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ENVIRONMENTAL CHANGES DURING THE LATE QUATERNARY IN TAIWAN AND ADJACENT SEAS: AN OVERVIEW OF RECENT RESULTS OF THE PAST DECADE (1990-2000)

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ABSTRACT

This review article reports the major progress of our understanding of the past environmental changes during the late Quaternary in Taiwan and its adjacent marginal seas.

Long giant piston cores obtained from the South China Sea have provided continuous paleoceanographic records in high resolution regarding the Asian monsoon, Western Pacific Warm Pool and sea-surface temperature changes for the late Quaternary. Hydrological conditions of the South China Sea have been modulated mainly by orbital forcing at 100-, 41- and 23-kyr periodicity during the past 350 thousand years (kyrs). Sea surface temperatures fluctuated by at least 4°C between glacial and interglacial periods and show strong cyclicity of 23 thousand years over the past 400 kyrs. Millennial variations comparable to those found in Greenland ice core and North Atlantic were documented from various proxies for the past 150 kyrs, implying a close teleconnection between Taiwan/adjacent seas with Greenland and North Atlantic.

Pollen and chemical analyses of cores taken from lakes allowed reconstruction of the paleoenvironmental changes during the past 20 kyrs on Taiwan. The last glacial period prior to 15 thousand years ago (ka) was characterized by cold and dry climates. The climatic amelioration responding to the deglaciation transition of the global climate took place between 15-10 ka. A short-lived reversal to a cold and dry climate corresponding to the Younger Dryas Event was evident from both marine and terrestrial records. The environment of the last 10 kyrs (the Holocene Epoch) has been relatively constant but kept fluctuating until 2500 years ago when the condition became the present one. Warm and wet climates prevailed during 9.7-7.1 ka, 6.2-5.5 ka and 2.5-1.5 ka

whereas a distinctive cold spell might have occurred between 5 to 3.5 ka. Conditions have fluctuated over the past 2500 years in response to the global Medieval Warmth and Little Ice Age.

Key words: environmental changes, Late Quaternary, Taiwan

INTRODUCTION

During the last decade, the increased awareness of global change and its possible impact on Taiwan has provided the necessary impetus for governmental funding and invoked scientists' primary concern to study the past environmental changes of Taiwan more closely. Hoping that one can be more intelligent about our common future by learning from the geologic records, we are using the past as a key to the present day's decision towards sustainable development. In retrospect, the last decade has witnessed a distinct growth of the "paleo-community" in Taiwan and a major advance on various lines of paleo-environmental studies. This review article presents a synthesis of research results of past environmental changes in Taiwan and adjacent seas around Taiwan.

Taiwan and its vicinity oceanic realm is situated in an advantageous position linking the north and south hemispheres in the Pole-Equator-Pole transect of Asia-Australia, known as the PEP II transect designated by the international Past Global Change Program (PAGES) under the International Geosphere Biosphere Program (IGBP) (PAGES, 1995). Taiwan is also unique as being a subtropical island located on the triple junction of the largest ocean (Pacific), the largest continent (Eurasia) and the largest marginal sea (South China Sea). During the late Quaternary Taiwan's environments have been under the regime of the East Asia monsoons, perturbed frequently by sea-level changes and punctuated by episodic tectonic events. The interplay of these factors has left complicated, yet meaningful and discernable clues in various geological records (i.e., sediments, corals, tree rings, geomorphology, etc). The multiform records had not been systematically explored in any integrated manner until the early 90's when Taiwan PAGES program was launched in 1992. The first phase of PAGES during 1992-1996 was a period of establishing research facilities, expertise and protocols (Wei *et al.*, 1997a). For the first time, corals and tree rings were studied to document historically recent environmental changes in Taiwan.

