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Long term changes in the ecosystem in the northern South China Sea during 1976–2004

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Abstract

Physical and chemical oceanographic data were obtained by seasonal monitoring along Transect N in the northern South China Sea (nSCS) during 1976–2004. Fluctuations of DIN (dissolved inorganic nitrogen), seawater temperature (SST and T_{av} – average temperature of the water column), N:P ratio and salinity (S_{av} and S_{200} – salinity at the 200 m layer) exhibited an increasing trend, while those of T_{200}, DO, P, Si, Si:N and SSS exhibited a decreasing trend. The annual rates of change in DIN, DO, T and S revealed pronounced changes, and the climate trend coefficients R_{xt}, which was defined as the correlation coefficient between the time series of an environmental parameter and the nature number, were 0.38 to 0.89 and significant ($p \leq 0.01$ to 0.05). Our results also showed that the ecosystem has obviously been influenced by the positive trends of both SST and DIN, and negative trends of both DO and P, e.g. before 1997, DIN concentrations in the upper layer were very low and N:P ratios were less than half of the Redfield ratio of 16, indicating potential N limitation. However, after 1997, all Si:P ratios were >22 and the N_{av}:P_{av} was close to the Redfield ratio, indicating potential P limitation, and therefore N limitation has been reduced after 1997.

Ecological investigation shows that there have been some improved responses of the ecosystems to the long-term environmental changes in the nSCS, and chlorophyll-*a* concentration, primary production, phytoplankton abundance, benthic biomass, cephalopod catch and demersal trawl catch have increased. But phosphorus depletion in upper layer may be related to the shift in the dominant species from diatoms to dinoflagellates and cyanophytes. The ecosystem response was induced by not only anthropogenic activities, but also global climate change, e.g. pronounced responses to ENSO. The effects of climate change on the nSCS were mainly through changes in the monsoon winds, and physical-biological oceanography coupling processes.

1 Introduction

The South China Sea (SCS) is the largest semi-enclosed marginal sea in Southeast Asia with an area of about 3.5×10^6 km^2, constituting one of the world's 50 Large Marine Ecosystems (Sherman, 2001). Our study area is the northern SCS (nSCS), bounded by the mainland of China on the north and northwest sides, Taiwan Strait on the northeast, Taiwan Island of China and Bashi Strait on the east side, and the Hainan Island on the west side. The nSCS is connected to the East China Sea through Taiwan Strait, and it is connected to the open ocean through Luzon Strait, where a deep sill (>2000 m) allows effective water exchange with the western Pacific. The topography of the area is characteristic of the incline from the coast of mainland China towards the southeast, with a gradient from the coastal zone (<50 m), continental shelf (<200 m), the slope and open sea (>200 m), to the deep sea (>3000 m) (Fig. 1).

The runoff from 29 rivers, with different sized input into the nSCS with total drainage area of 5.5×10^5 km^2, and an annual fresh water discharge of 3.8×10^{11} m^3 (Han et al., 1998). Among them, the Pearl River is the largest with a drainage area of 4.3×10^5 km^2 and a discharge of 3.3×10^{11} m^3 a^{-1} (Han et al., 1998). It carries a large quantity of suspended solids (8.3×10^7 t a^{-1}, Han et al., 1998) and dissolved nutrients (N=8.6×10^4 t a^{-1}; P=1.2×10^4 t a^{-1}; Si=184.3×10^4 t a^{-1}, Wang and Peng, 1996) into the nSCS. The Pearl River plume extends offshore to cover a large area of the nSCS (Yin et al., 2001). During the dry season in winter, the river plumes extend westward along the coast of Guangdong, due to the strong northeast monsoon; during the flood season in summer, the river plume extends well into the nSCS, and its southeastward and southward tongue can reach up to 17°00′ N, 112° E, about 550 km away from the river mouth (Cai et al., 2007; Xue et al., 2001a, b).

The meteorological forcing over the nSCS is dominated by the East Asian Monsoon (Sadler et al., 1985). The upper ocean circulation follows closely the alternating monsoons (Wyrtki, 1961). During winter northeast monsoon, along the northern boundary, the warm and saline Kuroshio Current water with oligotrophic properties intrudes

through Luzon Strait and flows westward along the continental margin of China to become the deep-water mass of the nSCS (Nitani, 1972; Shaw, 1991). The coastal water of the East China Sea flows southwestward through Taiwan Strait into the nSCS (Fang et al., 1998; Xue et al., 2004). On the contrary, during the summer southwest monsoon, the Guangdong Coastal Current flows eastward along the southern coast of mainland China, which eventually flows into the East China Sea through Taiwan Strait. The southwesterly winds also induce Ekman transport toward offshore and coastal upwelling. The deep water upwells and mixes with the upper water to form the SCS intermediate water, which flows out of the nSCS into the northwestern Pacific Ocean through Luzon Strait (Gong et al., 1992).

In the nSCS, the thermocline occurs all the year round, and the interannual change in its strength is pronounced (Yuan and Deng, 1997a, b; Shi et al., 2001). Previous studies focused on variations in seawater temperature and salinity distributions (Yang and Liu, 1998; Yuan and Deng, 1998), dissolved oxygen distribution (Lin and Han, 1998), pollution status along the coast of the nSCS (Li et al., 1998) and the health status and quality of the fisheries environment in the nSCS (Jia et al., 2005). Furthermore, it has been found that due to the combined effects of monsoons, topography, shape of the coastal line and the inertial effects, the mesoscale eddies (i.e. the cyclonic cold eddies and anti-cyclonic warm pools) are formed in the SCS (Zeng et al., 1989; Xu et al., 2001; Li et al., 2003; Chen et al., 2005). Recent studies revealed that the effects of coupling between physical – chemical – biological oceanographic processes on phytoplankton biomass and production are important for understanding the influence on the long-term environmental changes and the ecosystem dynamics of the SCS (Liu et al., 2002, 2007; Ning et al., 2004).

However, the long term changes in environmental conditions and the responses of the ecosystem in this region have not been well documented yet. The objective of this study was to analyze the 29 y term series of multidisciplinary observational data obtained during 1976–2004, aimed at understanding how the environment has changed and how the ecosystem and biological resources have responded to the environmental

changes in the nSCS.

2 Data and methods

In this study, data were obtained from winter and summer monitoring along transect N (Fig. 1, an observation transect, including six stations, crossing the nSCS, from the northwestern to southeastern), and maintained by the survey team of the State Oceanic Administration (SOA), China during 1976–2004. The data include physical [seawater temperature (T) and salinity (S)] and chemical parameters [dissolved oxygen (DO), phosphate (PO_4–P), silicate (SiO_3–Si), dissolved inorganic nitrogen (DIN, including NO_3–N, NO_2–N and NH_4–N)]. Seawater samples were obtained using Nansen bottles from the surface, 5, 10, 15, 20, 25, 30, 35, 50, 75, 100, 150 and 200 m (or 2 m above bottom, if the depth was <200 m) for T and S, and at the surface, 10, 20, 30, 50, 75, 100, 150 and 200 m (or 2 m above the bottom, if the depth was <200 m) for biogenic element determination. Seawater temperature was measured by using a reversing thermometer attached to the Nansen bottle, and salinity was measured by using induction salinometer, according to SOAC (1975) and NBTS (1991). Nutrients (nitrate, phosphate and silicate) were analyzed by standard spectrophotometric methods, and dissolved oxygen (DO) was analyzed by the Winkler procedure (Strickland and Parsons, 1972).

Annual mean values were the average for winter and summer which were derived from observations during February and August, respectively. The regional average was the average value for the all stations illustrated in Fig. 1. First, we took the values at the sea surface (SS), the depth of 200 m and the average through the water column for 0–200 m (integrated) for each parameter, since at the depth of 200 m concentrations of biogenic elements and other properties were relatively stable and much less influenced by the upper layers. Second, the regional means for each parameter on an annual scale were calculated. The average value for the water column was computed,

according to the following equation:

$$X_{av}=\frac{1}{b}\int_0^b X(z)dz \tag{1}$$

Where X is an environmental parameter; b is the water depth (200 m, or 2 m above bottom, if the water depth is shallower than 200 m) and z is the observation depth.

