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Quaternary Fluctuations in the Northern Hemisphere Trade Winds and Westerlies

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The mass accumulation rate and grain size of the total eolian component isolated from pelagic sediment in two North Pacific cores, piston core KK75-02 under the prevailing westerlies and Deep-Sea Drilling Project Site 503 beneath the trade winds, have been used to evaluate changes in the intensity of atmospheric circulation and source-area aridity over the past 700,000 yr. The eolian grain size, a direct indicator of wind intensity, fluctuates at periodicities similar to those calculated for the earth's orbital parameters of precession, obliquity, and eccentricity. Both sites display greater variability in wind intensity prior to 250,000 yr ago. Eolian accumulation rates, an indicator of source-area aridity, fluctuate at periodicities similar to those of the glacial–interglacial cycles. Lower eolian accumulation rates during colder (glacial) times most likely reflect increased glacial-age humidity at central Asian and Central American source areas.

INTRODUCTION

For more than 2 myr, the earth's climatic history has been characterized by oscillations reflecting times of accumulation and melting of massive ice sheets. Large changes in the earth's atmospheric circulation patterns and in circulation intensity occurred with these glacial–interglacial fluctuations. Attempts to model these changes have been hampered by the general lack of direct indicators with which to test and calibrate the models. However, eolian material, isolated from deep-sea sediments, provides direct and quantifiable information regarding changes in atmospheric circulation patterns and wind intensity (Rea and Janecek, 1981a, 1981b, 1982; Janecek and Rea, 1983). This study investigates variations in atmospheric circulation that have been deduced from changes in the accumulation rate and grain size of eolian material deposited over the past 750,000 yr.

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Eolian Sedimentation

Results of various studies indicate that atmospherically transported dust is a significant component of pelagic sediments (Griffin *et al.*, 1968; Windom, 1975; Johnson, 1979). Away from the mouths of rivers, patterns of sediment mineralogy (Windom, 1975; Leinen and Heath, 1981) are parallel to the zonal wind regimes and so are roughly perpendicular to boundary currents of the subtropical gyres. This observation serves to emphasize the rapid removal of small particles from the surface of the ocean by large amorphous aggregates and fecal pellet transport (Bishop *et al.*, 1977, 1978; Honjo, 1983). The rapid settling of those aggregates and pellets at hundreds of meters per day (Honjo, 1980, 1983) quickly removes eolian material (Scheideggar and Krissek, 1982) and other particulates from the effects of ocean-surface circulation resulting in minimal surface-current smearing of sedimentary input patterns.

The grain size of the eolian material deposited in the deep sea is determined by the

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intensity of atmospheric circulation and distance to source. Both air and land-based sampling (Johnson, 1976; Gillette *et al.*, 1978; Windom and Chamberlain, 1978; Glaccum and Prospero, 1980) and theoretical calculations (Windom, 1969; Jaenicke, 1979; Schutz *et al.*, 1981) suggest that beyond 1000 to 2000 km distance from the source, the size distribution of the grains changes very little. That is, the settling velocities of small eolian grains are less than the vertical velocity associated with atmospheric turbulence and those grains (which form a minor portion of the initial dust load) remain in suspension indefinitely (Gillette *et al.*, 1974; Jaenicke, 1979; Schutz *et al.*, 1981). Those equilibrium grains are carried global distances in the upper troposphere and are generally removed by rain out (Jackson *et al.*, 1973). At any distal location, therefore, changes in the size of these equilibrium grains should represent changes in the intensity of the zonal winds.

The flux of wind-borne dust to the ocean basins depends, in part, on the strength of the zonal winds, on distance from the source, and on the annual number of transporting episodes, but mostly on the climate of the source area (Rea and Janecek, 1981a; Rea *et al.*, 1985). For example, the annual cycle of Saharan dust reaching South America reflects the yearly climatic changes in Africa (Prospero *et al.*, 1981). Humid climates promote vegetation, thereby reducing the amount of dust available for wind erosion, transport, and subsequent deposition in the deep sea (Prospero and Nees, 1977; Prospero *et al.*, 1981). High precipitation rates would also increase the scavenging of eolian material by rain, thus decreasing the amount of deposition downwind (Windom, 1975; Parkin and Padgham, 1975). Thus, variations in the mass accumulation rate of the eolian material are taken to represent changes in the source-area climate.

