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Key Points:

- The South China Sea biological carbon pump does not rebound from the 1997/1998 El Niño to La Niña phase as expected
- The enhanced stratification and Kuroshio intrusion are responsible for the low opal:$CaCO_3$ ratio of sinking particles in the El Niño phase
- The deepened thermocline prevents the diapycnal nutrient supply and the recovery of the biological carbon pump in the La Niña phase

Supporting Information:

Supporting Information may be found in the online version of this article.

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Asymmetric Response of the Biological Carbon Pump to the ENSO in the South China Sea

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Abstract Biological carbon pump (BCP) inefficiency was first observed in the South China Sea (SCS) throughout the 1997–1999 El Niño Southern Oscillation (ENSO) event, but the BCP usually recovers its efficiency when the climate conditions change from El Niño to La Niña conditions in the Pacific Ocean. Enhanced stratification and Kuroshio intrusion led to weak mixing and oligotrophic conditions in the sunlit layer of the SCS during the 1997/1998 El Niño phase, but the particulate organic carbon (POC) flux was comparable to the climatological mean due to the ballast effect of increased lithogenic material and $CaCO_3$ flux. The deepened thermocline rendered the recovered mixing less effective in replenishing subsurface nutrients and subsequently lowered POC flux during the 1998/1999 La Niña phase. Both scenarios were characterized by decreased siliceous plankton but a stimulated calcareous plankton contribution, which reduced BCP efficiency, resulting in a unique asymmetric response to the ENSO in the SCS.

Plain Language Summary The El Niño-Southern Oscillation (ENSO) in the Pacific Ocean is one of the most important ocean-atmosphere coupled climatic phenomena on Earth, and the ENSO in turn influences marine biogeochemical cycles and the biological carbon pump (BCP). Usually, as climate conditions transition from the El Niño to La Niña phases, the weakened BCP rebounds to a highly productive level in the central and eastern Pacific. However, the BCP exhibits an asymmetric response to the ENSO in the South China Sea (SCS), the largest tropical marginal sea of the Pacific Ocean. We show that strengthened stratification of the upper water column and enhanced oligotrophic Kuroshio intrusion led to impoverished in bioavailable nutrients near the surface, caused fewer siliceous plankton compared to calcareous plankton, and thus resulted in an inefficient BCP in the 1997/1998 El Niño phase. In contrast, the deepened thermocline prevented the replenishment of nutrients from the subsurface, subsequently inhibiting the rebound of primary production and deep biogenic flux during the 1998/1999 La Niña phase. This study may aid in understanding the response of the BCP to ENSO events in marginal seas and improve predictions of global ocean carbon storage.

1. Introduction

The ocean's uptake and sequestration of carbon from the atmosphere plays an important role in the regulation of the global climate (Sigman et al., 2010). The biological carbon pump (BCP) is the key link between nutrient supply to the sunlit layer controlled by physical forcings, the maintenance of photosynthetic carbon fixation, and sinking particulate organic carbon (POC) storage in the ocean interior (Boyd et al., 2019). The El Niño Southern Oscillation (ENSO) is the dominant mode of interannual climate variability that in turn alters the marine biogeochemical cycles of global oceans (Messié & Chavez, 2012). With the increasing occurrence of extreme climate events under global warming, many attempts have been made to understand the impacts of El Niño and La Niño events on marine primary production and the export of organic carbon in the equatorial Pacific and adjacent areas (Chavez et al., 1999; Gierach et al., 2012; Kim et al., 2011, 2012). Notably, the observed responses of the BCP also show significant discrepancies among oceanic regimes (Strutton et al., 2008; Tseng et al., 2009). In addition, time series records of the BCP for a whole ENSO cycle, from El Niño to La Niño, are particularly lacking.

The South China Sea (SCS), which is the largest marginal sea of the tropical ocean, is situated between the Eurasian supercontinent and the West Pacific Warm Pool (Figure 1). Due to the marked land–sea thermodynamic gradient, the physical-biogeochemical conditions of the SCS are mainly governed by monsoonal transitions and are extremely sensitive to climate variation (Liu et al., 2002, 2013; Ning et al., 2004). In response, winter and

