Impact of the East Asian monsoon rainfall changes on the erosion of the Mekong River basin over the past 25,000 yr

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A B S T R A C T

Paleohydrological changes in the southern South China Sea (SCS) combined with clay mineralogy have been investigated along core MD01-2393 recovered off the Mekong River mouth in order to assess the impact of sea level and East Asian monsoon rainfall intensity on erosion and weathering during the last 25,000 yr. SSTS and δ18O values determined on Globigerinoides ruber were used to estimate past changes of local seawater oxygen isotope (δ18O w). The close position of the studied core to the Mekong River mouth at sea level lowstand likely played a role in the δ18O w fluctuations resulting from changes of the monsoon rainfall and runoff into the Mekong River. The smectite/(illite + chlorite) and kaolinite/(illite + chlorite) ratios combined with the illite chemistry index during the Holocene show higher chemical weathering of detrital material originating mainly from the lower reach of the Mekong River. At shorter time scales, periods of strong monsoon rainfall are associated with an intensification of erosion of the Mekong River lowland favored by the development of incised-valley systems inducing higher inputs of detrital material from the lower relative to the upper reach of the Mekong River. Our findings imply a rapid response of erosion processes of the Mekong River basin to the monsoon rainfall intensity changes.

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1. Introduction

Detrital sediments from the Arabian Sea, the Bay of Bengal and the South China Sea (SCS) have been used to reconstruct the erosional history of the Himalaya and Tibetan plateau at various timescales (France-Lanord et al., 1993; Derry and France-Lanord, 1996; Colin et al., 1999; Clift et al., 2002). At geological time scale, the importance of tectonic uplift and/or climate changes (e.g. monsoon rainfall and sea level variations) on the erosion and weathering of the Himalaya–Tibet complex remains uncertain because the evolution of the Asian monsoons could also be influenced by the uplift of the Tibetan plateau (Molnar et al., 1993).

The relationship between climate changes and erosion intensity can be assessed at shorter time scale (last 100 kyr) when tectonic uplift can be considered as negligible. At this time scale, Métivier and Gaudemer (1999) have shown that the discharge of the Asian largest rivers remained relatively stable through the Quaternary period. They suggested that the river network is able to buffer changes in hillslope erosion and keep the total discharge constant at the outlet. However, a recent compilation of seismic data from the margin seas of Asia indicates that sedimentary flux to the ocean varied sharply (Clift, 2006). Deposits from the Ganges–Brahmaputra delta have shown a strengthening of the sediment river discharge in the early Holocene induced by the reinforcement of summer Indian monsoon rainfall (Goodbred and Kuehl, 2000). These studies evidence rapid changes of sediment discharges delivered by large tropical fluvial systems to climate changes, at orbital timescales. Over the last climatic cycle, several deep-sea sediment records have shown that climate changes impact on erosion and weathering of the Himalayan river basins (Colin et al., 1999; Liu et al., 2004, 2005; Colin et al., 2006). These studies indicate high chemical weathering and low erosion by glacial scour during period of intensified Asian monsoon rainfall (Colin et al., 2006). In addition, a study of modern Taiwanese Rivers has shown the impact of major rainfall events on the physical erosion, at least in Taiwan mountains (Dadson et al., 2003). Consequently, the role of monsoon rainfall and sea level changes on erosion, weathering and export of sediments to the deep-ocean is not well understood and need further investigations.

The aim of the present paper is to document hydrological and clay mineralogical changes in the SCS, off the Mekong River mouth during the last 25,000 yr. Alkenone U37c37 and stable oxygen isotopes (δ18O) of planktonic foraminifiera Globigerinoides ruber were combined to calculate seawater oxygen isotope (δ18O w) and reconstruct past changes in SCS surface hydrology. The temporal evolution of δ18O w was compared to clay minerals to assess variations of East Asian monsoon rainfall reaching the Mekong River drainage basin and to reconstruct past erosion and weathering changes in the Mekong River basin.
2. Materials and methods

The Calypso core MD01-2393 (10°30.15′N; 110°03.68′E; water depth of 1230 m; 42.5 m long) was retrieved on the continental slope of the SCS 400 km off the Mekong River mouth during R/V Marion Dufresne 122/IMAGES VII-WEPAMA cruise in 2001 (Fig. 1). The MD01-2393 core extends back to marine isotope stage (MIS) 6 with no major hiatus or any visible turbidite layers (Liu et al., 2004). The sedimentological description of the deep-sea sequence indicates that the lithology is homogeneous and ranges from olive/dark clay to silt with foraminifera-rich or diatom-bearing nannofossil ooze.