Geologic Setting and Stratigraphy

Sediments in piston core KK75-02, raised east of the Hess Rise at 38°37.4′ N and 179°19.7′ E (Fig. 1) from 5475 m of water, range in composition from a siliceous clay to a clay-rich siliceous ooze. The predominant sedimentary components of KK75-02 are terrigenous clay, radiolarians, and diatoms with subordinate

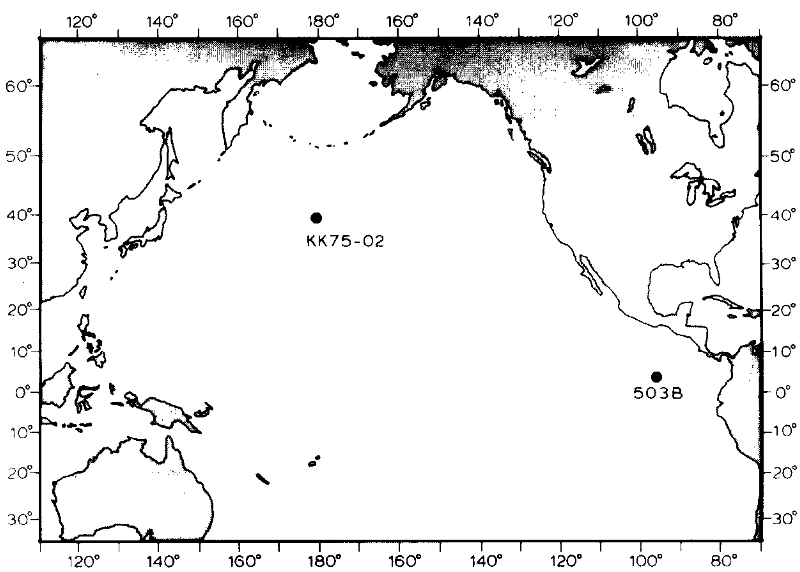

FIG. 1. Map showing the location of piston core KK75-02 and DSDP Site 503.

amounts of quartz, sponge spicules, and manganese micronodules.

Paleomagnetic reversal stratigraphy and radiolarian extinction levels (Fig. 2 and Table 1) were used as stratigraphic control for piston core KK75-02. Sedimentation rates were calculated between age horizons and found to be relatively constant, varying between 1.18 and 1.41 cm/1000 yr. The relative constancy of accumulation throughout the past 700,000 yr, as seen in this core, is typical for cores from the northwest Pacific (Robertson, 1975; Morley *et al.*, 1982) and suggests that no significant hiatuses occur in KK75-02 over this time interval.

Deep-Sea Drilling Project (DSDP) Site 503 lies north of the Galapagos spreading center and east of the East Pacific Rise (Fig. 1). Hole 503B, used in this study, is located at 4°03.02′ N and 95°38.32′ W at a depth of 3672 m. The section at Site 503 is composed of three sediment types, including silica-bearing nannofossil marl, calcareous–siliceous ooze, and siliceous nannofossil ooze.

High-resolution carbonate data at Hole 503B (Gardner, 1982) provide correlatable stratigraphic horizons and thus a basis for determining sedimentation rates. The Pacific carbonate cycles have not been dated directly but can be correlated with oxygen-isotope fluctuations which have been dated elsewhere (Shackleton and Opdyke, 1976). Hole 503B contains four transitions between high and low carbonate stages that correspond to glacial terminations II (B3/4), III (B5/6), IV (B7/8), and V (B9/10) (Rea, 1982) which have been assigned the ages 128,000, 251,000, 347,000, and 440,000 yr, respectively (Shackleton and Opdyke, 1976) (Fig. 2 and Table 1). Linear sedimentation rates were calculated between age horizons and found to be relatively uniform, varying between 1.0 and 1.3 cm/1000 yr (Table 1).

The sedimentation rates for KK75-02 and Site 503 are calculated between a limited number of stratigraphic horizons. Any glacial to interglacial fluctuations in sedimentation rate would probably be averaged out and thus may unknowingly influence our data.

METHODOLOGY

The basic data set for this study includes (1) the weight percentage of the total eolian load rather than just the weight percentage of quartz, which commonly comprises only 10 to 30% or less of the wind-transported material (Windom, 1969; Johnson, 1979;

