Long term environmental changes and the responses of the ecosystem in the northern South China Sea during 1976-2004

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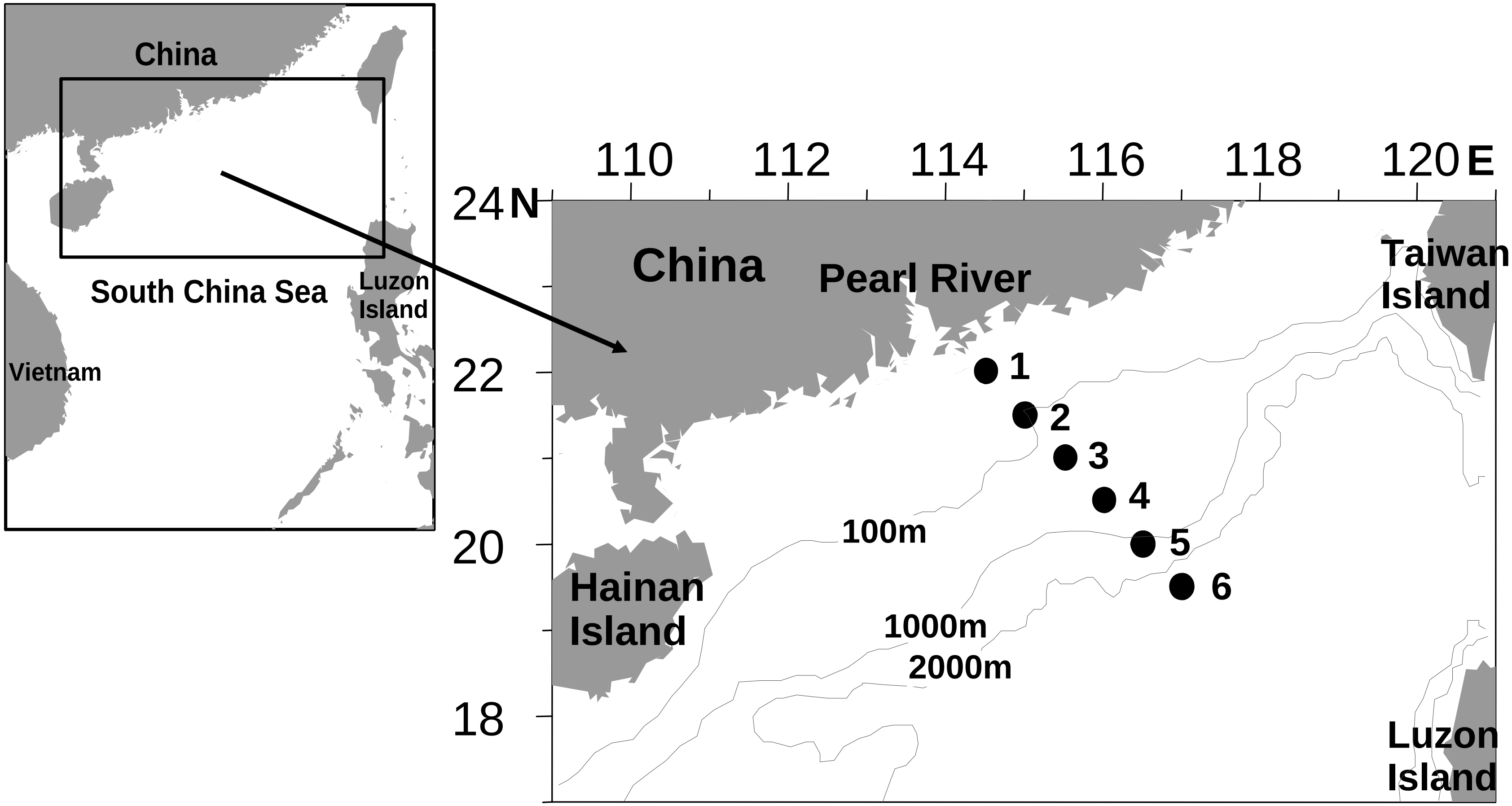


Fig. 1. Geographical locations of the oceanographic observation transect and stations and circulation sketch in the northern South China Sea (nSCS). The transect N from the Pearl River Estuary towards the southeastern nSCS is the main observation transect with 6 stations.