δ¹⁸O values, expressed in ‰ versus VPDB (Vienna Pee-Dee Belemnite standard) were determined on the planktonic foraminifera Globigerinoides ruber. 6 to 20 shells were picked in the 250–315 µm size range. Isotopic analyses were performed at LSCE on a MAT251 mass-spectrometer. Data are expressed versus VPDB after calibration with NSB19. The mean external reproducibility of carbonate standards is ±0.05‰ for δ¹⁸O.

SSTs were estimated in the same sediment horizons as for isotopes, from the C₃₇ alkenone unsaturation index, U₃₇ as defined by Prahl et al. (1988), following the analytical procedure described by Sicre et al. (1999). Gas chromatographic analyses were performed on a Varian Star 3400CX series gas chromatograph equipped with a fused silica 50 m CP-Sil-5 capillary column following the recommendations of Ternois et al. (1997) (0.32 mm i.d., 0.25 µm film thickness, Chrompack), and a flame ionization detector. U₃₇ ratios were calculated from chromatographic peak areas and converted into SSTs using the global temperature calibration published by Conte et al. (2006).

Variations of δ¹⁸Ow were calculated by solving the paleotemperature equation of Shackleton (1974) using alkenone SSTs:

\[
T = 16.94 - 4.38(\delta^{18}O_{carb} - \delta^{18}O_w) + 0.1(\delta^{18}O_{carb} - \delta^{18}O_w)^2.
\]

Seawater δ¹⁸O (δ¹⁸Ow) depends on changes in \(E - (P + R)\) and the mean ocean δ¹⁸O resulting from changes in continental ice volume.

![South China Sea map](image-url)
Local $\delta^{18}O_{\text{dw}}$ were obtained by subtracting the effect of continental ice melting on global seawater $\delta^{18}O$. The latter is assumed to be equal to the deglacial sea level curve of Lambeck and Chappell (2001) multiplied by a constant coefficient of 1.1%/130 m from Waelbroeck et al. (2002). We did not convert the $\delta^{18}O_{\text{dw}}$ values into salinity because of uncertainty resulting from possible changes in the slope of the $\delta^{18}O_{\text{dw}}$/salinity relationship.

Clay mineralogical determinations were performed by standard X-ray diffraction (XRD) on a Philips PW 1729 diffractometer with CuKα radiation and Ni filter, under 40 kV and an intensity of 25 mA. These analyses were done on the <2 µm carbonate-free fraction, following the procedure described by Holtzpfahl (1985). Three XRD runs were performed on the oriented mounts: (i) untreated; (ii) glycolated (12 h in ethylene glycol); and (iii) heated at 490°C for 2h. The semi-quantitative composition of the clay fraction was obtained using MacDiff software (Petchick, free-ware available from world wide web) by measuring the peak areas of glycolated samples for the main clay mineral groups of smectite (smectite + mixed-layers, 15–17 Å), illite (10 Å), and kaolinite/chlorite (7 Å) (Holtzpfahl, 1985). Relative proportions of kaolinite and chlorite were determined using the ratio of the 3.57/3.54 Å peak areas. The semi-quantitative composition of the clay fraction corresponds to the relative weight percentages of each clay mineral. Replicate analyses of a few selected samples gave a precision of ±2% (2σ). Based upon the XRD method, the semi-quantitative evaluation of each clay mineral has an accuracy of ~4%. The illite chemistry index was calculated from XRD diagrams and corresponds to the ratio of integrated 5 Å and 10 Å illite peak areas (Esquevin, 1969). Clay mineral content data have been already published at lower time resolution (every 900 yr) over the entire core (MIS1-6) (Liu et al., 2004).

### 3. Chronological framework

The age model of core MD01-2393 was established on the basis of the oxygen isotope curve and 5 accelerator mass spectrometry (AMS) $^{14}C$ dating (Table 1). Radiocarbon dates were performed on well-preserved calcareous tests of planktonic foraminifera Globigerinoides ruber and G. sacculifer (Table 1). After subtracting 380 yr ($\Delta T = −70$) to account for the average surface ocean reservoir effect (Dang et al., 2004), the conventional radiocarbon ages were converted into calendar ages using the Calib 5 program (Stuiver et al., 1998). For ages back to 24,000 cal yr BP we used the polynomial equation of Bard et al. (1998).