In order to show the interannual changes in environmental parameters in the nSCS, the time series of various parameters was determined. The parameters include physical parameters, such as SST, T_{av}, $T_{200\,m}$, SSS, S_{av}, S_{200}, and chemical parameters, such as SSDO, DO_{av}, DO_{200}, SSP, P_{av}, P_{200}, SSSi, Si_{av}, Si_{200}, SDIN, DIN_{av}, DIN_{200}, SNO_2–N, NO_2–N_{av}, NO_2–N_{200}, SNO_3–N, NO_3–N_{av}, NO_3–N_{200}, SNH_4–N, NH_4–N_{av}, NH_4–N_{200}, SN:P, N:P_{av}, N:P_{200}, SSi:N, Si:N_{av}, Si:N_{200}, where av=average for the whole water column and 200=200 m depth. Statistical test and linear regression analyses were conducted on time series (Chen and Ma, 1991) and climate trend coefficients (R_{xt}) were estimated. R_{xt}, was used to assess whether there was a significant linear climate-trend in a time series (Shi et al., 1995). This coefficient was defined as the correlation coefficient between the time series of an environmental parameter, $\{X_i\}$, and the nature number $\{i\}$, $i=1, 2, 3, \ldots n$. In this study, n is the total span of years covered by the data. The coefficient was computed from the following equation:

$$R_{xt}=\frac{\sum_{i=1}^{n}(x_i-\bar{x})(i-\bar{t})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2\sum_{i=1}^{n}(i-\bar{t})^2}} \tag{2}$$

Where $t=(n+1)/2$. Its significance level is determined from the Student t-test. A positive/negative value of R_{xt} indicates that the time series, $\{Xi\}$, has a linear positive/negative trend. In order to compare the environmental change rates between coastal/shelf waters with the slope/open sea, data for water depths <200 and >200 m, respectively were analyzed.

Biological oceanography data, such as chlorophyll-*a*, phytoplankton abundance, primary production, zooplankton biomass, benthos biomass, cephalopod catch, etc. were obtained during the period by marine ecosystem surveys conducted by the South China Sea Fisheries Research Institute (SCSFRI), the South China Sea Institute of Oceanography, Chinese Academy of Sciences and the Second Institute of Oceanography, SOA. For the observational methods, chlorophyll-*a* was determined by acetone extraction fluorescence method (Holm-Hansen et al., 1965) and often calibrated by spectrophotometry. Primary productivity were measured by using the ^{14}C tracer method established by Steemann-Nielsen (1952) and modified for scintillation counting by Wolfe and Schelske (1967). Phytoplankton samples were collected by vertical haul using a Judy net with a mesh size of 76 μm. The samples were preserved with Lugol's solution, and the species identification and cell counts were made using a microscope to get phytoplankton abundance (PA, Sournia, 1978). Zooplankton samples were collected by vertical haul using a plankton net with a mesh size of 505 μm, and the samples were preserved with neutral formaldehyde solution (5%). The species identification and individual counts were made using a stereo microscope, and the wet weight biomass (ZB) was measured by an electronic balance after removing the body surface water in the lab, according to SOAC (1975) and NBTS (1991). Benthic macrofauna samples were collected by using a grab with a sampling area of 0.1 m^2, and the animals were sorted after removing the mud by elutriation. The species identification and individual counts were made using a stereo microscope, and the wet weight biomass (BB) was measured gravimetrically after removing the body surface water in the lab (SOAC, 1975; NBTS, 1991). The nekton samples were collected by using a cystoid net with a mesh size of 20 mm, towed by a pair of boats at a speed of 3–4 kn for 1 h at each station (SOAC, 1975; NBTS, 1991).

3 Results

3.1 Environmental changes during the 29 y time series

3.1.1 Seawater temperature and salinity

The annual means of SST and T_{av} (the average temperature in the water column) exhibited highly significant increasing trends ($p \leq 0.01$), their annual rates were 0.078 and 0.090°C y^{-1}, while the temperature at 200 m (T_{200}) showed a highly significant decreasing trend with an annual rate of −0.108°C y^{-1} during the 29 y between 1976 and 2004 (Fig. 2, Table 1). During this period, the SST and T_{av} increased by 2.26 and 2.61°C, respectively, while T_{200} decreased by 3.10°C (Fig. 2, Table 1). The R_{xt} of the time series of SST, T_{av} and T_{200} were 0.89, 0.85 and −0.71, respectively, and the variation trends for this time series were significant ($p \leq 0.01$). The fluctuations of SST and T_{av} were in phase with the bottom layer temperature in the shallow water areas (<200 m), while those were in out of phase with T_{200} in the deep water areas (>200 m, Table 1).

During the observation period the annual rate of SSS exhibited a decreasing trend (−0.022 y^{-1}), while the annual rates of S_{av} and S_{200} exhibited increasing trend (0.007 y^{-1} and 0.005 y^{-1}, respectively, Fig. 3, Table 1). The SSS decreased by 0.653, while the S_{av} and S_{200} increased by 0.206 and 0.151. The R_{xt} values of time series of SSS, S_{av} and S_{200} were −0.41(P≤0.05), 0.38(P≤0.05) and 0.44($p \leq 0.02$), respectively (Table 1).

3.1.2 Concentration of dissolved oxygen (DO)

A significant ($p \leq 0.01$) decrease in DO concentrations was observed (Fig. 4, Table 1), and the annual rate was between −0.91 and −1.93 μmol L^{-1} y^{-1}. The regional mean of DO of the sea surface, the water column average and at 200 m significantly decreased by 26.5, 55.8 and 47.9 μmol L^{-1}. The R_{xt} values of time series for DO ranged from

−0.48 to −0.81 ($p \leq 0.01$, Table 1).

3.1.3 Concentrations of P, Si and N

Both P and Si concentrations exhibited decreasing trends (Figs. 5 and 6, Table 1). Their annual rates were −0.008 to −0.017 (for P) and −0.071 to −0.387 (for Si) μmol L^{-1} y^{-1}, respectively.

The concentrations of NO_3−N, NO_2−N, NH_4−N and dissolved inorganic nitrogen (DIN=NO_3+NO_2+NH_4) in the nSCS exhibited obvious increasing trends during 1989–2004 (Fig. 7, Table 1). The annual rates of the increases in DIN and NO_3−N were 0.38 to 0.81 and 0.34 to 0.71 μmol L^{-1} y^{-1}, respectively. The regional means of DIN values of the sea surface, water column average and 200 m layer increased by 8.06, 6.10 and 13.01 μmol L^{-1}, respectively. DIN concentrations in the 200 m layer were significantly higher than those of the average for the water column and at the sea surface; its annual rate was 1.61 times greater than that of the sea surface, and its multi-year average value during observation period was 3.9 times higher than that of the sea surface layer. The R_{xt} value for the time series of NO_3−N and DIN were between 0.55–0.74. The variation trends of the NO_3−N and DIN time series were highly significant ($p \leq 0.01$) (Table 1), except for the time series of NO_3−N_{200}, which was significant at the ($p \leq 0.03$). It was also found that the annual rate of DIN was higher in the shallow (<200 m) than in the deep water (>200 m) areas (Table 1).

3.1.4 Nutrient ratios

During 1989–2004, the nutrient ratios (N:P and Si:N) changed significantly, e.g. the N:P ratios increased by 1.04–2.75 y^{-1}, and it reached 28.1 (SSN:P) and 18.0 (N:P_{av}) in 2004 (Fig. 8, Table 1); the Si:N ratios decreased at an annual rate of −0.10∼−0.44 y^{-1}, and it dropped to 1.0 (SSSi:N) and 1.4 (Si:N_{av}) in 2004 (Fig. 9, Table 1). The variation trends of all time series of N:P and Si:N were highly significant ($p \leq 0.01$). The annual rates of increase in N:P and decrease in Si:N were higher in the shallow coastal water

(<200 m) than in deep continental shelf water (>200 m) (Table 1).

4 Discussion

4.1 Increasing trends and the response of the ecosystem

The positive increasing trends in SST and T_{av} in the nSCS during 1976–2004 are consistent with the increasing trends in the mean air temperature (AT) observed throughout the Northern Hemisphere (Houghton et al., 1997; Fu et al., 2006), South China (Chen et al., 1998; Zhai and Ren, 1997) and the annual means of AT and SST observed along the coast of the SCS (He et al., 2003; Martin and Arun, 2003). The increasing trends were also in phase with the changes in SST observed along the coast of the Yellow Sea and Bohai Sea (Lin et al., 2005, 2001). However, these annual rates of water temperature change were higher in the nSCS than in the Yellow Sea and the Bohai Sea (Lin et al., 2005, 2001).