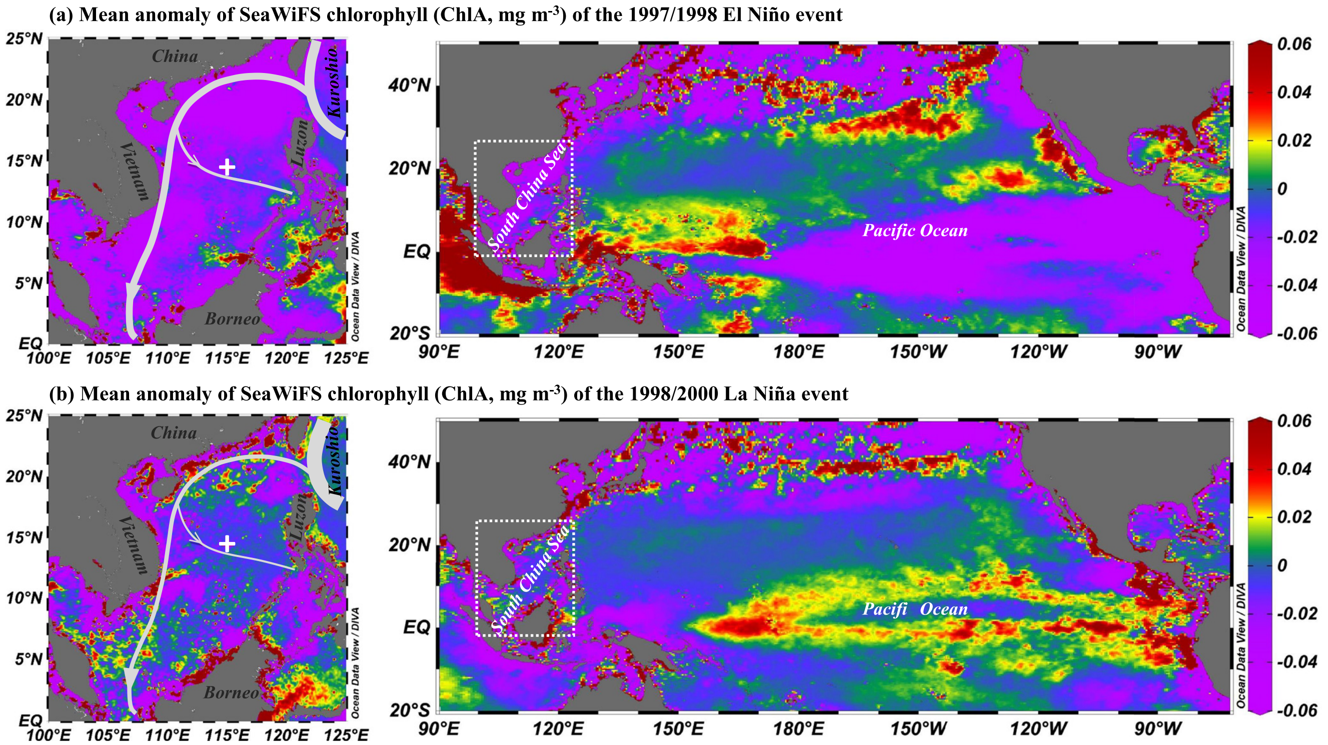

Figure 1. Mean anomaly of SeaWiFS surface chlorophyll (ChlA) comparisons for the 1997/1998 El Niño (September 1997–June 1998) and 1998/2000 La Niña (September 1998–March 2000) events in the Pacific Ocean and adjacent South China Sea (SCS). The SCS sectors in the left panels are close-up views. An obvious phytoplankton bloom took place in the eastern and central equatorial Pacific Ocean from the El Niño to La Niña phases, but the biological activity did not rebound at the same time in the SCS. The white cross in the left panels represents the site of the moored sediment trap (14.5°N, 115°E). The gray arrows represent the different conditions of SCS throughflow during the El Niño and La Niña phases.

summer are the productive seasons of the central SCS, while the intermonsoon periods (spring and autumn) are less productive (Li et al., 2017). Via the deep Luzon Strait and atmospheric circulation, ENSO events impact the SCS (Qu et al., 2004). Termed the Luzon Strait transport (LST), oligotrophic Kuroshio water intrudes into the SCS via the Luzon Strait, with a negative effect on nutrients in the sunlit layer of the northern SCS (Du et al., 2013; Qu et al., 2009). The LST varies as the bifurcation latitude of the North Equatorial Current shifts, which is strongly correlated with the ENSO (Nan et al., 2015; Yaremchuk & Qu, 2004). On the other hand, a shift in the scope of the intertropical convergence zone could directly impact the monsoon intensity and subsequent biological responses in the SCS (Tseng et al., 2009; C. Wang et al., 2006; Xiu et al., 2019).

