south, Lake Cari-Laufquen, a closed-basin lake located between the Pampas and Patagonia, is ringed by paleoshorelines indicating higher effective precipitation in the last glacial period. The highest shoreline (+52 m) dates to between 22 and >30 ka, and a shoreline at +38 m reflecting a lake with a factor of 5 greater area than at present has been dated to 19–21 ka (Galloway et al., 1988; Whatley and Cusminsky, 1999; Quade and Broecker, 2009). At Lake Potrok Aike in southern Patagonia, Haberzettl et al. (2009) conclude that the LGM was marked by both increased effective precipitation and higher eolian deposition relative to the Holocene based on Ca/Ti ratios, magnetic susceptibility and grain size data in lake sediments. As in East Asia, the low number of records and the possibility of dating errors demands further work, but the presently available studies suggest higher rather than lower moisture availability during glacial periods near dust sources in southern South America.

In North Africa, paleorecords suggest stronger relationships between dust emissions and aridity. Sedimentary dust fluxes are lowest during the African Humid Period (14.8–5.5 ka) (deMenocal et al., 2000), a period of high lake levels throughout northern Africa, and lake records indicate dry conditions during both the LGM and the Late Holocene (Gasse, 2000; Hoelzmann et al., 2004). The LGM appears to have been drier than the Late Holocene; for example, pollen assemblages in a transect of cores on the Northwest African margin indicate that the latitudinal extent of the Sahara was substantially broader at the LGM than at the present day (Dupont, 1993), and a proxy record of sea surface salinity in the Gulf of Guinea points to reduced discharge from the Niger and Sanaga rivers during the LGM (Weldeab et al., 2007).

Aridity is thus likely to have played a role in increasing LGM dust emissions from North Africa, most likely by expanding source areas in the modern Sahel. Given the evidence cited in Section 4 for stronger LGM winds in North Africa, additional work will be needed to determine the relative importance of aridity and gustiness in the factor of ~2 difference between LGM and Late Holocene dust fluxes from the region (Ruddiman, 1997; Bradtmiller et al., 2007; Jullien et al., 2007). The relative importance of aridity and wind strength in modern interannual variability in North African dust emissions is also an area of uncertainty (e.g., Engelstaedter et al., 2006). Additionally, future studies will need to determine why provenance indicators suggest no LGM–Late Holocene change in dust provenance (Grousset et al., 1998; Cole et al., 2009) while aridity records indicate that source areas should have expanded into the modern Sahel during the LGM.

Taken together, lake level records areas suggest that aridity is likely to have been locally important in increasing LGM dust emissions in North Africa, but that aridity was not a dominant driver of dust flux changes in East Asia and southern South America. While semi-arid conditions are a precondition for high dust emissions, with most major modern dust sources located in regions with <250 mm annual precipitation (Prospero et al., 2002), it appears that the importance of changes in aridity below this threshold may vary from region to region. This variability may relate to the fact that in North Africa, desiccated lake beds are a primary dust source (Prospero et al., 2002), while alluvial fans and braided stream systems appear to be the dominant dust sources in East Asia and Patagonia (Derbyshire et al., 1998; Sugden et al., 2009). Transitions from arid to hyperarid conditions in these latter regions may reduce dust emissions by limiting sediment supply to fans and stream systems (Goudie, 1983; Prospero et al., 2002).

5.2. Changes in vegetation density independent of aridity

In addition to aridity, low atmospheric pCO_2 has been proposed as a means of increasing dust emissions during glacial periods, either by directly restricting vegetation density (Mahowald et al., 2006) or by inhibiting vegetation regrowth after fire (Bond et al., 2003). Though high dust emissions correspond with low atmospheric pCO_2 on orbital time scales, highly resolved paleorecords suggest that pCO_2 does not exert tight controls on dust emissions. Atmospheric pCO_2 changes do not accompany high-amplitude dust flux changes in either hemisphere in MIS 3 (Fig. 2). During the last deglaciation, dust fluxes fall in Antarctica before pCO_2 has substantially changed, while in Greenland dust fluxes return nearly to glacial levels in the Younger Dryas, a period when pCO_2 was approaching interglacial levels (Fig. 1).

It is possible that vegetation density in some regions was reduced in glacial periods due to factors independent of aridity and pCO_2, allowing dust source areas to expand. Lower temperatures, increased winds and seasonality, and shorter growing seasons could all have plausibly limited overall vegetation density. In their model of LGM dust emissions, Mahowald et al. (2006) included simulations of LGM vegetation based upon prescribed pCO_2 and the model's estimates of LGM temperatures, precipitation and cloudiness. Discounting runs that include a strong CO_2 effect on vegetation (discussed above), reduced LGM vegetation accounted for ~40% of the LGM–preindustrial differences in dust emissions from mid and low latitude sources in their model. Takemura et al. (2009) found that vegetation changes had limited impacts on LGM emissions from North Africa but had strong effects on East Asian emissions, and they produced a similar estimate for the globally averaged importance of vegetation changes in LGM dust fluxes.

Models and observations of modern dust emissions corroborate the regional difference observed by Takemura et al. (2009). Changes in growing season (i.e., delaying the onset of vegetation growth in the spring) were found to have large impacts on modern dust emissions from East Asia in one model (Tegen et al., 2002), and modern observations indicate strong correlations between dust storm activity and vegetation indices in northern China (though not in the Tarim basin) (Zou and Zhai, 2004). In the Sahara, vegetation density does not appear to be a significant control on overall modern dust emissions (Engelstaedter et al., 2006). Future work is needed to test whether vegetation changes were capable of driving abrupt dust flux changes from East Asia (e.g., during Dansgaard-Oeschger and Heinrich events); alternatively, a long-term reduction in vegetation density could have allowed East Asian source areas to expand throughout the last glacial period, while changes in gustiness determined the timing and abruptness of responses to high-latitude temperature changes. The suggestion of large-scale source area expansions in East Asia by Maher et al. (2010) and Mahowald et al. (2006) also needs to be reconciled with the fact that provenance studies do not find significant LGM–Holocene differences in the sources of Greenland dust (Biscaye et al., 1997; Bory et al., 2003; A. Bory, pers. comm.).