The age model was established by linear interpolation between 5 calibrated ages for the first 11.6 m of the core (Table 1). The MD01-2393 core thus provides a continuous record since the last ~25,000 cal yr BP with an average sedimentation rate of about 40 cm/1000 yr.

### 4. Results and discussion

#### 4.1. Alkenone SST estimates

The $U_{37}^{s}$ derived SSTs range from mean values of ~24.5 °C during the last Glacial, to 27.5 °C for the Holocene (Fig. 2), implying a 3 °C warming. During the deglacial period, we observe a distinct cooling (~23.5–24 °C) between 18,450 and 15,500 cal yr BP, co-eval to the Oldest Dryas, and a temperature plateau during the Younger Dryas ~24.5 °C (Fig. 2). These features are consistent with previously published alkeneen SST reconstructions in the SCS region (Pelejero et al., 1999a,b; Kienast et al., 2001; Zhao et al., 2006; Steinke et al., 2008). They also share strong resemblance with the GISP2 ice core oxygen isotope record (Dansgaard et al., 1993) except for the weaker warming during the Bölling. Two major abrupt warmings around 15,100 and 10,900 cal yr BP, are attributed to the Bölling and Preboreal periods (Fig. 2). During the last 6000 cal yr BP, SSTs vary slightly between 27.5 and 28 °C, which is close to the modern annual SSTs in the upper 30 m of the surface ocean (27.9 °C).

#### 4.2. Foraminiferal and seawater $\delta^{18}O$ records

The oxygen isototope record of Globigerinoides ruber (Fig. 2) exhibits a similar $\delta^{18}O$ shift of 1.7–1.8% at the glacial/interglacial transition as previously reported in other cores from the SCS (Lee et al., 1999; Kienast et al., 2003). This termination is marked by sharp $\delta^{18}O$ increases observed during the Younger Dryas and the Oldest Dryas, respectively. Similar lighter values have been reported for $\delta^{18}O$ of G. ruber s.l. from MD01-2390 core (06° 38.12’N, 113° 24.56’E; water depth of 1545 m), located further away from the Mekong River mouth (Steinke et al., 2008) (Fig. 1). By contrast, $\delta^{18}O$ analyses on the morphotype G. ruber s.s. recorded only a brief episode of slightly lighter $\delta^{18}O$ values during Younger Dryas (Steinke et al., 2008).

In this same core, the Mg/Ca SSTs record from Globigerinoides ruber s.l. indicate cold temperatures during the Oldest Dryas (15–17 ka) whereas no cooling was observed during the Younger Dryas. On the other hand, SST values determined from G. ruber s.s. indicate a continuous warming since about 18 ka without a cooling phase during the Oldest Dryas, and a subtle decrease in temperature during the Younger Dryas. These differences between the two morphotypes likely reflect changing in depth habitats during the Deglaciation. In contrast to previous studies, alkenone SSTs do not follow the $\delta^{18}O$ record during the Younger Dryas suggesting important changes of the local hydrological budget $E - (P + R)$. In order to reconstruct the $\delta^{18}O_{\text{dw}}$ temporal evolution, we combined the $\delta^{18}O$ of G. ruber and alkenone SSTs to estimate the $\delta^{18}O_{\text{dw}}$ and compare it to clay mineralogy. These estimates have to be considered with cautious considering that the proxy carriers of $\delta^{18}O_{\text{dw}}$ (planktic foraminifera) and $U_{37}$ are different, and are therefore likely to present a different growth season.

The calculated $\delta^{18}O_{\text{dw}}$ values (Fig. 2) indicates a shift by about 0.5% between 12,500 cal yr BP (~1.2%) and the early Holocene (~0.7%) and further towards present time. Furthermore, during glacial times the amplitude of $\delta^{18}O_{\text{dw}}$ fluctuations is 2 or 3 times higher than the Holocene. $\delta^{18}O_{\text{dw}}$ data suggests that water salinity at MD01-2393 site, was lower during glacial time than the Holocene (Fig. 2), a result which is in agreement with those obtained by Steinke et al. (2006) for the eastward core MD01-2390 (Fig. 1).

