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Precipitation in the Yellow River drainage basin and East Asian monsoon strength on a decadal time scale

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ABSTRACT

Paleomonsoon strength is difficult to reconstruct. The strength of the East Asian monsoon and precipitation over large areas correlate well on a decadal time scale. Thus, monsoon strength can be reconstructed through proxies of sediments originating from large areas. In the present study, we investigated the characteristics of a sediment core from the Northern Yellow Sea Mud. The results showed that sedimentary characteristics are mainly controlled by discharge changes of the Yellow River. The relationships between median grain size (MZ), magnetic susceptibility (MS) and the SiO_2/Al_2O_3 ratio of sediments and spatially averaged precipitation around the Yellow River Drainage basin reveal that changes in MZ and MS are correlated with variation in precipitation. The agreement of temporal trends in MZ, MS and the monsoon strength index confirm that spatially averaged precipitation changes in the Yellow River Drainage basin on decadal time scale are driven by the monsoon strength. These characteristics of marine sediments from the Northern Yellow Sea Mud can thus be used as proxies for monsoon strength.

Introduction

The Asian monsoon climate system is an important part of the global climate system. Studies of patterns and forcing mechanisms of monsoon are important since about 60% of the world's population resides in monsoon regions, and safety and quality of human life are significantly influenced by precipitation related to the monsoon.

Monsoon strength is directly measured by land/ocean air pressure contrast, the instrumental records of which, however, have not been available until recently. Therefore, proxies of precipitation are commonly used to reconstruct changes in monsoon strength. Generally, high summer temperatures and low air pressure on the land cause more water vapor to be transported from the sea to the land, resulting in more precipitation on land. For example, the strength of the East Asian monsoon as measured by land/ocean air pressure contrast and precipitation in large areas of China correlate well (Guo et al., 2004). However, this correlation varies between southern and northern China on a decadal time scale (Ding et al., 2008). Nevertheless, spatially averaged precipitation in large areas of southern or northern China can each be used separately for monsoon-strength reconstruction. Terrestrial materials such as speleothems and lake sediments (Wang et al., 2000, 2005; Zhang et al., 2008; Tan et al., 2011) are also commonly used to reconstruct high-resolution monsoon changes. Although trends of these records are roughly consistent with each other on orbital time scales (Zhang et al., 2011; Zhou, 2011), they are quite different on a decadal time scale, potentially due to regional variability in the factors influencing precipitation (Tan, 2009). On the other hand, historical archives document high-resolution wet/dry changes over large areas (Zheng et al., 2006), but precipitation cannot be precisely reconstructed from them because it was not quantitatively recorded. Although deep-sea sediments record precipitation over large areas, the temporal resolution is generally not sufficient to reconstruct monsoon changes at the decadal time scale. Thus far, there has been a lack of materials that can be used to reconstruct changes in monsoon strength on a decadal time scale efficiently.

Sediments deposited in muddy marine deltaic areas have become one of the most important materials for the study of global change because of their high sedimentation rate, continuous deposition and large source area. There are four muddy areas on the continental shelves of the Yellow Sea and the East China Sea, including the Northern Yellow Sea Mud (NYSM), the Central Southern Yellow Sea Mud (CYSM), the Mud Area Southwest off Cheju Island (MASCI) and the Min-Zhe Coast Mud area (MZCM) (Liu, 1996). Environmentally sensitive grain size has been used as a proxy for winter monsoon strength over the past 2000 yr in both the MASCI and the MZCM (Xiao et al., 2005; Xiang et al., 2006). Xiao et al. (2006) reconstructed an 8000-yr winter monsoon series by using environmentally sensitive grain-size components in sediments in the MZCM, and discussed the relationship between winter monsoon and solar activity. Liu et al. (2010) reconstructed the winter monsoon strength changes since the mid-Holocene by combining median grain size (MZ), the chemical index of alteration, and the ratio of smectite to kaolinite. Quartz grain size has also been demonstrated to