An evident reduction in sea surface chlorophyll concentration was observed during the 1997/1998 super El Niño event in the SCS but without apparent recovery when the climate changed to the 1998/2000 La Niña phase (Figure 1). In comparison, the primary productivity changed from an exceptionally low level during the strong 1997/98 El Niño event to robust phytoplankton blooms during the strong 1998/2000 La Niña event in the equatorial Pacific Ocean (Figure 1, Brainard et al., 2018; Chavez et al., 1999; Gierach et al., 2012). Diatom abundance significantly decreased during El Niño conditions but increased during La Niña phases in the eastern equatorial Pacific Ocean (Rousseaux & Gregg, 2012). Based on sea surface chlorophyll, Liu et al. (2013) further demonstrated that intensified wind could not lead to a high chlorophyll concentration during the La Niña phase in the SCS. However, to date, studies have mainly focused on the sea surface chlorophyll of the SCS and have seldom assessed the impact of the ENSO on the capacity for carbon sequestration of the BCP. According to sinking particle flux data collected by time series sediment traps, this study provides the first information on the response of the BCP to super ENSO events (1997–2000) in the SCS.

2. Methods and Data

Sinking particles were collected by a bottom-tethered time series sediment trap (Mark VI, McLane) from April 1992 to April 1999 in the central SCS basin (14.5°N, 115.0°E; total water depth of 3800 m, trap depth of 1200 m, Figure 1). Before trap deployment, analytical grade NaCl (35 g l^{-1}) and $HgCl_2$ (3.3 g l^{-1}) were dissolved in sample cups (250 ml) with seawater from the trap depth. The samples with 30-day collection intervals were dried at 45°C for total particle flux and major component analysis after trap recovery. The trapping efficiency of the sediment trap and sinking particle dissolution were not considered in this study. Detailed analytical methods for the major components (POC, $CaCO_3$, opal, and lithogenic material) are described in detail in the Supporting Information S1 (Li et al., 2017; Müller et al., 1986).

Profiles of salinity and temperature were generated at the sediment trap station with a Seabird model SBE911 plus conductivity-temperature-depth recorder. The mixed layer depth (MLD) was defined as the layer of water having a density gradient less than 0.125 kg m^4 (Suga et al., 2004). At the trap station, the nitrate and Chl concentrations of discrete seawater samples were analyzed with standard methods (Strickland & Parsons, 1972) in June and December 1998, June 2012, and December 2014. The seawater samples were collected at 2, 30, 50, 75, 100, 150, 200, and 300 m.

The multivariate ENSO index (MEI) was used to indicate the occurrence of El Niño and La Niña events (Wolter & Timlin, 2011). The monthly sea surface temperature (SST), surface wind speed (WS), net heat flux (HF) and surface chlorophyll *a* (Chl) concentration data were obtained from the Advanced Very-High Resolution Radiometer, National Climate Data Center of the NOAA, Global Ocean Data Assimilation System and Sea-viewing Wide Field-of-view Sensor, with spatial resolutions of 1.1° × 1.1° km, 0.25° × 0.25°, 1° × 1° and 4° × 4° km, respectively. Monthly net primary production (NPP) of the sunlit layer was obtained from the NASA Ocean Biology Distributed Active Archive Center (Behrenfeld & Falkowski, 1997). The daily sea level anomaly data with a spatial resolution of 0.25° × 0.25° for the period of 1993–1999 were from the US Navy Modular Ocean Data Assimilation System product. For each variable, the anomaly was calculated as the difference between the monthly value and the climatological average for a given month and year. The depth of the 20°C isotherm (representing the thermocline depth) was obtained from the 2° × 2° long grid expendable bathythermograph (XBT) data of the upper 400 m of water (https://www.ncei.noaa.gov/products/world-ocean-database).

3. Results and Discussion

3.1. Remote Response of Physical Forcing to the ENSO

The continuous positive MEI (>0.5) from April 1997 to June 1998 indicated the occurrence of the warm ENSO phase, for example, El Niño, while negative values (<−0.5) persisted from August 1998 to March 2000, implying that the climate conditions had changed to the cold La Niña phase (Figure 2a). Through the atmospheric circulation between the Pacific Ocean and the SCS, the physical properties at the trap station may be significantly modulated by ENSO events (C. Wang et al., 2006; Xie et al., 2003). During this extreme event, the temporal variations in physical forcings (e.g., WS, HF, and SST, Figure S1 in the Supporting Information S1) were in phase with their seasonal climatological trends in the central SCS (red lines in Figure S1 in the Supporting Information S1) but with significant interannual fluctuations in their magnitudes. To better explore the interannual variabilities in the physical forcings, the nonseasonal variations, represented by the anomalies, were calculated by removing their climatological monthly mean values. As shown in Figure 2b, most of the monthly wind speed anomaly (WSA) values were negative during El Niño conditions in the central SCS, except in July 1997 due to the impact of two typhoons. In contrast, the monthly WSA values were almost positive during the La Niña phase. Moreover, the net heat flux anomaly (HFA) trend changed from positive to negative as the climate conditions changed from El Niño to La Niña conditions (Figure 2c). Consequently, the sea SST anomaly (SSTA) increased during the El Niño period but with a 4-month lag due to the buffer effect of the mixed layer (Qu et al., 2007), while it decreased during the La Niña phase (Figure 2d).