#### 4.3. Monsoon rainfall variability

Today, SSS in the southern SCS vary seasonally in response to the relative intensity of summer and winter East Asian monsoons. Low salinity waters in the SCS during summer reflect enhanced rainfall over the Asian continent that is responsible for a large river outflow (e.g. Mekong River, Red River...). On the contrary, saltier waters in...
winter result from weaker rainfall combined with the reinforcement of saline waters inflow through several shallow depth straits (water depth <40 m) from the Indo-Pacific warm pool (e.g. Karimata, Sunda and Malacca straits). The δ¹⁸Ow record of MD01-2393 (Fig. 2) thus appears to reflect past changes of the monsoon rainfall and/or the SCS surface hydrology modulated by the paleo-geography of the SCS due to sea level variations.

Taking into account the sea level composite record estimated for the Sunda shelf region (Geyh et al., 1979; Hesp et al., 1998; Hanebuth et al., 2000; Steinke et al., 2001), all straits between the Indo-Pacific and the southern SCS were fully re-opened between 10,000 and 11,000 cal yr BP when the sea level reached about 20–40 m. This last stage of the flooding of Sunda land was responsible for the establishment of modern surface water circulation, after connection with the tropical saline Indo-Pacific warm waters through the southern gateways. Hence, the δ¹⁸Ow short-term variations during the glacial times and the beginning of the Deglaciation are unlikely to result from exchange with the Indo-Pacific Ocean. The location of the core MD01-2393 was only ~100 km away from the paleo-estuary of the Mekong River during glacial sea level lowstand (Liu et al., 2004). Therefore, the low glacial δ¹⁸Ow values likely reflect local freshwater budget (E − (P + R)) and a main influence of the Mekong River. Assuming no major changes in the glacial surface SCS circulation pattern, short-term shifts of the δ¹⁸Ow record before at least 11,000 cal yr BP (Fig. 2) are likely due to variations of the monsoon rainfall intensity over the Mekong River drainage basin. Lighter δ¹⁸Ow values are caused by enhanced monsoon rainfall intensity on land and subsequent larger Mekong River discharge. Lighter δ¹⁸Ow values during glacial times and the Bolling/Allerod seem to be characterized by strengthened summer monsoon rainfall whereas heavier ones during the Younger and the Oldest Dryas indicate a return to drier conditions. Our results are in agreement with a weakening of the

Fig. 2. U³⁷⁷ SST, planktonic foraminifera G. ruber (white) δ¹⁸O (‰) and local δ¹⁸Ow records of core MD01-2393 plotted against age (cal ka BP). The chronology has been established by 5 AMS¹⁴C (indicated by arrows). The δ¹⁸O (‰) record of the GISP2 ice core from Greenland has been reported for comparison (Dansgaard et al., 1993).
summer monsoon during these two cold stages proposed by Steinke et al. (2008). More humid conditions during the Bolling/Allerod than the Younger Dryas event in Europe are in agreement with terrestrial and marine records at sites under the influence of the East Asian and Indian summer monsoons (e.g. Sirocko et al., 1996; Wang et al., 2001; Steinke et al., 2006).

Long-term changes of the δ¹⁸Ow toward heavier values during the last Deglaciation and Holocene should thus be associated to a landward displacement of the coastline upon shelf flooding and/or to a re-opening of the shallow straits. Such processes have been already observed by Steinke et al. (2006) for the south-eastern SCS. Considering the modern morphology of the shelf break in front of the Mekong River mouth and the sea level variations, the position of the Mekong River mouth could have migrated by about 350 to 400 km landward, between 13,000 and 8000 cal yr BP (Liu et al., 2005), thus accounting for the δ¹⁸Ow values over this time interval (Fig. 2).

However, despite the lesser influence of the Mekong River, the early Holocene (9900 to 5400 cal yr BP) δ¹⁸Ow values are presumably indicative of an intensification of the summer monsoon rainfall, in agreement with previous studies that report a Preboreal–early Holocene optimum of the East Asian summer monsoon (Wang et al., 1999, 2001; Herzschuh et al., 2006; Steinke et al., 2006) and Indian summer monsoon (e.g. Gasse et al., 1991, 1996; Sirocko et al., 1993; Van Campo et al., 1996). Wet Holocene period coincides with a larger summer insolation in the Northern Hemisphere and a steeper land–sea temperature gradient in the central Asia. Heavy δ¹⁸Ow values occur during the Holocene around 10,500, 8700–8000, 6300 and after 5000 cal yr BP suggesting lower intensity Asian summer monsoon rainfall may be attributable to higher proportion of winter monsoon (Oppo et al., 2003).

