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Anomalous biogeochemical conditions in the northern South China Sea during the El-Niño events between 1997 and 2003

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[1] Anomalous biogeochemical conditions were observed at the SouthEast Asian Time-series Study (SEATS) station in the northern South China Sea (SCS) during the 1997–98 and 2002–03 El Niño events. The time-series records showed decreases of monthly mean sea surface chlorophyll-a (S-chl) (and integrated primary production, IPP) by 42% (and 42%) and 13% (and 10%), respectively, below the climatological mean in the winter months (DJF) of the two events. The negative anomalies in S-chl and IPP corresponded to elevated sea surface temperature by 1.2°C and 0.4°C, respectively, above the climatological mean, while the mean wind speed was reduced by about 20% and 11%, respectively. Statistical analysis demonstrated the reduction in S-chl and IPP during El Niño events was caused by the diminished vertical mixing and strengthened stratification. Regional anomalies in hydrographic and biological conditions in the northern SCS (15–21°N and 112–119°E) were consistent with those found at the SEATS site. **Citation:** Tseng, C.-M., G.-C. Gong, L.-W. Wang, K.-K. Liu, and Y. Yang (2009), Anomalous biogeochemical conditions in the northern South China Sea during the El-Niño events between 1997 and 2003, *Geophys. Res. Lett.*, *36*, L14611, doi:10.1029/2009GL038252.

1. Introduction

[2] It has been shown in recent years that the oceanic and geologic conditions of the South China Sea (SCS) were sensitive to climate changes in the geological past, and, consequently, it has become an important site for paleo-oceanographic and –climatic studies [e.g., *Wang et al.*, 2005]. In addition, considerable attention has been given to the dynamics of contemporary carbon and nutrient cycling associated with biological response to atmospheric forcing (e.g., monsoons) in the upper layer of the SCS [*Liu et al.*, 2002; *Tseng et al.*, 2005, 2007]. Better understanding of the biogeochemical responses of the SCS to physical forcing will undoubtedly contribute to more precise reconstruction of paleoconditions.

[3] Previously it was reported that, during the 1997–98 El Niño, the Taiwan Strait, which is connected to the SCS, received decreased nutrient supply and, hence, sustained diminished biological activities [*Shang et al.*, 2005]. This was attributed to reduction of nutrient-rich water from the north under a weaker northeast monsoon in winter. Here we report decreases in sea surface chlorophyll-a (S-chl) in the northern SCS during the same El Niño event and also the 2002–03 one, but the phenomenon was caused by entirely different mechanisms. Our study was based on shipboard observations at the SouthEast Asian Time-series Study (SEATS) station (Figure 1), remotely sensed data, and numerical experiments. Additionally, the time-series anomaly in hydrographic and biological conditions in the Box S region of northern SCS (15–21°N and 112–119°E, water depth above 100m) (Figure 1) was further examined. Therefore, we provide observational evidence not only at the single site of the SEATS but also in the northern SCS region and further examine the physical processes that result in the biogeochemical manifestation. Among the two El Niño events examined here, the former was one of the strongest on record [*Chavez et al.*, 2002].

[4] The North Pacific Intermediate and Deep Waters enter the SCS from the West Philippine Sea through the Luzon Strait [*You et al.*, 2005, Figure 1]. The Kuroshio intrusion may occur in winter, bringing nutrient poor water to the upper water column of the SCS from the WPS [*Gong et al.*, 1992]. The upwelling of the sub-surface water is a major source of nutrients for supporting primary production in the SCS [*Liu et al.*, 2002]. *Chao et al.* [1996] suggest that, during an El Niño event, the surface wind speed (WS) and the vertical advective velocity in the SCS are reduced. If these were to occur, vertical mixing would have been weakened and stratification strengthened. Consequently, the surface water may become warmer, the supply of nutrients to and thus the phytoplankton biomass in the euphotic zone may be reduced. Here, we test these hypotheses of the effect of El Niño events on the biogeochemical conditions in the northern SCS.

