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Patterns of vegetation and climate change in the northern South China Sea during the last glaciation inferred from marine palynological records

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ABSTRACT

High-resolution marine palynological records from the northern South China Sea (SCS) provide new information concerning the regional history of vegetation and climate conditions during the last glaciation (~70–19 cal ka BP). The preservation of rich pollen from tropical and subtropical broadleaf trees (largely composed of evergreen *Quercus*, *Castanopsis*, and Euphorbiaceae) suggests that a southern subtropical climate prevailed during the last glaciation, including the period of the Last Glacial Maximum. Relatively higher percentages of such pollen taxa occurred during Marine Isotope Stage (MIS) 3, when *Phyllocladus* pollen from the south also increased, indicating a warmer terrestrial climate and a strengthened East Asian summer monsoon comparing to MIS 4 and 2. Moreover, the maximum percentages of such pollen occurred during the early MIS 3, implying that an optimal climate prevailed in this period. The reconstructed terrestrial climate corresponds well to marine evidence such as $\delta^{18}O$ values from planktonic foraminifer shell and records of sea surface temperature. This study confirmed that the regional terrestrial climate could be linked closely to changes in both global ice volume and the East Asian monsoon attributable to variations of the earth's orbital parameters. Modern palynological investigations and statistical analyses of the pollen percentages in the profiles indicate that *Pinus* pollen and spores are easily transported by water flow in the northern SCS. Therefore, their relative abundance peaks suggest that several wet intervals occurred during the last glaciation.

1. Introduction

Recently, increasing amounts of paleo-oceanographic research have been performed in the South China Sea (SCS), which has focused on the mechanisms driving regional climate change (Wang and Li, 2008; Wang et al., 2014a). Terrigenous pollen grains deposited on the seafloor can be used as a paleoclimatic proxy for coeval comparisons between marine and terrestrial paleoenvironmental conditions. Some pollen sequences have been reported from several periods of the last glaciation, such as drilling cores ODP 1144, SO 17940, and MD05-2904 from the northern SCS (Sun and Li, 1999; Sun et al., 2003; Chang et al., 2013) and lacustrine pollen documents from Leizhou Peninsula (Zheng and Lei, 1999), Chaoshan plain (Zheng and Li, 2000) and Huguangyan Maar Lake (Wang et al., 2012) in mainland China, and the island of Taiwan (Liew et al., 2006). However, high-resolution pollen records spanning most of the last glacial interval are poorly documented.

It is well known that the response of the climate system to orbital parameters is complex and frequently nonlinear because of the interactions between many factors such as ice volume, albedo, ocean currents, and greenhouse gases; therefore, understanding the forcing mechanisms of regional climate is difficult (Morley, 1997; Clemens and Prell, 2007; Wang et al., 2005). The northern SCS is an ideal location for the investigation of climatic interactions between high- and low-latitude areas, at orbital and millennial timescales, because of the co-influence of the northerly Siberian High (SH) and southerly Intertropical Convergence Zone (ITCZ) (Fig. 1), and because hemipelagic sediment provides long and continuous paleoclimatic records from the land and ocean (Wang and Li, 2008; Wang et al., 2014b).

In this article, based on the core MD05-2906 obtained from the northern SCS, a high-resolution marine palynological record that spans Marine Isotope Stage (MIS) 4–2 is presented. The environmental and climatological significance for key pollen taxa are validated and based on pollen data and regional paleoclimatic proxies, the effects of high-latitude climate processes on vegetation and climate during the last glaciation (~70–19 cal ka BP) are discussed. The findings of this study contribute a new understanding to the entire epicontinental vegetation history and possible climatic variability during the last glaciation in the northern SCS.