The increase in DIN in the nSCS during 1989–2004 was consistent with the rise of DIN observed throughout the global marginal seas and also consistent with the increase in DIN along the coast of the nSCS, such as Qinzhou Bay (Wei et al., 2003) and Daya Bay (Qiu et al., 2005). Along with the rapid economic development in China, DIN concentration in the Pearl River estuary and shelf of the China Sea has been dramatically increasing, due to the increasing urbanization near the coastal areas, resulting in more municipal sewage, agricultural fertilizer, mariculture waste etc. inputs (SOA, 2001). The DIN in waters of the Pearl River estuary has increased by about 4 times since 1986 (He et al., 2004) and the data in Table 2 indicate that DIN and NO_3–N concentrations in the Pearl River estuary and Qinjiang and Maolingjiang estuaries (northwestern SCS) have been markedly increasing. Significant inputs of DIN into the nSCS have occurred through river discharge, atmospheric dry and wet precipitation (Zhang et al., 1999) and the upwelling of the deep waters (Zhao et al., 2005). The mitigation of N limitation in the upper layer since 1998 was clearly related to these DIN inputs. The increase in the annual rate of DIN was higher at the 200 m layer

(DIN_{200}) than the water column average (DIN_{av}) and at the sea surface layer (SSDIN). This may be due to the fact that there was no uptake by phytoplankton at 200 m, and possible strengthening of the deep water upwelling. The increase in the annual rates of DIN and NO_3–N were much higher in the nSCS than in the Yellow Sea (Lin et al., 2005), and therefore, the previous status of N limitation in the nSCS has been reduced. Since 1998, the multi-annual mean of the water column average DIN concentration has reached 7.7 μmol L^{-1} and the maximal value of the annual mean even reached up 10.8 μmol L^{-1} in 2001 (Fig. 7b). During 1989–1997, the DIN_{av} was low, the multi-annual mean was 4.2 μmol L^{-1} and the lowest value of DIN_{av} was only 1.7 μmol L^{-1} in 1989.

The increase in the N:P ratio was due to an increase in DIN and a decrease in P concentration. Before 1997, the N:P ratios (SSN:P, $N:P_{av}$ and $N:P_{200}$) were lower than 10. Since 1998, these ratios have rapidly increased to 28, 18 and 16 in 2004, respectively (Fig. 8). In 2004, the average values of $N:P_{av}$ and $N:P_{200}$ were close to the Redfield ratio, and therefore favorable to phytoplankton growth (Richardson, 1997; Hu et al., 1989; Jiang and Yao, 1999). The high value of SSN:P (28) in 2004 was probably due to dry and wet precipitation. The peak value of SSN:P appeared in 2002 (up to 86, Fig. 8a), due to high rainfall and high Pearl River discharge, and this high ratio corresponded to the lowest surface salinity (Fig. 3a). Moreover, the fact that the annual rates of DIN and N:P were higher in the shallow water area (<200 m) than in the deep water area (>200 m) (Table 1) suggested the influence of the anthropogenic activities on the ecosystems of the shallow or coastal waters. These results agree well with Xu et al. (2008) who also showed that N input from the Pearl River has caused the nSCS to become P-limited.

4.2 Decreasing trends and the response of the ecosystem

The decreasing trends in SSS may be related to the increase in the freshwater discharge into the nSCS since 1990 and less vertical mixing, because of the presence of a permanent thermocline (Yuan and Deng, 1997a, b; Shi, 2001). It has previously

been observed that the occurrence of low SSS often corresponded to abnormally high discharge of the Pearl River (Xie and Zhang, 2003; Xu et al., 2008). During the period of 1990 to 2000, the Pearl River runoff increased by 22.5% in comparison with the mean discharge for 1960–1999 (Lei et al., 2003). In the 1990s (i.e. 1994, 1995, 1996, 1997, 1999) and 2002, SSS in the nSCS was especially low (Fig. 3a), which was induced by the Pearl River floods. Particularly in 2002, the strongest typhoon rain storm resulted in the historically greatest flood of the Pearl River, and therefore, resulting in the lowest SSS (32.2) in the nSCS during the study period (Lei et al., 2003; Xie and Zhang, 2003). In 1999, the SSS was below normal due to the influence of frequent typhoon rain storms (total of 28 typhoons, including 7 landed ones). Furthermore, in the summer of 1999, the Dongsha upwelling (Stations 3–6) was weak and the depth of the 20°C isopleth was deeper than 105 m. However, in 1998, although large floods of the Pearl River occurred, the SSS did not decrease, due to the strong upwelling as indicated by shallow (84 m) depth of the 20°C isopleths. Chai et al. (2001) pointed out that the strength of upwelling can be indicated by the depth of 20°C temperature isopleth in the SCS. The high SSS in 1993 was probably due to the reduced Pearl River discharge.

The decreasing trend in DO concentration (Fig. 4) can probably be attributed to three reasons: first, a small decrease in DO solubility in the seawater can be induced by the increase in the seawater temperature (Fig. 2); second, an increase in DO consumption, resulting from the decomposition of organic matter originating mainly from the Pearl River discharge and the decay of phytoplankton blooms with increasing frequencies in the coastal water (Peng, 1994; Tang et al., 2006). Before 1998, HABs (harmful algae blooms) occurred once or twice a year, but during 1998 to 2003, blooms increased to 10 to 20 a year in the nSCS (Tang et al., 2006), which was in phase with the dramatic decreasing trend in DO (Fig. 4); and third, the mixing between the surface water and the deep layers was reduced by the stronger thermocline, due to the rapid rise in SST since 1995 (Fig. 2a), resulting in less transfer of oxygen from the atmosphere to the deeper layers. In addition in 1998, the lowest value of DO was probably attributed to

the strongest upwelling, which occurred that year.

The decrease in P concentration is probably due to uptake by phytoplankton and less P supply from deep water, due to the presence of the permanent thermocline (Yuan and Deng, 1997a, 1997b; Shi et al., 2001). Furthermore, since 1998, the reduction in N limitation has increased the phytoplankton biomass and production (Table 3) and decreased the P concentration. Hong et al. (1983) reported that diatoms can take up 30 times more P than they need and store it for use when P is deficient. In the most years except for 1994 and 2000, the concentrations of P in the upper layer (<75 m) were even lower than the P concentration required for diatom growth (<0.1 μmol L^{-1}, Zou et al., 1983). The decreasing trends in Si concentration have probably been influenced by the decrease in Si concentration in the Pearl River runoff since the 1970s (Lei et al., 2003), but still adequate for diatom growth. At 200 m, the interannual fluctuations of both P and Si concentrations were high (Figs. 5 and 6) and probably attributed to the interannual changes in upwelling of deep water. In 1996 and 1999 the depth of the 20° isopleth was shallow (e.g. the average value from multi-stations was 93 m), high concentrations of P and Si (P_{av}=0.61 and 0.62 μmol L^{-1}, P_{200}=1.154 and 1.31 μmol L^{-1}, Si_{av}=25.18 and 19.55 μmol L^{-1}, and Si_{200}=42.12 and 44.28 μmol L^{-1}, respectively, in the two years) occurred. In contrast, during 2004 when the depth of the 20° isopleth was deep (e.g. ~105 m), concentrations of P (P_{av}=0.37 μmol L^{-1}, and P_{200}=1.13 μmol L^{-1}) and Si (Si_{av}=8.9 μmol L^{-1}, and Si_{200}=20.5 μmol L^{-1}) were obviously low.

4.3 Nutrient limitation

Since 1998, DIN concentrations have exhibited a pronounced increasing trend, and therefore the key nutrient concentration and ratio can be divided into two phases, i.e. before and after 1997 (Table 3). In the first phase, the average DIN concentrations was very low, SSDIN and DIN_{av} were 1.83 and 4.22 μmol L^{-1}, respectively, which were lower than the low limit of suitable N concentration for diatom growth (5.71 μmol L^{-1},

Chu, 1949); the average P concentration was also low, SSP and P_{av}, were 0.33 and 0.56 μmol L^{-1}, respectively, which is closed to the low limit of suitable P concentration for diatom growth (0.48 μmol L^{-1}, Zhao et al., 2000); however, Si concentrations (SSSi and Si_{av} were 12.38 and 14.82 μmol L^{-1}, respectively) outclassed the low limit of suitable for diatom growth (4.40 μmol L^{-1}, Harvey, 1957), therefore, Si pool was sufficient. N:P ratios were less than half the Redfield ratio of 16 (SSN:P and N:P_{av} were 5.5 and 7.5, respectively).

In contrast, for the second phase after 1997, the average DIN concentration has been clearly increasing (SSDIN and DIN_{av} were 5.75 and 7.78, respectively, Table 3), and exceeded the low limit of suitable N concentration for diatom growth (5.71 μmol L^{-1}, Chu, 1949), while the average P concentration has decreased (SSP and P_{av}, were 0.25 and 0.48 respectively, Table 3), consequently, there was a rapid increase in N:P ratios (SSN:P and N:P_{av} were 23.0 and 16.2, respectively), which were higher than the Redfield ratio (Richardson, 1997; Hutchins et al., 1998). Si concentration also decreased (SSSi and Si_{av} were 9.19 and 12.26) in this phase, resulting in rapid decrease in the ratio of SSSi:N (Si:$N_{av,}$) from 6.3 (2.5) to 1.6 (1.6) (Table 3).