2. Methods

[5] The SEATS station (18°N and 116°E) was occupied 19 times in approximately seasonal intervals between Sept. 1999 and Oct. 2003. The records were extended to the period from Jan. 1997 to Dec. 2003 by including remotely sensed data. In addition, archived hydrographic SST data from 18–19°N and 115–116°E were provided by the Ocean Data Bank of the National Center for Ocean Research of Taiwan (NCOR-ODB). On the SEATS cruises, the distributions of salinity, temperature and photosynthetically available radiation (PAR) were recorded with a SeaBird conductivity-temperature-depth (CTD) and a Biospherical quantum scalar irradiance sensor. The mixed layer depth (MLD, σ_θ gradient $\leq 0.1\ m^{-1}$) and the euphotic zone depth

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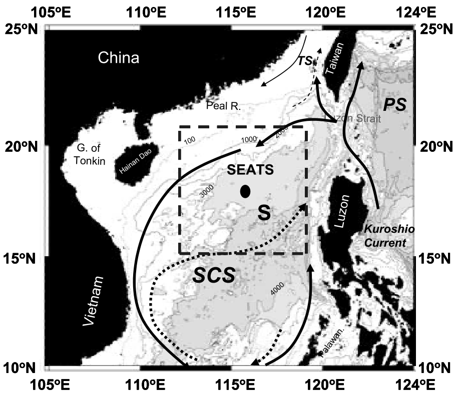

Figure 1. The location of the South–East Asian Time-series Study (SEATS) station with a study region (Box S, 15–21°N and 112–119°E, water depth above 100 m) in the northern South China Sea. Solid line, cyclonic gyre in the winter; dashed line, anti-cyclonic gyre. The flow path of the Kuroshio and its intrusion into the South China Sea are also shown. TS, Taiwan Strait; PS, Philippine Sea; SCS, South China Sea.

(EZD, PAR > 1% of the surface value) during each cruise were estimated.

[6] Seawater samples were collected with GO-FLO bottles mounted on a Rosette sampling assembly (General Oceanic). Sub-samples were quick-frozen with liquid nitrogen and returned to a shore-based laboratory for chemical analyses [*Strickland and Parsons*, 1984; *Pai et al.*, 1990]. The precision and detection limit for determinations of (nitrate + nitrite), (N+N) and soluble reactive phosphate (SRP) by using a 10-cm flowing cell were both similarly ±1% and 0.01 μM, respectively. The depth at the top of the nutricline (TND) was defined as the x-intercept of a plot of (N+N) in the nutricline against depth [*Tseng et al.*, 2005].

[7] Separate sub-samples were filtered onboard ship. The filters were stored at −20°C and then returned to the shore-based laboratory for the fluorometric determination of chlorophyll-*a* (Chl-a) [*Strickland and Parsons*, 1984]. Primary production was determined by measuring the uptake of added $^{14}HCO_3^{-1}$ during the incubation of discrete water samples at six depths within the top 100 m of the water column under trace-metal clean condition. The euphotic zone depth-integrated inventories of Chl-a (I-chl) and -integrated primary production (IPP) were estimated by the trapezoidal method.

[8] The sea surface temperature (SST) data were derived from the Advanced Very-High Resolution Radiometer (AVHRR) images. S-chl values were derived from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data obtained between Sept. 1997 and Dec. 2003 (http://oceancolor.gsfc.nasa.gov/ftp.html) by calibrating against the field observed data [*Tseng et al.*, 2005]. The SeaWiFS-derived S-chl and PAR data were also used to estimate IPP with the empirically vertical production model developed for the East Asia marginal seas [*Gong et al.*, 2003]. The daily WS data were estimated from the daily averaged data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). The ECMWF-WS and AVHRR-SST all agreed well with ship-board observations (Figures 2a and 2b).

[9] The monthly average SST anomaly in the Niño 3.4 region (5°S–5°N and 120–170°W) during the study period, provided by the Climate Prediction Centre (CPC), National Oceanic and Atmospheric Administration (NOAA) at the web-site http://www.cpc.ncep.noaa.gov/data/indices/sstoi.indices was used an index for identifying the occurrence of El Niño events. An El Niño event occurred when 3-month running mean of SST anomalies exceeded +0.5°C in the Niño 3.4 region, based on the 1971–2000 base period, in accordance with the CPC definition of El Niño.

[10] The inter-annual variability in environmental variables at the SEATS station and in northern SCS region (Box S, 15–21°N and 112–119°E) was depicted by anomalies. In order to accentuate the longer term seasonal and inter-annual variations, the monthly average anomalies were presented. Firstly, the climatological monthly mean SST, WS, S-chl and IPP were calculated for each month of the year. Then, the anomalies in SST (SSTA), WS (WSA), S-chl (S-chlA) and IPP (IPPA) were computed as the difference between the observed and climatological means for the particular month in the year.