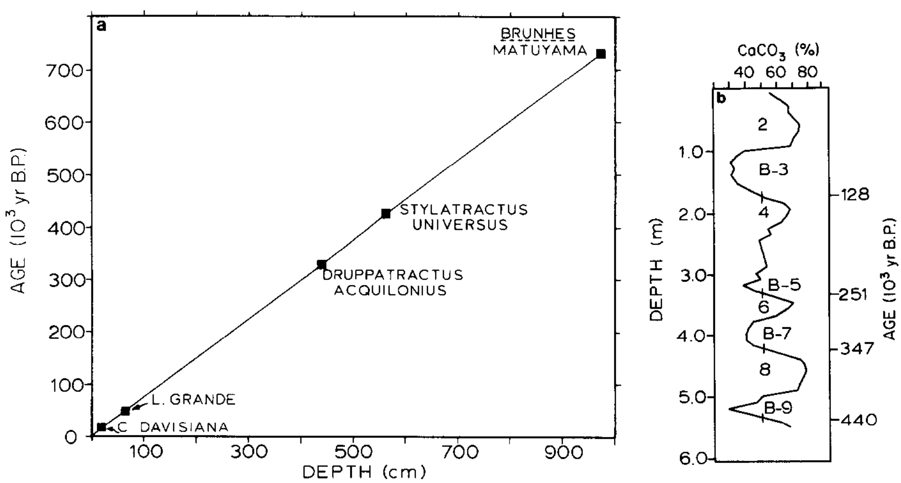

FIG. 2. (a) Age–depth plot for KK75-02. Radiolarian age datums are from Morley *et al.* (1982); depth of Brunhes/Matuyama reversal is from Hammond *et al.* (1979); age of Brunhes/Matuyama reversal is from Mankinen and Dalrymple (1979). (b) Carbonate variations at DSDP Site 503B. Data are from Gardner *et al.* (1982); ages are from Shackleton and Opdyke (1976). See text for details of correlation procedures.

TABLE 1. DETERMINATION OF LINEAR SEDIMENTATION RATES (LSR) FOR SITE 503 AND KK75-02

		Stratigraphic datum levels		
	$CaCO_3$-stage boundary	Depth (cm)	Age (1000 yr)	LSR of interval (cm/1000 yr)
Site 503				
Glacial-stage boundary				
Surface	Surface	0	0	
5/6 T-II	B3/4	171	128	1.34
7/8 T-III	B5/6	330	251	1.28
9/10 T-IV	B7/8	442	347	0.96
11/12 T-V	B9/10	532	440	1.18
KK75-02				
Horizon				
Surface		0	0	
C. davisiana maximum		20	17	1.18
L. grande extinction		65	49	1.41
D. acquilonius extinction		440	329	1.34
S. universus extinction		560	425	1.25
Brunhes/Matuyama reversal		975	730	1.36

Note. The depth and age of the Brunhes/Matuyama reversal at KK75-02 were taken from Hammond *et al.* (1979) and Mankinen and Dalrymple (1979), respectively. Age estimates of the radiolarian datum levels are from Morley *et al.* (1982). The carbonate curve at Hole 503B was interpolated from Gardner (1982). Assigned ages for the carbonate boundaries are from Shackleton and Opdyke (1976).

Glaccum and Prospero, 1980), and (2) the grain size of the eolian component.

The eolian component of pelagic sediments is isolated by treating the samples successively with acetic acid to remove calcium carbonate, with a buffered sodium citrate–sodium dithionite solution to remove oxides, hydroxides, and zeolites, and with warm sodium carbonate to remove opal. The residue predominantly consists of a mixture of fine-grained clays and quartz.

Grain-size (ϕ_{50} of Folk, 1974) analysis was carried out on the 6- to 10-ϕ (16 to 1 μm) size fraction at 0.5-ϕ intervals using a Coulter Counter Model Zb particle-size analyzer. Precision of this analysis is $\pm 0.03\ \phi$.

The total mass accumulation rate (MAR), or the flux of material to the sediment–water interface, is calculated from the linear sedimentation rate (LSR) and dry-bulk density (DBD) data using the relationship:

$$\text{LSR (cm/1000 yr)} * \text{DBD (g/cm}^3\text{)} = \text{MAR (g/cm}^2\text{/1000 yr)}.$$

The flux of eolian material was determined by multiplying the eolian weight percentage of a particular sample by the total MAR for that sample. A detailed description of the laboratory procedures and raw data for these sites can be found in Rea and Janecek (1981b) and Janecek (1983).

RESULTS

Eolian Accumulation Rates

The record of dust accumulation at KK75-02 exhibits significant fluctuations over the past 750,000 yr (Fig. 3). Eolian mass accumulation rates generally range between 300 and 450 mg/cm^2/1000 yr, with relative maxima centered about 45,000, 210,000, 310,000, 420,000, 600,000, and 720,000 yr. Two intervals, one centered at 120,000 yr and one centered at 540,000 yr, are characterized by severely reduced rates of less than 100 mg/cm^2/1000 yr. At the sample spacing utilized in this study, peaks