Studied sea area

The South China Sea (SCS) is the largest semi-enclosed marginal sea in the southeast Asia with an area of about 3.5×10^6 km^2, constituting one of the world LMEs (Sherman，2001). Our study area is the northern SCS (nSCS), bounded by the mainland of China on the north and northwest, Taiwan and Bashi Strait on the east, and the Hainan Island on the west side. The topography of the area is characteristic of the incline with a gradient from the coastal zone (< 50 m) to offshore (> 3,000 m) (Fig. 1).

Data and Statistical tests

- Physical and chemical 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 State Oceanic Administration (SOA), China during 1976-2004;
- Biological data, such as chlorophyll *a*, phytoplankton abundance, primary production, zooplankton biomass, benthos biomass, cephalopod catch, etc. were obtained by the South China Sea Fisheries Research Institute (SCSFRI), the South China Sea Ocean Research Institute and the Second Institute of Oceanography, SOA.

- Statistical tests and linear regression analysis were conducted on these time series and climate trend coefficients (Rxt) were estimated. Rxt, 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, { Xi } , and the nature number { i } , I = 1, 2, 3 …, n. In this study, n is the total span of years covered by the data. The coefficient was computed from the following equation:

$$Rxt = \frac{\sum_{i-1}^{n} (Xi - \overline{X})(i - \bar{t})}{\sqrt{\sum_{i-1}^{n} (Xi - \overline{X})^2 (i - \bar{t})^2}}$$

- Where t = (n+1)/2. Its significance level is determined from the Student t-test. A positive/negative value of Rxt indicates that the time series, {Xi}, has a linear positive/negative trend.