[11] The effect of physical forcing on the MLD and biogeochemical response was estimated by using a one-dimensional coupled physical-biogeochemical model (1-D model) [*Wang*, 2007]. *Mellor and Yamada*'s [1982] level-2.5 turbulent closure scheme was adopted for the model, which was driven by the heat flux and wind stress from the National Center for Environmental Prediction (NCEP) re-analysis data. The nitrogen-based biogeochemical module includes four compartments: (N+N), PP, zooplankton, and detritus with a variable Chl/PP ratio according to a photo-acclimation scheme. The model has been validated with observed SST and corroborated with observed S-chl in the SCS [*Liu et al.*, 2002; *Wang*, 2007].

3. Seasonal Patterns

[12] The records of various parameters during the study period are shown in Figure 2. Aside from EZD and TND, all of remaining parameters follow distinctive seasonal patterns as observed previously in shorter records [*Tseng et al.*, 2005]. The wind pattern was governed by the monsoons. The northeast monsoon (mean WS = 9.1 m/s) was stronger than the southwest monsoon (mean WS = 5.7 m/s) with the lowest WS in the inter-monsoonal periods. The SST oscillated between the low in the winter at 23 to 25°C and the high in the summer at 29 to 31°C, while the AT (not shown) showed a similar trend. There were winter maxima of the mixed-layer N+N (0.1∼0.4 μM) and SRP (0.02∼0.04 μM) and summer minima around their respective detection limits. Concomitantly, S-chl (>0.2 mg/m^3), I-chl (>25 mg/m^2) and IPP (>250 mg-C/m^2/d) reached maxima in winter and minima in summer (S-chl < 0.1 mg/m^3, I-chl < 15 mg/m^2, IPP < 150 mg-C/m^2/d). While both TND and EZD stayed within narrow ranges of 42 to 70 m (average = 55 ± 8 m) and 75 to 95 m (85 ± 6 m) respectively, MLD fluctuated between a low of 15 to 40 m (25 ± 9) in summer and a high of ∼95 m (71 ± 17) in the winter. The EZD was always deep enough so that the availability of light was unlikely to be the limiting factor of photosynthetic activities in the mixed layer. On the other hand, the seasonal fluctuations in MLD

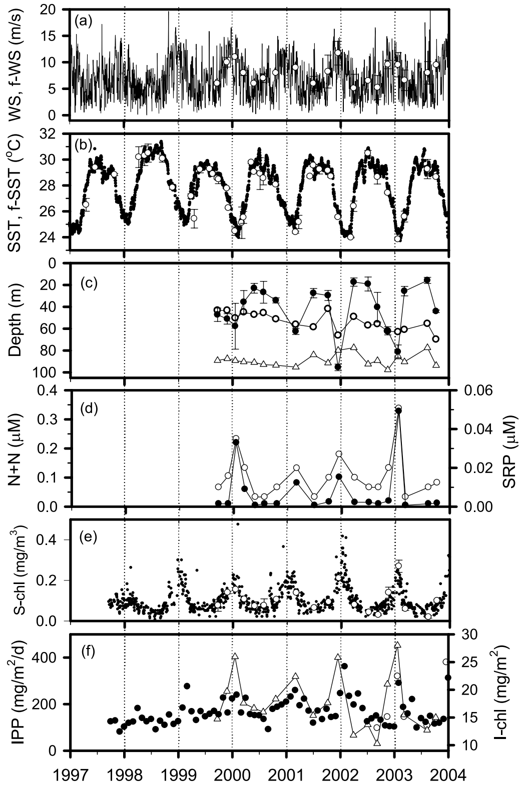

Figure 2. Time-series of records obtained for the SEATS station in northern South China Sea during the study period from Jan. 1997 to Dec. 2003. (a) Wind speed (WS) and field observed WS (○); (b) Remotely sensed sea surface temperature (SST, ●) and field observed sea surface temperature (f-SST, ○); (c) mixed layer depth (MLD, ●), top of nutricline depth (TND, ○) and euphotic zone depth (EZD, △); (d) averaged mixed-layer (N+N) (●) and SRP (○) concentrations; (e) SeaWiFs-derived (●), field observed S-chl (○); (f) I-chl (△) and SeaWiFs-derived (●), field observed (○) IPP. Please note the remotely sensed surface air temperature are not shown, because they are very close to the SST.

relative to the approximately constant TND were large enough so as to cause nutrient-availability to become the limiting factor of photosynthetic activities in summer. In winter, MLD became similar to or even deeper than TND. The effect of enhanced vertical mixing thus brought the nutrients in the upper nutricline up to the surface availably for photosynthesis activities and led to the higher S-chl, I-chl and IPP [*Tseng et al.*, 2005].

