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**Key Points:**
- The decadal variability of primary productivity was extracted from a coral $\delta^{13}C$ record by removing the influence of the $^{13}C$ Suess effect
- The coral-based primary productivity reconstruction for the past 150 years showed a pre-1920s increase and a post-1920s decrease
- The primary productivity of the northern South China Sea varied in phase with the intensity of the winter monsoon on decadal timescales

**Supporting Information:**
- Supporting Information S1
- Data Set S1

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# Links Between the Coral $\delta^{13}C$ Record of Primary Productivity Variations in the Northern South China Sea and the East Asian Winter Monsoon

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**Abstract** The decadal variability of ocean primary productivity (PP) has mainly been studied using relatively short term satellite data, limiting its in-depth analysis. Here, by removing the influence of the $^{13}C$ Suess effect, we extract the PP signal on decadal timescales using a record of coral $\delta^{13}C$ values from the northern South China Sea (NSCS), where the physical-biogeochemical conditions are influenced largely by the winter monsoon. Our results show that the PP in the NSCS increased from 1851 to the 1920s and decreased from the 1920s to 2007, and large superimposed decadal-scale changes were observed. The in-phase relationship observed between the PP reconstruction and winter monsoon records suggests that the changes in the PP in the NSCS are linked to decadal-scale changes in the winter monsoon. Considering that the winter monsoon intensity may weaken in the future under global warming, the PP in the NSCS might decrease in the coming decades.

**Plain Language Summary** Marine phytoplankton contributes roughly half of the global primary production and thus constitutes a vital component of the marine ecosystem that serves as the foundation of the marine food web. Due to the relatively short length of observation records, evaluations of the long-term changes in ocean primary productivity (PP) have suffered from large uncertainties, which have hampered further discussion of the decadal variability of PP in a long-term context. To discuss the decadal variability of the PP beyond the range of satellite observations, we present a coral-based PP reconstruction since 1851 CE from the northern South China Sea (NSCS), where the physical-biogeochemical conditions are influenced largely by the winter monsoon. Our results show considerable decadal variability of the PP in the NSCS superimposed on a pre-1920s increase and a post-1920s decrease. We also found an in-phase relationship between the decadal variability of the reconstructed PP and the winter monsoon records over the past 150 years, indicating that the PP in the NSCS is linked to changes in the winter monsoon forcing on decadal timescales. Considering that the winter monsoon intensity may weaken in the future under global warming scenarios, the PP in the NSCS might decrease in the coming decades.

## 1. Introduction

Marine phytoplankton contributes roughly half of the global primary production and thus constitutes a vital component of the marine ecosystem that serves as the foundation of the marine food web (Chassot et al., 2010; Field et al., 1998). In addition to ecological functions, marine phytoplankton plays an important role in global climate change and biogeochemical cycles (Murtugudde et al., 2002; Sabine et al., 2004). As a result of the relatively short length of available observation records, most studies have focused on the seasonal-to-interannual spatial variability of the primary productivity (PP) ranging from the regional scale to the global scale (Behrenfeld et al., 2006; Dave & Lozier, 2013; Ueyama & Monger, 2005). Moreover, studies on the decadal-scale changes in PP are relatively rare and suffer from large uncertainties (Antoine et al., 2005;

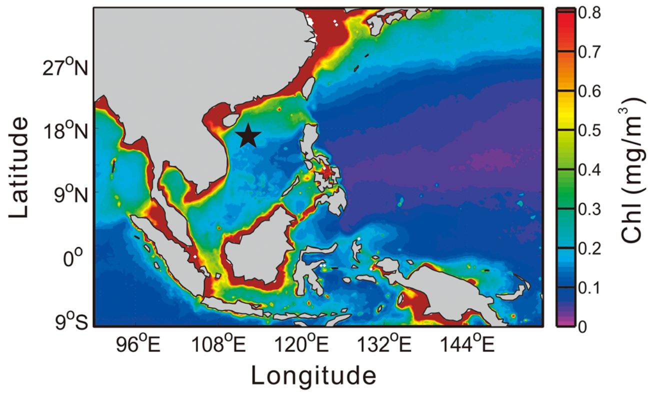


**Figure 1.** Location of our coral record (black star). The color shadings indicate the climatological mean of the winter (December to February) chlorophyll-a concentration (Chl) from 1998 to 2007 (McClain et al., 2004).

Gregg et al., 2005; Gregg & Conkright, 2002; Martinez et al., 2009). Therefore, high-resolution reconstructions of past PP are needed to improve our understanding of changes in the PP on decadal timescales and its association with climate variability.