4.4. Clay mineralogy variations and climatic significance

The relative abundance of the main clay minerals groups in core MD01-2393 is shown in Fig. 3. The clay fraction is dominated by smectite (22–61%), followed by illite (16–36%), kaolinite (10–32%) and chlorite (7–28%) (Fig. 3). In general, illite distribution is inversely correlated to smectite (Fig. 3). Glacial times are characterized by higher contents of illite (29–37%) than Holocene ones (19–27%), whereas smectites are higher in Holocene (32–61%) than in glacial sediments (22–35%). Chlorite abundances show a less pronounced Deglaciation decrease. On the other hand, kaolinite abundances display a significant shift from high to low values between 14,000 and 12,000 cal yr BP followed by a gradual increase from early to mid-Holocene before to decrease over the last 5000 cal yr BP.

![Fig. 3. Clay minerals analyses content (%) obtained of the carbonate-free (<2 μm size fraction) of core MD01-2393 plotted against age (cal ka BP).](image-url)
The Mekong River is the major sediment source to the SCS, with a modern mean sediment discharge of \( \sim 160 \times 10^6 \) t/yr (Milliman and Meade, 1983). Considering the short distance of the Mekong River to the MD01-2393 core, its drainage area can be considered as the primary sedimentary source. This is confirmed by \(^{87}\text{Sr}/^{86}\text{Sr}\) and \(\varepsilon_{\text{Nd}(0)}\) analyses performed in core MD01-2393 during the Holocene and MIS 2 displaying a consistent similarity with those of the modern Mekong River sediments (Liu et al., 2005, 2007). In addition, this finding rules out a significant contribution of sediment deriving from volcanic material (Miocene basalts located in the Mekong River basin) over the last 25,000 cal yr BP. On the base of these previous studies, mineralogical fluctuations in core MD01-2393 have been attributed to variations in Mekong River input (Liu et al., 2004).

The Mekong River, which is 4880 km in length, drains the high relief of the eastern Tibetan Plateau in its upper reach, and a large alluvial plain downstream. Illite–chlorite, smectite and kaolinite are distributed in different areas of the catchment basin. Both illite and chlorite primarily result from intensive physical weathering of rocks from the highland of the Mekong River basin (eastern Tibetan Plateau) (Liu et al., 2007). Smectite can be produced by chemical weathering of parent aluminosilicates and ferromagnesian silicates under warm and seasonal contrast of the monsoon conditions in the middle to lower reaches of the Mekong River, where bisialitic soils are well developed (Liu et al., 2005). In tropical environments, kaolinite is present in high abundances in ferrallitic soils that are mainly located in the middle reach of the Mekong River (Liu et al., 2005).

Therefore, kaolinite/(illite + chlorite) and smectite/(illite + chlorite) ratios can be used as proxies of the chemical weathering in the Mekong plain soils and/or physical erosion of the lower and upper reach of the Mekong River. Such mineralogical ratios are reported in the Fig. 4 and permit to describe mineralogical variations within the clay fraction (Fig. 4) that are characterized by distinct temporal evolution of smectite, illite–chlorite and kaolinite abundances.

The kaolinite/(illite + chlorite) ratio ranges from 0.2 to 0.75, with glacial values being lower (0.2–0.5) than Holocene (0.4–0.75) ones (Fig. 4) and were persistently higher during the Bölling–Allerod. This
mineralogical ratio presents two minima around 15,000 and 11,000 cal yr BP. Holocene values show large fluctuations centred at ~9000 and 6500–7000 cal yr BP. Since then, the kaolinite/(illite + chlorite) ratio decreases gradually until the present-day.

The smectite/(illite + chlorite) ratio varies from 0.4 to 1.5 and displays some similarities with the kaolinite/(illite + chlorite) ratio (Fig. 4). This is mostly induced by strong variations of the illite content in the clay size fraction. This ratio increases from about 14,300 cal yr BP, i.e. at the onset of the Bølling–Allerød, even if with lesser amplitude than the kaolinite/(illite + chlorite) ratio. Nevertheless, these ratios diverge over most of the Holocene. The late Holocene values are marked by a broad minimum centred at 5000 cal yr BP for the smectite/(illite + chlorite) ratio.