In 1996, paleoceanographers separated from the PAGES team and joined the International Marine Global Change Study (IMAGES). In the following year, 1997, the IMAGES team pioneered taking long, giant piston cores from the South China Sea and West Philippine Sea on board a French research vessel, the Marion Dufresne. The superb quality of these cores has opened opportunity for scientists to jump on the most frontal line research of past global changes. Long records in high-resolution from about a half dozen deep-sea cores have provided the scientists with first-hand records concerning the past changes of Asian monsoons, sea-surface temperature, paleo-productivity and hence the stability of West Pacific Warm Pool (WPWP).

This paper attempts to present a comprehensive summary of the environmental changes over various time-scales in the past 400 thousand years (kyrs) from both terrestrial and oceanic records. The overview is merely based upon literature published during 1990-2000 and ignores intentionally a great deal of new findings reported in various recent scientific meetings. The avoidance of citing unpublished results is merely to protect the original authors' right for future formal publication. The concise and somewhat abridged summary presented in this paper is meant to highlight some significant points and provide a quick annotated bibliography for specialists as well as generalists. Chronology of the discussed events is cited directly from the literature without any attempt at re-calibration. By no means does this report cover the whole gamut of the enriched paleo-records explored by these original authors. Contributions from scientists outside of Taiwan are also occasionally cited when it is appropriate. In its burgeoning phase of past environment study, many conclusions are considered preliminary and thought provoking.

LATE QRATERNARY RECORDS OF ADJACENT SEAS AROUND TAIWAN

The past 10 years have witnessed a major development of paleoceanography in Taiwan. About a dozen or more cores taken by the R/V Ocean Research I and foreign research vessels in various oceanic realms near Taiwan have been analyzed.

Min-Pen Chen, Chung-Ho Wang and their colleagues (e.g., Wang, *et al.*, 1986; Wang and Chen, 1990; Chen *et al.*, 1992a) pioneered studies of piston and gravity cores taken by the Ocean Research I from the adjacent seas of Taiwan during the late 80s' and early 90s'. These researches set a solid foundation for oxygen and carbon isotope stratigraphy for the Latest Quaternary. Basic survey of surface sediments off northeastern Taiwan (Chen *et al.*, 1992b) and eastern Taiwan (Sheu and Huang, 1989) provided good background data for further paleoceanographic inference. More recently, Chen *et al.*, (1998) and Ho *et al.*, (1998) compiled distribution data of planktic foraminifers in the South China Sea and analyzed its relationship to surface hydrography.

So far only short piston cores have been obtained and studied from the offshore areas of northeast and east Taiwan. It was inferred from the variation in planktic foraminiferal assemblages that the main path of the Kuroshio shifted to the east during the last Glacial Maximum (LGM) and not returned to its current position until 7.5 ka (Chen *et al.*, 1992a; Shieh and Chen, 1995). The summer sea-surface temperatures (SSTs) remained similar to today's at about 29-28°C through the late Quaternary, whereas the winter SSTs dropped by ~4°C to about ~18.5°C in areas off the east coast of Taiwan during the last glacial period (~20 ka) (Chen *et al.*, 1992a). Lou and Chen (1996) studied a piston core (25°00'N, 122°42'E, water depth 1480m) obtained from the western slope of the southern Okinawa Trough off northeastern Taiwan. They found that compared to the present the last glacial period had a higher content of biogenic materials ($CaCO_3$ and opal), lower terrigenous dilution and higher salinity (based upon higher Mg/Al ratio of bulk sediments), implying lower riverine run-off to the East China Sea Shelf. On the other hand, the post-glacial sediments contain higher terrigenous detritus and organic matter, suggesting a higher riverine influx under the humid and warm Holocene climate. Oxygen isotopic variation in two planktonic foraminiferal species show evidence of an increase of fresh-water input during the deglaciation period at about 11 -12 ka (Shieh *et al.*, 1997). A positive excursion of the $\delta^{18}O$ values at about 10 ka was interpreted as a sign of the presence of a Younger Dryas cooling at this area (Shieh *et al.*, 1997).