One potential proxy is the skeletal $\delta^{13}C$ values of scleractinian coral, which are thought to be sensitive to biological and/or environmental changes that alter the $\delta^{13}C$ value of oceanic dissolved inorganic carbon (DIC) as well as changes that influence metabolic and kinetic processes (Grottoli, 2002; McConnaughey, 1989, 2003; McConnaughey et al., 1997; Swart, 1983; Swart et al., 1996; Swart et al., 2010). One prominent factor that influences the coral $\delta^{13}C$ is the addition of $^{12}CO_2$ in the atmosphere as a result of the $^{13}C$ Suess effect (Böhm et al., 1996; Dassié et al., 2013; Swart et al., 2010). In addition, an enhancement of the sea surface PP can induce an increase in the $\delta^{13}C$ values of the oceanic DIC due to the preferential removal of seawater $^{12}CO_2$ during phytoplankton photosynthesis, while a decrease in the sea surface PP produces the opposite effect (Park & Epstein, 1960). Because the $\delta^{13}C$ values of coral skeletons are sensitive to changes in the $\delta^{13}C$ values of oceanic DIC (Deng, Wei, Xie, & Yu, 2013; Swart, 1983; Swart et al., 1996; Weber & Woodhead, 1970), changes in phytoplankton productivity may influence the skeletal $\delta^{13}C$ values of coral. Therefore, signals of long-term changes in PP may be extracted from the coral $\delta^{13}C$ composition by removing other factors, particularly the $^{13}C$ Suess effect.

The South China Sea (SCS), which extends from the Equator to 23°N and from 99°E to 121°E, is one of the largest marginal seas in the western Pacific (WP). The physical-biogeochemical conditions of the SCS are controlled mainly by the East Asian monsoon (Liu et al., 2002; Ning et al., 2004; Shaw & Chao, 1994). Seasonally, winter is the most productive season in the SCS due to the strong wind forcing of the winter monsoon during that period (supporting information Figures S1–S4) (Liu et al., 2002, 2013; Palacz et al., 2011); this wind forcing enhances vertical mixing and introduces nutrients into the euphotic zone (Liu et al., 2002; Tseng et al., 2005). Short-term satellite observations suggest that the PP in the SCS increased during the period from 1998 to 2010 (Liu et al., 2013; Palacz et al., 2011), when most of the tropics experienced a reduction in PP due to the strengthened thermal stratification associated with ocean warming (Behrenfeld et al., 2006; Dave & Lozier, 2013). Based on the observed "wind-nutrients-productivity" mechanism on the seasonal timescale, previous work attributed the increase in the PP in the SCS from 1998 to 2010 to the corresponding enhancement of the wind speed, especially those of the winter monsoon (Palacz et al., 2011). Although these studies represented a notable advance in understanding the driving mechanisms of the present-day changes in the PP in the SCS, the relatively short length of satellite observation records hampers any further discussion of changes in the PP on decadal timescales, a scale on which considerable variability has been revealed in East Asian Winter Monsoon (EAWM) records (Jiang et al., 2018; Wang et al., 2012; Wang & Chen, 2014).

To discuss the decadal variability of the PP in the SCS, we present a 157-year, monthly resolved coral carbon isotope record from a massive *Porites lutea* colony from Yongxing Island (16.84°N, 112.33°E) of the Xisha Islands in the northern South China Sea (NSCS; Figure 1). After subtracting the influence of the $^{13}C$ Suess effect on the record of coral $\delta^{13}C$ values, the coral $\delta^{13}C$ residual ($\delta^{13}C$) is suggested to capture the decadal variability of the PP in the NSCS associated with the EAWM variability. Based on this record of coral $\delta^{13}C$, we investigate the variations in the PP in the NSCS on decadal timescales and the relationship of the PP with the EAWM over the past 150 years.

## 2. Materials and Methods

A 2-m-long core was drilled in late June 2008 from a living *Porites lutea* coral head at a water depth of 6 m off Yongxing Island, Xisha Islands (16.84°N, 112.33°E). Monthly resolution subsamples (~15 samples per year) for stable isotope analysis were drilled along the maximum growth axes identified in the X-ray radiographs (Figure S5). Isotope data were analyzed using a ThermoFisher MAT-253 Isotope Ratio Mass Spectrometer