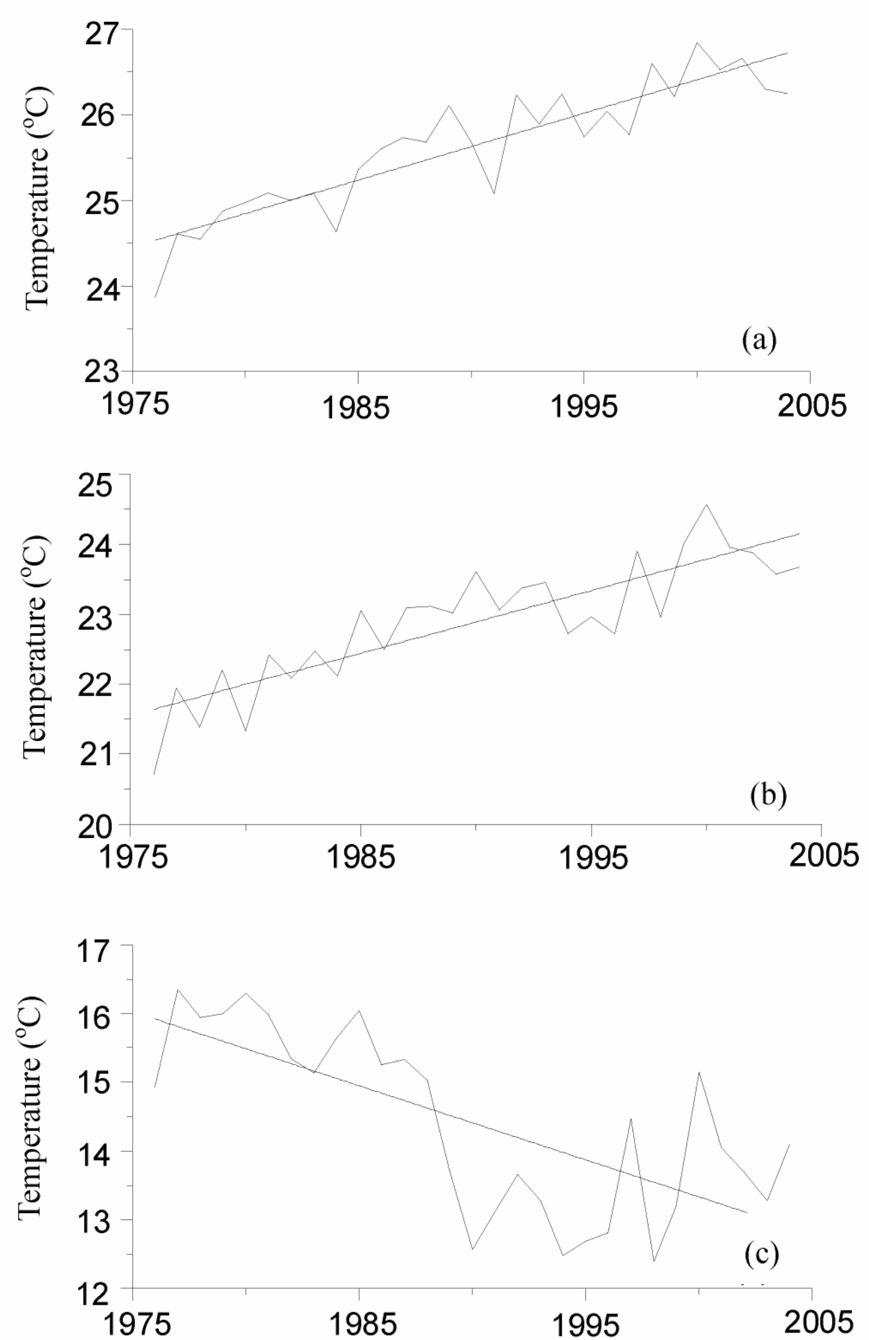


Fig. 2. Variation trends of seawater temperature in the nSCS during 1976-2004. (a), (b) and (c) show annual mean of the sea surface temperature (SST), annual mean of the water column average temperature (Tav) and annual mean of the temperature at the depth of 200 m (T200). The lines are the linear regressions.