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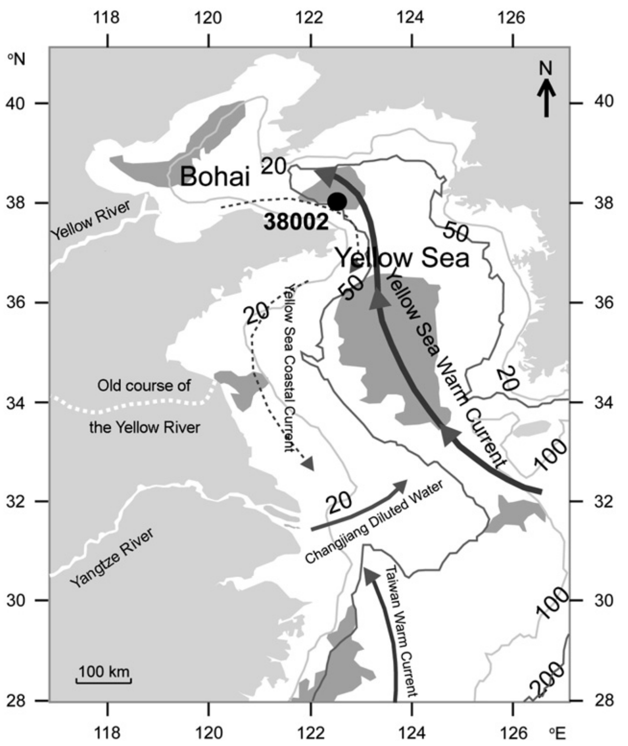

Figure 1. Location of the sampling site (map is modified from Yuan and Hsueh, 2010; Liu et al., 2007). Topographic lines are shown in light grey, mud areas are shown in dark grey, and coastal currents are marked by dashed lines and arrows.

record information of winter monsoon changes (Qiao et al., 2011). In these studies, coastal currents, which are influenced by winter monsoon, are thought to be the primary factor controlling sedimentary characteristics including grain size. However, Yang and Chen (2007) studied a profile of mud-rich sediments near the Yangtze estuary, and found that changes in grain size were related to summer (as opposed to winter) monsoon precipitation, which affects the discharge of the Yangtze River. These seemingly discrepant results in different areas suggest that the utility of grain size in muddy sediments for reconstructing monsoon strength needs to be further investigated.

In this study, we investigated the relationship between monsoon strength and characteristics of grains in muddy sediments at the NYSM. The NYSM is located north of the Shandong Peninsula of China. Materials in the NYSM are mainly from the Yellow River and transported across the Bohai Bay along the Shandong Peninsula (Fig. 1). Because materials around Bohai Bay are transported by rivers in regions affected by the monsoon, The NYSM is an ideal site to study the impact of monsoon on muddy sediments.

Site location, samples and methods

In 2009, we collected a 34-cm-long sediment core from the NYSM area, M38002, at Station 38002 (122°30.21′ E, 37°59.92′ N, water depth 49.2 m; Fig. 1) using a box-corer during "The Offshore Sea Opening Research Cruise (Autumn)" on the scientific survey ship "Kexue 1," Institute of Oceanology, Chinese Academy of Sciences. The sediment core was divided into 0.5-cm intervals resulting in 68 sub-samples, which were analyzed for magnetic susceptibility (MS), grain size, and Si and Al abundances.

Samples received the following treatment for grain-size analysis. 10–20 ml H_2O_2 solution (30%) was added, and the mixture was heated to 100°C for 0.5 h to remove organic matter. Subsequently, samples were bathed in 10 ml HCl solution (10%) for 48 h to remove calcareous cement and shell materials. All samples were fully desalted by adding 10 ml $(NaPO_3)_6$ (10%) and dispersed by ultrasonic treatment for 10 minutes before measurement.

Grain-size distributions were measured using a Mastersizer 2000 (Malvern Instruments) at the Lab of Soil and Environmental Changes, Taishan University, China. The measurement range of the instrument is 0.02 − 2000 μm, the resolution is 0.01 Φ, and the repeated measurement error is less than 2%.

