

A unique seasonal pattern in phytoplankton biomass in low-latitude waters in the South China Sea

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[1] A distinctive seasonal pattern in phytoplankton biomass was observed at the South East Asian Time-series Study (SEATS) station (18°N, 116°E) in the northern South China Sea (SCS). Surface chlorophyll-*a*, depth-integrated chlorophyll-*a* and primary production were elevated to 0.3 mg/m³, ~35 mg/m² and 300 mg-C/m²/d, respectively, in the winter but stayed low, at ≤0.1 mg/m³, ~15 mg/m² and 110 mg-C/m²/d as commonly found in other low latitude waters, in the rest of the year. Concomitantly, soluble reactive phosphate and nitrate+nitrite in the mixed layer also became readily detectable in the winter. The elevation of phytoplankton biomass coincided approximately with the lowest sea surface temperature and the highest wind speed in the year. Only the combined effect of convective overturn by surface cooling and wind-induced mixing could have enhanced vertical mixing sufficiently to make the nutrients in the upper nutricline available for photosynthetic activities and accounted for the higher biomass in the winter.

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1. Introduction

[2] As a result of the different seasonality in the light-, temperature- and turbulent- regimes at the different latitudes, the seasonal patterns in phytoplankton biomass and primary production in the upper oceans also vary with latitude [Heinrich, 1962]. In low-latitude waters, the seasonal variations should be the least distinct. At these latitudes, because of the high insolation year round, the upper water is well stratified and winter convective overturn induced by seasonal surface cooling is minimal. As a result, outside of the upwelling zones, the upper water in the tropics and subtropics is permanently oligotrophic and phytoplankton biomass and primary production are low through out the year although local forcings may lead to minor variations at any time. The recent time-series study in the subtropical Pacific at the Hawaii Ocean Time-series (HOT) station indicates that this low-latitude pattern holds

at least as far north as 23°N where the station is located [Karl *et al.*, 1996]. The South East Asian Time-series Study (SEATS) station is located at 18°N in tropical waters in the northern South China Sea (SCS). Here, we report that while the SEATS station is located at a lower latitude than that of the HOT station, the seasonal pattern in phytoplankton biomass and primary production at the SEATS station is distinctly different from the general low-latitude pattern as a result of a unique combination of environmental conditions: a shallow nutricline, monsoon-enhanced wind-induced mixing and winter convective overturn by surface cooling. In addition, the confinement of the semi-enclosed basin that favors a basin-scale upwelling induced by monsoons [Chao *et al.*, 1996; Liu *et al.*, 2002] further distinguishes the SEATS station from those in the open ocean.

2. Methods

[3] The SEATS station, located at 18°N and 116°E (Figure 1), was occupied eleven times in approximately seasonal intervals between June, 2001 and December, 2003. The distributions of salinity, temperature and photosynthetically available radiation (PAR) were recorded during each occupation of the station with a SeaBird model SBE9/11 conductivity-temperature-depth (CTD) recorder and a Biospherical model QSR-240 4π quantum scalar irradiance sensor. The mixed layer depth (MLD) and the euphotic zone depth (EZD) during each cruise were estimated as the depth above which the density gradient was ≤0.1 σ_θ unit m⁻¹ and the depth at which the PAR had been reduced to 1% of the surface value, respectively.

[4] Discrete seawater samples were collected with GO-FLO bottles mounted onto a Rosette sampling assembly (General Oceanic). Sub-samples were analyzed for soluble reactive phosphate (SRP) and nitrate+nitrite (N + N) on-board ship. SRP was determined manually with the standard molybdenum blue method [Strickland and Parsons, 1984] with a precision of ±1% and a detection limit of 0.01 μM. (N+N) was measured with the standard pink azo dye method that has been adapted for use with a flow injection analyzer [Strickland and Parsons, 1984; Pai *et al.*, 1990]. The precision and detection limit in the determination of (N + N) were ±1% and 0.03 μM. 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. Separate sub-samples were filtered onboard ship. The filters were stored on dry ice and then returned to the shore-based laboratory for the fluorometric determination of chlorophyll-*a* [Strickland and Parsons, 1984]. Primary production was determined by measuring the uptake of added ¹⁴HCO₃⁻ during the incubation of discrete water samples at eight depths within the top 100 m of the water column under trace-metal clean

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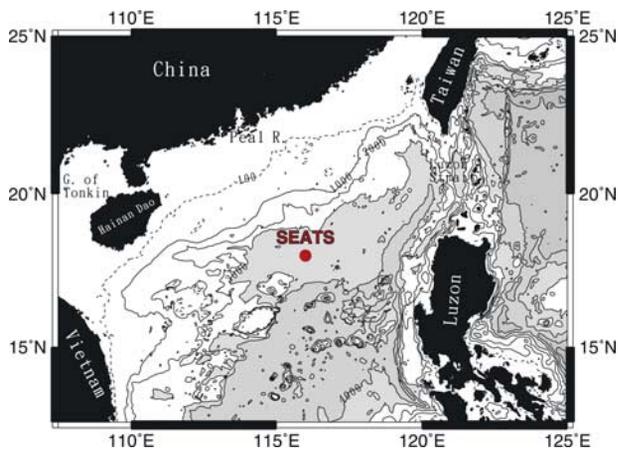


Figure 1. The location of the South East Asian Time-series Study (SEATS) station.

condition. The euphotic zone depth-integrated inventories of chlorophyll-*a* (I-chl) and primary production (IPP) were estimated by the trapezoidal method.