Based on the studies on the kinetics of nutrient uptake, the thresholds of SiO_3–Si, DIN and PO_4–P for phytoplankton growth have been estimated to be 2.0, 1.0 and 0.1 μmol L^{-1}, respectively (Justic et al., 1995). In the present study area, the values of all the nutrient parameters were over these threshold concentrations, except for those in the first phase, when the mean of SSDIN was close to the threshold of N (Table 3). According to chemical stoichiometry, in the first phase both SSN:P and N:P_{av} was lower than 10, and SSSi:N, Si:N_{av} and BSi:N were all over 1, indicating potential N limitation. In the second phase SSN:P and BN:P were higher than 22, and N:P_{av} was equal to the Redfield ratio. All Si:N ratios ranged from 1.3 to 1.6, Si:P ranged 25.5 to 53.8 (Table 3), which indicated that potential P limitation increased and N limitation decreased. Furthermore, Si was always sufficient during the observation period, even in the second phase when its concentration decreased (Table 3).

4.4 Response of ecological environment to ENSO events

ENSO is global climatic event. When El Nino occurs, the warm pool of the western Pacific Ocean moves eastward, whereas it moves westward during La Nina (White et al., 1985; Takeuchi, 1987; Zhang and Huang, 1993). The nSCS is located to the west of the warm pool, however, the response of the ecosystems of the nSCS to ENSO has not been well documented yet. In the present study, pronounced responses to ENSO were found. During the observation period, 9 El Nino events (1976, 1982–1983, 1986–1987, 1991, 1993, 1994, 1997, 2002 and 2004) and 4 La Nina events (1981, 1988, 1995 and 1998–1999) occurred (Wang and Gong, 1999; Qin, 2003; Mcphaden, 2004; Levimson, 2005). In general, whenever El Nino/La Nina occurred, SST and T_{av} was low/high in the nSCS (Fig. 2, Table 4).

In the area southwest of Dongsha Islands, near Station 4 (19–20° N, 116–117° E, Fig. 1), pronounced responses to ENSO were observed. In general, whenever an El Nino event occurred, T_{av} was low, and during a La Nina event, T_{av} was high (Fig. 10a). In comparison of fluctuations in T_{av}, S_{av}, DO_{av}, PO_4-P_{av}, SiO_3-Si_{av}, DIN_{av} and sea surface Chl-*a* at Station 4 in the nSCS in summer during ENSO events, we found that in general, maximum/minimum values of T_{av} and DO_{av} corresponded to La Nina/El Nino events, and each maximum/minimum values of S_{av}, and nutrients (PO_4-P_{av}, SiO_3-Si_{av} and DIN) corresponded to El Nino/La Nina events (Fig. 10). Furthermore, in comparison of the average values of the environmental parameters in summer of El Nino years with those of La Nina years, T_{av} and DO_{av} were lower by 1.89°C and 20.2 μmol L^{-1}, respectively; S_{av} was higher by 0.31 psu; PO_4-P_{av}, SiO_3-Si_{av} and DIN_{av} were higher by 0.15, 6.41 and 3.42 μmol L^{-1}, respectively; sea surface Chl-*a* concentration higher by 0.14 mg m^{-3}, i.e. higher by 1.8 times (Table 5), even higher by 0.83 times than the average value of normal years (1980, 1990, 2000, 2001 and 2003, for which mean Chl-*a*=0.12±0.05 mg m^{-3}).

According to Takano et al. (1998) and Liao et al. (2006), there is a cyclonic eddy in the sea area around Station 4 (near Dongshan Islands) in summer. Whenever a

medium and strong El Nino occurs, the summer monsoon is weak (Zhang et al., 2003; Zhu et al., 2000), which induces the cyclonic eddy to strengthen, leading to strong upwelling, resulting in low T_{av} and DO_{av}, and high S_{av}, nutrients and Chl-*a* induced by phytoplankton growth. During a La Nina event, the opposite occurs.

4.5 Response of the ecosystem and living resources

Although the frequency of observation on various biology and fisheries parameters was less than that for physical and chemical parameters which reflected the long term changes in the environmental processes, some responses of the ecosystems to these environmental changes in the nSCS was still evident.

Comparing the biology and fisheries data between the two phases, the average values of chlorophyll-*a*, primary production, phytoplankton abundance, benthos biomass, cephalopod catch and demersal trawl catch increased by 6.4, 1.4, 2.4, 0.7, 7.2 and 2.8 times, respectively during the second phase, except for zooplankton abundance which decreased by about 50% (Table 6). The decrease in zooplankton abundance may be related to the increase in its predators, such as fish, cephalopods, etc. (Fig. 11). The R_{xt} values of the cephalopod and demersal trawl catches were 0.89 and 0.88 respectively, and highly significant ($p \leq 0.01$). The increase in both the cephalopod and demersal trawl catches could be attributed to the improvement of demersal trawl fishing techniques, and also to the increase in stock and production of low trophic levels, induced by the reduction in N limitation in the nSCS.

In addition, after 1997, phosphorus depletion in surface waters during summer coincided with a shift in the dominant species in phytoplankton community from diatoms to dinoflagellates and cyanophytes (Ning et al., 2004). Peng et al. (2006) pointed out that dinoflagellates composed more than 60% of the total phytoplankton abundance in the HK Southeast Anti-Cyclonic Eddy and Hainan Island East Anti-Cyclonic Eddy of the nSCS, where P concentration were near detection limits in the summer of 2004.

Our above observations were highly consistent with the results obtained by the multidisciplinary investigations for assessing the environmental health status and the fish-

eries environment quality in the nSCS during 1997–2002 (Jia et al., 2005). They reported that both primary production and phytoplankton abundance were somewhat higher (averaging 409.7 mg C m^{-2} d^{-1}, and 837×10^3 cell m^{-3}, respectively), the benthic biomass (averaging 11.3 g m^{-2}) was at normal levels, the zooplankton biomass (averaging 22.1 mg m^{-3}) was low and nutrients were also low, i.e. the mean values of PO_4–P=0.28 μmol L^{-1} and DIN=3.63 μmol L^{-1}. The latter values are much lower than those we observed and the average index of ecological environment quality of fishing ground is 0.58, indicating it was in good condition (Jia et al., 2005).

The first phase (before 1997) represents the initial status of the biology and fisheries during the study period, and the second phase (after 1997) represents the response of the ecosystem to the changed environment, particularly since 1998, when the occurrence of N limitation was significantly reduced. These ecosystem responses discussed above were clearly the result of environmental changes induced by not only climate change, but also anthropogenic activities.

5 Conclusions

The fluctuations in environmental parameters in the nSCS during 1976–2004 displayed different patterns, i.e. temperature (SST and T_{av}), salinity (S_{av} and S_{200}), dissolved inorganic nitrogen (DIN) and N:P annual rates increased, while DO, P, Si, Si:N, SSS and T_{200} annual rates decreased. The climate trend coefficients, R_{xt} of these time series were all over 0.38 (n=29) or 0.50 (n=16), and highly significant ($p\leq0.05$), except for the time series of P and Si.

The increasing trends in SST and T_{av} were consistent with the rise of the mean air temperature (AT) in the Northern Hemisphere and southern China. The increase in SST and T_{av} and decrease in SSS in the nSCS led to strengthening of the thermocline and halocline, less mixing of deep water to the surface and thus a decrease in the P supply from deep waters. The increasing trend in DIN may have been influenced by the Pearl River discharge, and atmospheric dry and wet deposition, which

are related to anthropogenic activities, coastal upwelling and cyclonic eddies. The nSCS always experienced limitation of N before 1997, and the situation in the upper layer sea water has been mitigated since 1998, due to the increase in N concentration and decrease in P, which resulted in not only the positive trends in N:P ratios which are now close to the Redfield ratio, but also the decreasing trend in Si:N ratios, and the indication of potential P limitation. The decrease in DO concentration may be linked to the increase in seawater temperature and the increase in the concentration of organic matter inputs mainly from the Pearl River and phytoplankton blooms, particularly since the 1990s. Chlorophyll-*a*, primary production, phytoplankton abundance, benthos biomass, cephalopod catch and demersal trawl catch have increased, and zooplankton abundance decreased. These ecosystem responses resulted from environmental changes induced by not only climate change, but also anthropogenic activities. After 1998, phosphorus depletion in upper layer may be associated with a shift from diatoms to dinoflagellates and cyanophytes.

Pronounced responses of the environmental parameters to ENSO were observed. The effects of climate change on the nSCS were mainly through changes in monsoon and its causative links, monsoon – circulation – nutrients – primary production.