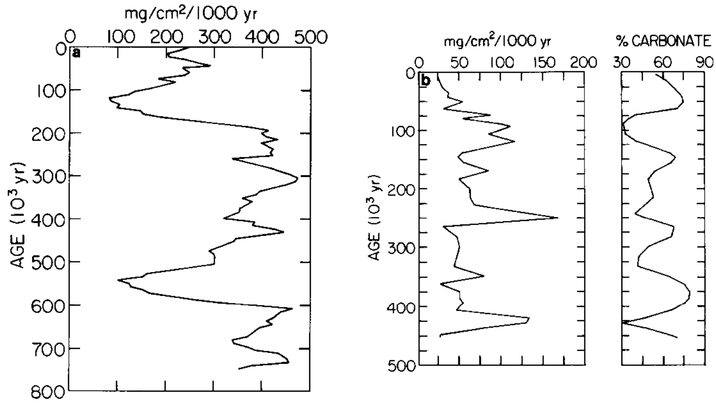

FIG. 3. (a) KK75-02 eolian mass accumulation rates. (b) DSDP Site 503 eolian accumulation rates and percentage of calcium carbonate. Low carbonate intervals represent interglacial time and high carbonate intervals represent glacial times.

in eolian accumulation occur at approximately 125,000-yr intervals, a similar periodicity to that for the glacial to interglacial oscillations.

The eolian accumulation rates calculated at Hole 503B vary by nearly an order of magnitude from 24 to 169 mg/cm^2/1000 yr (Fig. 3). Lower rates, generally less than 60 mg/cm^2/1000 yr, occur during high carbonate stages (glacial intervals) 2, 4, 6, and 8. Increased eolian accumulation rates, generally greater than 100 mg/cm^2/1000 yr, are associated with low carbonate stages (interglacial times) B-3, B-5, and B-9. Eolian accumulation rates for carbonate stage B-7 do not appear to fit this general pattern.

Eolian Grain Size

The median grain size of the eolian material at KK75-02 ranges from 8.81 to 8.37 ϕ (Fig. 4), equivalent to a factor of 2.5 range in grain mass (assuming constant grain density). At Hole 503B the size of the eolian grains ranges from 8.79 to 8.25 ϕ, equivalent to a factor of 3.1 range in grain mass (Fig. 4).

Most studies which relate particle size to some parameter of wind speed make use of Stokes settling law (Parkin, 1974; Windom, 1975; Dauphin, 1980, 1983). These models, however, are developed for nonequilibrium transport and use a "coarseness coefficient" instead of actual grain size to hindcast wind conditions.

In order to determine past wind intensities quantitatively from our grain-size data, we have adapted a model developed by Gillette *et al.* (1974), as this model is more appropriate for our data sets. Our concept of equilibrium transport, however, is derived from modeling studies of atmospheric transport (Jaenicke, 1979; Schutz *et al.*, 1981) and data from sea-floor sediments (Janecek, in press) which suggest that the total eolian load reaches an equilibrium size distribution (i.e., no further changes in size

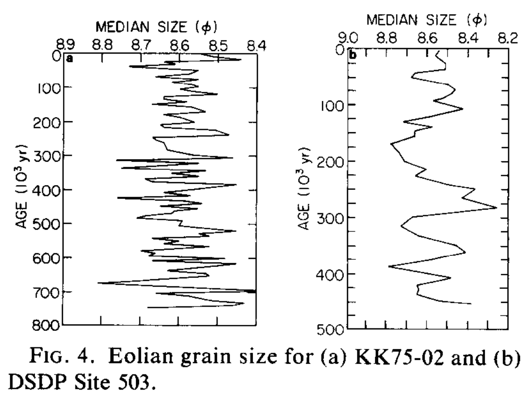

FIG. 4. Eolian grain size for (a) KK75-02 and (b) DSDP Site 503.

with transport) approximately 2000 km or farther downwind (Rea *et al.*, 1985).

Gillette *et al.* (1974) examined the settling of particles in a one-dimensional model in which sedimentation and diffusion are in equilibrium and in which the diffusion coefficient may be described as a linear function of height and the concentration of dust with height may be described by

$$\frac{\partial}{\partial z}\left(kU_*z\frac{\partial c}{\partial z}\right) + V_{sed}\frac{\partial c}{\partial z} = 0 \qquad (1)$$

where k is von Karmann's constant (approximately equal to 0.4), U_* is the friction velocity (a product of the drag coefficient and velocity), z is the vertical distance from the ground, V_{sed} is the Stokes sedimentation velocity, and c is the concentration of dust.