[5] The 5-day averaged sea surface temperature (SST) at the location of the SEATS station between June, 2001 and December, 2003 were derived from AVHRR (Advanced Very-High Resolution Radiometer) images. Six-hour averaged air temperature at 2 m above the sea surface was obtained from NCEP (National Center for Environmental Prediction). Surface chlorophyll-*a* concentrations (S-chl) were derived from SeaWiFS (Sea-viewing Wide Field-of-view Sensor) images. The daily averaged wind field data at a nearby location at 17.5°N and 115°E was obtained from the ECMWF (European Centre for Medium-Range Weather Forecasts). The SeaWiFS-derived S-chl were adjusted by using the relationship between the values observed, $(S\text{-chl})_{\text{ob}}$, in a small number of samples during the cruises and the SeaWiFS-derived, $(S\text{-chl})_{\text{SWi}}$, values such that: $S(\text{chl})_{\text{ob}} = 0.73 (S\text{-chl})_{\text{SWi}} - 0.02$ ($r^2 = 0.8$, $n = 10$). The NCEP air temperatures agreed well with ship-board observations (Figure 2b).

[6] The effect of wind-mixing on the MLD was estimated by using the East Asian Marginal Seas (EAMS) model [Wu and Hsin, 2005]. The EAMS model was a three dimensional hydrodynamic model based on the Princeton Ocean Model [Blumberg and Mellor, 1987]. Its domain covered 99 to 140°E and 0 to 42°N at a horizontal mesh size of $1/8^\circ$ in 26 vertical sigma levels. The model solves the three-dimensional primitive equations for momentum, salt and heat. The boundary conditions at the open boundaries were derived from a large-scale West Pacific Ocean model which is based on the Miami Isopycnic Coordinate Ocean Model (MICOM) [Liang, 2002]. The EAMS model has been validated with observed temperature and salinity data in the SCS and corroborated with observed velocity data from both bottom-mounted and shipboard Acoustic Doppler Current Profiler (ADCP) in the Taiwan Strait [Wu and Hsin, 2005].

3. Seasonal Patterns in Environmental Conditions

[7] Temporal variations in wind velocity, SST, air temperature, MLD, EZD and TND and the average concen-

trations of SRP and (N + N) in the surface mixed layer between June, 2001 and December, 2003 are shown in Figures 2a–2d. There was a distinct seasonal pattern in wind velocity, SST and air temperature. Wind speed was the highest during the northeast monsoon in the winter, reaching speeds of >12 m/s (Figure 2a). A less pronounced secondary maximum was found in the summer during the southwest monsoon. Wind speeds were the lowest (<4 m/s) during the inter-monsoon periods. The transition from the northeast to the southwest monsoon in the spring lasted for more than a month. The reverse transition in the fall was noticeably more abrupt (Figure 2a). SST varied between a maximum of $\sim 31^\circ\text{C}$ in the summer to a minimum of $\sim 23^\circ\text{C}$ in the winter. The variations in SST stayed closely in phase with those in air temperature although the amplitude was slightly reduced. Although the maximum wind speed and the minimum SST were both found in the winter, they were slightly offset from each other with the former occurring slightly ahead of the latter.

[8] The depressed SST and higher wind speed in the winter suggest that vertical mixing could be enhanced in that season by convective overturn. This convection was reinforced by wind-driven turbulence. The effects of these processes were reflected in the seasonal variations in the MLD and the concentrations of the nutrients. During most