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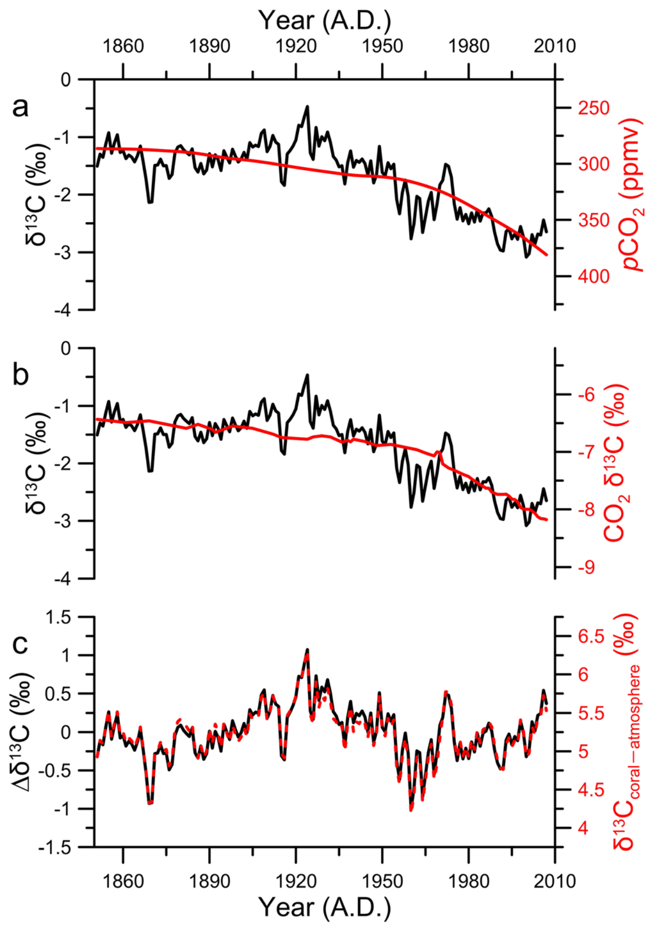


**Figure 2.** Temporal variations in the annually averaged coral $\delta^{13}C$ values, atmospheric $CO_2$ concentration, atmospheric $CO_2$ $\delta^{13}C$ values, and coral $\delta^{13}C$ residue ($\delta^{13}C$). (a) Temporal variations in the coral $\delta^{13}C$ (black line) and the atmospheric $CO_2$ concentration (red line) (Keeling et al., 2001). (b) Temporal variations in the coral $\delta^{13}C$ (black line) and the atmospheric $CO_2$ $\delta^{13}C$ (red line) (Francey et al., 1999; Keeling et al., 2001). (c) Temporal variations in the $\delta^{13}C$ (black line) and the $\delta^{13}C_{coral\text{-}atmosphere}$ (red dashed lines). The atmospheric $CO_2$ concentration and the atmospheric $CO_2$ $\delta^{13}C$ were interpolated to an annual resolution before analysis.

with an automatic Kiel IV carbonate reaction device (supporting information). Data were interpolated to 12 points per year (supporting information).

## 3. Results and Discussions

### 3.1. Coral $\delta^{13}C$ and $^{13}C$ Suess Effect

Our record of coral $\delta^{13}C$ values spans 157 years, from 1851 to 2008 (Figure S6). The annually averaged (arithmetic mean of the monthly data) coral $\delta^{13}C$ values ranged from −3.08‰ to −0.47‰, with an average value of −1.69‰ and displayed a remarkable long-term decreasing trend (Figure 2). We suggest that the decreasing trend in the record of coral $\delta^{13}C$ reflects a decrease in the $\delta^{13}C$ values in the oceanic DIC due to the intrusion of $^{13}C$-depleted anthropogenic $CO_2$ into the ocean, which is recognized as the oceanic $^{13}C$ Suess effect (Böhm et al., 1996). The centennial-scale decreasing trend in the coral $\delta^{13}C$ values over the past 150 years has also been found in other coral records, and the mechanism has typically been attributed to the oceanic $^{13}C$ Suess effect (Dassié et al., 2013; Deng et al., 2017; Swart et al., 2010). This interpretation is further supported by the similar decreasing rate between our coral $\delta^{13}C$ (−0.0096 ± 0.0038‰/year) and the $\delta^{13}C$ of the atmospheric $CO_2$ (−0.0094 ± 0.0030‰/year) for the period 1851–2007 (Figure 2b) (Francey et al., 1999; Keeling et al., 2001). Moreover, the record of coral $\delta^{13}C$ was highly correlated with the atmospheric $CO_2$ concentration ($r = -0.81$, $n = 157$, $p < 0.01$) and with the $\delta^{13}C$ of the atmospheric $CO_2$ ($r = 0.82$, $n = 157$, $p < 0.01$).