For the boundary conditions $c = c_0$ for $z = z_0$ and $c = 0$ as z goes to infinity

$$c = c_0\,(z/z_0)^{V_{sed}/kU_*} \qquad (2)$$

where c_0 is the initial dust concentration and z_0 is the initial reference elevation. In other words when upward motions of the air are greater than the settling velocities of the eolian material particles, loss by sedimentation is a lengthy process. Thus, a V_{sed}/U_* that is sufficiently small would correspond to nonsettling particles and a large V_{sed}/U_* would correspond to settling particles. Gillette *et al.* (1974) experimentally determined values for V_{sed}/U_* that correspond to nonsettling particles. Their results showed that particles less than 14 μm have sufficiently small V_{sed}/U_* values to remain suspended indefinitely. The eolian samples in this study have a negligible weight percentage in the size fraction larger than 14 μm and, thus, have values of V_{sed}/U_* that correspond to nonsettling particles.

The model developed by Gillette *et al.* (1974) can be used in combination with the grain-size results presented here to determine relative changes in wind intensity in the geologic past. First, we assume that V_{sed}/U_* is the only changing parameter in Equation (2). This is a reasonable assumption, as z and z_0 have probably remained constant in the past and since the particles in the size range of interest (less than 14 μm) are in equilibrium with the transporting wind, the ratio c/c_0 should also remain constant. Thus, changes in U_* must be balanced by changes in V_{sed}. Assuming gravity and air and particle densities have remained constant, the significant term in V_{sed} is the square of the particle diameter. By comparing, in a ratio form, the squares of particle diameters from two different samples the relative change in U_* can be determined. Thus, the ratio of high-to-low wind intensities, R_w, is the ratio of the squares of the grain sizes of two different samples D_H^2 and D_L^2 : $R_w = D_H^2/D_L^2$. Wind intensities can be computed for every change in grain size.

Using these computations to compare peak-to-trough grain-size values down the core, the average range in high-to-low wind intensities at KK75-02 is about 22%. The amplitude of these fluctuations in the westerlies decreased from 27% before 250,000 yr ago to 17% more recently. The average change in high-to-low wind intensities at Site 503 is about 36%. As at KK75-02, the amplitude of the trade-wind fluctuations decreased since 250,000 yr ago from an average of 47 to 26% more recently.

Spectral Analysis of Eolian Grain Size

The fluctuations in eolian grain size (wind intensity) at both sites do not generally correspond to the long-term glacial–interglacial oscillations as do the mass accumulation rates; rather they exhibit much higher frequency oscillations. To define the temporal nature of these grain-size fluctuations more precisely, the statistical technique of spectral analysis was applied to the grain-size time series at each site.

The spectrum calculated for the KK75-02 grain-size time series is characterized by three discrete peaks which correspond to

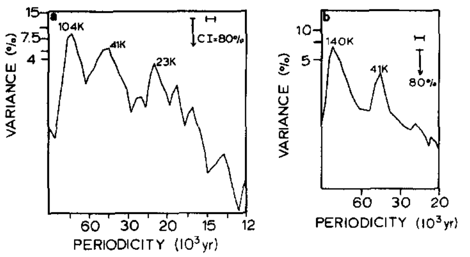

FIG. 5. Spectra calculated for eolian grain size for (a) KK75-02 and (b) DSDP Site 503. Sample spacing was interpolated to 6000 yr for KK75-02 and 10,000 yr for DSDP Site 503. Spectra for the cores are expressed as the natural log of the variance as a function of frequency. The spectral estimates were calculated using the University of Michigan Interactive Data Analysis System (MIDAS). The spectral analysis techniques in this program are based on the methodology of Jenkins and Watts (1968). A one-sided confidence level of 80% (Pisias *et al.*, 1973) is attached to the spectral estimates and is calculated from the χ^2 distribution using $2n/m$ degrees of freedom, where n = the number of data points and m = the number of lags.

periods of 104,000, 41,000, and 23,000 yr (Fig. 5). These are similar to the periods calculated for the earth's orbital parameters of eccentricity, obliquity, and precession, respectively (Berger, 1978).

The calculated spectrum for the eolian grain-size time series at Hole 503B is dominated by two discrete peaks that correspond to periods of 140,000 and 41,000 yr (Fig. 5). The 41,000-yr period is similar to that calculated for obliquity (Berger, 1978). If present, the precessional periodicity would not be detected at the sample spacing utilized in this study. The lower frequency peak (140,000-yr period) is not readily explainable but may be related to the eccentricity parameter. However, the record at Site 503 may be too short to attach much significance to this long-period oscillation.

To investigate further the relationship between the earth's orbital parameters and the dominant frequency components in the eolian grain-size records at KK75-02 and Site 503, digital bandpass filters were applied to the two time series to isolate the significant eolian frequency components that correspond to eccentricity, obliquity, and precession. The filtered components were plotted in the time domain with the calculated curves for the corresponding parameters of obliquity, precession, and eccentricity (Figs. 6 to 8).

