Climate-controlled multidecadal variability in North African dust transport to the Mediterranean

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ABSTRACT

High-resolution laser ablation–inductively coupled plasma–mass spectroscopy scanning of resin-embedded laminated sediments is used to detail variability in the composition and magnitude of recent eolian dust deposition in the Eastern Mediterranean. The composition of dust accumulating in the anoxic Atalante basin varies in response to the strength of the summer blocking mode of Mediterranean climate. Dust sources located upwind on the westerly airflow are favored during phases of weaker blocking (hence stronger summer westerlies). This mode is in turn correlated to the pronounced multidecadal oscillation in Mediterranean sea-surface temperature (related to the Atlantic Multidecadal Oscillation), suggesting that coupled ocean-atmosphere dynamics control the large-scale transport of dust in the region. Variable precipitation in dust source regions may also exert an influence on the relative flux of dust from each source, and hence the net composition of dust deposited in the basin. Persistent oscillations in the composition of deeper sediments indicate that the basin offers a high-potential archive for reconstruction of climate-controlled variability in dust transport prior to the instrumental era.

INTRODUCTION

The mobilization and export of dust particles from North Africa is a phenomenon of global importance, attracting an increasing level of interest as the impacts on radiative budgets (Li et al., 2004), cyclone activity (Evan et al., 2006), and marine productivity (Jickells et al., 2005) are better understood. Due to these teleconnections, short time-scale variability in the quantity and composition of exported dust may influence weather patterns and carbon cycling in distal regions of the globe. Such variability may equally be viewed as a response to climatic oscillations in dust source regions. This dual role as both forcing and respondent integrally ties dust transport into the mechanisms underlying short-term climate change. However, while interdecadal variability in the export of dust westward across the Atlantic has been shown to primarily reflect the extent of drought conditions in the Sahel (Prospero and Lamb 2003), the controls on northward transport toward the circum-Mediterranean have remained more difficult to resolve. Aridity may drive the initial mobilization of North African dust (Goudie and Middleton, 1992), but wind patterns ultimately dictate its export to distal locations (Moulin et al., 1997). The atmospheric pressure fields of the circum-Mediterranean region therefore exert an important influence on the transport pathways of dust after mobilization. These pressure fields are characterized by recurrent patterns known as modes, which are highly seasonal and interannually variable in strength (e.g., Jacobeit et al., 2003; Xoplaki et al., 2003).

Deconvolving the effects of aridity and wind patterns on dust transport to the Mediterranean is possible by monitoring present-day dust export (Israelevich et al., 2002) or investigating high-resolution archives of dust deposition, such as Alpine ice cores (Sodemann et al., 2006) and laminated Mediterranean sediments. Of these, only sediments offer the long, continuous record of sea-level dust deposition that is required to investigate multidecadal variability. Here we present geochemical profiles of a laminated sediment sequence from the brine-filled Atalante basin in the Eastern Mediterranean (Fig. 1A), where anoxic conditions preserve the chronology of incoming sediment fluxes. The basin is located within 500 km of the drainage systems of southern Greece, which may supply a background fraction of river-derived terrestrial material to the sediments. However, these river systems undergo maximum discharge during the winter months, in association with westerly driven precipitation (Fig. 1A). In contrast, sediment trap aluminum fluxes in the Eastern Mediterranean show maxima in the summer months, when the atmospheric dust load