Measurements of low-frequency magnetic susceptibility were carried out using the Bartington MS2 susceptibility meter at Nanjing University, Nanjing, China. The amounts of SiO_2 and Al_2O_3 were measured using XRF-1800 (X-Ray Fluorescence) Spectrometry (Shimadzu Corporation) at the Physical and Chemical Science Experimentation Center of the University of Science and Technology (USTC), Hefei, China. The

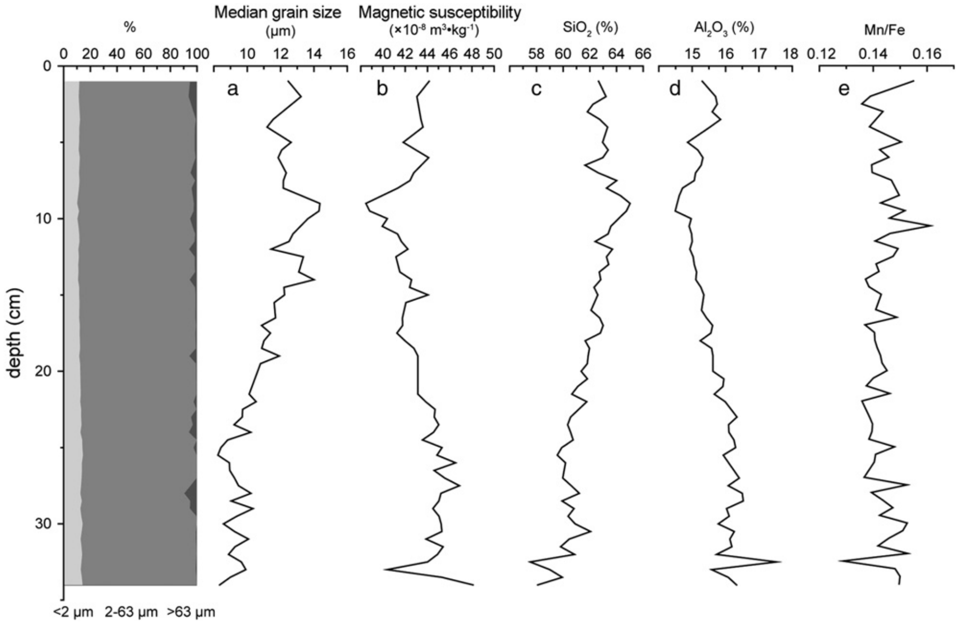

Figure 2. Profiles of sedimentary characteristics of core M38002.

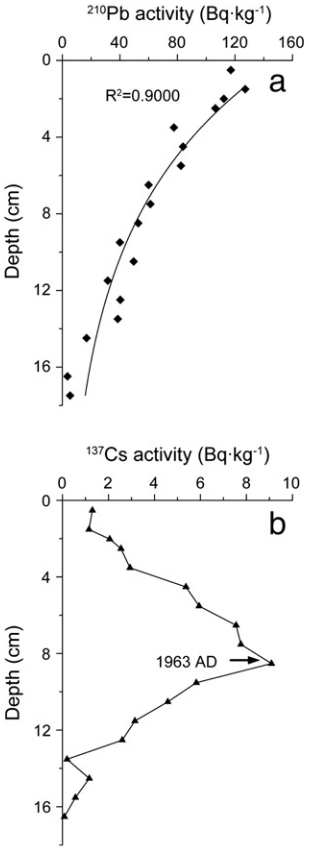

Figure 3. Activity profiles of ^{210}Pb (a) and ^{137}Cs (b) for the sediment core M38002.

contents of Fe and Mn were measured using Atomic absorption spectrophotometry (Model PZ-1100).

Radioactivity was measured by a germanium detector manufactured by AMETEK Company at the Institute of Polar Environment, USTC, Hefei, China. The samples were dried to constant weight at a temperature of 50°C, homogenized using a mortar and pestle, and passed through a 120-mesh sieve. Samples (5–10 g) were then packed into standard counting geometries for gamma spectrometry and sealed and stored for about one week to allow radioactive equilibration between ^{226}Ra and its daughter product ^{214}Pb. Spectra were continuously measured for 24 h to obtain enough counts. The resulting spectrum files showed ^{210}Pb activity with a peak at 46.5 keV.