DISCUSSION

As with many paleoenvironmental proxy indicators, fluctuations in the mass accumulation rate and grain size of eolian material occur on the same temporal scales as the major glacial to interglacial oscillations that have characterized the past few million years of earth history. This result is not unexpected as the mechanisms that control ice growth and decay should also produce significant changes in atmospheric circulation and source-area climate and, thus,

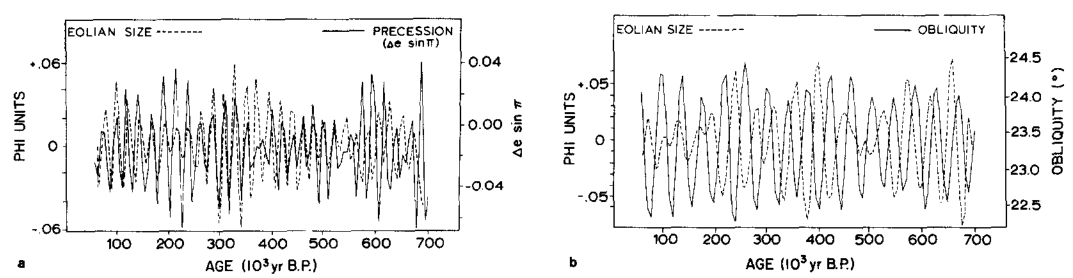

FIG. 6. Variations in (a) the precessional index and KK75-02 23,000-yr component of grain size and (b) obliquity and KK75-02 41,000-yr component of grain size plotted in the time domain. Digital bandpass filters centered 0.024 cycles/1000 yr (41,000-yr period) and 0.043 cycles/1000 yr (23,000-yr period) were applied to the grain-size time series. Positive deviations in the grain size represent coarser material.

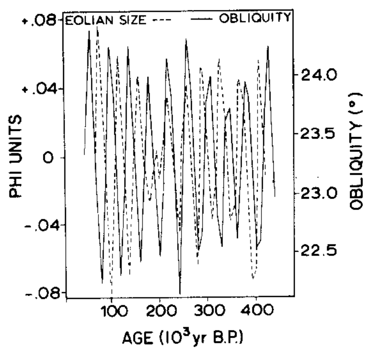

FIG. 7. Variations in obliquity and the Site 503 41,000-yr component of grain size plotted in the time domain. A digital bandpass filter centered at 0.024 cycles/1000 yr was applied to the Site 503 eolian grain-size time series. Positive deviations in the grain size represent coarser material.

changes in the contribution of eolian material to the deep sea.

The eolian accumulation rates and grain size do not exhibit a long-term covariance over the 700,000-yr record. All other climatic factors being equal, stronger winds should be able to carry more and larger particles. Accordingly, a rough covariance between the eolian accumulation rates and the grain size might be expected to exist. Previous work on long-term integrated eolian samples, each sample spanning 20,000 to 50,000 yr in age, shows that a rough covariance exists between the eolian grain size and accumulation rate over the past 65 myr (Janecek and Rea, 1983). These differences may be partly the result of aliasing due to different sample densities. However, if the response of the intensity of atmospheric circulation and source-area aridity to climate-forcing functions are different enough in the short term, a covariance may not be found. For example, if the source-area climate is such that little material is available for erosion and transport but atmospheric circulation is intense, relatively larger grains (but less material) will be transported. Conversely, times characterized by high aridity and relatively less intense winds may result in a large amount of dust input characterized by a small equilibrium grain size. The results of this study suggest that, at the time scales utilized, the temporal response of the intensity of atmospheric circulation and source-area aridity to climate forcing are different enough that eolian accumulation rates and grain size (i.e., source-area climate and wind intensity) vary independently.

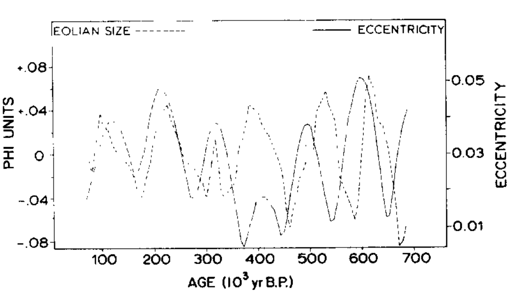

FIG. 8. Variations in eccentricity and the KK75-02 104,000-yr component of grain size plotted in the time domain. A digital bandpass filter centered at 0.0096 cycles/1000 yr (104,000-yr period) was applied to the grain-size time series. Positive deviations in the grain size represent coarser material.