2. Regional setting

The northern SCS is bordered by southern mainland China, Hainan Island, and Taiwan Island, and it is connected to the East China Sea (ECS)

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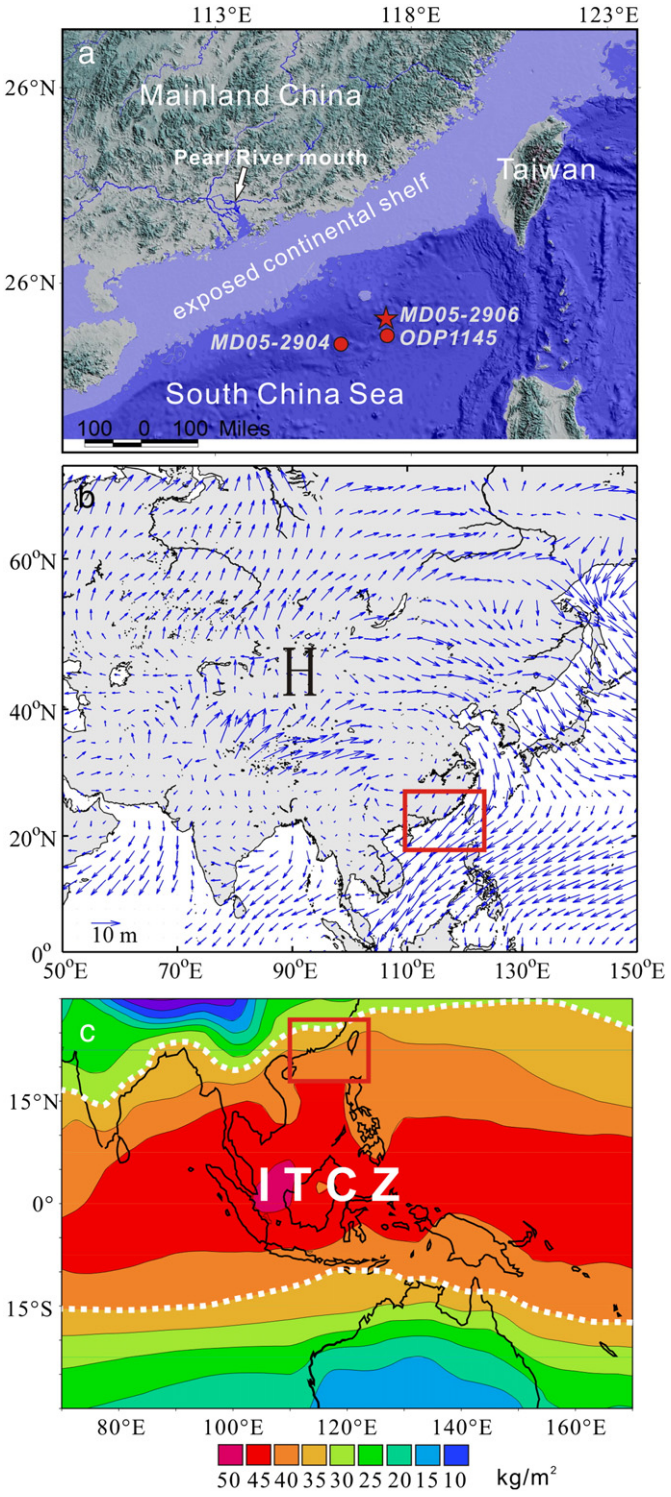

Fig. 1. Map (a) and major climatic system of the northern SCS (b, c). Gray shading in (a) indicates possible exposed continental shelf (−120 m from current sea level) during the Last Glacial Maximum. (b) Winter mean surface winds (vectors) during Dec–Feb of 1948–2013: 'H' marks the center of the Siberian High. (c) shows the monthly average precipitable water during 1979–2014 (based on NCEP-DOE Reanalysis 2 data). Heavy rainfall regions within ~15° of the equator in both hemispheres is thought to be the mean position of the ITCZ (outlined by white dashed lines) (Berry and Reeder, 2014). The climatological data were downloaded from http://www.esrl.noaa.gov/psd/data/gridded/reanalysis. Fig. 1a is the research area denoted by the rectangle in (b) and (c).

and Pacific Ocean by the Taiwan and Bashi straits (Fig. 1a). The climate is subtropical and tropical with high temperatures (18 °C–24 °C annually) and heavy precipitation (>1,000 mm annually) on average (Zhao et al., 1999). During the winter, the East Asian winter monsoon (EAWM) driven by the SH brings dry and cold air from the northern high latitudes (Fig. 1b). The ITCZ is characterized by a precipitation maximum that moves within approximately 15° of the equator in both hemispheres (Berry and Reeder, 2014). In summer, as the ITCZ moves northward (Fig. 1c), the study region is under the strong influence of the summer monsoon from the south and southwest, with high temperatures and heavy rainfall.