3.2. Asymmetric Response of the BCP

As a response, the surface Chl decreased by 16% compared with the climatological mean during the El Niño period, and it recovered to or was slightly higher than the climatological levels during the La Niña period in the

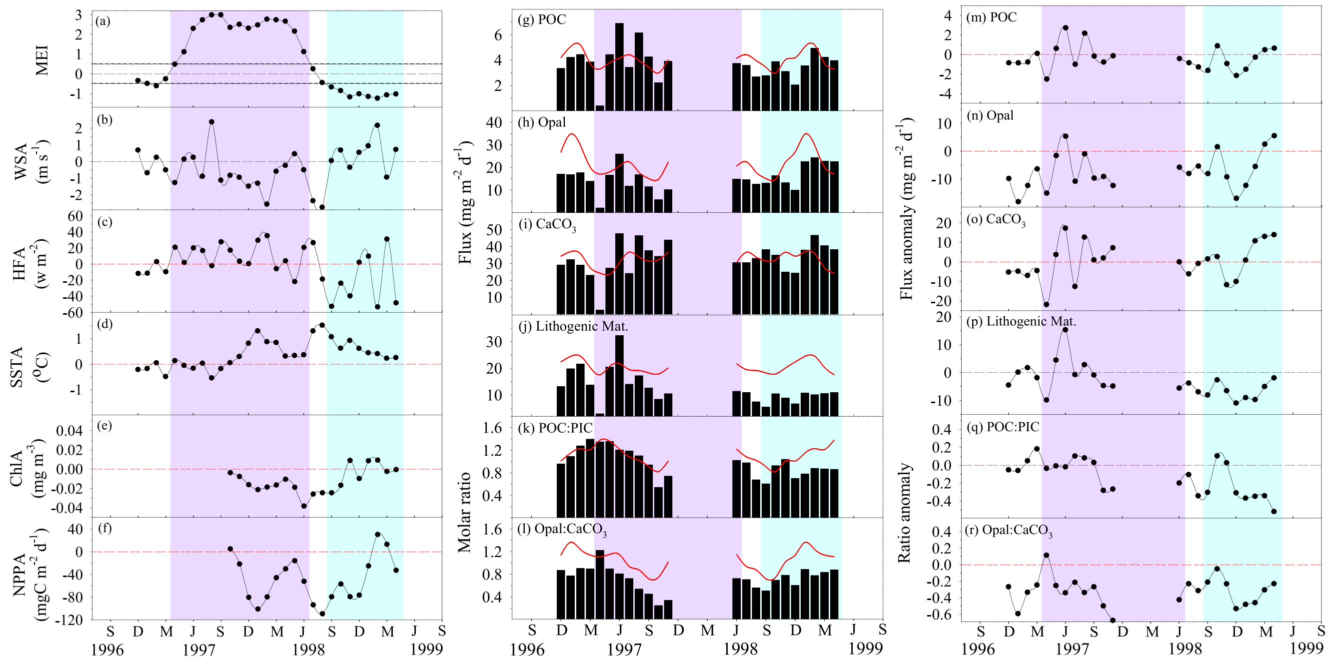

Figure 2. Time series of monthly anomalies of physical and biogeochemical data during 1997–1999 at mooring station SCS-C (14.5°N, 115°E): (a) multivariate ENSO index (MEI), (b) wind speed anomaly (WSA), (c) net heat flux anomaly (HFA), (d) sea surface temperature anomaly (SSTA), (e) surface chlorophyll anomaly (ChlA), (f) net primary production anomaly (NPPA), (g) POC flux, (g) opal flux, (i) $CaCO_3$ flux (j) lithogenic flux (k) surface chlorophyll (Chl) (l) net primary production (NPP) (m) POC anomaly (n) opal anomaly (o) $CaCO_3$ anomaly (p) lithogenic material anomaly (q) POC:PIC molar ratio anomaly and (r) opal:$CaCO_3$ molar ratio anomaly. Purple and cyan indicate 1997/1998 El Niño and 1998/1999 La Niña events, respectively. The red dashed lines present the monthly climatology means of specific components or molar ratios in the left and right panels, whilst the red curves represent their climatological monthly values in the middle panel. On the *x* axis, "J" and "D" denote the months of June and December, respectively.