### 3.2. Constructing the Coral $\Delta\delta^{13}C$ Series by Removing the Influence of the $^{13}C$ Suess Effect

Although the long-term decreasing trend in the coral $\delta^{13}C$ values followed the pace of the increase in the atmospheric $CO_2$ concentration and the decrease in the $\delta^{13}C$ values of atmospheric $CO_2$, large decadal variations were observed in the record of coral $\delta^{13}C$ but were absent in the records of atmospheric $CO_2$ concentrations and $\delta^{13}C$ (Figure 2), indicating that the decadal variability of coral $\delta^{13}C$ could not be attributed to the $^{13}C$ Suess effect. To remove the influence of the $^{13}C$ Suess effect on the coral $\delta^{13}C$, we defined the coral $\delta^{13}C$ residual ($\Delta\delta^{13}C$) as the residual of the ordinary least squares regression between the coral $\delta^{13}C$ values and atmospheric $CO_2$ concentration records (supporting information and Figure 2c). The similarity between the $\Delta\delta^{13}C$ and the $\delta^{13}C_{coral\text{-}atmosphere}$ (the difference between the coral $\delta^{13}C$ and the $\delta^{13}C$ of atmospheric $CO_2$) supports the conclusion that this method is able to reliably remove the expected influence of the Suess effect by calculating the $\Delta\delta^{13}C$ (supporting information and Figure 2c). To isolate the decadal component of the coral $\Delta\delta^{13}C$, we applied a low-pass filter with an 11-year cutoff to the coral $\Delta\delta^{13}C$ using the software PAST (Hammer et al., 2001).

### 3.3. Ruling Out the Influence of the Kinetic Effect

Kinetic effect is associated with changes in the $\delta^{13}C$ and $\delta^{18}O$ compositions of coral skeletons in response to growth rates, where higher coral $\delta^{13}C$ and $\delta^{18}O$ values occur when the growth rate is slow and lower values occur when the growth rate is fast (Aharon, 1991; McConnaughey, 1989, 2003). A previous study indicated that coral with a growth rate of less than 0.4 cm/year may exhibit high levels of isotopic disequilibrium (McConnaughey, 1989). Another study, however, did not find a significant relationship between the growth rates and the coral $\delta^{13}C$ values (Swart et al., 1996). The growth rates of our coral record ranged from 0.68 to 2.15 cm/year with an average value of 1.28 cm/year (Figure S10). The low common variance (~4%) between the coral $\Delta\delta^{13}C$ and the growth rate ($r = -0.21$, $n = 157$, $p < 0.01$) indicated that the influence of the kinetic effect on the coral $\Delta\delta^{13}C$ can be neglected.

### 3.4. Ruling Out the Influence of the Metabolic Effect

In addition to the $^{13}C$ Suess effect, the metabolic effect has been suggested to be responsible for changes in coral $\delta^{13}C$ values (McConnaughey, 1989; Swart, 1983; Swart et al., 1996). The metabolic effect can induce additional changes in coral $\delta^{13}C$ values through changes in the photosynthesis and respiration of the coral-zooxanthellae symbiotic system (Grottoli, 2002; McConnaughey, 1989; Swart et al., 1996). An enhanced photosynthesis process of endosymbiotic zooxanthellae results in an increase in coral $\delta^{13}C$ values due to the preferential consumption of $^{12}CO_2$ in the internal calcification pool, and a reduction in the photosynthesis process results in the opposite effect (McConnaughey et al., 1997; Swart et al., 1996). An increase in the solar irradiance can enhance the photosynthesis of endosymbiotic zooxanthellae and therefore lead to an increase in coral $\delta^{13}C$ values (Swart, 1983; Weber & Woodhead, 1970). Previous studies have suggested that the seasonal variations in the coral $\delta^{13}C$ values in the SCS were mainly controlled by solar insolation (Shimamura et al., 2008; Sun et al., 2008; Yu, 2012; Yu et al., 2002). Recently, however, several studies have shown that variations in the coral $\delta^{13}C$ values in the SCS and in the solar insolation were unrelated on decadal timescales over the past 150 years (Deng, Wei, Xie, Ke, et al., 2013; Deng et al., 2017). To investigate the relationship between the solar insolation and the coral $\delta^{13}C$ values in our study, we compared the decadal variability of coral $\Delta\delta^{13}C$ and the local sunshine duration (duration of direct solar irradiance greater than 120 W/m$^2$) for the period 1970–2007 (Figure S11) and found a nonsignificant correlation between them ($r = -0.35$, $n_{\mathrm{eff}} = 6.77$, $p_{\mathrm{adj}} = 0.22$; where $p_{\mathrm{adj}}$ is the *p value* adjusted for the loss of degrees of freedom using the method of Trenberth (1984)). In addition, the comparisons between the decadal variability of the coral $\Delta\delta^{13}C$ and the two reconstructed solar irradiance over the past 150 years revealed nonsignificant correlations (TSI: $r = -0.25$, $n_{\mathrm{eff}} = 18.7$, $p_{\mathrm{adj}} = 0.15$; solar flux: $r = -0.18$, $n_{\mathrm{eff}} = 13.8$, $p_{\mathrm{adj}} = 0.27$) (Figure S12) (Ball et al., 2012; Krivova et al., 2010; Lockwood et al., 2009; Vieira & Solanki, 2010). Therefore, solar insolation is unlikely to be responsible for the changes in the coral $\Delta\delta^{13}C$ on decadal timescales.