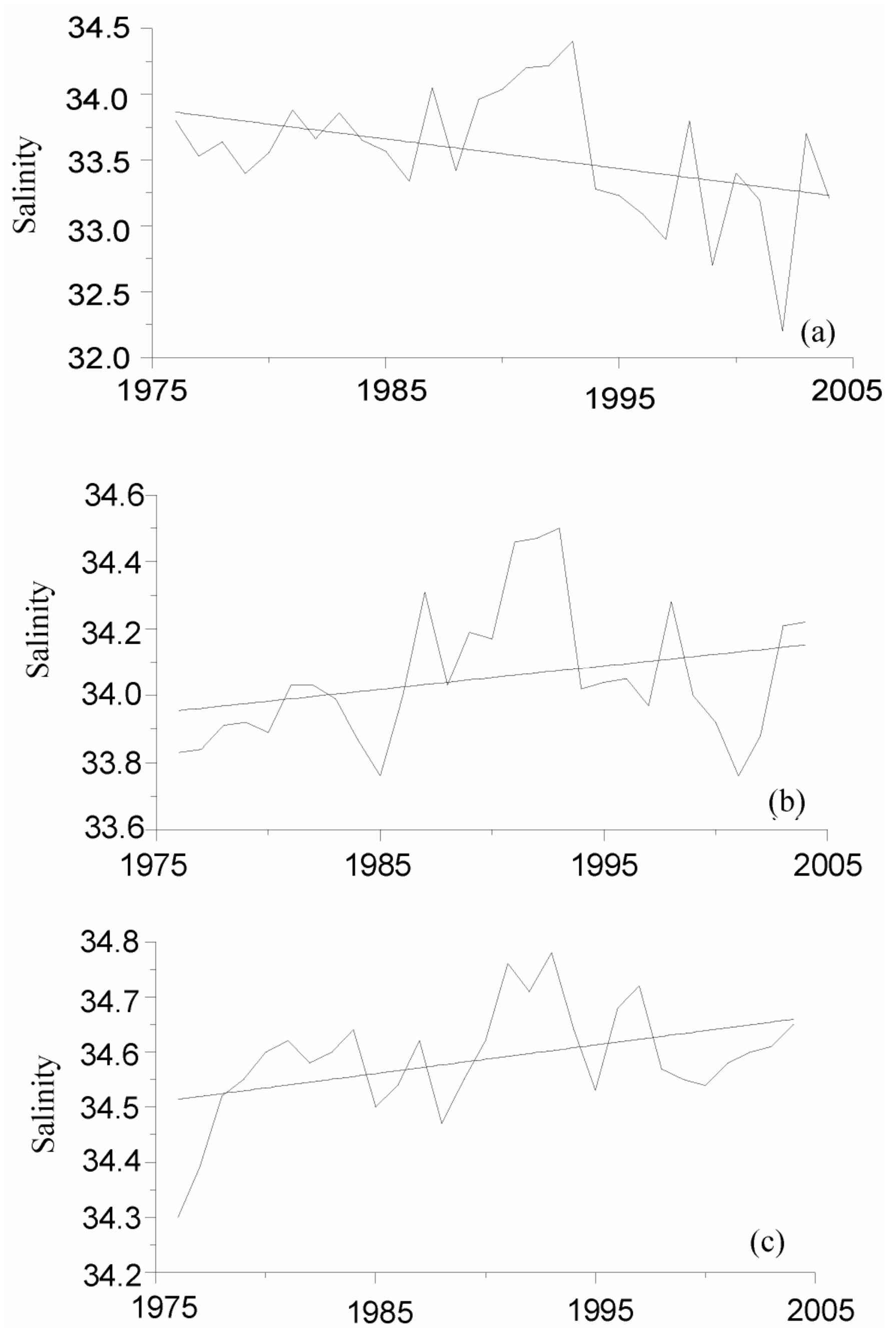


Fig. 3. Similar to Fig. 2, but for salinity:

a) SSS, b) S_{av}, and (c) S_{200}.

The positive increasing trends in SST and Tav in the nSCS during 1976-2004 were consistent with the increasing trends of the mean air temperature (AT) observed throughout the Northern Hemisphere (Houghton *et al.,* 1997; Fu *et al*., 2006), and South China (Chen *et al.,* 1998; Zhai and Ren, 1997) .