central SCS (Figure 2e). Similarly, the NPP of the sunlit layer decreased by 17% compared with the climatological mean during the El Niño period, but it was still lower (13%) than the climatological mean during the La Niña phase (Figure 2f). However, although satellite-derived NPP could show the relative variation in primary production, this measure was overestimated compared to that from field data in the SCS (Shih et al., 2021). With respect to sinking particle fluxes, there were no significant seasonal trends in either climate phase (Figures 2g–2j), while the seasonal climatology exhibited bimodal patterns in the winter and summer monsoon periods (red curves in Figures 2g–2i). To quantify the influence of ENSO events on the sinking particle flux, the flux anomalies of specific components (Figures 2m–2p) were calculated by removing the monthly climatological patterns reported by Li et al. (2017). The monthly climatological mean of each component was assessed by computing the average monthly fluxes from the weighted mean value of each biogenic flux at the trap station during the sampling period from1993 to 1999 (Li et al., 2017). On average, the POC flux (3.94 mg m^{-2} d^{-1}) was comparable to the climatological value (3.82 mg m^{-2} d^{-1}) during the El Niño period, while the POC flux (3.57 mg m^{-2} d^{-1}) negatively deviated from the climatological value (4.0 mg m^{-2} d^{-1}) during the La Niña phase, with a decrease of 10.9%. However, according to one-way anlysis of variance (ANOVA), the POC fluxes during La Niña ($F = 1.044$, $p = 0.324$) were not significantly different from the monthly climatology mean. The phytoplankton functional group also shifted with the occurrence of ENSO events. During both events, the $CaCO_3$ flux positively responded to climate forcing, with increases of 5.2% and 10.2% compared to the climatological values in the El Niño and La Niña phases, respectively. In contrast, the opal flux negatively deviated from its climatological levels during both events, decreasing by 31.7% and 19.9% in the El Niño and La Niña phases, respectively. Previous taxonomic studies also found that the diatoms in the 1987/1988 El Niño period was approximately 2 orders of magnitude lower than that in other periods (Ran et al., 2011, 2015). Furthermore, the average lithogenic particle flux (14.08 mg m^{-2} d^{-1}) increased by 4.9% compared to the climatological value (13.42 mg m^{-2} d^{-1}) in the El Niño period but decreased by 42.2% during the La Niña phase. Based on multiple linear regression analysis, both lithogenic particles and $CaCO_3$ were important ballast minerals in addition to opal in the SCS (Table S1 in the Supporting Information S1). Hence, the comparable POC flux with climatology may be attributable to the enhanced ballast effect induced by the positive anomaly of lithogenic particle and $CaCO_3$ fluxes during the 1997/1998 El Niño period.

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The reduction of POC flux may be related to the decreased ballast effect induced by the negative anomalies of opal and lithogenic fluxes during the 1998/1999 La Niña period.

On average, the POC:PIC and opal:$CaCO_3$ molar ratios of the sinking particles were lower than the climatological values throughout the ENSO event (Figures 2k–2l, and Figures 2q–2r). In combination with the trend of opal and $CaCO_3$ fluxes, the observed records indicated that siliceous plankton were suppressed compared to calcareous plankton in the central SCS, even during the strong La Niña phase. As a result, the biological pump was weakened during the El Niño period but showed no recovery when the climate condition changed to the La Niña phase in the central SCS. Accordingly, this may have led to a decrease in oceanic carbon sequestration via the BCP during both climate phases in the SCS.

3.3. Influence of Stratification and Kuroshio Intrusion

The above results suggest that primary production and especially the sinking particle flux (opal and $CaCO_3$) significantly impacted during the 1997/1998 El Niño period in the central SCS. The strengthened stratification of the water column and enhanced oligotrophic Kuroshio intrusion could be responsible for the weakened BCP in this period.

In the SCS basin, fluctuation of the mixed layer depth (MLD), regulated by monsoon transition and surface cooling, is one of the most important factors controlling nutrient replenishment (Tseng et al., 2005). As shown in Figure 2b, an apparent negative WSA and a positive HFA indicated strengthened stratification in the upper water during the 1997/1998 El Niño event. Data from shipboard CTD cast confirmed the prominent stratification of the water column during the 1997/1998 El Niño event. A 30 m MLD, which was extremely shallow compared with the climatological MLD depth of 50 m, was observed in June 1998 (Figure 3a). This result indicated that strong stratification in the water column weakened the nutrient supply from the subsurface to the euphotic zone via water mixing at the trap site during the El Niño period. Simultaneously, these anomalous biogeochemical conditions were also observed in the northern SCS basin, with sharp declines in MLD, nitrate concentration and primary production (Tseng et al., 2009).