The northern South China Sea also witnessed cold winters during the LGM: the SSTs were about 18°C, which is ~6°C lower than today' (Wei *et al.*, 1998). Wang and Wang (1990) reported that the difference in SST between the last glacial and interglacial in the northern

South China Sea is 6 - 9°C for winter and 2-3°C for summer, the amplitudes are much larger than the CLIMAP estimation (< 2°C) for the tropical western Pacific. It is clear that the glacial-interglacial variation has been greatly amplified in the South China Sea.

The intensity of winter monsoons is inferred to be stronger during the LGM than it is today. Consequently, surface ocean was better mixed and yielded higher biological productivity (Wei *et al.*, 1996; 1997b; 1998c; Huang, *et al.*, 1997). Higher terrigenous flux during the LGM, together with higher biological production, resulted in higher sedimentation rates, and higher accumulation of carbon and carbonate during the LGM (Chen *et al.*, 1997; Wei *et al.*, 1998c). Concomitantly, carbonate was well preserved during the last glacial period. A carbonate preservation spike occurred at ~12 ka, synchronous with the global preservation event of Termination I, whereas stronger carbonate dissolution occurred during the Holocene (Chen *et al.*, 1997; Wei *et al.*, 1997b, 1998c). A short-lived cooling of 1°C in winter sea-surface temperature, centered at about 11 ka, appears to be the local expression of the Younger Dryas cooling in the northern South China Sea (Wei *et al.*, 1998c).

Several high-resolution records obtained from the South China Sea show clear patterns of millennial-scale variations, which can correlate well with similar climatic changes observed from GISP2 ice core. For instance, Chen *et al.*, (1999) found that there are rapid millennial-scale changes during oxygen isotope stages 2 and 3 as reflected by the relative abundance pattern of planktic foraminifera, particularly, that of *Globorotalia inflata*, a good indicator of low SST and deep mixed level depth. Huang *et al.*, (1999) revealed also that the carbonate content (%$CaCO_3$) in bulk sediments in a long piston core taken from southwestern South China Sea (MD97-2151) shows clear millennial-scale variations. Planktic $\delta^{18}O$ fluctuation in the same core clearly exhibits millennial variation in surface water hydrology, either caused by temperature, salinity, or a combination of both (Lee *et al.*, 1999). These results suggest that such millennial climatic variation has been a global phenomenon during at least the past 150,000 years. Whether there is a teleconnection between Greenland, North Atlantic and the South China Sea has raised much discussion. It is attributed to the effects of shifts in the latitudinal position of the westerly winds and the Siberia High Pressure System. The southward shift of this system during cold periods (which caused Heinrich Events in the North Atlantic) would increase the strength of East Asia winter monsoon and caused the northern South China Sea to be colder (Chen and Huang, 1998; Chen *et al.*, 1999).

For the first time, long paleoceanographic records of the past 350 kyrs, yet still in high resolution, were reported from the South China Sea. In concert, Wei *et al.*, (2000) established a planktic foraminiferal oxygen isotopic record of the last 350 kyrs from Core MD97-2142 while Yu *et al.*,(2000) reported the sea surface water temperature variations reconstructed from planktic foraminiferal assemblages through the past 400 kyrs. Both studies found that the western margin of the Western Pacific Warm Pool (WPWP) in the southeastern South China Sea has been highly unstable during the last four glacial-interglacial cycles, yet the variation has been modulated by orbital forcing with periodicities of 100, 41 and 23 kyrs. The $\delta^{18}O$ signal appears to lead slightly in obliquity and precession bands than the tropical Indian Ocean (Wei *et al.*, 2000). The reconstructed SSTs show a fluctuation of 3-4°C with the domination of precession cyclicity over the past four glacial-interglacial cycles (Yu *et al.*, 2000). During most of the time, the $\delta^{18}O$ values are lower than that from the Sulu Sea. The difference in $\delta^{18}O$ between the South China Sea and the Sulu Sea is relatively higher during the interglacials, implying that higher precipitation and continental runoff on the Indochina Peninsula during the interglacial periods (Wei *et al.*, 2000).