4. Inter-annual Variability and Anomalies

[13] It is apparent that both the observed peaks of S-chl and IPP were exceptionally low in the winter of 1997–98 and moderately low in the winter of 2002–03 (Figures 2e and 2f). The records of the monthly SST anomaly in the Niño 3.4 region ($SSTA_{N3.4}$), SSTA, WSA, S-chlA and IPPA during the study period at the SEATS station and in the Box S of the northern SCS are respectively shown in Figure 3. The El Niño events in 1997–98 (occurred from May 1997 to April 1998) and 2002–03 (May 2002 to March 2003) were clearly indicated as periods of positive $SSTA_{N3.4}$, which reached maxima of almost +3 and +2°C. Correspondingly, at the vicinity of the SEATS station and in the northern SCS, periods of negative WSA and positive SSTA were recorded in 1997–98 and 2002–03. During the 1997–98 event, the negative peaks of the WSA matches that of the $SSTA_{N3.4}$ closely, but the SSTA peak lagged behind by about 4 months and prolonged for a longer period of time about 11 months after $SSTA_{N3.4}$ had returned to zero. SSTA was slightly out of phase with $SSTA_{N3.4}$.

[14] The most striking feature in the SeaWiFS S-chl records observed at the SEATS and in the northern SCS region was the large and sharp spike of negative S-chlA during the 1997–98 winter with a maximum drop of ~50% relative to climatology in January (Figure 3c). S-chlA was more modest during the summer with a reduction of ~30% from the climatological mean. The negative S-chlA for the 2002–2003 event was less pronounced but still significant, −40% on average in Dec. 2002. Both the SeaWiFS-derived IPP at the SEATS station and in the Box S in the northern SCS had also similar patterns and showed significant negative anomalies (Figure 3d), corresponding to about −42% and −10%, relative to the climatology, during the winter of the 1997–98 and 2002–03 events. Anomalies in hydrographic and biological response to the El Niño effect at the SEATS station were closely in phase with those in the Box S of northern SCS (Figure 3). It indicated the El Niño

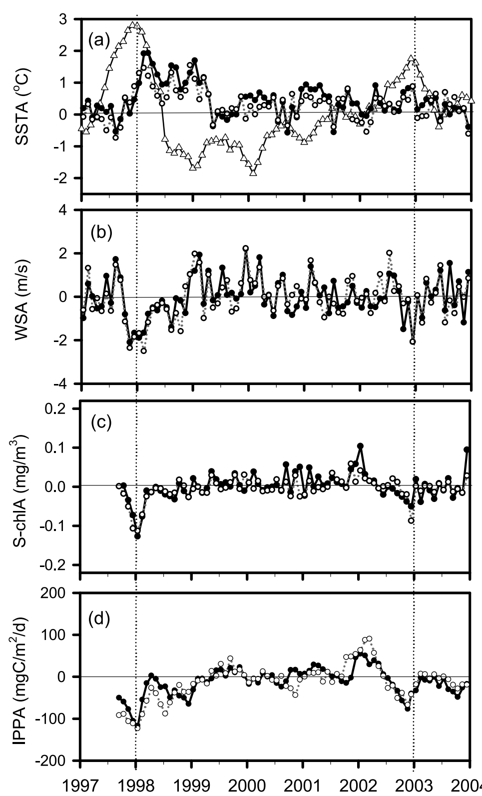

Figure 3. Monthly anomalies in (a) SST (SSTA), and Niño 3.4 ($SSTA_{ñ3.4}$, △), (b) WS (WSA), (c) S-chl (S-chlA), and (d) IPP (IPPA) at the SEATS station (●: SEATS) and in the Box S region of northern SCS (○: NSCS). The vertical dashed lines through Figures 3a–3d indicate the times in the mature phase of the El-Niño.