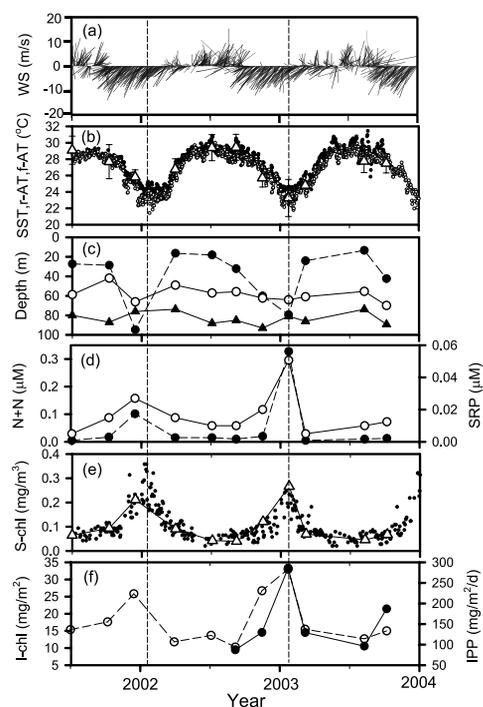


Figure 2. Variations in (a) wind speed (WS) and wind vector, (b) sea surface temperature (SST, ●), remotely sensed air temperature (r-AT, ○) and field observed temperature (f-AT, Δ), (c) mixed layer depth (MLD, ●), top of nutricline depth (TND, ○) and euphotic zone depth (EZD, ▲), (d) averaged mixed-layer (N+N) (●) and SRP (○) concentrations, (e) SeaWiFS-derived (●) and field observed S-chl (Δ), and (f) I-chl (○), and IPP (●) between June 2001 and Dec. 2004. The vertical dashed lines indicate the times of occurrence of maximum S-chl and I-chl in the winter of 2002 and 2003.

of the year, the MLD was shallow, being between 20 and 40 m. In the winter, the MLD reached 90 m. Summer MLD were comparable to those found in low latitude waters and much shallower than those found in temperate and polar waters [Bathen, 1972]. Concomitantly, there was a winter maximum in the average concentration of SRP and (N + N) in the mixed layer. Their concentrations hovered around their respective detection limits of 0.01 and 0.03 μM in the summer and reached readily detectable concentrations of 0.03 to 0.06 μM and 0.1 to 0.3 μM respectively in the winter. There was no evidence of a similar deepening of the MLD and an elevation of the concentrations of the nutrients during the southwest monsoon in the summer, indicating that vertical mixing by the weaker wind during the summer monsoon was insufficient to mix nutrients into the mixed layer.

[9] The EZD stayed within a narrow range of 75 to 90 m and did not exhibit any systematic seasonal pattern. EZD was deeper than MLD at all times except in winter, 2002. Even then, the difference in depth was small. Thus, as reported in other low latitude waters, the availability of light was not the primary control of photosynthetic activities at the SEATS station. On the other hand, whereas there was also no systematic seasonal pattern in TND as it stayed within a narrow range of 50 to 70 m throughout the year, it was comparable to the MLD in the winter and deeper than the MLD in the rest of the year. Thus while nutrients in the upper nutricline were largely unavailable for supporting photosynthetic activity during most of the year, they could become more readily available in the winter when vertical mixing was enhanced. The TND was shallower than the EZD throughout the year, indicating some nutrients were available near the bottom of the euphotic zone, where the light was much attenuated and the productivity was usually quite limited [Liu *et al.*, 2002]. In comparison to the TND at HOT (mean: 120 ± 20 m, range: 80~160 m) [Karl *et al.*, 2003], the TND at SEATS was shallow and less variable, probably as a result of the basin-scale upwelling mentioned previously [Chao *et al.*, 1996; Liu *et al.*, 2002].

4. Seasonal Patterns in Chlorophyll-a and Primary Production

[10] Temporal variations in S-chl, I-chl and IPP are shown in Figures 2e and 2f. A distinct winter maximum (S-chl >0.2 mg/m^3 , I-chl >25 mg/m^2 and IPP >250 $\text{mg-C}/\text{m}^2/\text{d}$) and a summer minimum (S-chl <0.1 mg/m^3 ; I-chl <15 mg/m^2 and IPP <150 $\text{mg-C}/\text{m}^2/\text{d}$) were found in all cases. In comparison, the concentrations of S-chl, I-chl and IPP ranged between 0.05 and 0.1 mg/m^3 , <15 and ~ 30 mg/m^2 , and, ~ 200 and ~ 900 $\text{mg-C}/\text{m}^2/\text{d}$ respectively at the HOT station and between 0.05 and 0.3 mg/m^3 , <15 and ~ 35 mg/m^2 , and, ~ 100 and ~ 1000 $\text{mg-C}/\text{m}^2/\text{d}$ at the BATS station [Karl *et al.*, 2003]. The minimum values in S-chl and I-chl were similar to those observed in oligotrophic waters in the middle of the oceanic gyres [Winn *et al.*, 1995; Leonard *et al.*, 2001]. The maximum values approached those found in waters in the temperate zone [Leonard *et al.*, 2001]. The concurrence of high S-chl, I-chl and IPP in the winter indicates that the elevated S-chl was the result of an increase in photosynthetic activities by an increase in phytoplankton biomass and the major

phytoplankton phyla found were diatoms and coccolithophores (Y.-L. Chen-Lee, private communication, 2004). Winn *et al.* [1995] had reported a similar seasonal trend in the concentration of S-chl at the HOT station. However, the elevated S-chl in the winter was not accompanied by a corresponding increase in primary production. The changes in S-chl were thus attributed to phytoplankton photoadaptation or the entrainment of chlorophyll from the subsurface chlorophyll maximum instead.