TEPHRA AND MICROTEKTITES

Kuo-Yen Wei, Teh-Quei Lee and Shipboard Scientific Party of IMAGES III/MD106-IPHIS Cruise (Leg II) (Wei *et al.*, 1998a, b) filed two preliminary reports on the finding of discrete tephra layers recognized from Cores MD97-2142 and 97-2143. The initial findings pioneered a series of enthusiastic pursuits of marine tephrochronolgy in the South China Sea and West Philippine Sea. Lee *et al.*, (1999) first reported the possible deposit of the Youngest Toba Tuff (YTT) at the transition boundary between the marine oxygen isotopic stages 5 and 4 (MIS5/4) in Site MD 97-2151. Detailed analyses of major and minor elements, Sr isotopic ratio, and SEM examination of the tephra further confirmed the eastern dispersal of coarse (> 63μ) glass shards over 1500 km northeast of the Toba Caldera in Sumatra to the South China Sea at 71±5 thousand years ago (ka) (Song *et al.*, 2000). This points to the need of a re-estimation of the eruptive volume and its environmental impact of the youngest Toba eruption event. In a short discussion forum on Buhring's *et al.*,(2000) finding of the YTT from two other cores in the South China Sea, Chen *et al.*, (2000) further demonstrated the necessity of chemical analyses of phenocrysts and isotopes in tephra to have an affirmative identification of the ash source. With such rigorous approaches, the Oldest Toba Tuff (OTT) has been found in the bottom section of the MD 972142 (Chen, personal communication).

Lee and Wei (2000) reported also the finding of the Australasian microtektites from the South China Sea (MD97-2142) and West Philippine Sea (MD97-2143). The quantity of the newly discovered microtektites in these two cores amounts to the total ever found in all previous deep-sea cores. Taking the advantages of the cores' closeness to the source area, Indochina Peninsula, and the great abundance of microtektites in a well-dated chronological frame, Lee and Wei (2000) re-evaluated the age, size and location of the impact crater. They concluded that the impact took place at 793 ka (slightly prior to the Brunhes/Matuyama geomagnetic reversal) at about 12°N, 106°E with a crater size of ~90 km in diameter.

TERRESTRIAL ENVIRONMENTS OF TAIWAN DURING THE LAST GLACIAL

A long palynological record obtained from a sub-alpine lake (Toushe Basin) in central Taiwan indicates that at about 100 ka the climate was warm and then progressively turned to dry and cool before entering a severe cold phase of the last glacial between 21 and 16 ka (Liew and Huang, 1996). Less humid conditions than today prevailed in Taiwan during the LGM (Liew *et al.*, 1999).

In the GLOCOPH Special Issue published by Tohoku University (Japan) 1999, Liew and Tseng (1999) summarized the climatic events during last glacial to Recent recognized from lacustrine sediments and palynological records of Taiwan. There is a distinct contrast between the cold-dry last glacial maximum and the warm-wet Holocene. The transition from glacial to post-glacial condition heralded first at 17 ka (calendar year) by an abrupt change in tree/herb ratio that major forest elements increased suddenly. A further remarked Holocene/Pleistocene transition is characterized by the rise of *Castanopsis* and the dominance of ferns at about 15 ka (see also Kuo and Liew, 2000). The vegetation distribution had displaced vertically by about 800 m between the last Glacial and the Holocene, implying a 4.8°C increase in temperature in the western foothill region of Taiwan (Huang *et al.*, 1997a). Liew *et al.*, (1998) inferred that during the LGM (21 - 16 ka), the upland forests in East Asia became half open while most of the lowlands were occupied by grassland.

Pollen record also indicates that there was a short retreat to dry and cold condition at 12. 5 - 11.5 ka (calendar age) corresponding to the Younger Dryas Event. The wet and warm conditions resumed after 9.7 ka with clear optimal conditions during 9.7 - 7.3 ka, 6.2 - 5.6 and 2.5 - 1.5 ka. Particle size analysis of sediments in Taipei Basin suggests that the Holocene witnessed more flooding events (Liew and Tseng, 1999).