Previous studies of dust input into the deep sea (Rea and Janecek, 1981a, 1981b, 1982; Sarnthein *et al.*, 1981; Janecek and Rea, 1983) also suggest that the accumulation of eolian material depends more on the aridity of the source area rather than on wind strength. Climatic conditions in eolian source areas during the Quaternary, however, are somewhat problematic. In general, most of the temperate and tropical world was more arid during the height of the last glaciation (Williams, 1975; Gates, 1976; Manabe and Hahn, 1977; Sarnthein, 1978).

It is not clear, however, whether this relative aridity lasted throughout an entire glacial period or occurred in all regions. For example, African lake-level records show more humid conditions during much of the early and middle portions of the last glacial age but much more arid conditions in the latter stages (Butzer *et al.*, 1972; Frenzel, 1973; Lamb, 1977; Street and Grove, 1979). Pollen records from tropical Australia suggest the last glacial age was more arid than the present interglaciation (Kershaw, 1978).

but temperate portions of Australia may have been wetter (Bowler *et al.*, 1976; Webster and Streten, 1978). In the southwestern United States and Mexico there may also have been wetter conditions during glacial times (Brakenridge, 1978; Sarnthein, 1978, Adam and West, 1983) but the data are not consistent (Watts and Bradbury, 1982; Galloway, 1983). Similarly, more humid conditions may have prevailed in parts of northwest Africa during glacial times (Parkin and Padgham, 1975; Diester-Haass, 1976). The Andes, too, were apparently wetter during glaciations (Peterson *et al.*, 1979; Huesser, 1983; Hooghiemstra, 1984). These data suggest that the flux of eolian material to a particular core site may be characterized by a strong regional input overprinted on general global climatic conditions.

The eolian accumulation record at Site 503 suggests that the dominant source areas for the site, Central America and northwestern South America, were more humid during glacial times. The eolian mass accumulation rates also lend some insight as to what portions of the glacial–interglacial cycles were most arid. At Hole 503B, times of maximum eolian accumulation correspond to or are somewhat younger than the carbonate indicators of glacial terminations, which themselves are 5000 to 10,000 yr younger than corresponding isotopic terminations. Thus, the eolian accumulation maxima appear to occur 5000 to 10,000 yr after major reductions in ice volume. The exact relationships, however, must await simultaneous analyses of ^{18}O and eolian samples.

KK75-02 is located well below the carbonate compensation depth and therefore does not contain carbonate material. Thus, direct correlations of carbonate fluctuations and oxygen isotopes (as proxy indicators of ice volume) with eolian mass accumulation rates cannot be made for this core. However, in order to provide a rough approximation of the relationship of eolian accumulation rates with the glacial cycles, eolian MAR values from KK75-02 can be correlated by radiolarian stratigraphy (Morley *et al.*, 1982) to the generalized isotope curve constructed by Emiliani (1978) (Fig. 9). In general, the maximum accumulation rates occur during interglacial (odd-numbered) isotope stages. Although there is not a complete one-to-one correlation, this plot suggests that the central Asian source areas may also have experienced increased humidity during glacial times.

The eolian mass accumulation rates at KK75-02 exhibit two extreme minima, one at 125,000 yr (interglacial stage 5) and another around 550,000 yr during glacial stage 14. The younger minimum does not fit into the humid glacial scenario although the older one does. These intervals of low dust input (and possibly the others) may be the result of a latitudinal shift in wind patterns and thus the supply of material to the site rather than changes in the climatic conditions in the source areas. Phase relationships between the eolian grain size and the orbital parameters also suggest that shifts in the positions of the zonal winds may, in part, affect the flux of dust at the times scales under consideration here.

The variance spectra for the eolian grain-size time series at KK75-02 and DSDP Site

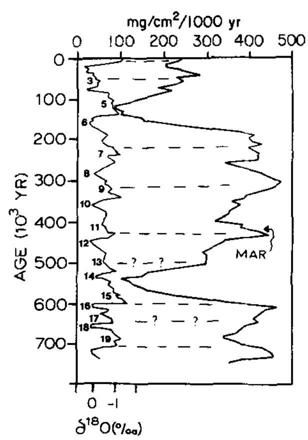

FIG. 9. KK75-02 eolian mass accumulation rates plotted with the generalized oxygen-isotope curve constructed by Emiliani (1978).

503 (Fig. 5) are characterized by frequencies similar to those calculated for the orbital parameters of eccentricity, obliquity, and precession (Berger, 1978). This result is a further confirmation of the work of many investigators (Hays *et al.*, 1976; Pisias, 1976; Kominz *et al.*, 1979; Morley and Hays, 1981; Imbrie, 1982) who have shown that frequencies similar to those for the orbital parameters of eccentricity, obliquity, and precession account for much of the variance in the climatic spectra calculated for proxy climatic indicators from deep-sea sediments.