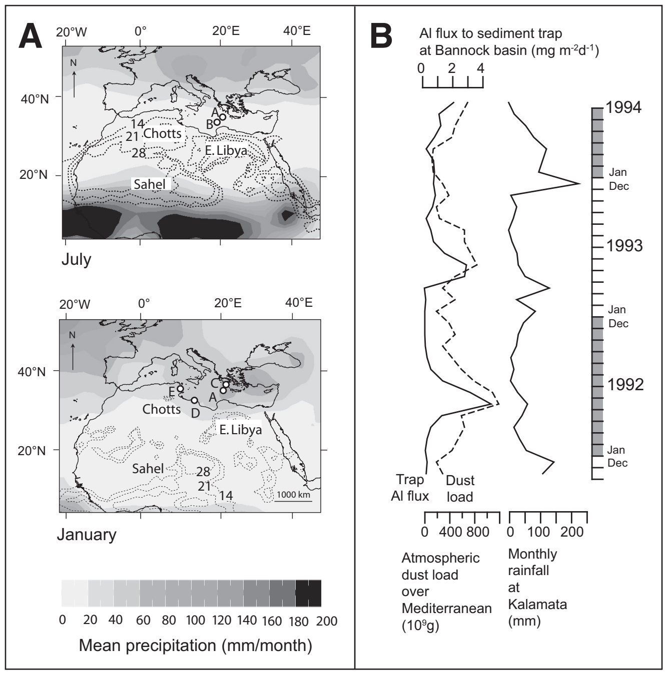

Figure 1. A: Precipitation and aerosol density. Shading is mean precipitation calculated from CAMS_OPI (climate anomaly monitoring system and outgoing longwave radiation precipitation index) monthly precipitation climatology (1979–1995) on a 2.5° × 2.5° lat-long grid using IRI/LDEO (International Research Institute for Climate and Society–Lamont-Doherty Earth Observatory) Climate Data Library (http://iridl.ldeo.columbia.edu/). Dotted line contours are days per month (in July and January 1981) with absorbing aerosol index ≥ 1.0, redrawn from Prospero et al. (2002). Locations: A—Atalante basin, B—Bannock basin, C—Kalamata, Greece, D—Tripoli, Libya, E—Sfax, Tunisia. Ionian Sea region used for calculation of sea-surface temperature (SST) series from Hadley Centre data (http://hadobs.metoffice.com/hadisst/data/) is 14°–23°E, 30°–38°N; Mediterranean region used in calculations of summer climate variability by Xoplaki et al. (2003) is 10°W–38°E, 26°–47°N; Sahel region used for calculation of summer precipitation series is 17°W–17°E, 11°–19°N. B: Aluminum flux in Bannock basin sediment trap (redrawn from Rutten et al., 2000), atmospheric dust load over the Mediterranean (redrawn from Rutten et al., 2000; Dulac et al., 1996) and monthly precipitation at Kalamata, Greece.

from North Africa is at its highest (Fig. 1B). These observations suggest that the flux of terrestrial material to the Atalante basin is dominated by eolian dust, and therefore that any changes in the composition of the terrestrial sediment component are primarily related to dust transport. Using elemental microanalysis of resin-embedded sediment, we investigate multidecadal variability in dust composition over the past 140 yr. We then compare these time series with those of instrumentally recorded summer climate variability in the Mediterranean and in the regions of North Africa where the principal sources of dust transport to the Mediterranean are located (Fig. 1A).

METHODS

Sediment multicore NU15MC (35°18.38′N, 21°23.59′E) was recovered from 3440 m water depth in the Atalante basin in the Eastern Mediterranean during cruise NU05 of the R/V *Universitatis* in 2005. A series of 16 samples was taken at 3 mm resolution from the core top, to construct a ^{210}Pb activity profile (for full details of methodology, see the GSA Data Repository[1] and Boer et al., 2006). An intact 4.5-cm-long sediment block was excavated parallel to the ^{210}Pb samples in an aluminum tray, desalinated, and resin embedded in a nitrogen-filled glove box (Jilbert et al., 2008). The embedded block was cut to reveal the laminated internal surface, which was then polished. Laser ablation–inductively coupled plasma–mass spectroscopy (LA-ICP-MS) scans were made at ETH Zürich, Switzerland, after mounting the embedded block in a sealed ablation chamber under the target of a laser beam (Ø120 μm, repetition rate 20 Hz, λ193 nm for optimum ablation into particles of uniform size). The chamber was moved under the beam at a steady speed of 25 μm/s to create an ablation trace on the sample surface, and ablated material was transported in a He-Ar mixture to the ICP-MS, where isotope specific ion currents were measured at a frequency of 0.8 data points/s. The resulting sampling resolution was therefore 30 μm (vertical) by 120 μm (lateral). (For further details of data processing, see the Data Repository.)