HOLOCENE CLIMATE

Lake deposits on Taiwan offer high-resolution records of Holocene paleoenvironmental changes. Calculating from 210Pb activities and ^{14}C dating, Chen *et al.*, (1997) documented that the sedimentation rates of alpine and subalpine lakes in Taiwan were fairly constant during the past several thousand years, mostly ranging between 0.06 and 0.16 cm/yr. The sedimentation rates of low-land lakes are 10-20 folds higher than those alpine/subalpine lakes, ranging from 0. 5 to 3.2 cm/yr, except for Dapu Reservoir (6.4 cm/yr).

Remarkable last glacial/Holocene transition from cold-dry to warm-wet conditions was indicated by the rise of *Castanopsis* since ~12 ka. A warming trend is evident from pollen record (high %pteridophytes) from the central Taiwan for the period 9700 to 7100 yr BP (Kuo and Liew, 2000). Warm and wet conditions prevailed until 4850 yr BP both in northern Taiwan (Chen and Liew, 1990) and in central Taiwan (Kuo and Liew, 2000). Humid and warm conditions were at their climax during two particular periods, namely, 9700 - 7100 and 6200 - 5500 ^{14}C yr BP, while the latter is more distinctive (Kuo and Liew, 2000). It began to turn to cool and dry after 4900 yr BP and the condition continued to ~2500 yr BP when warm-wet conditions resumed, although to a lesser extent when compared to the period of 6200 - 5500 yr BP. Sea-level of the Taiwan Strait appears to reach its highest level at about 4700 yr BP (Chen and Liu, 1997).

The period between 4900 and 3450 yr BP witnessed a major drop of temperature (Kuo and Liew, 2000), concluding the end of the mid-Holocene Megathermal (coined by Hafsten, 1970; also known as mid-Holocene Hypsithermal). Nevertheless, the record from Chitsai Lake in central Taiwan appears to yield different results. According to Liew and Huang (1994), between 4850 - 3900 yr BP, the climate was still warm and wet until 3700 yr BP when the situation turned into colder and drier conditions. A conspicuous drop of *Pulleniatina obliquiloculata* in the planktic foraminiferal assemblages during the period between 3 and 5 ka in the South China Sea (Chen and Huang, 1998) and Okinawa Trough (Li *et al.*, 1997) appears to support the existence of a brief cold event centered at about 4000 yr BP. The SSTs at the northern South China Sea site were estimated to be ~24°C, with a drop of 4°C from today's (Chen and Huang, 1998, Figure 7). From a nearby site, Core RC26-16, Wei *et al.*, (1998c) documented also a drop of ~3.5°C in winter temperature at about 4 ka.

Pollen records suggest that since 2000 yr BP, the vegetation became similar to that of today, implying the existence of a generally warmer condition than before (Liew and Huang, 1994; Liew *et al.*, 1995; Liew *et al.*, 1998; Liew and Hsieh, 2000). The warm and wet conditions are especially evident for the period between 2.0 - 1.5 ka (Liew and Tseng, 1999; Liew and Hsieh, 2000). Changes in pollen assemblage in northern Taiwan (Shunglienpi) suggest that the rise of temperature at this period is in the range of 1-2°C (Liew and Hsieh, 2000). High frequency of ferns in the pollen diagram dominated by subtropical tress suggests that this period was very humid (Liew *et al.*, 1998; Liew and Hsieh, 2000). A concomitant coarsening of sediment grains in Taipei Basin suggests an increase of precipitation or flooding frequency (Liew and Tseng, 1999). The fresh-water spike as indicated by a distinctive excursion in $\delta^{18}O$ of planktic foraminifera at about 2.4 ka form a core offshore northeast Taiwan (Wang *et al.*, 1994) appears to support this interpretation (Liew and Hsieh, 2000). Sea level in the Taiwan Strait was documented to be 1.3 to 1.5 m higher than today's at times of 2020 and 1810 yr BP (calendar age at 1680 and 1410 yr BP) (Chen and Liu, 1996). The various lines of evidence all point to an amelioration condition characterized by warm and humid climate, increased precipitation and high sea-level during 2.5 and 1.5 ka.