5.3. Sea level changes

It has also been suggested that the exposure of continental shelves by low sea levels increased dust source areas, driving increased dust emissions in glacial periods (De Angelis et al., 1997). Elevated proportions of calcium in ice core dust during glacial periods have been linked to inputs from shelf sources (e.g., De Angelis et al., 1992). Calcium carbonate is a substantial component of many loess deposits (e.g., Pye, 1995), but it is difficult to estimate the importance of shelf sources from loess carbonate contents due to the effects of decalcification and authigenic carbonate deposition on measured carbonate percentages (Pye, 1995; Quade et al., 1995; Hesse and McTainsh, 2003).

As previously pointed out by Wolff et al. (2006), significant mismatches exist between dust flux and sea level records during the last deglaciation; dust fluxes in Antarctica begin falling ~3 kyr before sea level begins rising substantially (Fig. 1). As ice core records reflect changes in both dust emissions and transport, the early drop in Antarctic dust fluxes could reflect changes in atmospheric dynamics governing transport paths and the atmospheric residence time of dust rather than changes in dust emissions from southern South America. More difficult to explain with changes in transport paths alone is the fact that dust fluxes rise substantially in both Greenland and China's Huguang Maar lake during the Younger Dryas despite the fact that approximately half of the deglacial sea level rise was accomplished by this time (Fig. 1). More generally, relationships between dust emissions and either sea level or pCO_2 should cause synchronous dust flux changes in both hemispheres, but the two hemispheres' dust records are not in phase on millennial time scales (Figs. 1 and 2).

5.4. Glaciogenic sediments

Finally, some global dust models indicate that higher glacial dust fluxes were driven in large part by an increase in the supply of fine-grained sediment due to glacial erosion (Reader et al., 1999). On a global scale, this mechanism is unlikely to act as a first-order control on dust levels, given that glacial activity has been minimal throughout the Late Quaternary in most dominant dust source areas, including North Africa, South Africa, Australia, and the deserts of north-central China and Mongolia. Glaciogenic sediment supply may have been locally important in Patagonian dust emissions; Sugden et al. (2009) have suggested that recession of outlet glaciers during warm periods trapped sediments in proglacial lakes, limiting sediment supply to outwash plains that served as strong dust sources. Though this mechanism is likely to have been less important in dust source areas in central Argentina and the Altiplano due to their lack of extensive outwash plains, it may have worked in concert with wind strength to determine the timing and magnitude of dust flux changes observed in the South Atlantic and Antarctica.

Mahowald et al. (1999, 2006) suggest that glacial outwash plains in central Asia and Siberia were important dust sources for Greenland during the last glacial period. The loess deposits present in these regions indicate that they were much greater dust sources in glacial periods than in interglacials (e.g., Machalett et al., 2008). The significance of these sources for glacial–interglacial and stadial–interstadial changes in dust deposition in the North Pacific and Greenland remains untested. Provenance data in North Pacific sediments and Greenland support an East Asian source for dust (Nakai et al., 1993; Jones et al., 1994; Weber et al., 1996; Biscaye et al., 1997; Bory et al., 2002, 2003), and data from Greenland

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show no change in provenance between the LGM and the present (Biscaye et al., 1997; Bory et al., 2002, 2003; A. Bory, pers. comm. 2010). Nd isotope and Ar/Ar ages from core-top (~Holocene) sediments and sediments throughout the last 12 Myr in the North Pacific indicate negligible change in dust sources over this period (Nakai et al., 1993; Jones et al., 1994; Pettke et al., 2000). These results suggest either that Siberian and central Asian sources were less important than East Asian sources in Greenland and the North Pacific during both glacials and interglacials or that these sources are not distinguishable using the provenance tools employed to date.

6. Conclusions

This synthesis provides multiple lines of support for gustiness as a first-order control on Late Quaternary global dust levels. Paleorecords demonstrate strong links between high-latitude temperatures, seasonality and dust fluxes; climate models suggest that increased meridional temperature gradients and seasonality under LGM conditions would cause greater gustiness in dust source regions, a finding supported by dust grain size records and proxies for wind-driven mixing in Huguang Maar lake; and modern observations clearly document the sensitivity of dust emissions to wind gusts. Together, these elements establish the gustiness hypothesis as a robust potential explanation for the global consistency of glacial–interglacial dust flux changes.

We find that past changes in atmospheric pCO_2 and sea level do not display consistent relationships with dust flux records. Other proposed drivers may play important local roles: during glacial periods reduced vegetation may have allowed East Asian dust sources to expand, glacial activity may have significantly increased fine-grained sediment supply in Patagonia, and increased aridity may have expanded source areas in North Africa. Gustiness, however, may provide the best available mechanism for communicating changes in high-latitude temperatures to dust source areas throughout each hemisphere and for explaining the global consistency of glacial–interglacial dust flux changes.

Further tests of the gustiness hypothesis are needed, including additional maximum grain size records from proximal eolian deposits, lake-based records of wind intensity, and high-resolution regional modeling of LGM conditions in dust source areas. Additionally, well-dated shoreline records from closed-basin lakes will be essential in further testing the relationship between aridity and glacial dust emissions; pollen records and modeling efforts are needed to constrain the importance of changes in vegetation density, particularly during abrupt climate changes; and provenance data are needed to test for past changes in dust source areas.

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