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Recent 4000 years of climatic trends based on pollen records from lakes and a bog in Taiwan

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ABSTRACT

In this study, pollen records from lakes and bog in Taiwan were used to reconstruct regional climatic trends for the last 4000 years. The study sites included Chitsai and Li-yu Lakes (central Taiwan), Dongyuan Bog and Lake (southern Taiwan), and Sonlou Lake (northeastern Taiwan). The results provide an integrated approach to identify subtle changes during this period, despite local differences and some minor chronological differences. Based on radiocarbon dating, the climatic trends can be summarized as: a relatively prominent cold period, 3870–1920 BP (1920 BC–30 AD) and a period of successive warm/cold fluctuations; a warm period, 1920–1590 BP (30AD–360 AD, corresponding to the Roman Warm Period, RWP); followed by a cooling period 1590–1190 BP (360 AD–760 AD, corresponding to the Migration Period Cooling, MPC); a warm period 1190–650 BP (760 AD–1300 AD, corresponding to Medieval Climate Anomaly, MCA); and a cold period: 650–100? BP (1300 AD–1850? AD, corresponding to the Little Ice Age, LIA). Two cold peaks during the period corresponding to the LIA and relatively less humid conditions during the period corresponding to the MCA were also identified.

1. Introduction

Climatic trends in the recent several millennia in the subtropical monsoon region are important and interesting because of the connections between climate change and the development of ancient human cultures (Cullen et al., 2000; Brooks, 2006). Pollen records recorded in sediments in lakes and bogs can show major changes in both temperature and humidity, and these records might complement records from stalagmites in China which mainly reflect changing humidity conditions.

Taiwan is a subtropical mountain island whose climate is dominated by the East Asian monsoon. Warm-wet summers and cool-relatively dry winters prevail, and the whole island is generally humid. However, climatic trends in the monsoon region for the last several millennia in this area are not well known. A record is available from Chitsai Lake in Taiwan (Liew and Huang, 1994). High resolution pollen records from four lakes and a bog in Taiwan were available to summarize some of the evidence for climatic trends during recent millennia. These sites include Li-yu Lake (Nantou), Dongyuan Bog (Pingtung), Sonlou Lake (Ilan) and Duck Pond (Taipei) (Fig. 1). They covered both high and low altitudes, in northern and southern Taiwan. The objective of this study was to compile new pollen records from these sites and interpret the climatic trends in Taiwan with the viewpoint of covering a larger area than the reconstruction from Chitsai Lake alone provided (Liew and Huang, 1994).

Altitudinal zones of vegetation exist in the mountains of Taiwan. In central Taiwan, from lower to upper they are *Ficus-Machilus* Zone (tropical; below altitude 500 m; 23–26 °C); *Castanopsis-Machilus* Zone (subtropical; 500–1500 m in altitude; 17–23 °C); Lower *Quercus* Zone (warm-temperate; 1500–2000 m; 14–17 °C); Upper *Quercus* Zone (temperate; 2000–2500 m; 11–14 °C); *Tsuga-Picea* Zone (cool temperate; 2500–3100 m; 8–11 °C); *Abies* Zone (cold temperate; 3100–3600 m; 5–8 °C); and Alpine Zone (cold; higher than 3600 m; < 5 °C) (Su, 1984, 1985). In mountains further south and north, similar altitudinal zones exist but the spacing of zones is compressed due to the effect of massenerhebung (treeline variations controlled by topography; Su, 1984). Chitsai Lake (23°45′10″N; 121°14′10″E, 2890 m asl), is located in the altitudinal vegetation zone of *Tsuga-Picea* (2500–3100 m) in central Taiwan, and is an alpine lake with a surface area of 2.2 ha and sedimentation rate ~0.8 mm/y. A core by hand auger was obtained in 1993 and pollen was studied using a 3 cm sampling interval. The sediment core was dated to approximately 5000–500 BP, and no evidence for