The evolving nutrient environment may be related to the observed ecosystem changes in the nSCS such as increase in biological productivity. More long-term series observations on the structure and function of ecosystems and the relationships with environmental changes are needed in the SCS in the future.

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Table 1. The annual rate, climate trend coefficients (R_{xt}) and the amplitude of fluctuations of the environmental parameters in the nSCS during 1976–2004 (units: $^{\circ}C\,y^{-1}$ for annual change in temperature, and $\mu mol\,L^{-1}\,y^{-1}$ for DO and nutrients).

	Annual rate			R_{xt} [a]			Amplitude of fluctuation[b]			Mean ±SD[c]		
	Mean <200 m	Mean >200 m	Mean area whole	Mean <200 m	Mean >200 m	Mean whole area	Mean <200 m	Mean >200 m	Mean whole area	Mean <200 m	Mean >200 m	Mean whole area
SST	0.078	0.063	0.078	0.84^{A}	0.80^{A}	0.89^{A}	2.67	3.28	2.97	24.75±1.82	26.06±0.67	25.63±0.74
T_{av}	0.089	0.095	0.090	0.80^{A}	0.85^{A}	0.85^{A}	4.07	4.41	3.86	23.49±0.97	22.42±0.95	22.29±0.89
T_{200} [d]	0.045	−0.107		0.45^{B}	0.71^{A}		2.90	3.94		20.36±0.86	15.41±1.30	
SSS	−0.007	−0.015	−0.022	−0.19	−0.35	-0.41^{C}	3.61	2.30	2.20	33.10±0.78	34.01±0.40	33.55±0.48
S_{av}	0.008	0.005	0.007	0.32	0.34	0.38^{C}	0.97	0.71	0.74	33.89±0.30	34.22±0.19	34.05±0.21
S_{200} [d]	0.005	0.005		0.30	0.44^{B}		0.42	0.48		34.34±0.20	34.59±0.10	
SSDO	−0.964	−0.927	−0.913	-0.46^{B}	-0.52^{A}	-0.48^{A}	80	85	83	426.5±76.0	425.4±15.0	434.6±15.9
DO_{av}	−1.857	−2.037	−1.926	-0.67^{A}	-0.82^{A}	-0.81^{A}	102	92	94	422.6±33.0	384.9±21.0	402.3±20.3
DO_{200} [d]	−2.230	−1.653		-0.70^{A}	-0.63^{A}		99	104		376.3±28.0	317.2±22.4	
SSP	−0.011	−0.004	−0.008	−0.41	−0.30	−0.31	0.54	0.76	0.45	0.31±0.14	0.32±0.11	0.32±0.12
P_{av}	−0.008	−0.007	−0.009	−0.29	−0.35	−0.37	0.32	0.63	0.50	0.39±0.12	0.69±0.17	0.52±0.13
P_{200} [d]	−0.006	−0.017		−0.22	-0.50^{D}		0.48	0.78		0.57±0.17	1.19±0.21	
SSSi	−0.642	−0.284	−0.071	−0.19	−0.30	−0.22	12.19	12.90	11.50	9.93±3.46	10.33±4.81	10.20±3.71
Si_{av}	−0.284	−0.240	−0.161	−0.24	−0.19	−0.16	17.84	21.46	17.86	11.51±6.05	15.15±7.40	12.64±7.17
Si_{200} [d]	−0.038	−0.387		−0.06	−0.19		17.57	32.50		14.98±5.16	26.80±9.53	
SSDIN	0.613	0.391	0.504	0.70^{A}	0.63^{A}	0.74^{A}	17.27	9.69	11.85	4.44±4.24	3.73±3.00	4.09±3.29
DIN_{av}	0.416	0.343	0.381	0.75^{A}	0.61^{A}	0.73^{A}	9.68	10.53	10.53	4.71±2.63	6.33±2.65	6.71±2.60
DIN_{200} [d]	0.721	0.813		0.73^{A}	0.64^{A}		15.71	20.13		7.61±4.68	16.08±6.03	
$SSNO_3$	0.457	0.342	0.456	0.70^{A}	0.54^{D}	0.66^{A}	12.05	9.56	9.74	2.62±3.09	2.45±2.99	2.55±2.85
NO_{3av}	0.345	0.324	0.335	0.71^{A}	0.58^{B}	0.67^{A}	8.46	9.85	8.13	2.98±2.31	5.09±2.68	4.01±2.37
NO_{3200} [d]	0.582	0.711		0.68^{A}	0.55^{C}		13.57	20.55		5.57±4.05	14.53±6.17	
SSN:P	3.61	1.89	2.75	0.55^{C}	0.54^{D}	0.63^{A}	126.55	52.65	84.02	20.5±30.7	14.9±16.8	17.8±21.2
$N:P_{av}$	1.66	0.75	1.21	0.70^{A}	0.57^{B}	0.69^{A}	40.26	23.24	28.65	14.0±11.3	10.7±6.3	12.3±8.4
$N:P_{200}$ [d]	1.51	1.04		0.74^{A}	0.64^{A}		31.26	27.3		13.8±8.6	14.0±7.8	
SSSi:N	−0.52	−0.46	−0.44	-0.75^{A}	−0.39	-0.67^{A}	12.32	22.68	9.69	4.1±3.3	5.4±5.7	4.3±3.2
N_{av}	−0.46	−0.15	−0.22	-0.71^{A}	−0.46	-0.70^{A}	13.05	5.62	5.41	3.4±3.1	2.9±1.6	2.8±1.5
$Si:N_{200}$ [d]	−0.32	−0.10		-0.75^{A}	-0.65^{A}		7.29	2.8		2.87±2.02	1.85±0.8	

[a] Significance: $^{A}p \leq 0.01$, $^{B}p \leq 0.02$, $^{C}p \leq 0.03$, and $^{D}p \leq 0.05$.

[b] The amplitude is the difference between maximal annual mean value and minimal one during the observation period. It indicates quantitative characteristics of the fluctuation processes of a parameter during the observation period. Standard deviation is symbolized as $X\delta n-1$.

[c] Mean ±SD is the multi-year's mean value and standard deviation during the observation period.

[d] When the water depth <200 m, data for the bottom layer are used; when the water depth >200 m, data for 200 m were used.

Table 2. Changes in annually average concentration (μmol dm^{-3}) of NO_3–N and dissolved inorganic nitrogen (DIN), including NO_3–N, NO_2–N and NH_4–N, from discharges of the Pearl River and other rivers.

Observation year	Location of the observation	Parameter, value	Data source
1980–1985	southern Hong Kong waters (outside Pearl River estuary)	NO_3–N, 1-3	Han et al. (1990)
1986	Pearl River estuary	DIN, 19.3	He et al. (2004)
1987	Pearl River estuary	NO_3–N, 28.0 DIN, 31.7	Wang and Peng (1996)
1990	Pearl River estuary	DIN, 34.6	He et al. (2004)
1995	Pearl River estuary	DIN, 36.4	He et al. (2004)
1996	Pearl River estuary	NO_3–N, 39.8	Cai (2002b)
1999 (summer)	Pearl River estuary	NO_3–N, 48.9 DIN, 51.9	Lin et al. (2004)
1999 (summer)	Pearl River estuary	DIN, 53.2	Guan et al. (2003)
2002	Pearl River estuary	DIN, 76.4	He et al. (2004)
1983	Qinjiang and Maolingjiang estuaries (northwestern SCS)	DIN, 4.0	Wei et al. (2002)
1990	Qinjiang and Maolingjiang estuaries (northwestern SCS)	DIN, 11.3	Wei et al. (2002)
1999	Qinjiang and Maolingjiang estuaries (northwestern SCS)	DIN, 25.8	Wei et al. (2002)

Table 3. Comparison of key nutrient concentration (μmol L^{-1}) and the ratio between the two phases before 1997, the first phase and after 1997, the second phase.

Nutrient and ratio	mean in the first phase	mean in the second phase
SSDIN	1.83	5.75
DIN_{av}	4.22	7.78
BDIN	12.77	20.33
SSP	0.33	0.25
P_{av}	0.56	0.48
BP	0.49	0.48
SSSi	12.38	9.19
Si_{av}	14.82	12.26
BSi	27.54	25.85
SSN:P	5.5	23.0
$N:P_{av}$	7.5	16.2
BN:P	26.1	42.4
SSSi:N	6.3	1.6
$Si:N_{av}$	2.5	1.6
BSi:N	2.2	1.3
SSSi:P	37.5	36.8
$Si:P_{av}$	26.5	25.5
BSi:P	56.2	53.8

Table 4. Annual mean of SST and T_{av} along transect N in the nSCS in El Nino and La Nina years during 1976–2004 (unit: °C).

