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Paleohydrological changes in northeastern Taiwan over the past 2 ky inferred from biological proxies in the sediment record of a floodplain lake

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ABSTRACT

Taiwan is particularly sensitive to changes in monsoonal precipitation and to the frequency of typhoon-induced heavy precipitation events. Many parts of this mountainous subtropical island have high erosion rates that produce high sedimentation rates in lakes and offshore ocean basins, and evidence suggests that these rates have varied in the past. A high-resolution 2 ky record of changes in sediment delivery to Dahu, a floodplain lake in northeastern Taiwan, that suggests changes in precipitation has been inferred from organic matter, pollen, and spores in a 12 m sediment core and from the organic matter compositions of soil, catchment plants, and fluvial suspended sediment. From 0 to 1400 AD, the lake experienced repeated flood events, principally resulting from overflows of the "old" Ilan River, one of tributaries of the Lanyang River, that were briefly interrupted ~1000 AD by decreased precipitation and/or only localized rainfall. The record of heavy precipitation can be linked to the northward shift of the ITCZ. During the early Little Ice Age, 1400–1600 AD, local erosion fluctuated in association with deforestation and farming, during which the ITCZ shifting varied as well. A decrease in precipitation since 1600 AD is linked with the southward migration of the ITCZ.

1. Introduction

Taiwan is situated on the southeastern margin of subtropical Asia and is significantly influenced by alternations of the prevailing East Asian (EA) summer and winter monsoons, which are dominant controls on regional precipitation (Chen et al., 2007). In addition, heavy rainfall induced by episodic tropical cyclones in the warm season frequently results in severe floods and massive landslides and consequently damages buildings and impacts human life (e.g., Hong et al., 2010; Tsou et al., 2011). The heavy precipitation is also responsible for the high erosion rates in Taiwan and the high deposition rates of sediments in the Okinawa Trough north of Taiwan throughout the Pleistocene (Li, 1976; Dadson et al., 2003; Wei et al., 2005). To improve understanding of the climatic linkages between modern times and the past, this study describes evidence of details of changes in local hydrology in northeastern Taiwan during the last 2 ky.

Worldwide variations in subtropical precipitation during the past 2 ky have been documented from archives as different as $\delta^{18}O$ values of stalagmites from China (Cosford et al., 2008), titanium concentrations in marine sediment from the Cariaco Basin off northern South America (Haug et al., 2001), and organic matter deposition in floodplain lakes of Amazonia, Brazil (Moreira et al., 2014). These paleohydrological alterations are attributed to shifting of the Intertropical Convergence Zone (ITCZ), which also affected the intensity of the EA summer monsoonal circulation. Moreover, Anderson et al. (2010) found changes in the production of planktonic foraminifers in the upwelling area of the

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northern Arabian Sea that suggest that the weakest Indian summer monsoon occurred ca. 1500 years BP and a strengthening trend has developed towards the present. Historical documents and tree-ring records from mainland Asia also show that the EA summer monsoon failed and extreme drought occurred during the Little Ice Age (LIA) (Cook et al., 2010, and references therein). However, precipitation variability in Taiwan is affected by the interplay of the EA summer monsoon and the winter monsoon, which also brings rain to this island, unlike in the Asian mainland. Hence, the effects of the ITCZ shifting may be different in Taiwan than elsewhere. In fact, paleohydrological reconstructions using palynological data and tree-ring records (Tsou, 1998; Wang et al., 2011) and lacustrine diatom assemblages (Wang et al., 2013) suggest that climate in northern Taiwan was wetter and not drier during the LIA.

Given the special paleohydrologic setting of Taiwan, the aims of the present study are: 1) to provide a high-resolution reconstruction of both the climatic and hydrological variations in northeastern Taiwan over the last 2 ky using a combination of biological proxies, 2) to infer variations in intensity of the EA monsoonal circulation and migration of the ITCZ, 3) to consider the impacts of anthropogenic activities, such as deforestation and farming, especially for the last half millennium in which local populations expanded and created large land-use impacts on the study region, and 4) to explore whether the multiple proxies can differentiate changes in origins of sedimentary materials. Biological proxies derived from lacustrine sediments can be informative for reconstructing paleohydrological changes and differentiating the delivery of organic matter from algal and vascular plant origins (e.g., Meyers, 1994; Meyers, 1997; Lambert et al., 2008; Yang et al., 2011a, 2011b; Wang et al., 2013). The biological proxies employed here are TOC (%), TN (%), TOC/TN, pollen, and fern spores, which collectively yield information about the sources of sedimentary organic materials, the density of land-plant cover, and the moisture availability in the watershed of the lake.