In addition to upper water stability related to atmospheric forcing, large-scale oceanic circulation could also impact the nutrient inventory of the SCS. Oligotrophic Kuroshio intrusion diluted the nutrient inventory in the SCS basin (Du et al., 2013). The LST, an important component of the SCS throughflow, could bring oligotrophic Kuroshio water into the SCS, which had apparent interannual variability associated with the swing of the North Equatorial Current bifurcation latitude (NECBL) due to ENSO events (Nan et al., 2015; Qu et al., 2004). According to Simple Ocean Data Assimilation (SODA) reanalysis data, the upper 300 m of the LST was approximately 0.8 Sv stronger during the 1997/1998 El Niño event than under normal conditions, and accompanied by the northward NECBL (Xiao et al., 2017). Correspondingly, the mean salinity in the top 300 m in June 1998 (34.46 ± 0.22) was higher than that in June 2012 (34.19 ± 0.46), with the largest differences (0.41–0.85) in the top 70 m (Figure 3a). This hydrographic feature indicated the presence of a higher fraction of Kuroshio surface water in the central SCS during the 1997/1998 El Niño period, which usually had higher salinity and temperature and fewer nutrients than the SCS upper water (Du et al., 2013; Gong et al., 1992). The vertical profiles of nutrients confirmed this speculation, showing undetected nitrate concentrations in the upper 100 m in June 1998, while the nitracline was at a normal depth (50–75 m) in June 2012 (Figure 3b). Consequently, the combined effect of enhanced stratification in the upper water and intensified intrusion of oligotrophic Kuroshio surface water could render the nutrient supply insufficient for photosynthetic activities and account for the lower biomass, particularly of the siliceous plankton during the 1997/1998 El Niño event.

3.4. Influence of the Deepened Thermocline

Unlike the eastern equtorial Pacific, recovery of sinking particle fluxes in the central SCS during the 1998/1999 La Niña was not observed (Figures 2m–2p), although it had higher WS and lower HF than climatological conditions during this period (Figures 2b and 2c). The deepened thermocline and nutricline could be triggers for the unrecovered BCP under La Niña condition.

As shown in Figure 3c, the deepened MLD (~50 m) in December 1998 implied that the atmospheric forcing-induced upper water mixing had recovered from the El Niño state. However, there was no obvious biological activity