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human disturbance was found in the record (Liew and Huang, 1994). The pollen record indicated that 3870 to 1920 BP (Stuiver et al., 2014; 3700–2030 BP in Liew and Huang, 1994) was a cold period, based on radiocarbon dating. A clear vegetation change from cold to warm conditions occurred at about 1920 BP, when the higher elevation forest species *Tsuga* regressed, and the middle altitude forest species, *Cyclobalanopsis* and *Alnus*, increased in abundance (Fig. 3). Following this period, climatic changes can be further divided into four intervals based on the changes in the forest species composition:

1920–1590 BP, a relatively warm period;
1590–1190 BP, a relatively cold period;
1190–~700 BP? a relatively warm period;
~700 BP? to present, a relatively cold period until the recent past.

We compared the pollen record from Chitsai Lake to the records from four other lakes and a bog in Taiwan to understand regional paleoenvironmental changes.

A brief description of the four sites is provided here (Fig. 1). Sonlou Lake, northeast Taiwan, (24°41′30″ N; 121°31′30″) is located at 1240 m asl. with average annual temperature 15 °C (January temperature 8.8 °C; July temperature 21.5 °C) and precipitation of 4400 mm. The estimated sedimentation rate is 1.1 mm/y during the last 3300 y (Wu, 2011). There is some evidence of human disturbance within the recent 150 y, according to the appearance of secondary species such as *Mallotus* and *Trema* in the uppermost 10 cm.

Duck Pond in Taipei (25°10′27″ N, 121° 33′8″ E) is located at 760 m elevation, with average annual temperature 18.4 °C and precipitation 4456 mm. The estimated sedimentation rate is 0.27 mm/y during the last 1300 yr (Chen et al., 2009).

Li-yu Lake (23° 57′50″N; 120°59′25″E) is located in central Taiwan at 550 m asl with annual temperature 20–21 °C and precipitation 2100 mm. The estimated sedimentation rate varies from 0.8 to 2 mm/y, except between 1620 and 1230 BP when it was up to 7 mm/y A previous study found evidence for human disturbance around Li-yu Lake since 2000 BP (Chang, 2006).

Dongyuan peat bog and Lake are located in Pingtung (Bog:22° 12′ N; 120°50′ E with 300 m asl; Lake: 22° 10′ N; 120°50′ E with 330 m asl) and annual temperature is 21 °C and precipitation 2144 mm. The estimated sedimentation rate of the bog is 1.1–2.6 mm/y for the last 3000 y, and is ~0.9 mm/y in Dongyuan Lake. No clear evidence of human disturbance was found (Lee, 2004; Lee et al., 2010). Under the monsoon, the climates of these sites are mainly the summer rain climate type. Sonlou and Duck have wet climates according to Su (1985).

2. Methods

Pollen extraction in the cores of Chitsai Lake, Li-yu Lake, Dongyuan Bog and lake, and Sonlou Lake followed the standard method: use of potassium hydroxide liquid (10% KOH) to break down matrix and to dissolve humic material; acetolysis to remove cellulose; and heavy liquid ($ZnCl_2$) to float the palynomorphs. Usually, 400 pollen grains were counted. Each taxon in the pollen diagram is presented by percentage based on pollen sum. In the pollen diagram of Chitsai (Fig. 3), the total sum is total pollen and spores, while in the diagrams of Sonlou Lake (Fig. 4) and Li-yu Lake (Fig. 5) only arboreal elements are presented and the percentage of each taxon is based on total arboreal pollen. Pollen diagrams of Dongyuan Bog and Lake (Lee et al., 2010) and Duck Pond (Chen et al., 2009) are documented in the references listed. Radiocarbon dates of core samples of these sites are listed in Table 1 and Fig. 6. The time resolution of sampling interval in Chitsai Lake is ca. 40 y; Li-yu Lake ca. 30–100 y; Dongyuan Bog, 40–90 y in the last 3000 y; and Sonlou Lake ca. 50 y.