Results

The entire sediment core consists of muddy sediments and showed a relatively stable composition of clay, silt and sand (Fig. 2a). The upper 23 cm of the core is mainly light yellow oxidied layers, whereas the lower part is mainly dark grey. Median grain size (MZ) of the sediments varies between 8 and 15 μm, with the finest sediment occurring around 34–25 cm in depth. There is a gradual upward trend of MZ from 25 to 14 cm in depth, with the coarsest part occurring between 14 and 9 cm in depth, with a decreasing trend in the upper 9–0 cm (Fig. 2b). Magnetic susceptibility (MS) varies between $38\times10^{-8}\ \mathrm{m^3\cdot kg^{-1}}$ and $48\times10^{-8}\ \mathrm{m^3\cdot kg^{-1}}$, and appears to be negatively correlated with MZ (Fig. 2c). Concentration of SiO_2 ranges from 56% to 66%, with a similar trend as MZ, indicating the enrichment of silicate minerals in coarse contents (Fig. 2d). In contrast, Al_2O_3 concentration follows a similar trend as MS (Fig. 2).

The chronology of the core was determined by the ^{210}Pb–^{137}Cs dating method (Fig. 3), using a Constant Initial Concentration (CIC) computer model (Appleby, 2001). The excess ^{210}Pb activity showed a simple exponential relationship with depth (Fig. 3). From the ^{210}Pb profile, the age of the ^{137}Cs peak at 8.5 cm was determined to be 1961 AD, very close to the presumed ^{137}Cs peak age of 1963 AD. This correspondence validates the accuracy of the ^{210}Pb dating. For this reason we use ^{210}Pb as the primary age control on our core. From ^{210}Pb data the average sedimentation rate was then calculated to be $0.13\ \mathrm{cm\cdot yr^{-1}}$, consistent with earlier results (Li et al., 2002; Qi et al., 2004). The time period recorded by the core is about 254 yr (1755–2009 AD), as estimated by extrapolation of this average sedimentation rate.

Discussion

We first examine the relationship between the concentration of coarse contents (>63 μm) in the sediments and summer-monsoon precipitation. Comparison of coarse contents with the wet/dry index of northern China (Zheng et al., 2006) shows that the concentration of coarse contents increases during wet periods, and declines in dry periods (Fig. 4), suggesting that summer-monsoon precipitation controls the sedimentary characteristics in core M38002, likely by affecting runoff of rivers. There is one exception where coarse contents did not increase during 1880–1905 AD, but precipitation in northern China strengthened significantly. According to the flood index time-series for the Yellow River (Luo and Le, 1996), there was no extra-large flood event during this period (Fig. 4), indicating that temporal distribution of precipitation was relatively homogeneous, and that the discharge of the Yellow River was not strong enough to transport coarse contents to the 38002 Site. In contrast, there was no statistically significant correlation ($R = 0.21$, $P = 0.27$) between the MZ of the core and the winter monsoon index (D'Arrigo et al., 2005). Taken together, these results indicate that sedimentary characteristics of the 38002 Site are largely controlled by summer-monsoon precipitation around the Yellow River drainage basin as opposed to winter-monsoon strength.

We then investigated the relationships among MZ, MS and the SiO_2/Al_2O_3 ratio. Materials carried by the Yellow River are mainly from the Loess Plateau, where MZ and MS of loess are inversely correlated (Liu and Ding, 1998). MS is elevated by pedogenesis, which creates more