### 3.5. Ruling Out the Influence of River Runoff

Because the kinetic and metabolic effects were ruled out as possible drivers, the remaining explanation for the decadal variability of the coral $\Delta\delta^{13}C$ is the natural variation in the $\delta^{13}C$ values of oceanic DIC. River runoff can influence the $\delta^{13}C$ in coastal seawater by introducing river water with a more negative $\delta^{13}C$ value than that of seawater (Deng, Wei, Xie, & Yu, 2013; Palmer et al., 2001). The largest river discharge in the NSCS is from the Pearl River Estuary located on the South China Coast (22.1°N, 113.8°E) (Dong et al., 2004). In the wet season (April–September), an intense river discharge from the Pearl River Estuary leads to the development of a strong nearshore salinity front at ~21°N (Dong et al., 2004; Li et al., 2018). As Yongxing Island (16.84°N, 112.33°E) is located far from the salinity front, the influence of river discharge at our study site should be very limited. Considering that the coral $\delta^{18}O$ from the Xisha Islands could be used as a reliable proxy for salinity changes on decadal timescales (Han et al., 2019), we correlated the decadal variability of the coral $\Delta\delta^{13}C$ with the $\delta^{18}O$ values from the same coral colony over the past 150 years ($r = 0.22$, $n_{\mathrm{eff}} = 27.53$, $p_{\mathrm{adj}} = 0.13$) (Figure S13). This result further confirmed the limited effect of river discharge on the $\delta^{13}C$ values of the DIC at our study site.

### 3.6. Ruling Out the Influence of Ocean Circulation

As the surface water $\delta^{13}C$ values show a ~0.3‰ difference between the SCS and the WP (Chou et al., 2007), changes in the ocean circulation may influence the surface water $\delta^{13}C$ values in the SCS. The water exchange between the SCS and the WP is through the Luzon Strait (Qu et al., 2009). The strong mixing of the water mass occurs mainly in the northeastern SCS close to the Luzon Strait (Chou et al., 2007; Lin et al., 1999). In consideration of the long distance between the Xisha Islands and the Luzon Strait and the low surface velocity in the Xisha area (Yu et al., 2007; Yu & Qu, 2013), the contribution of the WP water intrusion to the surface water $\delta^{13}C$ at our study site may be limited. This conclusion is supported by the weakening of the Luzon Strait transport (LST) over the past two decades (Nan et al., 2013). Since the surface water $\delta^{13}C$ in the SCS is ~0.3‰ lower than that in the WP (Chou et al., 2007), the weakening of the LST should lead to the decrease of the surface water $\delta^{13}C$ at our study site (Figure S14). However, our coral $\Delta\delta^{13}C$ indicated an increase of the surface water $\delta^{13}C$ over the past two decades (Figure S14). The