2. Study area

The Ilan Plain is an extensive alluvial fan in northeastern Taiwan. It has a high sediment accumulation rate because of the combination of rain-induced erosion of surrounding mountains and regional subsidence from the southwestward extension of the Okinawa Trough (Letouzey and Kimura, 1985; Wei et al., 2003). Fig. 1A shows the geomorphology of the Ilan Plain, revealing that discharge from the Lanyang River system is the most important source of sediments for the flood plain, with minor contributions from the Ilan River and other rivers. High denudation rates in the mountainous areas and magnified discharge rates in the rivers are principally attributed to the typhoon-induced intense precipitation events that are common to this region (Kao and Liu, 2000; Galewsky et al., 2006; Hilton et al., 2008). A high supply of sedimentary materials to ODP Site 1202 (Wei et al., 2005) and its vicinity in the Okinawa Trough (Huh et al., 2006) provides evidence of a long term high denudation rate. It is important to note that a map drawn in 1904 by the Temporary Taiwan Land Survey Bureau (TTLSB, 1904), Taiwan Governor-General Office documents the Lanyang River system meandered and regularly dispersed sediments across the flood plain until a levee was completed in 1924 (Chen, 1960).

Dahu (Lake Da), (24° 44.352′ N, 121° 41.358′ E), and its watershed are located on the northwestern margin of the Ilan Plain at the northeastern foot of the Hsuehshan Range (Fig. 1). Dahu has an area of ~10 $\times$ 10^4 m^2 and is situated at ~17 m above sea level (a.s.l.). The area of the catchment is ~58 $\times$ 10^4 m^2, and its elevations range from ~17 to 217 m a.s.l. The lake has an average water depth of ~2 m, and it has been used for irrigation since at least the early twentieth century. Dahu can receive sediments from overflows of the massive amounts of suspended materials that have long been carried by the Lanyang and Ilan rivers and that are recorded on both land and the seafloor. For example, Chen et al. (2012) document high sedimentation rates in the Dahu basin at various time intervals in the middle and late Holocene.

Three potential sources of organic matter in the sediments for Dahu are autochthonous production, allochthonous pedogenic materials from the lake catchment, and suspended materials overflowing from the Lanyang and Ilan rivers. Organic matter in the sediment loads of these rivers is principally eroded from slates of the surrounding mountain systems as documented by comparisons of the concentrations of organic carbon (TOC %) and nitrogen (TN %), TOC/TN ratios, and the carbon isotope ratios of organic matter ($\delta^{13}C_{org}$ values) of metamorphic rocks from the Hsuehshan Range with those of sediments, rocks, suspended particulate matter, soils, and plants in the Lanyang River drainage basin (Liu et al., 1987; Kao and Liu, 2000).

The climate of the region is moist and subtropical. Detailed instrumental records of rainfall and air temperature in Ilan County, northeastern Taiwan, for the period 1936–2010 AD are available from the Central Weather Bureau (CWB) (http://www.cwb.gov.tw). The annual mean temperature is ~22.2 °C. The seasonal variation in the monthly mean temperature is significant, varying from ~16.0 °C in January to ~28.3 °C in July. The annual precipitation is high, averaging 2763 mm, with strong seasonality apparent from the lowest and highest monthly rainfalls ranging from 122 mm in April to 445 mm in September. Precipitation in September, October and November accounts for 44% of the annual record. Rainfall in autumn can be related either to late-season typhoon events or to convection activities embedded within the northeasterly monsoon flow during the passage of mid-latitude cold fronts (Chen and Chen, 2003).

The plant communities of the lowlands and hills in Ilan are mainly of a subtropical evergreen forest, which is strongly affected by the EA winter monsoon (Chiou et al., 2010). Chen (2004) has conducted a systematic survey of vegetation in the Lanyang River drainage basin. The vegetation of the surrounding mountains consists of subtropical to warm temperate evergreen broad-leaved forests dominated by Lauro-Fagaceae elements, generally in the *Machilus–Castanopsis* Zone and the *Quercus* Zone. The representative wood species, for instance, include *Machilus japonica* var. *kusanoi*, *Castanopsis cuspidate* var. *carlesii* f. *sessilis*, *Castanopsis cuspidate* var. *carlesii*, *Machilus japonica*, *Pasania kawakamii*, *Cyclobalanopsis sessilifolia*, and *Fagus hayatae* (Chen, 2004).

3. Materials and methods

3.1. Core collection

The 35 m long Core DH-7B was obtained from Dahu using a hydraulic piston corer, section by section, in January 2008 (Fig. 1B). During subsampling, pieces of wood, plant debris, microcharcoal, and leaves were found in several layers. Detailed information of lithology and ^{14}C dating is given by Chen et al. (2012). Biological proxies in sediments of the upper 12 m of the core, covering the past two thousand years, were studied in this work. A total of 449 samples, spaced at 0.5 cm for the upper 130 cm and at 5 cm for the remainder, were used for measurements of total organic carbon and nitrogen concentrations and stable isotopic compositions of organic carbon. These samples were stored at 4 °C until analysis. For palynological analysis, another 132 samples at respective intervals of 5 cm, 10 cm and 20 cm for the upper 3 m, 3 to 9 m, and 9 to 12 m were studied.

3.2. Chronology

The age model for Core DH-7B is based on ^{210}Pb analysis for the upper 25 cm of sediments and AMS ^{14}C analyses from the remainder of the upper 12 m of the core (Table 1). Particulate organic material – two pieces of wood, a leaf and other plant debris – was isolated for AMS ^{14}C dating at the Rafter Radiocarbon Laboratory, Institute of Geological and Nuclear Sciences, New Zealand. The ^{14}C dates were then calibrated using CALIB Rev 6.0.2 (http://calib.qub.ac.uk/calib/;