Based upon the $\delta^{13}C$ of organic carbon of bulk sediments in a high resolution record of the Yuen-Yang Lake in the northern Taiwan (24°34'40"N, 121°23'50"E, 1,673 m), Yeh *et al.*, (1995) also suggested that climatic condition fluctuated over the past 4000 years. The wettest interval was at about 2000 yr BP while 2800, 2300 and 1400 yr BP witnessed dry climatic conditions. It appears that various studies gave rise to different interpretations. The choice of dating materials for carbon-14 dating must play a crucial role to reconcile the discrepancies. Another source of different interpretation comes from the nature of proxy. For instance, from the study of an alpine lake in the southern Taiwan, the Great Ghost Lake (22°52'15"N, 120°51'15"E, Alt. 2,150 m), Lou *et al.*, (1996) offered also different interpretations concerning the climate condition of the past 2000 years. Based upon C/N ratio and the brightness of sediments, they suggested that after 2000 yr BP, the conditions on the high mountains of southern Taiwan had turned to colder and drier, signifying the onset of the Katathermal period. Intervening in the Katathermal was a short period of warmth from 1000AD to 1300AD comparable to the Medieval Warm Period of Europe. The climate became cold and dry during 1320AD to 1850AD, corresponding to the Little Ice Age (Lou *et al*, 1996). Lou *et al* (1997) further suggested that the following intervals are particularly dry and cold: 0 AD, 500 AD, 700 AD, 900 AD, 1,350 AD and 1,500 AD. The alternation of dark and light colored sediments shows a periodicity of 450 years, which is in good agreement with the oscillation of solar intensity (Chen *et al.*, 1993).

Similar results have been derived from records of C/N ratio and sediment brightness from other alpine lakes, for instance, Chia-Min Lake (Alt. 3,310 m) and Yuen-Yang Lake (24° 34'40"N, 121°23'50"E, 1,673 m). Both records, consistent with a previous study of the Chi-Tsai Lake (23°45'10"N, 121°14'10"E, Alt. 2890 m), support the notion that the Holocene megathermal terminated at about 2.2 ka, followed by a cold/dry period of the Katathermal for the past 2.2 kyrs (Lou and Chen, 1997). Within the Katathermal, a short interval during 820 - 1320 AD corresponding to the Medieval Warmth, and a cold/dry interval after 1320 AD corresponding to the Little Ice Age were recognized (Lou and Chen, 1997).

ANNUAL TO SEASONAL RECORDS OF TREE-RINGS

Tree-ring studies began in the early 90s'. Sheu and Chiu (1995) established a protocol for extracting cellulose from tree ring for carbon isotopic analysis. In viewing the large variability in $\delta^{13}C$ across tree rings and around rings in different radial directions, they cautioned against direct use of such variation for seasonal climatic signals before filtering out physiological effects. With such caution, Sheu *et al.*, (1996) analyzed a 120-year old (1873-1992AD) Taiwan fir (*Abies kawakamit*) growing at an elevation of 3,844 m in Southern Taiwan. Growth profiles of annual ring-width and ring area suggest that the growth of the tree has been stable since 1950. The increasing trend and high variability in $\delta^{13}C$ of the tree rings grown during the juvenile stage (1873-1950 AD) was affected by the canopy effect. Consequently, only the $\delta^{13}C$ record of the stable growth stage (1950-1992AD) is reliable for inferring climatic changes. An empirical equation relating the growing season (May-October) temperature with $\delta^{13}C$ was established. It shows that the $\delta^{13}C$ responded negatively with temperature with a regression coefficient of $-0.46^{0}/_{00}{}^{\circ}C^{-1}$ (Sheu and Chiu, 1996). Owing to its low correlation coefficient (r=0.562), however, the equation can only reconstruct a general trend of past temperatures without much assurance in it.