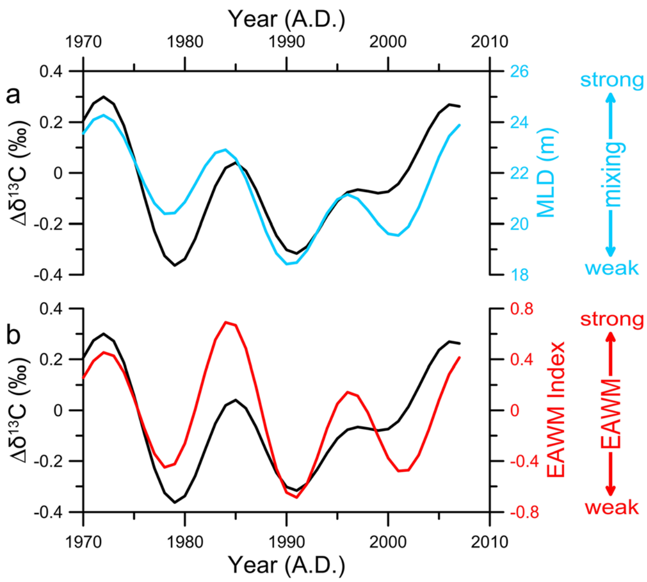


**Figure 3.** Comparison among the coral $\delta^{13}$C, the mixed layer depth (MLD) and the East Asian Winter Monsoon (EAWM). (a) Comparison between the decadal variability of the coral $\delta^{13}$C (black line) and the MLD (blue line) (Carton & Giese, 2008; de Boyer Montégut et al., 2004); (b) Comparison between the decadal variability of the coral $\delta^{13}$C (black line) and the EAWM meridional wind index (red line) (Wen et al., 2014; Kalnay et al., 1996). The series were smoothed with an 11-year low-pass filter to highlight the decadal variability.

correlations between the coral $\Delta\delta^{13}$C and the LST are very low and non-significant for the period 1993–2007 (coral $\Delta\delta^{13}$C- total LST: $r = 0.034$, $n_{eff} = 7.70$, $p_{adj} = 0.47$, for 3-year moving averages; coral $\Delta\delta^{13}$C- surface LST: $r = -0.13$, $n_{eff} = 6.61$, $p_{adj} = 0.39$, for 3-year moving averages). Moreover, we compared the decadal variability of the coral $\Delta\delta^{13}$C and the upper-layer (0–745 m) LST over the past 50 years produced by the ocean model (Figure S15) (Yu & Qu, 2013). The nonsignificant correlation between the coral $\Delta\delta^{13}$C and the upper-layer LST on decadal timescales further supports the limited contribution of the ocean circulation to the surface water $\delta^{13}$C at our study site ($r = -0.04$, $n_{eff} = 15.76$, $p_{adj} = 0.44$, for the period 1950–2007).

### 3.7. The Decadal Variability of the Primary Productivity Revealed in the Coral $\Delta\delta^{13}$C

Changes in the PP could alter the $\delta^{13}$C values of the oceanic DIC and, in turn, influence the coral $\delta^{13}$C (Descolas-Gros & Fontugne, 1990; Swart, 1983). Although a direct comparison yields a high correlation between the coral $\Delta\delta^{13}$C and the annually averaged Chl at our study site (3-year moving average: $r = 0.69$, $n_{eff} = 4.63$, $p_{adj} = 0.09$, for the period 1998–2007) (McClain et al., 2004), we suggest that the robust relationship between the coral $\Delta\delta^{13}$C and the PP in the NSCS on decadal timescales is arbitrary due to the limited length of the satellite observations. Because the PP in the tropics is closely associated with the vertical mixing process of the water column (supporting information Figures S1 and S2) (Behrenfeld et al., 2006; Falkowski et al., 1998), we correlated the decadal variability of the coral $\Delta\delta^{13}$C with the annually averaged mixed-layer depth (MLD) at our study site (15–17°N, 111–113°E) for the period 1970–2007 ($r = 0.80$, $n_{eff} = 6.76$, $p_{adj} < 0.05$) (Carton & Giese, 2008; de Boyer Montégut et al., 2004). Decadally, the increase in the coral $\Delta\delta^{13}$C was coeval with the deepening of the MLD, indicating enhanced mixing conditions of the water column (Figure 3a). A deeper (shallower) MLD can increase (decrease) the PP by enhancing (inhibiting) the vertical nutrient supply in the water column and, in turn, lead to an increase (a decrease) in the oceanic DIC $\delta^{13}$C and in the coral $\Delta\delta^{13}$C (Behrenfeld et al., 2006; Descolas-Gros & Fontugne, 1990; Falkowski et al., 1998). This is further supported by the correlation between the decadal variability of the coral $\Delta\delta^{13}$C and the diatom assemblages record (a proxy for the nutrient levels of the upper water column (Wang et al., 2012)) from the Huguang Maar Lake in the NSCS ($r = 0.56$, $n_{eff} = 9.60$, $p_{adj} = 0.05$; Figure S16). Although the local settings of the Huguang Maar Lake (21.15°N, 110.28°E) and our study site (16.84°N, 112.33°E) have some differences, neither were influenced by river runoff and their biogeochemical behaviors showed similar seasonal patterns (Wang et al., 2008, 2012). In addition to the high nutrient levels, the upwelled water from the deeper layer generally contains DIC with lower $\delta^{13}$C values than the surface water (Lin et al., 1999; Wong et al., 2007). Thus, the enhanced vertical mixing in winter likely decreased the $\delta^{13}$C values of the surface water if only physical mixing is considered. Our result, however, indicated that the enhanced PP in winter has a stronger influence to draw down the seawater $^{12}CO_2$ than the influx of the DIC with lower $\delta^{13}$C values associated with the vertical mixing at our study site. This interpretation is further supported by the field surveys on the coral reef systems in the NSCS, which suggested that the seawater carbonate chemistry of the coral reef was primarily controlled by biological processes (Chen et al., 2015; Dai et al., 2009; Yan et al., 2011, 2016). These results suggest that the decadal variability of the coral $\Delta\delta^{13}$C can be used as a reliable proxy for the PP in the NSCS.