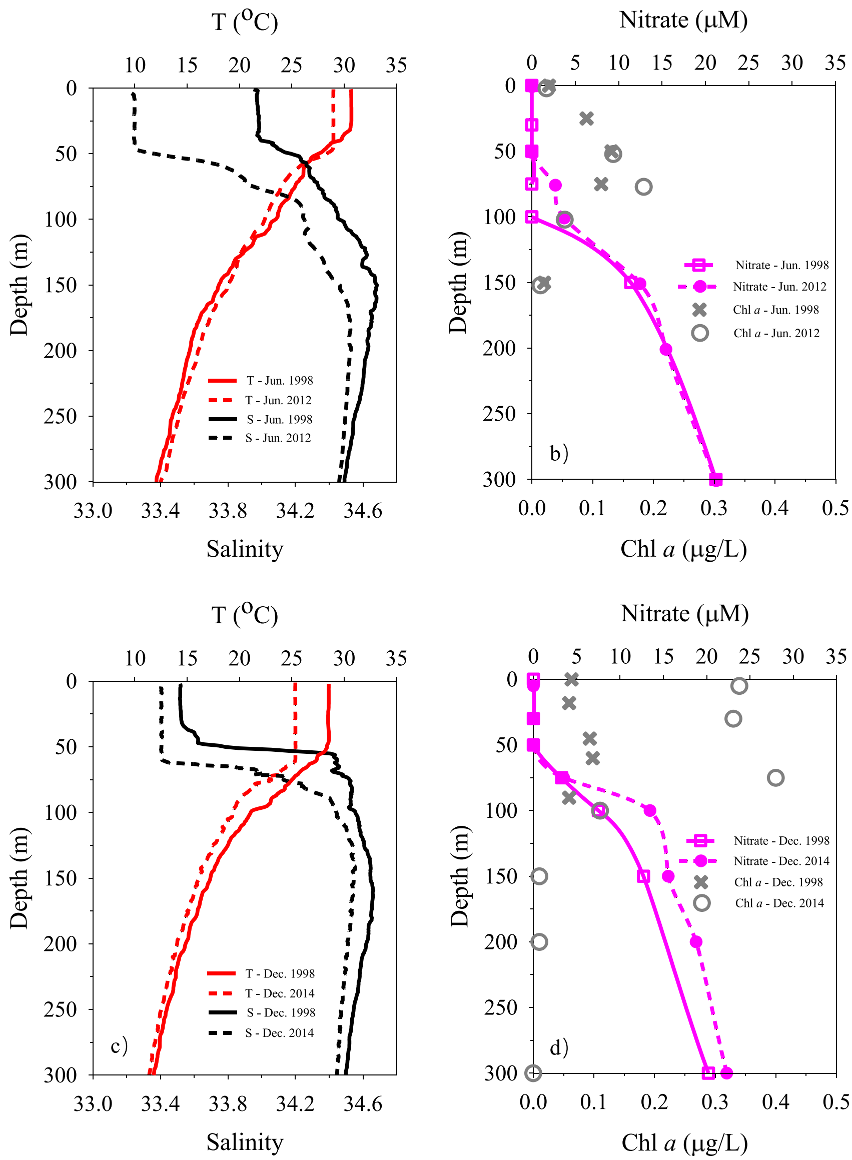

Figure 3. Vertical profiles of (a) salinity and temperature and (b) nitrate and chlorophyll-*a* concentrations of the upper 300 m water column during the 1997/1998 El Niño phase (June 1998) and normal conditions (June 2012) at the mooring station (14.5°N, 115°E). Same for c and d, but in the 1998/2000 La Niña phase (December 1998) and normal conditions (December 2014). Normal conditions ($-0.5 < \text{MEI} < 0.5$) were defined as the absence of El Niño and La Niña events.

rebound, as occurred in the eastern Equatorial Pacific Ocean (Chavez et al., 1999; Kawahata & Gupta, 2004; Turk et al., 2011; X. Wang et al., 2005) and the California Current System (Marinovic et al., 2002; Shipe et al., 2002). According to Xiao et al. (2017), the upper 300 m of the LST was approximately 0.48 Sv weaker during the 1998–1999 La Niña event than under normal conditions, which was associated with 1.2 Sv stronger Kuroshio transport and a southward NECBL. These results excluded the negative potential impacts of excess oligotrophic Kuroshio intrusion into the SCS on nutrient inventory, primary production and the sinking particle flux.

In contrast, the correlation analysis between the SSTA and WSA data revealed that SST quickly increased during the 1997/1998 El Niño event but did not decrease along with the strengthened WS and weakened HF during the 1998/1999 La Niña event (Figure S2 in the Supporting Information S1). This phenomenon means that other physical processes may adjust the hydrographic structure of the water column and thus prevent nutrient replenishment from the subsurface. According to the monthly sea surface height anomaly (SSHA) for the meridional section of 115°E, the significant positive SSHA indicated the occurrence of basin-scale downwelling induced by