Other studies of tree rings of Taiwan fir and red cypress from central Taiwan allowed reconstructing the past summer and winter temperatures of the alpine mountain area during the past 300 years (Tsou and Liu, 1996). The results show that the tree-ring widths from *Abies kawakamii* are correlated positively with May-July temperature, whereas the tree-ring widths of an endemic species, Taiwan red cypress (*Chamaecyparis formosensis*), are correlated with winter temperature, but inversely correlated with the number of foggy days (Tsou and Liu, 1996, 1998). Tsou and Liu (1996) found that the May-July temperature curve shows a significant low during the Little Ice Age, but does not show any obvious warming trend during the 20th century. The years of 1786 AD and 1840 AD are found to be of extreme warmth whereas 1826 AD is a year of extreme cold. The records also show periodicity of 2, 9-10 and 17-20 years. Winter temperatures reconstructed were warmer during the year of ENSO and cooler during the La Nina events (Tsou and Liu, 1998).

MONTHLY RECORDS OF CORALS

The empirical relationship between [Sr/Ca] concentration ratio in corals vs. SST has been established in southern Taiwan. The temporal resolution is better than monthly, can even be approaching weekly, while the SST can be constructed with an error less than 0.2°C (Lee *et al.*, 1995; Shen *et al.*, 1996). On the other hand, the documented annual variability of Sr/Ca ratio in the sea-water may itself cause an estimation error of about 0.7°C (Shen *et al.*, 1996).

ANTHROPOGENIC IMPACTS

Concentrations of trace metals in sediment cores of two pristine subalpine lakes (Great Ghost Lake and Small Ghost Lake) have been used as base lines against which anthropogenic impacts were evaluated. Wann and Chen (1996) found that there is a sharp increase of acid-leached lead in the topmost sediments of these two lakes while the Pb-206/Pb-207 ratio shows a corresponding decreasing trend. Since both lakes are located in isolated mountains, such lead pollution is mainly contributed by atmospheric fallout, and is hence attributed to the worldwide lead emissions from automobiles since 1940. Several proxies derived from diatom assemblages, such as the decreased pH and saprobility and enhancement of the amounts of total C and N in the topmost sediments also suggest an acidification of the lake related to increased deposition of atmospheric pollutants over the last century (Wu *et al.*, 1997).

SYNOPSIS

Long -term hydrographic conditions in the South China Sea have been modulated by orbital forcing and show strong periodicity of 100, 41 and 23 kyrs. Situated in the western margin of the West Pacific Warm Pool (WPWP), the South China Sea was not stable at all during most of the late Quaternary. The sea-surface temperatures fluctuated by ~4°C between glacial and interglacial while salinity may also show large variation as the South China Sea was semi-closed during most of the time. During the last glacial, it is clear that the winter monsoons were stronger while summer monsoons were weaker than today's. Biological productivity was higher, so was the accumulation of carbonate on the sea floor and the influx of terrestrial sediments. The transition between the last glacial and the Holocene took place between 18 and 10 ka with a short-lived Younger Drays-like cold reversal event around ~11 ka. The SSTs of the northern South China Sea rose by 3°-4°C from glacial to interglacial. The temperature rise during the last deglaciation in the foothill region of western central Taiwan was about 5°C.

Pollen records suggest that there were three warm-wet periods during the Holocene: 9.7-7.1 ka, 6.2-5.5 ka and 2.5-1.5 ka. Marine records suggest also the existence of a short-lived cold period centered at about 4 ka. Nevertheless, alpine mountain areas appear to show that a major cooling occurred after 2.2 ka. Within the last 2000 years, climatic fluctuations are resonant with the globally recorded Medieval Warm Period (1000-1300 AD) and the Little Ice Age (1300-1850 AD). Tree-ring studies suggest that the years of 1786 AD and 1840 AD were of extreme warmth whereas 1826 AD was extremely cold. The tree-ring records also show periodicities of 2, 9-10 and 17-20 years. Signs of atmospheric pollutants over the last century are evident from several isolated, alpine lakes.

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