[11] The seasonal pattern in phytoplankton biomass at the SEATS station was unique among low-latitude waters. In the equatorial region in both the Atlantic and the Pacific, under the influence of equatorial upwelling, maximum S-chl was found during the boreal summer between August and October when upwelling was intensified. Away from the influence of equatorial upwelling in the Pacific Equatorial Divergence and the eastern Tropical Pacific, there was no conspicuous seasonal pattern in the concentration of S-chl (<0.4 mg/m^3) [Dandonneau *et al.*, 2004]. In the Indian Ocean, maximum S-chl was found everywhere in the summer and early fall in the Arabian Sea during the southwest monsoon and a late-winter bloom only in the north during northeast Monsoon [Banse and English, 2000].

5. The Relative Contributions of Monsoon-Enhanced Wind Forcing and Surface Cooling to Seasonal Changes in Photosynthetic Activity at the SEATS Site

[12] While the maximum S-chl occurred in the winter together with the higher wind speed and lower SST, the correspondence was not exact (Figures 2a, 2b, and 2e). In both the winter of 2002 and 2003, the maximum S-chl occurred after the maximum wind speed had been reached. On the other hand, it occurred ahead of the minimum SST in winter 2002 and approximately concurrently with the minimum SST in winter, 2003. These patterns of variability suggest that the changes in S-chl might not have been linked to the enhanced wind mixing or to convective overturn by surface cooling alone. If the seasonal variations in photosynthetic activities were controlled by the availability of nutrients as a result of the deepening of the MLD, the relative contributions of these two processes may be assessed by simulating their individual and combined influence on the depth of the MLD. Starting with the vertical distribution of temperature in the upper 150 m in the summer of 2002, when the MLD was ~ 20 m and the mixed layer temperature was $\sim 31^\circ\text{C}$ (Figure 3), if the mixed layer was cooled to the SST in the winter of 2003 at 24°C , the MLD was increased by ~ 45 m to ~ 65 m. When the effect of wind stress at the observed wind speed of ~ 10 m/s in the winter of 2003 was applied to the distribution of temperature in the summer of 2002 by using the EAMS model [Wu and Hsin, 2005], the MLD was deepened to 43 m. Thus, in neither case did the resulting MLD exceed the TND in the summer of 2002, which was located at ~ 65 m, to make the nutrient-rich water below the TND available for photosynthetic activities in the mixed layer. These MLD were also shallower than the observed MLD of 80 m in the winter of 2003. On the other hand, when the effect of wind forcing was superimposed on that of winter convective overturn, the MLD was deepened to 90 m. This MLD was deeper than

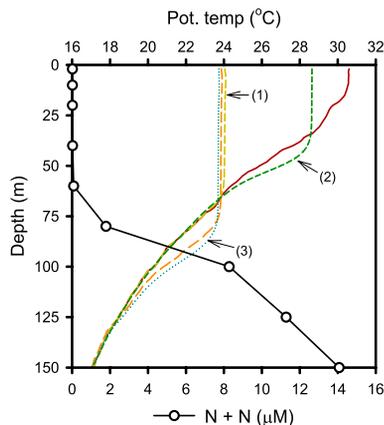


Figure 3. The observed distributions of temperature (solid line) and (N + N) (○) in summer, 2002 and temperature (dashed line) in winter, 2003 and the simulated distributions of temperature in winter, 2003 as a result of surface cooling convective overturn alone (1), wind mixing alone (2) and surface cooling enhanced by wind mixing (3).

the TND in the summer of 2002 and, the concentrations of (N+N) and SRP at the depth were ~ 5 and $\sim 0.5 \mu\text{M}$ respectively. Thus, only when wind-reinforcement was allowed to be superimposed on winter convective overturn on the relatively shallow nutricline would the resulting MLD be deep enough so that the nutrients in the upper nutricline might be made available readily for primary production and the observed seasonal pattern in phytoplankton biomass and primary production might be accounted for.

6. Conclusion

[13] In contrast to most low latitude waters, where both phytoplankton biomass and primary production are low and without distinct seasonal patterns, a distinct seasonal pattern with a winter maximum was observed at the SEATS station. This was the result of a unique combination of environmental conditions whereby enhanced vertical mixing over a shallow nutricline by winter convective overturn was reinforced by wind-induced mixing. Individually, neither convective overturn nor wind forcing was sufficient for accounting for the observed seasonal patterns. However, the deepening of the MLD resulted from the combined effect of these two processes was sufficient for making the nutrients in the upper nutricline available for fueling the elevated phytoplankton growth in the winter.

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