RESULTS AND DISCUSSION

Major Element Compositional Variability

Compositional variability within the sediment was investigated by principal component analyses (PCA) of the full 4.5 cm of LA-ICP-MS data. The PCA was performed on the concentration data of all major terrestrial element oxides, and $CaCO_3$, and shows a dominant axis 1 (eigenvalue 0.94) on which $CaCO_3$ scores positive and all major terrestrial elements score negative (Fig. 2A). Mixing between calcium carbonate (assumed to be of marine biogenic origin) and terrestrial material thus accounts for the primary signal of compositional variability in the sediment. This is confirmed by the depth profiles of the axis 1 score and the total major terrestrial element oxides (Na_2O, MgO, Al_2O_3, SiO_2, K_2O, MnO, Fe_2O_3), which show a strong inverse correlation (Fig. 2B).

Axis 2 then identifies compositional variability within the terrestrial component of the sediment. Si and Al plot at opposite ends of the axis, with Na, K, Fe, and Mg falling between (Fig. 2A). After normalization to aluminum, all the major terrestrial elements show a depth profile similar to that of the axis 2 score (Fig. 2B). The similarity between all the major element/Al ratios indicates that the dust deposited in the Atalante basin originates primarily from two sources with distinct elemental compositions. The PCA axis 2 score thus reflects the ratio of the input from these sources at a given depth in the sediment.

[1]GSA Data Repository item 2010004, supplementary information to climate-controlled multidecadal variability in North African dust transport to the Mediterranean, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

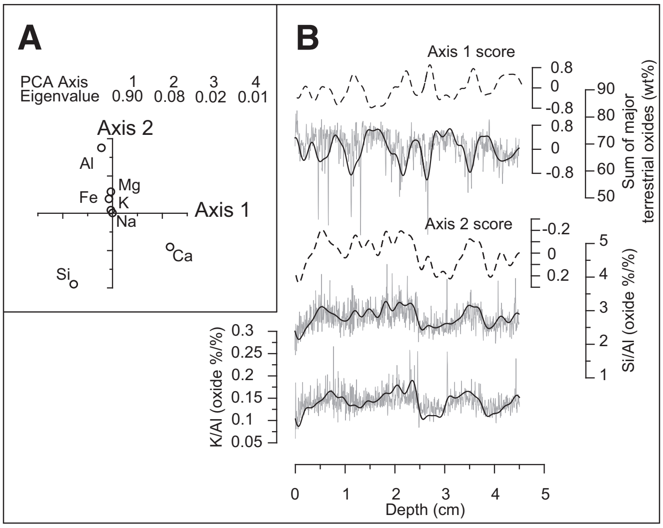

Figure 2. Principal component analyses (PCA) of laser ablation–inductively coupled plasma–mass spectroscopy compositional data from NU15MC. A: Crossplot of major terrestrial element oxides and $CaCO_3$ total concentration data on PCA axes 1 and 2, and eigenvalues of all identified axes. B: Depth series of axes 1 and 2 (dashed lines, lowpass filtered at 2.5 mm), and representative compositional ratios. Total major terrestrial element oxides: Na_2O, MgO, Al_2O_3, SiO_2, K_2O, MnO, Fe_2O_3. Solid black profiles—2.5 mm lowpass filter.