El Nino										
Year	1976	1982 (1983)	1986 (1987)	1991	1993	1994	1997	2002	2004	Mean ±SD*
SST	23.87	25.82 (25.09)	25.60 (25.73)	25.08	25.89	26.24	25.77	26.66	26.25	25.64 ±0.75
T_{av}	21.13	21.40 (23.40)	23.09 (23.32)	21.46	21.65	21.79	22.25	22.98	22.62	22.27 ±0.83
La Nina										
Year		1981	1988		1995	1998	1999			
SST		25.09	25.68		25.74	26.61	26.21			25.87 ±0.58
T_{av}		23.28	23.72		24.00	24.07	24.51			23.92 ±0.46

* Mean ±SD is the multi-year mean value ±(SD), standard deviation for the El Nino/La Nina years.

Table 5. The mean of the ecological parameter for the water column (0–200 m) and sea surface Chl-*a* concentration at Station 4 in summer of El Nino/La Nina years during the study period (units: °C for temperature, psu for salinity, μmol L^{-1} for DO and nutrients and mg L^{-1} for Chl-*a*.)

El Nino Year	1976	1982 (1983)	1986 (1987)	1991	1993	1994	1997	2002	2004	Mean ±SD[c]
T_{av}	21.13	21.40 (23.40)	23.09 (23.32)	21.46	21.65	21.79	22.25	22.98	22.62	22.26 ±0.80
S_{av}	34.18	34.14 (34.16)	34.13 (34.2)	34.45	34.82	34.41	34.19	33.85	34.17	34.25 ±0.25
DO_{av}	365.6	380.1 (387.3)	355.1 (364.9)	379.2	337.3	368.5	339.0	354.2	357.8	362.6 ±16.0
PO_4-P_{av}				0.23	0.71	0.36	0.56	0.44	0.56	0.48 ±0.17
SiO_3-Si_{av}				25.36	16.22	13.38	8.96	11.65	10.56	14.36 ±5.94
DIN_{av}				3.20	3.85	6.19	4.29	12.51	8.12	6.36 ±3.50
Chl-*a*[cc]		0.31						0.17	0.18 ±0.08	0.22

BGD
5, 3737–3779, 2008

Table 5. Continued

La Nina Year	1981	1984	1988	1995	1998	1999	Mean ±SD[c]
T_{av}	23.28	25.30	23.72	24.00	24.07	24.51	24.15 ±0.70
S_{av}	33.89	34.06	34.01	33.60	34.18	33.90	33.94 ±0.20
DO_{av}	391.7	431.0	388.2	380.8	308.7	396.2	382.8 ±40.3
PO_4-P_{av}				0.20	0.23	0.56	0.33 ±0.20
SiO_3-Si_{av}				10.00	5.20	22.32	7.95 ±12.45
DIN_{av}				3.50	3.00	2.31	2.94 ±5.98
Chl-*a*[cc]		0.08, 0.06			0.08	0.09	0.08

[c] Mean ±SD is the multi-year mean value ± standard deviation for the El Nino/La Nina years.
[cc] The Chl-*a* data were derived from SeaWiFS during 1998–2004, from Nimbus-7 CZCS in 1980 and 1984, provided by Chen, X. from The Third Institute of Oceanography, SOA, China for 1982, Fan (1985) and Huang (1992) for 1990, respectively.

Table 6. Comparison of the multi-year mean values of chlorophyll-*a* (Chl-*a*), primary production (PP), phytoplankton abundance (PA), zooplankton biomass (ZB), benthos biomass (BB), cephalopod catch (CC) and demersal trawl catch (DTC) in the nSCS between two periods, i.e. before and after 1997 (units: $mg\,m^{-3}$, $mg\,C\,m^{-2}\,d^{-1}$, $\times 10^3$ cell m^{-3}, $mg\,m^{-3}$, $g\,m^{-2}$, $\times 10^4$ t, and $\times 10^4$ t, respectively) [a].

Parameter	First phase (Data source)	Second phase (Data source)
Chl-*a*	0.29 (Fan, 1985)[b]	2.16 (Cai et al., 2002a, SOAC 2003)[c]
PP	185.7 (Fan, 1985)[b]	442.5 (Ning et al., 2004; Jia et al., 2005; Hao et al., 2007)
PA	161.5 (Lin, 1985)	542.7 (Jia et al., 2005)[b]
ZB	44.5 (Zhang, 1984; Chen 1985; Qian et al., 1990a, b; Huang et al. 1990; Chen 1992)	22.05 (Jia et al., 2005) [d]
BB	6.6 (Shen, 1985)	11.3 (Jia et al., 2005)
CC	1.2 (Guo and Chen, 2000)	9.8 (Guo and Chen, 2000)
DTC	89.0 (Guo and Chen, 2000)	334.8 (Guo and Chen, 2000)

[a] The data listed in the table are the mean of the water column of the multi-year average for each parameter from different sources, except for BB, CC and DTC which are only treated by the multi-year average.
[b] The data were provided by Chen, X. from The Third Institute of Oceanography, SOA, China.
[c] The data was from the National Science Foundation of China (NSFC) project under the contract No. 90211021.
[d] The data from Jia et al. (2005) are the annual mean of the multi-year mean for each season during 1997–2002.

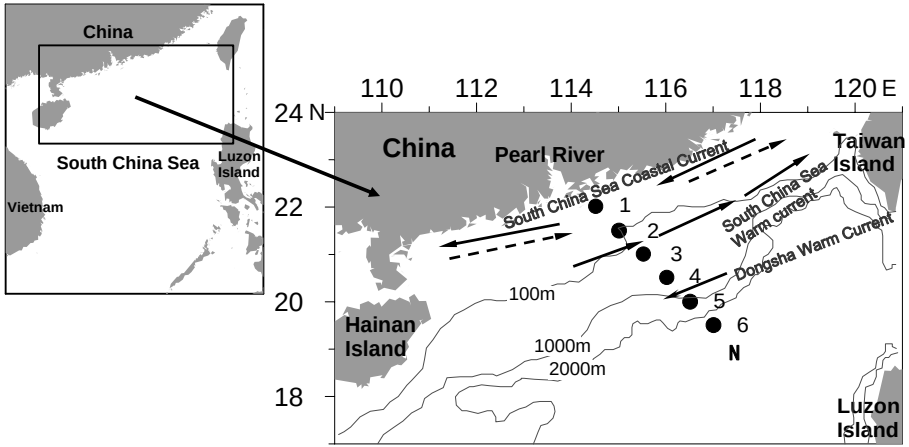

Fig. 1. Geographical locations of the transect and stations and circulation in the northern South China Sea (nSCS) (Su, 1998; Xue et al., 2004). The transect N from the Pearl River Estuary towards the southeastern nSCS is the main observation transect with 6 stations (full circle).

BGD
5, 3737–3779, 2008

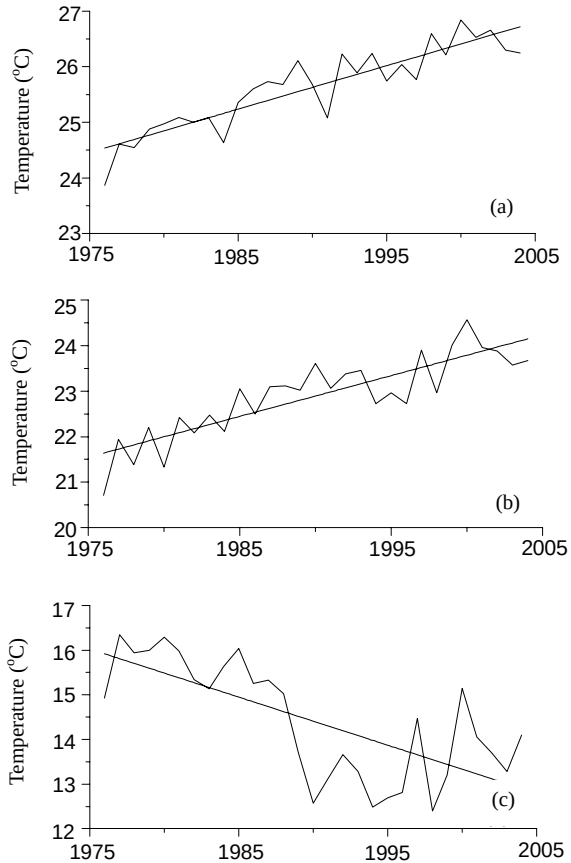

Fig. 2. Variation trends in seawater temperature in the nSCS during 1976–2004. **(a)**, **(b)** and **(c)** show the annual mean of the sea surface temperature (SST), water column average temperature (T_{av}) and the temperature at the depth of 200 m (T_{200}), respectively. The lines are linear regressions.