In addition, chemical weathering could induce a leaching of Fe/Mg from the illite crystal lattice (Esquevin, 1969; Chamley, 1989). Al-rich illites are characterized by higher chemical state of illite (high illite chemistry index) (Esquevin, 1969). The illite chemistry index (Esquevin, 1969) has been used to estimate sediment weathering state (Liu et al., 2007) and to constrain sedimentary sources (Gingele, 1996; Lamy et al., 1999; Ehrmann et al., 2007). In the SCS, Liu et al. (2007) have shown that the illite chemistry index is correlated to the chemical weathering state of the river sediments. They have demonstrated that high physical erosion in river basin (e.g. Red River) is associated with strong inputs of Fe-Mg-rich illite. On the contrary, river basins undergoing higher chemical weathering (e.g. lower reach of the Mekong river basin) are associated with a lower illite content dominated by Al (Al-rich illite) (Liu et al., 2007).

The illite chemistry index of core MDO1-2393 sediments ranges from 0.34 to 0.68 with an average value of 0.48 (Fig. 4). It shows similar variations during glacial time as the other mineralogical ratios, punctuated by short-term fluctuations (Fig. 4). High values between 16,000 and 9500 cal yr BP suggest a more Al-rich composition of illite. It is worthy to note that during the glacial period the δ18Ow decrease corresponds to an illite chemistry index increase similarly to the kaolinite/(illite + chlorite) and/or smectite/(illite + chlorite) ratios (Fig. 4). However, the amplitudes of variations of the illite chemistry index are different from those of both mineralogical ratios. This is mainly due to the fact that the illite chemistry index is independent from the mineralogical composition of the clayey fraction.

### 4.5. Climate impact on erosion within the Mekong River basin

Higher kaolinite/(illite + chlorite) and smectite/(illite + chlorite) ratios during the Holocene than the glacial period can be explained by two processes: (1) weaker physical erosion in the highland, a concurrent enhanced supply of detrital material from the lower and middle reach of the Mekong River and/or (2) an intensification of chemical weathering of primary minerals from soils of the lower reach of Mekong river basin during periods of strong hydrological conditions.

Fig. 4a, show a comparison between the sea level variations and the smectite/(illite + chlorite) and kaolinite/(illite + chlorite) ratios. Two major sea level rises of about 40 m (from 14,300 and 11,700 cal yr BP) and 50 m (9600 and 6600 cal yr BP) respectively occurred over the Sunda shelf. Given the morphology of the continental shelf off the Mekong River, a rapid landward displacement of the coastline could have occurred between 13,000 and 8000 cal yr BP (Liu et al., 2005). However, its present position was reached since about 6600 cal yr BP. Smectite/(illite + chlorite) and kaolinite/(illite + chlorite) ratios display an abrupt increase ~1500 yr before major modification of the SCS palaeogeography implying that sea level oscillations could not be responsible for such mineralogical changes.

In addition, sea level lowstand periods do not show stronger erosion of tropical soils (kaolinite and smectite) in lowlands by incision of the lower Mekong valley and/or of paleo-rivers on the emerged continental plateau during the last Glacial and the subsequent release of a large amount of unaltered minerals (illite and chlorite). Physical erosion would result from glacial scour and frost action in the highland of the Mekong Rivers basin. On the contrary, we suggest that during the Holocene, erosion of the highland is reduced and that high sea level allows the rivers to flow over a larger area of the lower reaches of the Mekong River basin. Detrital minerals produced by physical erosion in the highlands could be less efficiently transported to the ocean and would experience a significant chemical weathering in the lowland of the Mekong River basin.