Calculation of Age Model and Total Dust Accumulation Rate

Due to the undisturbed sedimentation regime within the Atalante basin, the ^{210}Pb activity profile of NU15MC shows a near-pristine exponential decline with depth (Fig. 3A). The offset between the constant rate of supply (CRS) and constant flux–constant sedimentation (CF/CS) age models increases from <5 yr (at 0–2 cm depth) to 5–10 yr (at 2–4 cm depth). The CRS age model may be considered superior, as it allows for nonstationary mass accumulation rates (see the Data Repository), and the non-constant ratio of carbonate to terrestrial material (Fig. 2B) implies variability in the accumulation of one or both components. Therefore, we use the CRS age model as the basis for the calculation of dust accumulation rates (Fig. 3B; Fig DR1 in the Data Repository) and time series of PCA axis 2 (Fig. 3B). Confidence in the age model is improved by the addition of a deep sample, which confirms the stability of the background (unsupported) ^{210}Pb activity at 77 mBq/g sediment (Fig. 3A).

Climatic Time Series

To deconvolve the effects of source region aridity and atmospheric transport pathways on the composition and magnitude of the dust flux to the Eastern Mediterranean, we compared our data with a number of key instrumental time series (Fig. 3B). To focus on multidecadal variability, all series are shown as 10 yr running means of the raw data (original data resolutions indicated in Fig. 3 caption). We show wet season precipitation time series that represent three potential source regions of dust transport to the Atalante basin: the Chotts of Tunisia and northeast Algeria, the East Libyan Desert (both having winter rains), and the multiple more distant sources in the Sahel (having summer rains; Fig. 1A).

Assuming that dust from any source is transported primarily in the summer months (Fig. 1B), we also plot time series of summer climate parameters in the Mediterranean region. The first canonical correspondence analysis mode of Mediterranean summer air pressure variability since 1950 (Xoplaki et al., 2003) describes the leading pattern of interannual variability in the summer air pressure fields over the Mediterranean region. When the mode is in a positive phase, high-pressure blocking conditions are prevalent over central Europe; when the mode is negative,