The record of coral $\Delta\delta^{13}$C provides context for the decadal variability of the PP in the NSCS over the past 150 years relative to the instrumental period. The reported increase in the Chl in the NSCS over the instrumental period (~0.03 mg/m$^3$ for the period 1998–2007) manifests in the coral $\Delta\delta^{13}$C as a modest change on decadal timescales (~0.4‰) (Figure 4) (Palacz et al., 2011). Moreover, the record of coral $\Delta\delta^{13}$C also reveals a large multidecadal fluctuation in the PP over the past 150 years (~1.2‰) with an increasing trend from 1851 to the 1920s and a decreasing trend from the 1920s to 2007 (Figure 4). Assuming a linear relationship between the coral $\Delta\delta^{13}$C and the Chl, the multidecadal fluctuation of ~1.2‰ in the coral $\Delta\delta^{13}$C values indicated a large

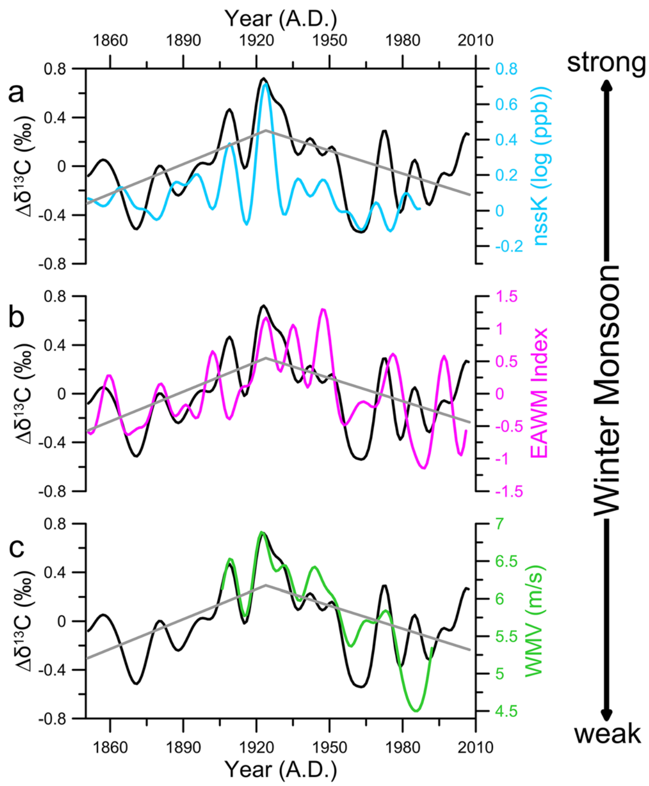


**Figure 4.** Comparison between the decadal variability of the coral $\delta^{13}$C and the proxy-based winter monsoon records. (a) Comparison between the decadal variability of the coral $\delta^{13}$C (black line) and a reconstruction of the Siberian High derived from the ice core nssK (blue line) (Meeker & Mayewski, 2002). (b) Comparison between the decadal variability of the coral $\delta^{13}$C (black line) and the detrended coral REE-based EAWM index (purple line) (Jiang et al., 2018). (c) Comparison between the decadal variability of the coral $\delta^{13}$C (black line) and the coral-based winter monsoon velocity in the NSCS (green line) (Liu et al., 2008). The series were smoothed with an 11-year low-pass filter to highlight the decadal variability. The ice core record was interpolated to an annual resolution before analysis.

variation of the Chl with the amplitude of ~0.09 mg/m$^3$ over the past 150 years. These results highlight the limitations of previous studies based on relatively short duration satellite observations, further underscoring the value of assessing the decadal variability of the PP using proxy records.