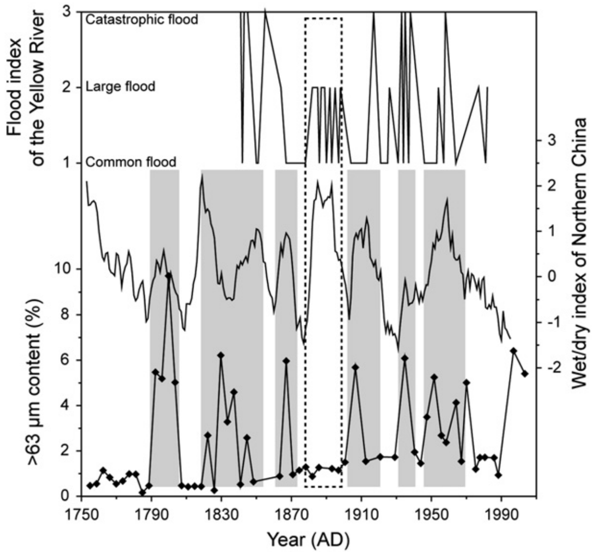

Figure 4. Comparison of coarse contents (>63 μm) in core M38002 with wet/dry index of Northern China (data from Zheng et al., 2006) and flood index of the Yellow River (data from Luo and Le, 1996). Numbers of 1, 2 and 3 in the flood index of the Yellow River denote common, large flood and catastrophic floods, respectively. Grey boxes highlight intervals of coarse sedimentation. The dashed box shows an interval of inconsistency between concentrations of coarse contents and wet/dry index when no catastrophic flood occurred.

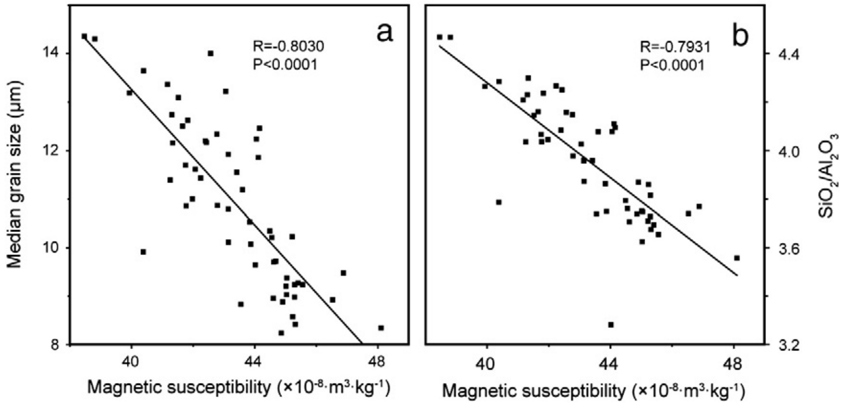

Figure 5. Correlations between MS, MZ and SiO_2/Al_2O_3 ratio of sediments in the Core M38002.

fine grains on the Loess Plateau (Zhou et al., 1991). In addition, the SiO_2/Al_2O_3 ratio is generally used as an indicator of pedogenesis in soil profiles, and is negatively correlated with pedogenesis (Peng and Guo, 2001) and thus also with MS. Indeed, we observe strong negative correlations between MZ and MS ($R = -0.8030$, $P < 0.0001$, Fig. 5a), and between SiO_2/Al_2O_3 ratios and MS ($R = -0.7931$, $P < 0.0001$, Fig. 5b).

Because MS is sensitive to reducing conditions, we carefully ruled out the possibility of reductive diagenesis in the M38002 core. First, we determined the Mn/Fe ratio, an index of oxidation-reduction environment of sediments (Lu et al., 2003) in each subsample but did not observe apparent changes along the entire core (Fig., 2f). Second, we observed that the relationship between MS and MZ is preserved throughout the core (Fig. 5). Third, we did not observe any decrease in MS in Core M38002, although it should decrease significantly in the presence of reductive diagenesis, (Liu et al., 2005). Fourth, Liu et al (2005) studied the magnetic properties of a sediment core retrieved from 52 m depth in muddy water, and found no evidence of reductive diagenesis in the uppermost 2.35 m. Our sediment core was obtained from a similar sedimentary environment, and was shorter than 2.35 m (0.34 m). Taken together, these lines of evidence suggest that our sediment core is unlikely to have undergone reduction, and the primary MZ signal is likely preserved.