However, at shorter time scales, intensification of the glacial East Asian monsoon rainfall (lower δ18Ow values) coincide with an increase of kaolinite/(illite + chlorite) ratio and/or smectite/(illite + chlorite) ratio and/or an Al-rich composition of illite (higher illite chemistry index) implying a higher chemical weathering of the sediments supplied by the river (Fig. 4). The same observations can be made during the Deglaciation with an abrupt increase of both mineralogical ratios at 14,000 cal yr BP associated to lighter δ18Ow. This wet period is followed, between 12,200 and 10,900 cal yr BP, by a decrease of kaolinite/(illite + chlorite) ratio and lighter δ18Ow implying a reduction of monsoon rainfall. The early Holocene is characterized by heavy monsoon rainfall across the SE Asian continent, in particular between 9000 and 5500 cal yr BP (Fig. 4). Lower δ18Ow than late Holocene ones, and both mineralogical ratios suggest wet conditions and high chemical weathering. It’s worth to note that the lower mineralogical ratios and drier conditions around 8500–8000 cal yr BP (Fig. 4) as previously observed in several terrestrial and marine records in the tropical monsoon regions (e.g. Casse, 2000; Majewski et al., 2004; Herzschuh et al., 2006). During the late Holocene period, kaolinite/(illite + chlorite) ratio decreases until present-day synchronously with an increase of the sea-surface salinity, whereas smectite/(illite + chlorite) ratio shows a different trend with a minimum centred at about 5000 cal yr BP (Fig. 4).

In summary, our proxies of chemical weathering indicate a short response after summer monsoon rainfall peaks, during the last 25,000 cal yr BP. It seems unlikely that such rapid increases of the monsoon rainfall could be responsible for higher production of smectite and kaolinite from primary minerals in plain soils of the lower and middle reach of the Mekong River. Chemical denudation rates and soil formations in tropical environment can be efficient but probably not enough to respond so rapidly to short-term monsoon rainfall intensity fluctuations. We propose that high monsoon rainfall conditions promoted the development of the incised-valley complex and fluvial erosion of the lower reach of the Mekong River basin and of the exposed glacial shelf. This process may be responsible for a higher physical erosion of soils from the lowland of the Mekong River basin and the transport of large quantity of smectite and kaolinite to the SCS during both glacial and interglacial periods. Khadikar and Rajshekhar (2005) already reported major incision of the Mahi River valley (western India) caused by intensive summer Indian monsoon rainfall at the early Holocene during sea level highstand. Short-term variations of the mineralogy of the Mekong River sediment supply suggest a monsoon rainfall control of detrital material inputs to the ocean and no major buffer effect in flood plain, in agreement with previous results obtained on the Andaman Sea sediments cores (Colin et al., 2006).

### 5. Conclusions

High-resolution clay mineral records and local freshwater fluctuations over the past 25,000 cal yr BP from core MDO1-2393 located off the Mekong River mouth are discussed in relation to the East Asian monsoon and its impact on the erosion and weathering of the Mekong River catchment basin. Changes in the local δ18Ow have been estimated combining U37C~SSTs and δ18O of the planktonic foraminifera (Globigerinoides ruber). The SST record shows a 3 °C warming
over the last Deglaciation in two abrupt steps co-eval with the onset of the Bölling and Preboreal periods.

Glacial times are characterized by lower salinitywaters resulting from higher freshwater export so the SCS by the Mekong River favoured by a low sea level and closer position of core site to the Mekong River mouth. Several δ18Ow episodes during the last glacial period are attributed to rapid variations of the monsoon rainfall intensity. The Deglaciation is associated with a shift flooding, a landward migration of the coastline and an increase of water salinity, implying a reduction of the influence of freshwater rivers input and input of saltier waters from the Pacific.

Since the main contributor of sediments to the core MD01–2393 is the Mekong River, smectite/(illite + chlorite) and kaolinite/(illite + chlorite) ratios as well as the illite chemistry index allowed us to establish the relative contribution of detrital material originating from the lowland (kaolinite and smectite) and highland (illite and chlorite) of the Mekong River basin. Mineralogical ratios and illite chemistry index combined with the δ18Ow record suggest a tight control of the erosion of the Mekong River drainage basin by the monsoon rainfall rather than by relative sea level changes. The Preboreal–early Holocene summer monsoon optimum (9000–6300 cal yr BP) as well as short-term rapid increasing of monsoon rainfall led to a higher proportion of weathered sediments originating from the low and middle reach of the Mekong River.

Short-term variations of the weathering state of detrital materials are unlikely due to an immediate response of chemical weathering in plains but rather to a change of the erosion area in the Mekong River basin. Periods of strong East Asian monsoon rainfall are associated with an intensification of physical erosion of the Mekong River lowland favoured by the development incised-valley systems. This induces higher input of detrital material from the lower relative to the upper reach of the Mekong River.

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