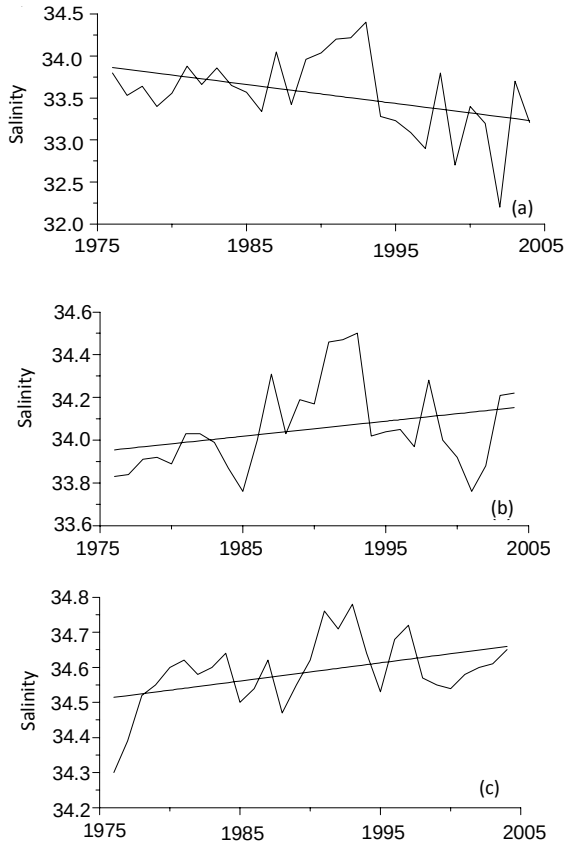

Fig. 3. Variation trends in seawater salinity in the nSCS during 1976–2004. **(a)**, **(b)** and **(c)** show the annual means of sea surface salinity (SSS), water column average salinity (S_{av}) and salinity at 200 m (S_{200}), respectively. The lines are linear regressions.

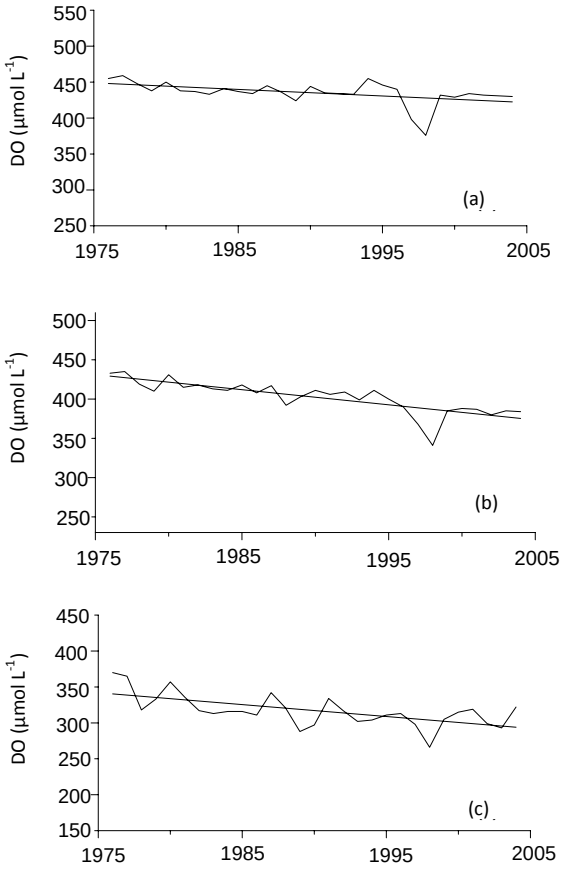

Fig. 4. Variation trends in dissolved oxygen (DO) concentration in the nSCS during 1976–2004. **(a)**, **(b)** and **(c)** show the annual means of sea surface DO (SSDO), water column average DO (DO_{av}) and DO at the 200 m (DO_{200}), respectively. The lines are linear regressions.

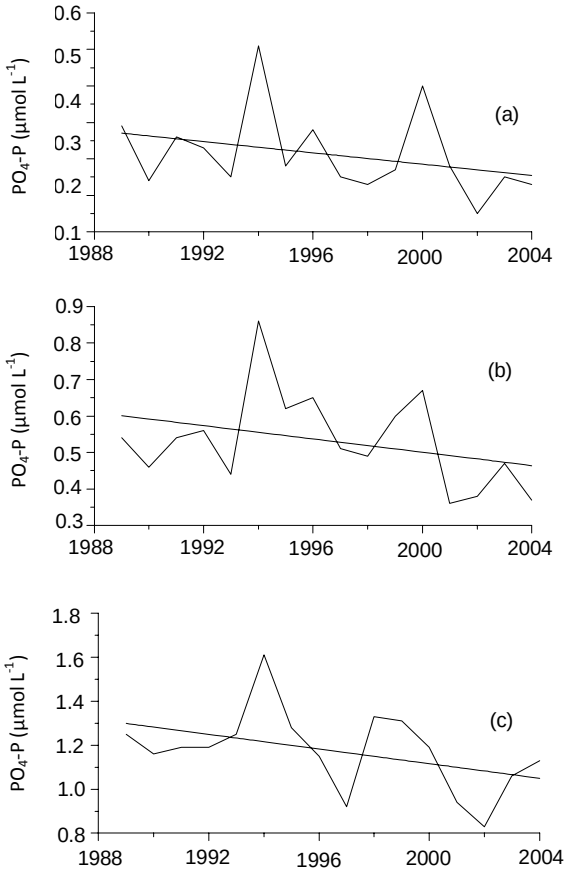

Fig. 5. Variation trends in P concentrations in the nSCS during 1976–2004. **(a)**, **(b)** and **(c)** show the annual means of sea surface P (SSP), water column average P (P_{av}) and P in the 200 m layer (P_{200}), respectively. The lines are linear regressions.

BGD
5, 3737–3779, 2008

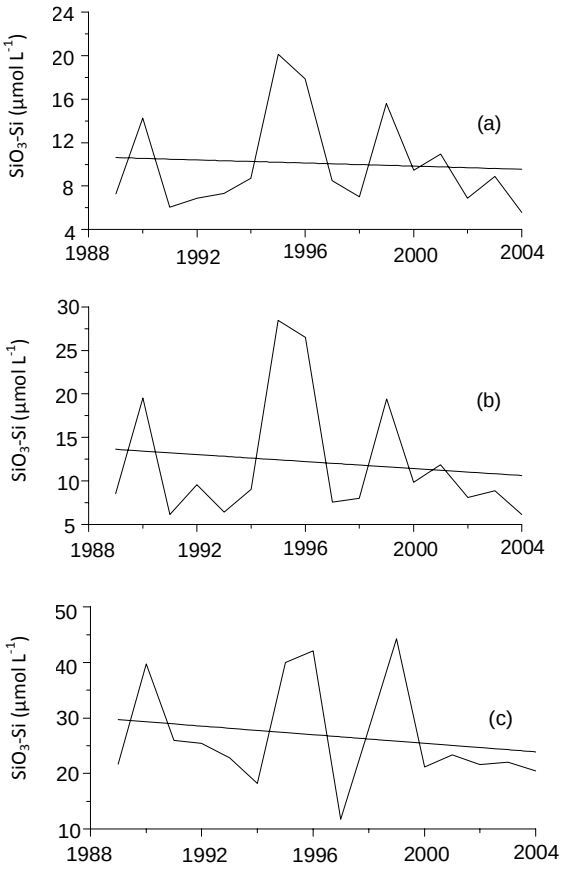

Fig. 6. Variation trends in Si concentrations in the nSCS during 1976–2004. **(a)**, **(b)** and **(c)** show the annual means of sea surface Si (SSSi), water column average Si (Si_{av}) and Si in the 200 m layer (Si_{200}), respectively. The lines are linear regressions.

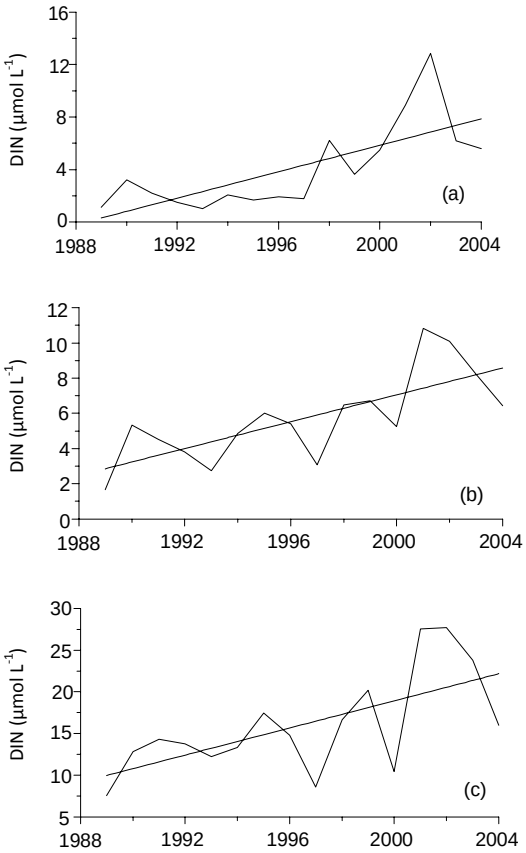

Fig. 7. Variation trends in dissolved inorganic nitrogen (DIN) concentrations in the nSCS. **(a)**, **(b)** and **(c)** show the annual means of sea surface DIN (SSDIN), water column average DIN (DIN_{av}) and DIN at the 200 m layer (DIN_{200}), respectively. The lines are linear regressions.