The continental topography around the northern SCS is characterized by widespread hills (mostly <1,000 m). The submarine topography of the northern SCS comprises a broad continental shelf, continental slope, and deep-sea basin, with a gradual descent from northern parts to the central basin. The continental shelf is one of the broadest in the world, which has been exposed considerably during glaciations periods (Wang and Li, 2008) (Fig. 1a). The major rivers that carry vast amounts of terrestrial material from South China into the northern SCS include the Pearl River and the Hanjiang River (Zhao et al., 1999) (Fig. 1a).

The warm and humid climate in South China favors rich flora. The regional vegetation is generally characterized by tropical and subtropical broadleaf evergreen forests that are composed mainly of Fagaceae (*Castanopsis* and *Quercus*), Lauraceae, Theaceae, Hamamelidaceae, and Magnoliaceae (Wu, 1980). The tropical vegetation elements gradually increase as the latitude decreases. The zonal vegetation changes from middle subtropical evergreen broadleaved forest to south tropical monsoon forest and tropical moist rainforest in Southeast China (Fig. 2). Modern vegetation maps show strong modification by human vegetation patterns. For example, natural broadleaved forests have been replaced by cropland and pine forests (mainly *Pinus massoniana*) (light green), and *P. massoniana* is a secondary successional plant following deforestation in hilly regions (Fig. 2).

3. Material and methods

The core MD05-2906 (20°08.16′N, 117°21.59′E) was drilled in the continental slope near Dongsha Island at a water depth of 1,636 m (Fig. 1). A total of 36.72 m of the core is composed of olive and gray clay; the lowest segment (from 14.47 to 36.47 m) was analyzed in this study, whereas palynological work on the upper segment (from 1.91 to 14.39 m) was performed by Dai and Weng (2015).

The chronology of the core is based on AMS ^{14}C dating and oxygen isotope correlation with the adjacent cores ODP 1145 (Oppo, 2005) and MD05-2904 (Ge et al., 2010) (Fig. 1). Although drilling cores (also including ODP 1144) from the northern SCS have different sedimentary rates, their oxygen isotope curves are comparable (Fig. 3). Five planktonic foraminiferal samples (mixed species of *Globigerinoides ruber* and *Globigerinoides sacculifer*) were dated by BETA Analytics, USA (Table 1). Radiocarbon ages were calibrated based on the CALIB 6.0 program with the Marine 09 database (Stuiver and Reimer, 1993), which constructs a probability distribution of calibrated ages for any given radiocarbon age (Table 1). Stable oxygen isotope analysis was conducted using an Isotope Ratio Mass Spectrometer at the State Key Laboratory of Marine Geology, Tongji University, China. Based on 4-cm resolution and 2-cm sample thickness, 556 planktonic foraminiferal samples (*G. ruber*) were analyzed.

For the palynological analysis, based on 8-cm resolution and 2-cm sample thickness, 275 samples were used. A tablet of *Lycopodium* spores containing 27,637 ± 593 grains was added to each sample prior to chemical treatments to calculate the pollen concentration. Hydrochloric and hydrofluoric acids were used to remove carbonates and silicates; then, the residues were sieved over a 7-μm mesh screen in an ultrasonic water bath sink to remove tiny impurities and facilitate pollen identification. At least 200 pollen grains and even more spores were counted under a Leica light microscope (400× magnification).

A pollen diagram was created using TILIA 2.0.29 (Grimm, 1991 and the updated version subsequently). The pollen percentages are based on the total pollen sum, and the pollen concentrations and ratios of the spores to pollen grains are also expressed in the diagram. Pollen zonation was based on the results of a constrained cluster analysis (CONISS), in which the selected taxa included *Pinus*, alpine conifers,