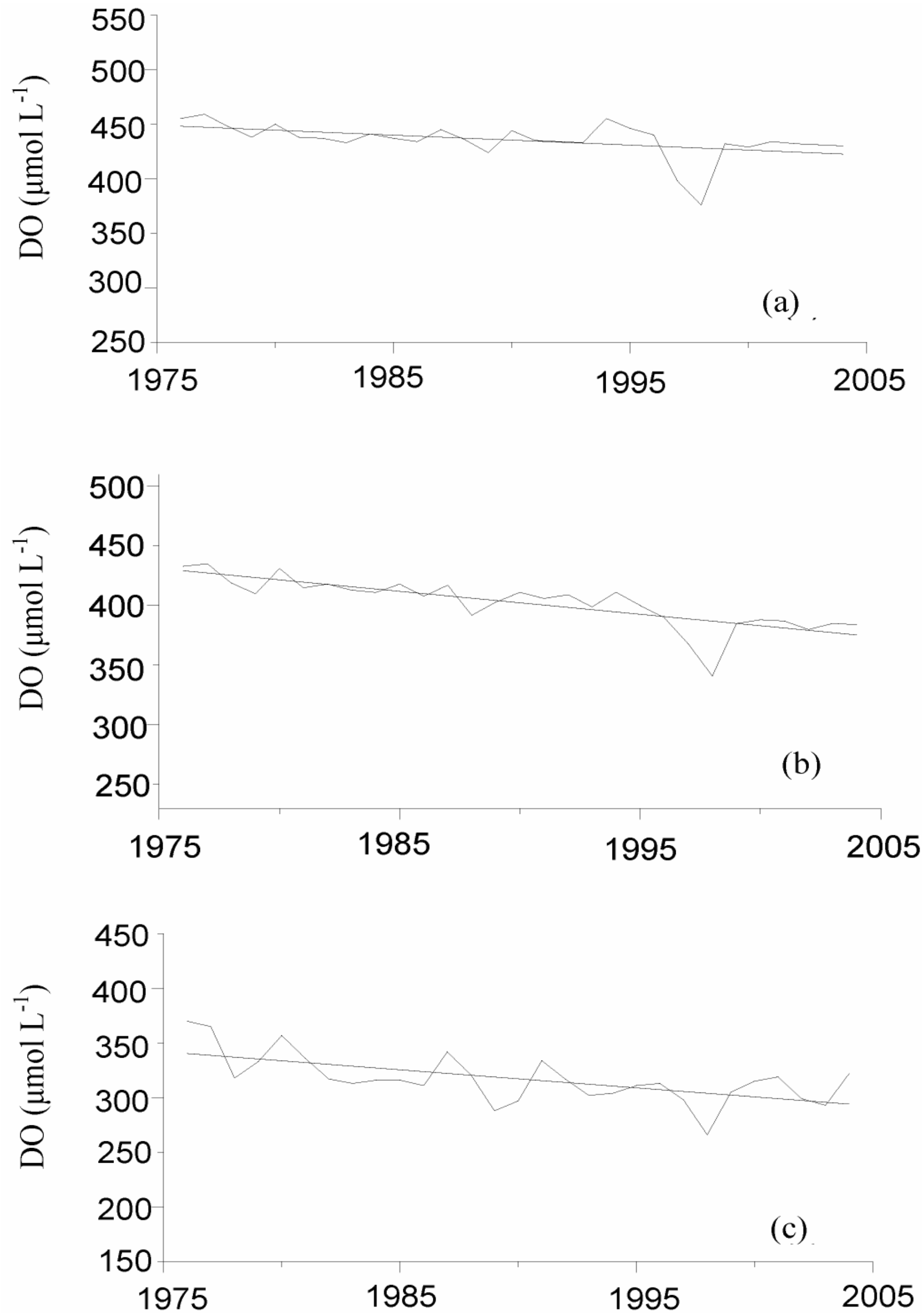


Fig. 4. Similar to Fig. 2, but for DO concentration: a) SSDO, b) DO_{av}, and (c) DO_{200}.

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.

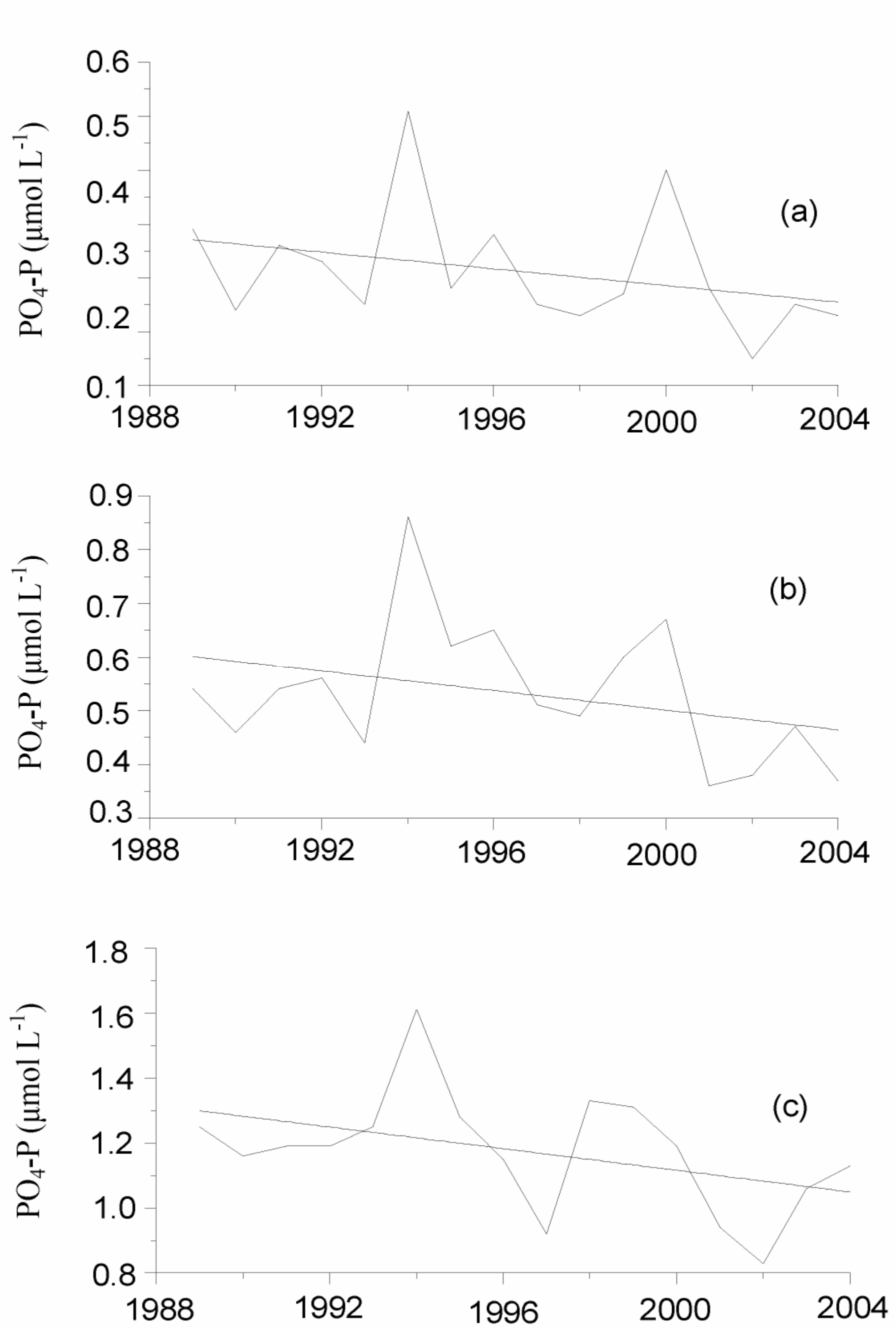


Fig. 5. Similar to Fig. 2, but for PO_4 concentration:
a) SSP, b) P_{av}, and (c) P_{200}.