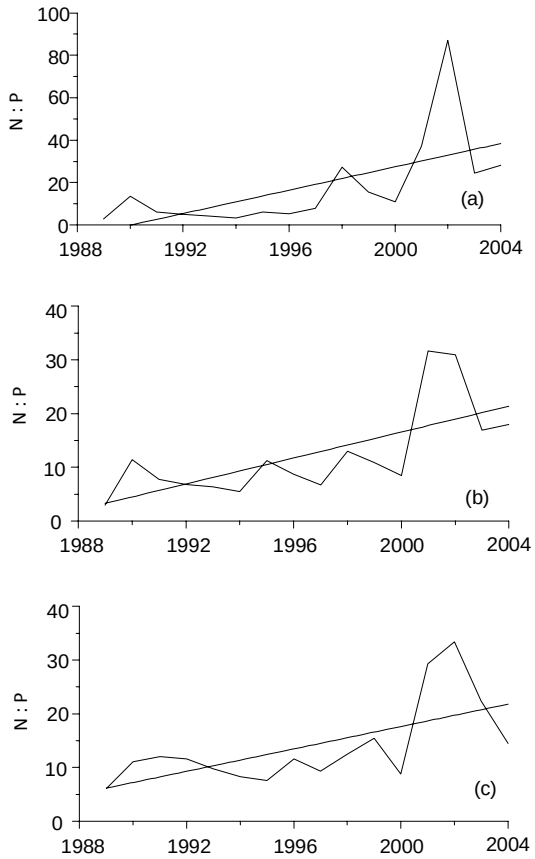

Fig. 8. Variation trends in N:P ratios in the nSCS during 1976–2004. **(a)**, **(b)** and **(c)** show the annual means of sea surface N:P (SSN:P), water column average N:P ($N:P_{av}$) and N:P at the 200 m layer ($N:P_{200}$), respectively. The lines are linear regressions.

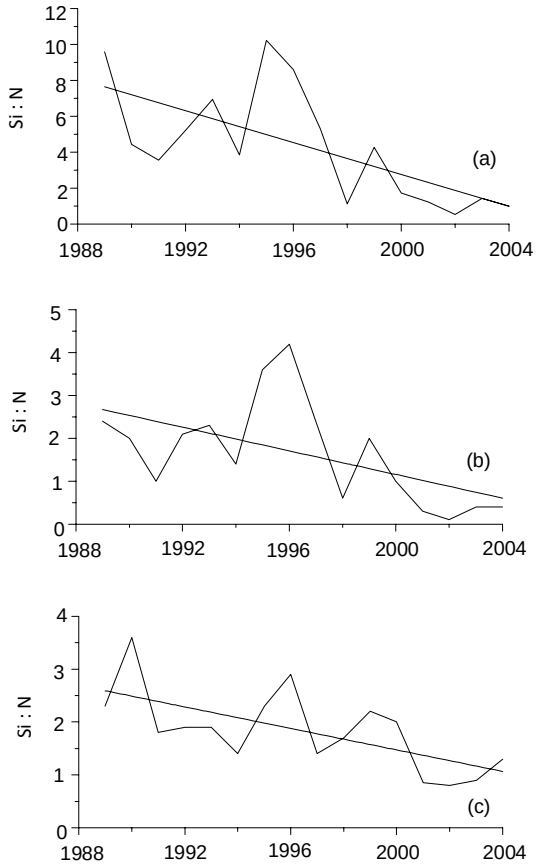

Fig. 9. Variation trends in Si:N ratios in the nSCS during 1976–2004. **(a)**, **(b)** and **(c)** show the annual means of sea surface Si:N (SSSi:N), water column average Si:N ($Si:N_{av}$) and Si:N at the 200 m layer ($Si:N_{200}$), respectively. The lines are linear regressions.

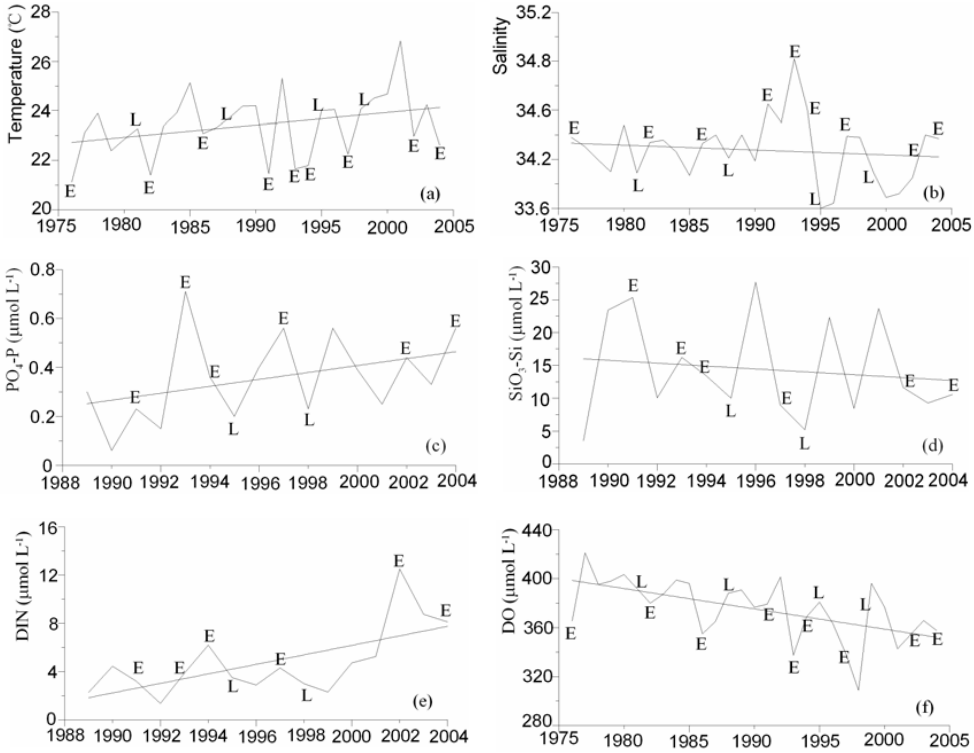

Fig. 10. The interannual changes of the water column average values of **(a)** seawater temperature, **(b)** salinity, **(c)** PO_4-P, **(d)** SiO_3-Si, **(e)** DIN and **(f)** DO at Station 4 in the nSCS in summer, showing the responsive relations of these parameter fluctuation processes on ENSO events (the E is representative of El Nino events happened in the year, and the L is representative of La Nina events occurred in the year).

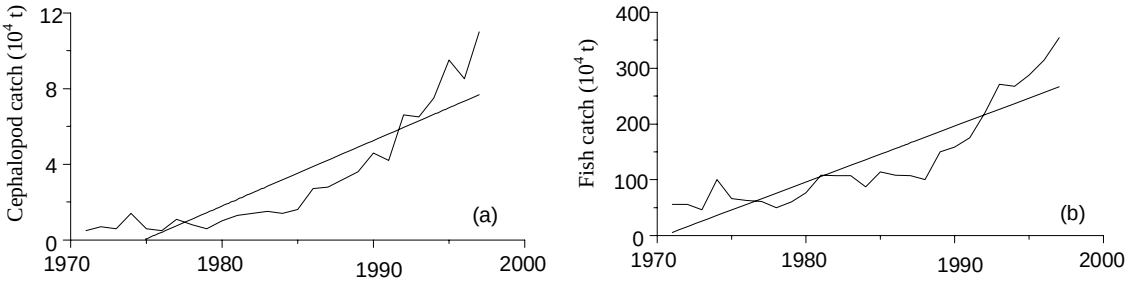

Fig. 11. Variation trends in catches of cephalopods and fish in the nSCS. **(a)** cephalopods; **(b)** fish (Data from Guo and Chen, 2000).

BGD
5, 3737–3779, 2008