Table 1
Radiocarbon dates from Chitsai Lake, Li-yu Lake, Dongyuan Bog, and Sonlou Lake. (CALIB Radiocarbon Calibration, version 7.0).

Location	Lab. number	Depth (cm)	Conv age (^{14}C BP)	1σ cal. Age (cal. BP)	2σ cal. Age (cal. BP)
Chitsai Lake	NTU-1723	35	1000 ± 90	792–1041	708–1172
	NTU-1729	170	2650 ± 60	2739–2843	2539–2921
	NTU-1733	220–230	3240 ± 60	3396–3556	3357–3608
	NTU-1746	312–317	4300 ± 50	4829–4959	4709–5037
Li-yu Lake	R28804/1	47	177 ± 30	0–283	0–295
	R28804/2	132	1297 ± 35	1185–1281	1179–1292
	R28804/3	210	1423 ± 30	1301–1339	1291–1370
	R28804/4	290	1629 ± 35	1419–1566	1414–1605
	R28804/5	414	1713 ± 30	1565–1691	1556–1699
	R28804/6	638	2511 ± 30	2504–2721	2489–2739
	R28804/7	656.5	2523 ± 30	2514–2736	2491–2744
Dongyuan Bog	TU-2	204–210	850 ± 60	692–894	680–910
	TU-3	271–276	1130 ± 40	969–1070	960–1174
	TU-5	353–354	1330 ± 40	1187–1298	1181–1307
	TU-6	414–415	1870 ± 40	1739–1868	1712–1890
	TU-4	475–84	2500 ± 40	2495–2719	2434–2742
	TU-1	519–532	2620 ± 40	2735–2772	2623–2844
Sonlou Lake	WK-25802	108–110	1129 ± 30	982–1061	962–1172
	WK-23789	132–134	1241 ± 30	1093–1261	1074–1267
	WK-237900	168–170	1623 ± 30	1420–1558	1413–1594
	Beta-279796	212–214	1860 ± 40	1735–1862	1707–1885
	Beta-279797	276–278	2460 ± 40	2439–2700	2364–2708
	WK-23792	364–366	3149 ± 30	3349–3440	3265–3448

3. Results

The cold/warm trend in the record from Chitsai Lake (Liew and Huang, 1994; Liew et al., 2002) can serve as a reference for interpreting regional trends for all the sites in this study (Fig. 2). The integrated results from these sites in Taiwan can be compared with climatic trends found in previous studies, with particular attention to periods such as the LIA (Little Ice Age), MCA (Medieval Climate Anomaly), MPC (Migration Period Cooling), and the RWP (Roman Warm Period) in Europe (Wanner and Bronnimamm, 2012).

Among the sites in the current study, Chitsai and Sonlou Lakes are located at relatively higher elevations compared to Li-yu Lake, Dongyuan peat bog, and Duck Pond. In the record of Chitsai Lake, the warm period corresponding to the RWP and the previous prominent cold period are well documented (Liew and Huang, 1994). The pollen record in Sonlou Lake indicates the vegetational and climatic conditions of the somewhat recent events such as that of cold and warm periods corresponding to LIA and the MCA in Europe (Wanner and Bronnimamm, 2012). Overall, the pollen records from the four sites in this study show general trends (Fig. 2).

3.1. Cold period 3870–1920 BP (1920BC–30 AD)

In Chitsai Lake, the stable cold period is represented by Local Pollen Zone 2 (Fig. 3), indicated by increased abundance of *Tsuga* and decreased abundance of *Cyclobalanopsis* and *Alnus* compared with the previous zone. This might correspond to the widely reported cold period in China beginning at about 4 ka (Chen and Wang, 2012; Liu and Feng, 2012). However, the drier conditions occurred earlier, based on the observation that Chitsai Lake deposits change from mud to peat at ca. 4890 BP.

The prominent cold period is also seen in the record from Dongyuan Lake (Lee et al., 2010). This indicates that the intermediate forest species were more abundant in contrast to lowland forest species between 4100 and 2100 BP. In Sonlou Lake, the cold