Because grain size in Core M38002 is primarily determined by river discharge, we investigated whether MZ, MS, and the SiO_2/Al_2O_3 ratio can be used to indicate precipitation. MZ, MS and the SiO_2/Al_2O_3 ratio of the M38002 sediment core compared with annual instrumental precipitation around the Yellow River drainage basin from 1951 to 2002 AD (Fig. 6) show that they have similar trends. This indicates that river discharge, and hence summer-monsoonal rainfall, controls these sedimentary characteristics. Among them, MS and instrumental precipitation were negatively correlated ($R = -0.80$, $P = 0.005$), and both changed abruptly around 1960s. These results suggest that MZ, MS, and the SiO_2/Al_2O_3 ratio can be used to indicate historical precipitation.

The control on precipitation of the summer monsoon in the Yellow River drainage basin is well-documented. For example, Guo et al. (2004) found that precipitation in northern China increased when the summer monsoon strengthened. When the summer monsoon strengthens, the strength of southerly wind increases, which then

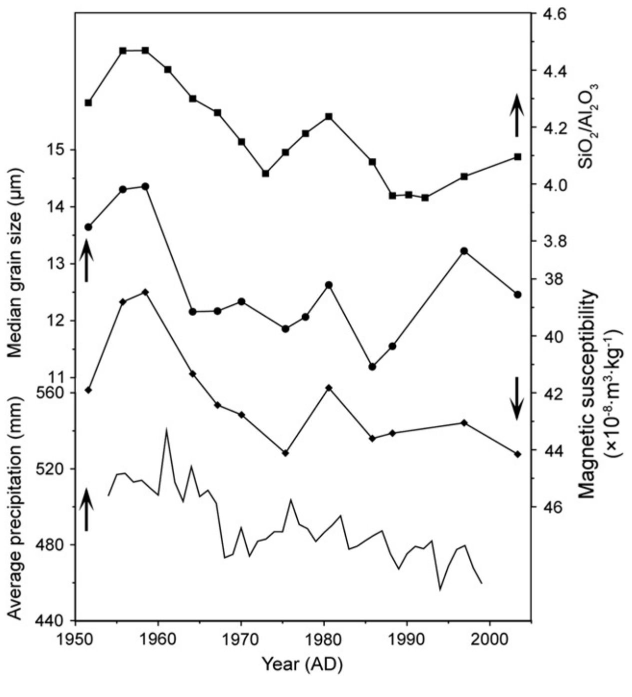

Figure 6. Comparison of MZ, MS and SiO_2/Al_2O_3 ratio of sediment core M38002 with instrumental annual precipitation around the Yellow River Drainage basin (7-point running average).

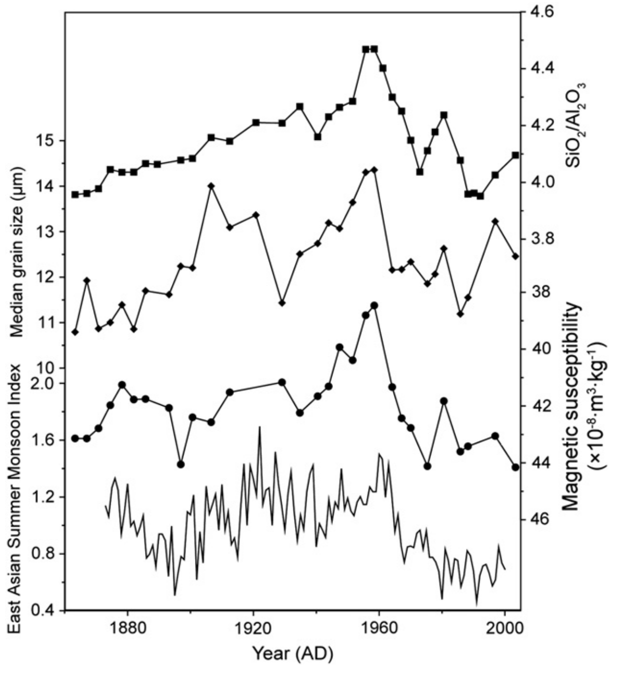

Figure 7. Comparison of MZ, MS and SiO_2/Al_2O_3 ratio of sediment core M38002 with the summer monsoon index (data from Guo et al., 2004).