In general, the 41,000-yr (both cores) and the 23,000-yr (KK75-02) grain-size components show that times of minimum Northern Hemisphere summer insolation, low obliquity, and high precessional values, correlate with times of coarsest grain size. Such an orbital configuration has been shown to be critical for rapid ice growth (glaciation) in the Northern Hemisphere (Milankovitch, 1941). These results suggest that atmospheric circulation over the North Pacific intensified during times of ice growth in the Northern Hemisphere.

Alternatively, the strong positive correlation between grain size and the precessional index at KK75-02 might also be interpreted in terms of seasonality and/or a north–south movement of the wind belts over a site; both of which would be sensitive to changes in precession.

The 104,000-yr grain-size component at KK75-02 exhibits a relationship with eccentricity that appears to conflict with the 41,000- and 23,000-yr results. In general, coarsest grain size correlates with high eccentricity values, implying that the intensity of the prevailing westerlies increased during interglacial times, opposite to the conclusion drawn from the 23,000- and 41,000-yr results. These data may not actually conflict, however, as times conducive to rapid ice buildup are not necessarily glacial periods but rather the ends of interglacial periods.

Alternatively, the 104,000-yr component of grain size at KK75-02 may be recording latitudinal shifts in the position of the zonal winds. At present the core of the westerlies jet averages 43° to 45° N in the winter and 45° to 50° N in the summer (Barry and Chorley, 1976), a position just north of KK75-02. Gates (1976) has shown with general circulation models that during the last glacial maximum (18,000 yr B.P.) the most intense portion of the westerlies shifted approximately 20° south in response to a southerly shift in the zone of the maximum meridional gradient resulting from the expansion of Northern Hemisphere ice (CLIMAP, 1981). Correlation of coarsest material in the 104,000-yr component of eolian grain size with high eccentricity values suggests that the zone of maximum westerly intensity shifted to a position south of KK75-02 during glacial times. Such a shift in the core of the westerlies would result in relatively less intense winds (and finer equilibrium grain size) over the site during glacial times.

The spectra of eolian grain size support our age and sedimentation rate models and suggest that glacial to interglacial fluctuations in sedimentation rate are minimal at these sites. If our age models were not valid, the grain-size spectra most likely would exhibit more random (less coherent) frequencies. Changes in the phase relationships between the orbital parameters and particular grain-size components at KK75-02 around 550,000 yr ago (Figs. 6–8) suggest that some variations in sedimentation rate did occur at time scales not detectable with our stratigraphy.

Calculations based on the magnitude of the grain-size fluctuations in both cores indicate a change in high-to-low wind intensities by an average of 22% at KK75-02 and 36% at Site 503, suggesting that the trade winds were more variable than the westerlies. These values are similar to those based on other indirect proxy indicators for changes in zonal wind intensity between glacial and interglacial times. Using multivariate statistical analyses of quartz and several other sedimentary parameters from eastern equatorial Pacific cores, Molina-Cruz (1977) suggested that the speed of the trade winds increased 30 to 50% from interglacial to glacial times. Atmospheric circulation models based on sea-surface paleotemperatures (Gates, 1976) for glacial conditions suggest an intensification of the westerlies by more than 50% during glacial times. The data presented here agree with the models for intensification of the westerlies and trade winds but indicate the intensification may be less than that suggested from the use of sea-surface temperature data.

CONCLUSIONS

The accumulation rate and grain size of the eolian component isolated from KK75-02 in the North Pacific and DSDP Site 503 in the equatorial Pacific reveal significant changes in source-area aridity and wind intensity over the past 750,000 yr. Eolian accumulation rates are generally higher during interglacial times, suggesting that the source areas in central Asia and Central America were wetter and more vegetated, not more arid, during glacial times. Eolian grain-size spectra have significant concentrations of variance at frequencies corresponding to those for eccentricity, obliquity, and precession. The results of this study, when combined with other Quaternary eolian investigations, suggest that regional climatic signals may strongly overprint global trends, particularly in regards to increased aridity during glaciations. For example, an analysis of quartz and other sedimentary components in cores off northwest Africa by Parkin and Padgham (1975) showed that land north of Dakar was especially arid during glaciations whereas land south of Dakar was wetter during glaciations. Thiede (1979) found an increase in quartz content at 18,000 yr B.P. relative to the present in cores off southwest Australia and attributed the change to increased aridity during the glacial maximum. Even though this study and others do not find a consistent source-area aridity signal they all indicate that the zonal winds were more vigorous during glacial times.

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