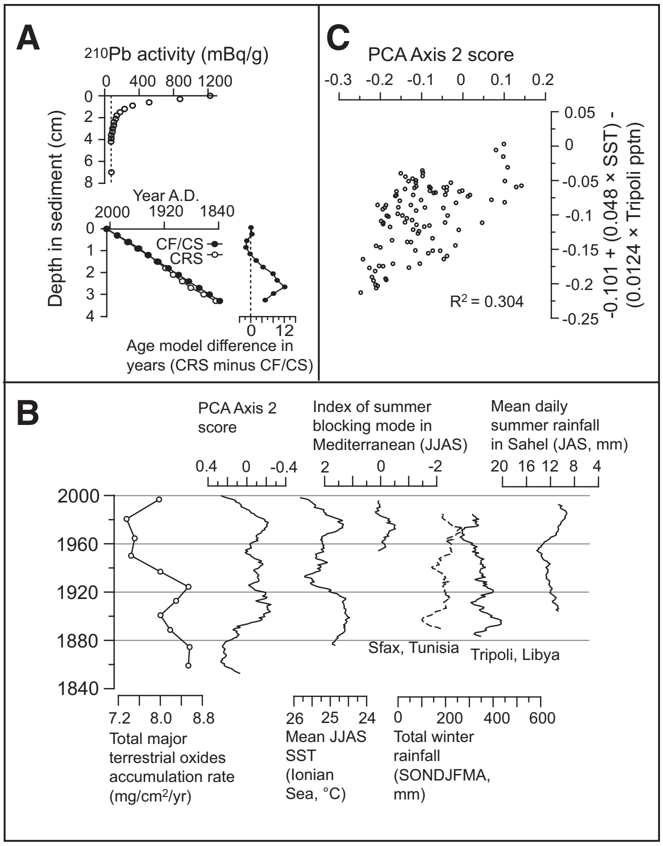

Figure 3. A: ^{210}Pb depth profile for NU15MC and associated constant rate of supply (CRS) and constant flux–constant supply (CF/CS) age models. Measurement error in duplicates is within size of symbol at this scale. Vertical dashed line indicates modeled supported ^{210}Pb activity. B: Time series of NU15MC compositional data and relevant climatic parameters. Note reverse scales for some parameters. All profiles except dust accumulation rate are presented as 10 yr moving averages of following original data resolutions: principal component analysis (PCA) axis 2 score = subannual; all instrumental data = annual. C: Scatter plot of observed 10 yr running mean PCA axis 2 score versus predicted score based on multiple regression equation including 10 yr running means of Ionian summer sea-surface temperature (SST) and Tripoli winter precipitation, both detrended and normalized to unit variance (A.D. 1884–1984; limited by length of Tripoli data series). JJAS—June, July, August, September; JAS—July, August, September; SONDJFMA—September to April, inclusive.

blocking is reduced and the westerly zonal airflow over the Mediterranean and Europe is stronger. The multidecadal behavior of this summer blocking mode correlates positively with the summer sea-surface temperature (SST) pattern of the Mediterranean (Xoplaki et al., 2003). Hence, the longer SST time series approximates the mean pattern of summer atmospheric circulation over the Mediterranean. The presented summer SST curve for the Ionian Sea shows a multidecadal structure similar to that of the whole Mediterranean, and the North Atlantic, and as such may be viewed as a record of the interhemispheric SST pattern often referred to as the Atlantic Multidecadal Oscillation (see Zhang and Delworth, 2006).

Transport Pathways and Dust Composition

A striking correlation exists between the time series of PCA axis 2 and the SST curve (Fig. 3B). The variable composition of dust transported to the Eastern Mediterranean on multidecadal time scales therefore appears to be strongly influenced by the rearrangement of summer atmospheric pressure fields in association with SST variability. As mean atmospheric transport pathways vary, so does the ratio of dust transported from the major sources supplying the Atalante basin sediments. Considering the position of the potential sources with respect to the basin, a shift toward cooler temperatures and a stronger summer westerly flow (e.g., in the interval A.D. 1960–1980) would be expected to favor transport from the Tunisian-Algerian Chotts, due west of the Atalante basin, over transport from the East Libyan Desert, due south (Fig. 1A). Conversely, warmer intervals such as the mid-twentieth century would be expected to show a decreased relative contribution from the Chotts, as the summer airflow becomes more meridional in character. Therefore, the observed two-source mixing can be explained in terms of variable relative supply from these regions, whereby low axis 2 values indicate an enhanced relative supply from the Chotts. However, we do not exclude the possibility that dust from the more distant Sahel source regions also reaches the Atalante basin. Since transport of Sahel dust to the Mediterranean occurs primarily via capture by the westerlies of particles carried north at high altitude (Pye, 1987), the magnitude of a Sahel component in the Atalante dust record should also be sensitive to the strength of the blocking mode. Theoretically, dust carried to the basin by the westerlies with a constant ratio of Sahel to Chotts material would also generate a single source in the elemental data.

Precipitation and Dust Composition

Although atmospheric transport pathways appear to exert the major influence on the composition of the dust flux to the Atalante basin, aridity controlled changes in the availability of dust may play an additional role in dictating the flux from each source. Winter precipitation at Sfax, Tunisia, shows a distinct anticorrelation with that at Tripoli, Libya, highlighting the sensitivity of the North African coastal climate to the trajectory of winter storms and cyclogenesis in the Mediterranean (Fig. 3B). Both time series are typical for their regions and represent the longest available precipitation records in the vicinity of the Chotts and the East Libyan Desert. Multiple regression analysis of the normalized series shows that the correlation between SST and the PCA axis 2 score is slightly improved by the addition of Tripoli precipitation as a second predictor ($R^2 = 0.30$ versus 0.29). The regression equation is: PCA axis 2 = $-0.101 + (0.048 \times \text{SST}) - (0.0124 \times$ Tripoli precipitation) (Fig. 3C). The negative correlation between Tripoli precipitation and PCA axis 2 supports the initial interpretation that low PCA axis 2 scores reflect an enhanced relative contribution of westerly derived (Chotts) dust, since wetter conditions in Tripoli would be expected to indicate reduced dust availability from East Libya. However, the dominance of the SST predictor in the regression suggests that the influence of source region precipitation on dust composition is minor.