Table 1. Comparison of Environmental Variables in the Winter (DJF) of El Niño Year With Climatological Winter

Variables		El Niño Winter 1997–98	El Niño Winter 2002–03	All Winters Climatology Mean
WS (m/sec)	O_R[a]	7.3 ± 1.4 (80%)[b]	8.1 ± 1.2 (89%)	9.1 ± 1.4
AT (°C)	O_R	25.2 ± 1.1 (107%)	24.5 ± 1.3 (104%)	23.6 ± 0.5
SST (°C)	O_R	25.9 ± 0.5 (105%)	25.2 ± 1.0 (102%)	24.8 ± 0.7
MLD (m)	O_C	39 ± 15[c]	68 ± 13 (n = 2)	71 ± 17 (n = 4)
	E	44 ± 7 (78%)	50 ± 6 (88%)	57 ± 5
	M	53 ± 6 (78%)	56 ± 12 (83%)	67 ± 3
N+N (μM)	O_C	-[d]	0.17 ± 0.22 (n = 2)	0.18 ± 0.11 (n = 4)
	E	0.11 ± 0.05 (50%)	0.18 ± 0.11 (85%)	0.21 ± 0.07
	M	0.11 ± 0.04 (49%)	0.19 ± 0.12 (84%)	0.23 ± 0.04
S-Chl (mg/m^3)	O_R	0.10 ± 0.01 (58%)	0.15 ± 0.05 (87%)	0.17 ± 0.01
	M	0.12 ± 0.04 (50%)	0.19 ± 0.09 (79%)	0.24 ± 0.02

[a]O_R, Remotely sensed observation; O_C, Cruise observation; E, Empirical output; M, Model output.
[b](%) denotes the percent of the climatology mean.
[c]Estimated from mooring data [*Shiah et al.*, 1999].
[d]Not available.

effect significantly caused the changes in basin-wide biogeochemical conditions.

5. Physical Mechanisms Controlling Anomaly in S-chl due to the El Niño Effect

[15] We further examined the anomaly relationship of S-chlA with WSA and SSTA together during the El Niño periods from Sept. to March in 1997–98 and 2002–03, corresponding to the sharp spike of negative S-chlA. The relationship that the S-chlA correlated positively with WSA and negatively with SSTA was obtained in the following:

$$\mathrm{ChlA} = 0.004(\pm 0.013) + 0.024(\pm 0.009) \times \mathrm{WSA} - 0.029(\pm 0.017) \times \mathrm{SSTA}$$
$$r^2 = 0.60,\ N = 14, p < 0.01. \quad (1)$$

[16] It demonstrated that the decreasing S-chl during the El-Nino event was significantly associated with the reduced surface WS and enhanced SST together (Figures 2 and 3).

[17] *Tseng et al.* [2005] suggested that the thickening of the MLD in the winter could be explained by the enhancement of vertical mixing by surface cooling and the higher wind speed in the northern SCS. Therefore, the MLD should increase with decreasing SST and increasing WS, while the concentrations of the nutrients should decrease with increasing temperature in the surface layer due to stronger stratification until it reaches undetectable levels above a certain temperature [*Tseng et al.*, 2005]. These statements are empirically validated by the following relationships obtained on the SEATS cruises:

$$\mathrm{MLD\,(m)} = 89.3(\pm 65.4) + 5.2(\pm 1.8) \times \mathrm{WS} - 3.2(\pm 2.1) \times \mathrm{SST}$$
$$r^2 = 0.61,\ N = 19,\ p < 0.001 \quad (2)$$

The second is valid for SST below about 26°C:

$$[\mathrm{N+N}](\mu\mathrm{M}) = -0.11(\pm 0.03) \times \mathrm{SST} + 2.95(\pm 0.64)$$
$$r^2 = 0.80,\ N = 7, p < 0.001 \quad (3)$$

That is, as SST increases and WS decreases during an El Niño event, MLD should decrease and the concentration of the nutrients should also decrease in the northern SCS. For instance, while these relationships were applied to the conditions during the 1997–98 and 2002–03 El Niño events, the MLD and (N+N) in the mixed layer were only 44 ± 7 m, 0.11 ± 0.05 μM, and 50 ± 6 m, 0.18 ± 0.11 μM during the winters of 1997–98 and 2002–03, respectively (Table 1). These shallow MLD relative to an approximately constant TND of 55 m and lower (N+N) concentrations would be consistent with the suppressed S-chl during the El Niño event.