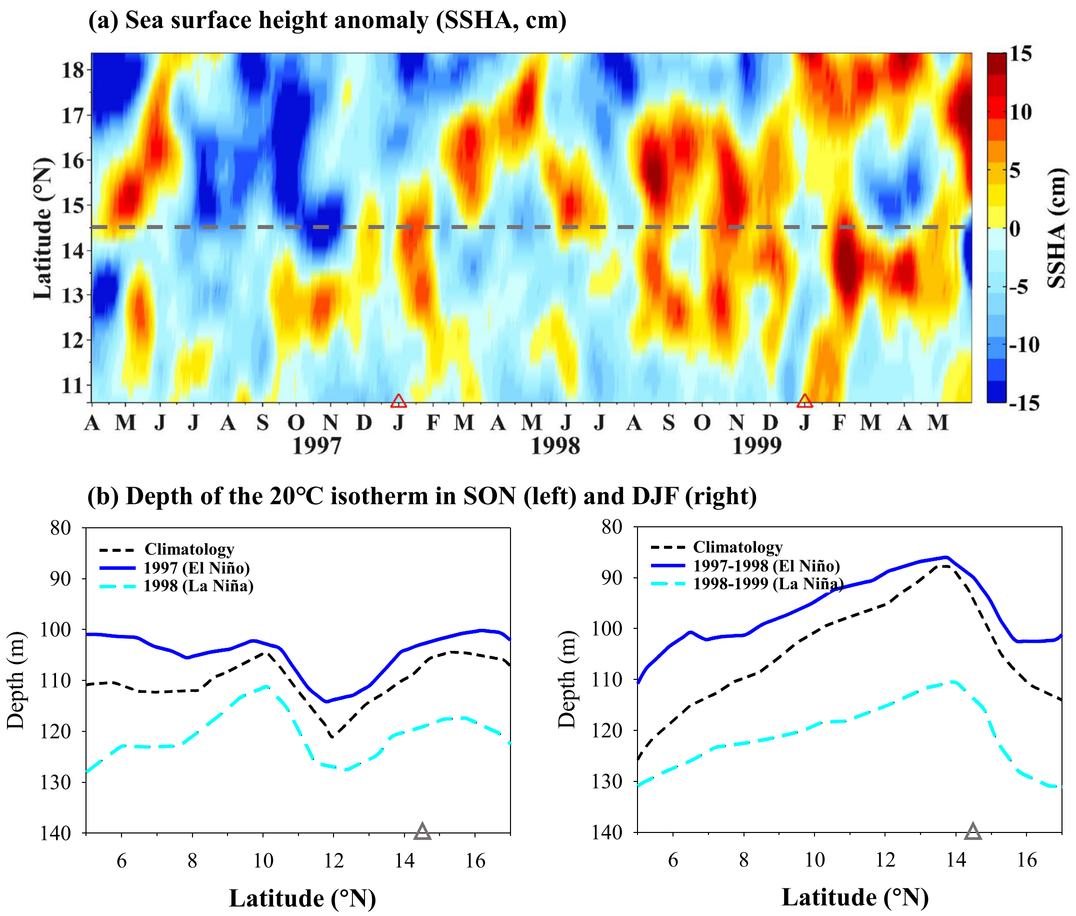

Figure 4. (a) Time-latitude variation in the daily sea surface height anomaly (SSHA) at the meridional section of 115°E in the SCS basin. To highlight interannual variability, the climatological sea level anomaly has been removed. The gray dashed line represents the mooring station. The red triangles on the *x* axis represent the beginning of the year. (b) Comparison of the seasonal mean depth of the 20°C isotherm (representing thermocline depth) in autumn (September-November, SON) and winter (December-February, DJF) under the 1997/1998 El Niño phase (blue line), 1998/1999 La Niña phase (cyan long dashed line), and climatological level (black short dashed line) at the meridional section of 115°E in the SCS basin. The gray triangles on the *x* axis represent the mooring station.

anticyclonic anomalous circulation during the 1998/1999 La Niña event (Figure 4a). More detailed examination reveals that the occasionally passing anticyclonic eddies may have impacted the moored sediment trap station from January 1999 to April 1999 (Figure S3 in the Supporting Information S1). Due to the convergence effect, the accumulation of seawater must drive a deepened thermocline in the SCS basin (D. Wang et al., 2002). Based on XBT data of the upper ocean (0–400 m), the depth of the thermocline (denoted by the isotherm of 20°C) deepened continuously from September 1998 to February 1999 (Figure 4b). Compared with the climatological value, the thermocline was approximately 20–25 m deeper at the trap station area in the 1998/1999 winter. Moreover, due to the reduction in SCS throughflow, heat loss also decreased in the SCS during the La Niña period (Xiao et al., 2017), resulting in a deepened and stronger thermocline than that in a normal year. Field observations of discrete subsurface water samples showed lower nitrate and Chl concentrations in December 1998 than those in December 2014 at the trap station (Figure 3d). On the other hand, based on a 1-D model coupled with a simple nutrient-phytoplankton-zooplankton-detritus biogeochemical scheme developed for the SCS, deepening of the thermocline by 25 m would have caused a drop in Chl of 23% (Liu et al., 2013). Combined with the sinking biogenic fluxes and their ratios, it is evident that the deepened thermocline had a strong negative effect on primary production and siliceous phytoplankton, leading to an inefficient BCP in the central SCS during the 1998/1999 La Niña period.

4. Conclusions

Our study first investigates how climate transitions affect the BCP in the largest marginal sea in the tropical and subtropical Pacific Ocean. The results showed that the BCP was weakened under strong stratification and oligotrophic conditions during the 1997/1998 El Niño event but did not recover when the climate shifted to the 1998/1999 La Niña event in the SCS. The abnormal changes in atmospheric forcings (WS and HF) and basin-scale circulations (Kuroshio and SCS throughflow) deepened the thermocline/nutricline, driving reduced nutrient supply to the euphotic zone, as well as subsequent asymmetric responses of primary production and sinking biogenic particle flux to super ENSO events in the central SCS. As super ENSO events are predicted to occur more often, a weakened BCP in the SCS may be more common. Knowledge of the negative impact of the ENSO on the BCP is a step forward in documenting such a response, but more systematic studies are needed to evaluate the alteration of marine ecosystems and carbon cycles in response to frequent multi-scale physical forcings in the SCS during the era of anthropogenically forced global change.

Data Availability Statement

Data sets for this research are available at this site (https://doi.org/10.5281/zenodo.5144469).

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