The Sahel summer precipitation record also shows a positive correlation with the time series of PCA axis 2, although the height of the Sahel drought in the 1970s and 1980s lags the corresponding PCA axis 2 minimum by ~10–15 yr (when presented as 10 yr running means, as in Fig. 3B). We interpret this correlation to represent the simultaneous forcing of Sahel precipitation by SST patterns, either in the Mediterranean (Rowell, 2003) or more directly in the North Atlantic, which shows a similar multidecadal SST evolution (e.g., Zhang and Delworth, 2006), rather than a precipitation-induced change in the composition of Sahel dust transported to the Mediterranean. Such a shift may occur as the relative importance of the multiple Sahel dust sources varies with regional aridification, but its influence on the Atalante record remains difficult to quantify.

Controls on Total Dust Accumulation Rate

The total dust accumulation rate in the Atalante Basin shows a general decreasing trend from A.D. 1860 to the present day, onto which multidecadal variability is superimposed (Fig. 3B). The construction of the accumulation rate profile and its interpretation is discussed in the Data Repository.

Implications

Although an influence of the North Atlantic Oscillation (NAO) on dust transport to both the Atlantic and Mediterranean has been suggested (Moulin et al., 1997), the NAO index has a lower correlation with Mediterranean climate parameters in summer, when most dust is transported to the region, than in winter. Hence, the Mediterranean summer modes identified by Xoplaki et al. (2003) offer more appropriate indices with which to compare our data. Their link to SST patterns confirms that coupled ocean-atmosphere dynamics are responsible for multidecadal changes in large-scale dust transport routes. The suggestion that the strength of summer blocking may influence North African dust transport to the Mediterranean was first made by Moulin et al. (1998). Our data show that this influence is manifest as a variable ratio of dust transport from different sources, most likely in the North African coastal region.

Ultimately, a study of the composition of dust collected in the source regions, alongside material from shipboard filters (e.g., Stuut et al., 2005) and sediment traps (e.g., Ratmeyer et al., 1999), will be required to expand the potential of the Atalante record for paleoclimate reconstruction. We observe persistent oscillations in the terrestrial composition of the sediment in the full ~50 cm of NU15MC, a continuation of those coupled to climate variability in the ^{210}Pb-dated core top (Fig. DR2), suggesting that the basin contains an unprecedented natural archive of climate-controlled dust transport to the Mediterranean during the Holocene.

CONCLUSIONS

High-resolution geochemical profiling of laminated sediments in the Atalante basin describes multidecadal changes in the composition of dust transported to the Eastern Mediterranean from source regions in North Africa. PCA analysis of the major element composition of the sediment reveals a pronounced signal of multidecadal variability in the terrestrial component, which can be explained in terms of two-source mixing. This signal, expressed as oscillations in sedimentary Si/Al, K/Al, Mg/Al, Na/Al, and Fe/Al, correlates to the multidecadal SST pattern of the Mediterranean over the past 140 yr. The coupling of SST variability to climate modes, i.e., the mean arrangement of atmospheric pressure fields over the Mediterranean region, is proposed as a mechanism for this correlation. During warmer intervals, more prevalent blocking conditions reduce the strength of westerly airflow over the Mediterranean during the summer dust transport season, thus reducing the relative input of dust from sources in Tunisia and Algeria, and potentially the Sahel, and favoring alternative sources such as the East Libyan Desert. Precipitation variability (hence aridity) in these source regions may exert an additional forcing on the net composition of the dust flux to the basin by altering the availability of dust for mobilization.

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