### 3.8. The Winter Monsoon Forcing of the Primary Productivity in the NSCS on Decadal Timescales

Studies based on satellite observations have suggested that the seasonal-to-interannual changes in the PP in the NSCS are driven mainly by winter monsoon winds, which enhance nutrient pumping by strengthening vertical mixing (Liu et al., 2002, 2013; Palacz et al., 2011). To validate the relationship between the PP and the winter monsoon on decadal timescales, we correlated the decadal variability of the coral $\Delta\delta^{13}$C and MLD with the EAWM meridional wind index for the period 1970–2007 ($\Delta\delta^{13}$C-EAWM: $r = 0.66$, $n_{\mathrm{eff}} = 7.28$, $p_{\mathrm{adj}} < 0.05$; MLD-EAWM: $r = 0.87$, $n_{\mathrm{eff}} = 5.78$, $p_{\mathrm{adj}} < 0.01$) (Figure 3) (de Boyer Montégut et al., 2004; Carton & Giese, 2008; Kalnay et al., 1996; Wen et al., 2016). The significant correlations between these factors indicate that in addition to seasonal-to-interannual timescales, the winter monsoon and the resultant vertical mixing are also the main drivers of changes in the PP in the NSCS on decadal timescales. The decadal-scale "wind-nutrients-productivity" mechanism is further supported by proxy-based EAWM reconstructions, including reconstructions of the Siberian High derived from the non-sea salt potassium (nssK) concentration in Greenland ice cores, the strength of the EAWM retrieved from the rare earth element compositions in coral from the Xisha Islands and the winter monsoon velocity in the NSCS inferred from the coral-based winter sea surface temperature gradient (Figure 4) (Jiang et al., 2018; Liu et al., 2008; Meeker & Mayewski, 2002). The decadal variability of the coral $\Delta\delta^{13}$C presented significantly positive correlations with that of the proxy-based EAWM reconstructions over the past 150 years ($\Delta\delta^{13}$C-nssK: $r = 0.64$, $n_{\mathrm{eff}} = 11.04$, $p_{\mathrm{adj}} < 0.05$, for the period 1851–1987; $\Delta\delta^{13}$C-rare earth element: $r = 0.53$, $n_{\mathrm{eff}} = 10.9$, $p_{\mathrm{adj}} < 0.05$, for the period 1851–2006; $\Delta\delta^{13}$C-winter monsoon velocity: $r = 0.73$, $n_{\mathrm{eff}} = 5.64$, $p_{\mathrm{adj}} < 0.05$, for the period 1906–1992). Based on the consistency between the coral $\Delta\delta^{13}$C and the EAWM reconstructions over the past 150 years, we suggest that the increase in the PP before the 1920s and the decrease after the 1920s were possibly due to the strengthening and weakening, respectively, of the EAWM during these periods (Figure 4). As studies of the decadal variability of the EAWM are rare, the mechanism responsible for the 1920s shift remains unclear. Coincidentally, the weakening of both the EAWM and the PP since the 1920s has corresponded to the onset/acceleration of global warming (Hansen et al., 2010; Jones et al., 1999). Global warming preferentially warms high-latitude continents relative to the oceans and, in turn, weakens both the land-sea thermal contrast and the land-sea pressure gradient, leading to the weakening of the EAWM (Hong et al., 2016; Hu et al., 2000). This weakening could result in a decrease in the PP in the NSCS by weakening the vertical mixing therein and limiting the amount of nutrients introduced into the euphotic zone (Behrenfeld et al., 2006; Falkowski et al., 1998; Liu et al., 2002, 2013).

## 4. Conclusion

Our record of coral $\Delta\delta^{13}$C in conjunction with EAWM records indicates that the decadal variability of the PP in the NSCS over the past 150 years has been controlled primarily by the EAWM and the resultant vertical mixing of the water column. The pre-1920s increase and the post-1920s decrease in our coral-based PP record for the NSCS correspond to the strengthening and the weakening, respectively, of the EAWM during these periods. Studies based on coupled models have suggested that the EAWM may weaken in the future because of the reduction in the land-sea thermal contrast under emissions-driven global warming scenarios (Hong et al., 2016; Hori & Ueda, 2006; Hu et al., 2000). Therefore, the PP in the NSCS will likely decrease in the coming decades due to the projected weakening of the EAWM, and this decrease may significantly impact the marine ecosystem and the biogeochemical cycles in the NSCS. High-resolution reconstructions of the PP from other regions are needed to achieve an in-depth understanding of the changes in the PP under global warming scenarios.

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