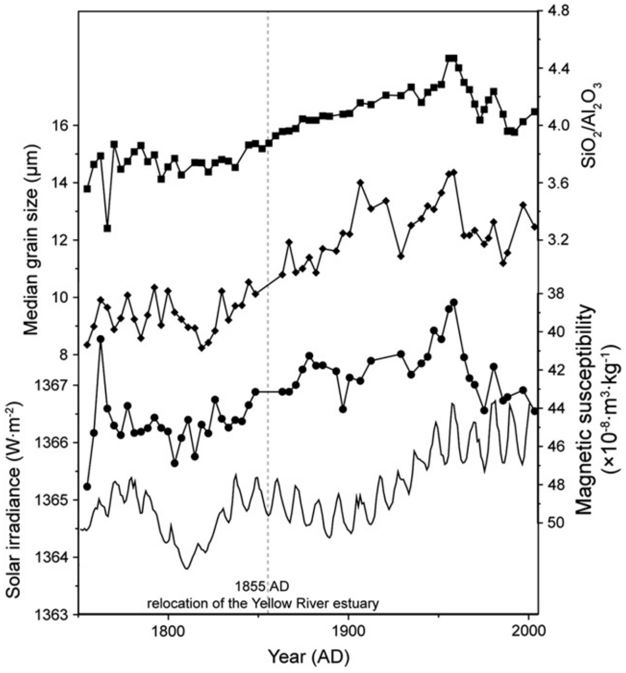

Figure 8. Comparison of MZ, MS and SiO_2/Al_2O_3 ratio of sediment core M38002 with solar irradiance (Lean, 2000).

results in more precipitation in northern China. As the summer monsoon weakens, a corresponding southward shift of major seasonal rainfall zone follows (Ding et al., 2008). Because MZ, MS, and the SiO_2/Al_2O_3 ratio are good indicators of precipitation as shown above, this strong causal relationship between summer-monsoon strength and precipitation suggests that MZ, MS, and the SiO_2/Al_2O_3 ratio can also be used as proxies for summer monsoon strength. Indeed, we found very similar trends of MZ, MS, and the SiO_2/Al_2O_3 ratio as the East Asian summer monsoon index reconstructed from air-pressure records (Fig. 7). For example, MS is strongly negatively correlated with the monsoon index ($R = -0.64$, $P < 0.001$).

The use of MZ, MS, and the SiO_2/Al_2O_3 ratios in near-shore marine sediments to indicate summer-monsoon strength has important implications. Precipitation proxies used in China are typically applicable only to small regions and may not be indicative of overall monsoon strength. MZ, MS, and the SiO_2/Al_2O_3 ratios of sediments in muddy areas such as the NYSM in this study, on the other hand, record precipitation and thus summer monsoon strength over large areas. Our reconstruction of historical summer-monsoon strength using MZ, MS, and the SiO_2/Al_2O_3 ratio provides useful information for investigating decadal-scale forcing of summer monsoon. For example, our proxies and solar irradiance (Lean, 2000) show similar trends during the past 250 yr (Fig. 8). The correlation coefficient between the MS profile and solar irradiance is as high as -0.60 ($P < 0.0001$). This result supports the notion that solar irradiance plays an important role in driving monsoon changes (Wang et al., 2005; Zhang et al., 2008).

Conclusions

We present a novel method for reconstructing paleomonsoon strength using physical and chemical characteristics of muddy deltaic marine sediments. Reconstruction of paleomonsoon strength by air-pressure contrast is limited by the short duration of instrumental records, and the terrestrial monsoon records are highly variable and often influenced by the region-specific factors. In the present study, high-resolution MZ, MS and SiO_2/Al_2O_3 ratio profiles of sediments in the NYSM were used for reconstructing precipitation changes in large areas around the Yellow River drainage basin, and related monsoon-strength changes. The results indicate that characteristics of sediments in the NYSM are good proxies for precipitation and summer-monsoon strength.

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