[18] Furthermore, the 1-D coupled physical-biogeochemical model, driven by wind stress and heat flux, put the above hypotheses in action and successfully simulated the annual cycles of SST, (N+N) and S-chl with the predicted MLD in reasonable agreement with observations. Overall speaking, the modeled SST and S-chl correlated with the AVHRR and SeaWiFS data reasonably well with regression relationships as follows.

$$\mathrm{SST_{mod}} = 1.05(\pm 0.06)\mathrm{SST_{AVHRR}},$$
$$r^2 = 0.81, N = 84, p < 0.0001 \quad (4)$$

$$\mathrm{S-chl_{mod}} = 1.5(\pm 0.2)\mathrm{S-chl_{SWi}},$$
$$r^2 = 0.72,\ N = 76,\ p < 0.0001 \quad (5)$$

The modeled monthly MLD clearly showed that the maximum MLD occurred in the winter, whereas the minimum occurred in the inter-monsoon periods of minimum WS. The modeled MLD linearly corroborated with the results from the empirical equation (2) with regression relationship as below.

$$MLD_{mod} = 1.1(\pm 0.1)MLD_{empirical}, \quad r^2 = 0.85,\ N = 84,\ p < 0.0001 \qquad (6)$$

Based mainly on modeling results (Table 1), we found that these low values of biological variables were matched by relatively shallow winter MLDs, 45–55 m and 45–70 m, of the 1997–98 and 2002–03, respectively, as compared to 60–95 m in other years; the modeled average N+N concentrations in the mixed layer were also relatively low (<0.2 μM). Additionally, the model successfully predicted the negative S-chlA for the two El Niño events (Table 1). According to the model exercise, it demonstrated during the El Niño event, the reduced surface WS and enhanced SST resulted in the vertical mixing weakened and stratification strengthened in the SCS. As a result, the supply of nutrients to and thus the phytoplankton biomass in the euphotic zone was reduced.

[19] The hydrological and biological conditions obtained from observations and model output at the SEATS station during the winter months of the two El-Niño events are compared with the climatological mean values (Table 1). The strong dependency of the S-chl on wind speed (Figure S1 of the auxiliary material) suggests the importance of wind mixing in controlling the S-chl.[1] During the 97–98 event, one of the strongest on record, the S-chl was the lowest, lower than those during the 02–03 event. Although the average conditions of the three winter months during the 02–03 event were not much different form the climatological mean values, two out of its three winter months showed anomalously weak wind and low S-chl (Figure S1), which were very close to those observed during the 1997–98 event. Significant correlation of S-chl with WS and SST was obtained.

$$Chl = 0.84(\pm 0.28) + 0.021(\pm 0.005)WS - 0.034(\pm 0.012)SST \quad r^2 = 0.53,\ N = 18, p < 0.01 \qquad (7)$$

It demonstrated that the winter S-chl correlated positively with WS and negatively with SST. The exceptionally low Chl and productivity during the El Niño years in the SCS were most likely attributed to the low wind stress and high SST that restricted nutrient supply.

6. Conclusions

[20] Through time-series records, we had observed the occurrence of an El Niño in the winter of 1997–98 and 2002–03 significantly affect the hydrographic and biological conditions at the SEATS station. The significance of the SEATS station for better understanding of inter-annual variation in the biogeochemistry of the whole SCS was actually manifested. The effect of the El Niño occurred not only at the SEATS station but also in the whole northern SCS. Biological activities at the SEATS station in northern SCS decreased significantly during the 1997–1998 and 2002–2003 El Niño events. In the winter months (DJF) of the two events, on average, wind speed was lower by 20% and 11%, respectively, and the SST were 1.2 and 0.4°C above the climatological mean of 24.7°C. In response, the S-chl was reduced by 42% and 13% and IPP by 42% and 10%, respectively. The results through an 1-D coupled physical-biogeochemical model and empirical relationship both demonstrated the reduction in S-chl and nutrients during El Niño year was greatly caused by the diminished vertical mixing as a combined result of the warming of the mixed layer, weaker wind speed and reduction in basin-wide vertical advection.

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