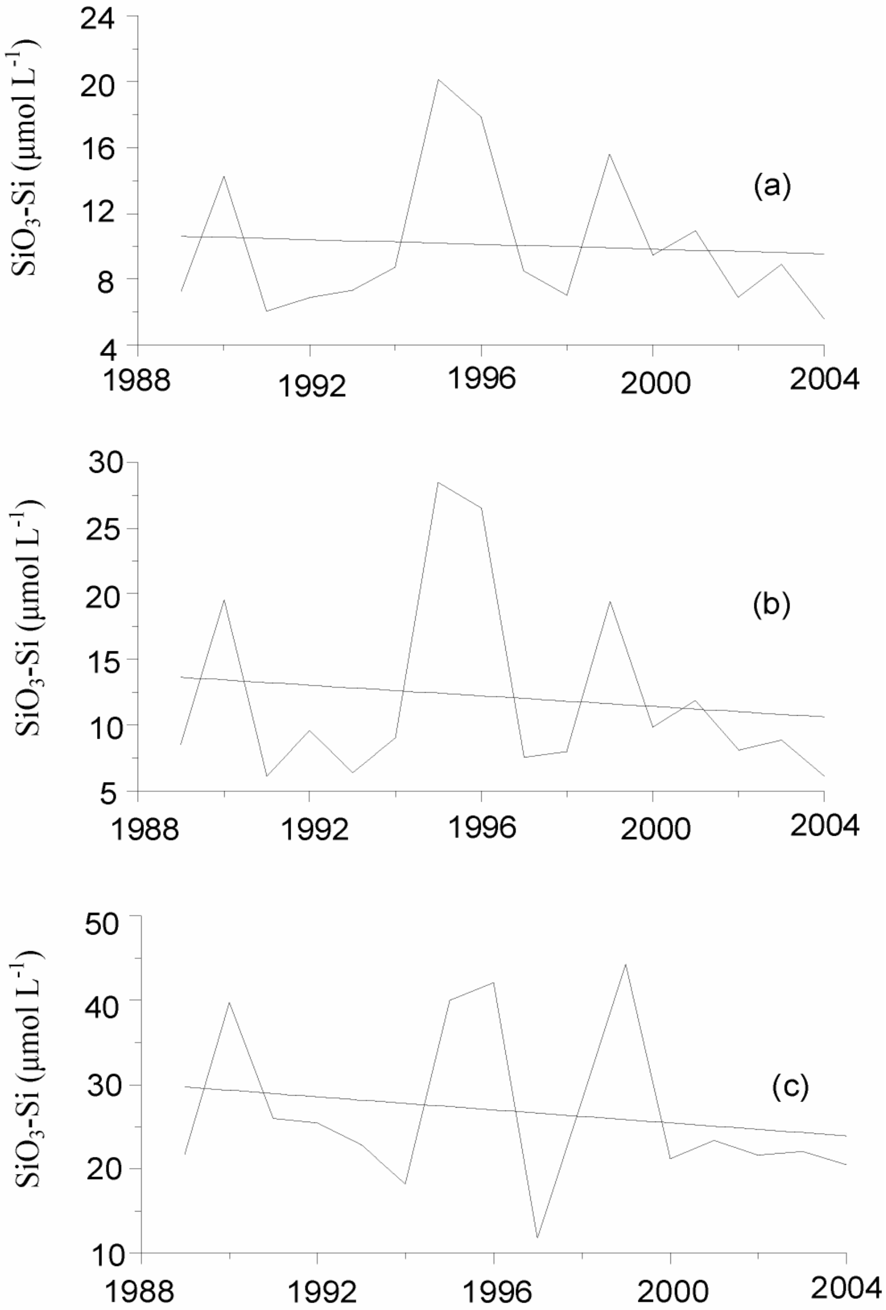


Fig. 6. Similar to Fig. 2, but for SiO_3 concentration:
a) SSSi, b) Si_{av}, and (c) Si_{200}.

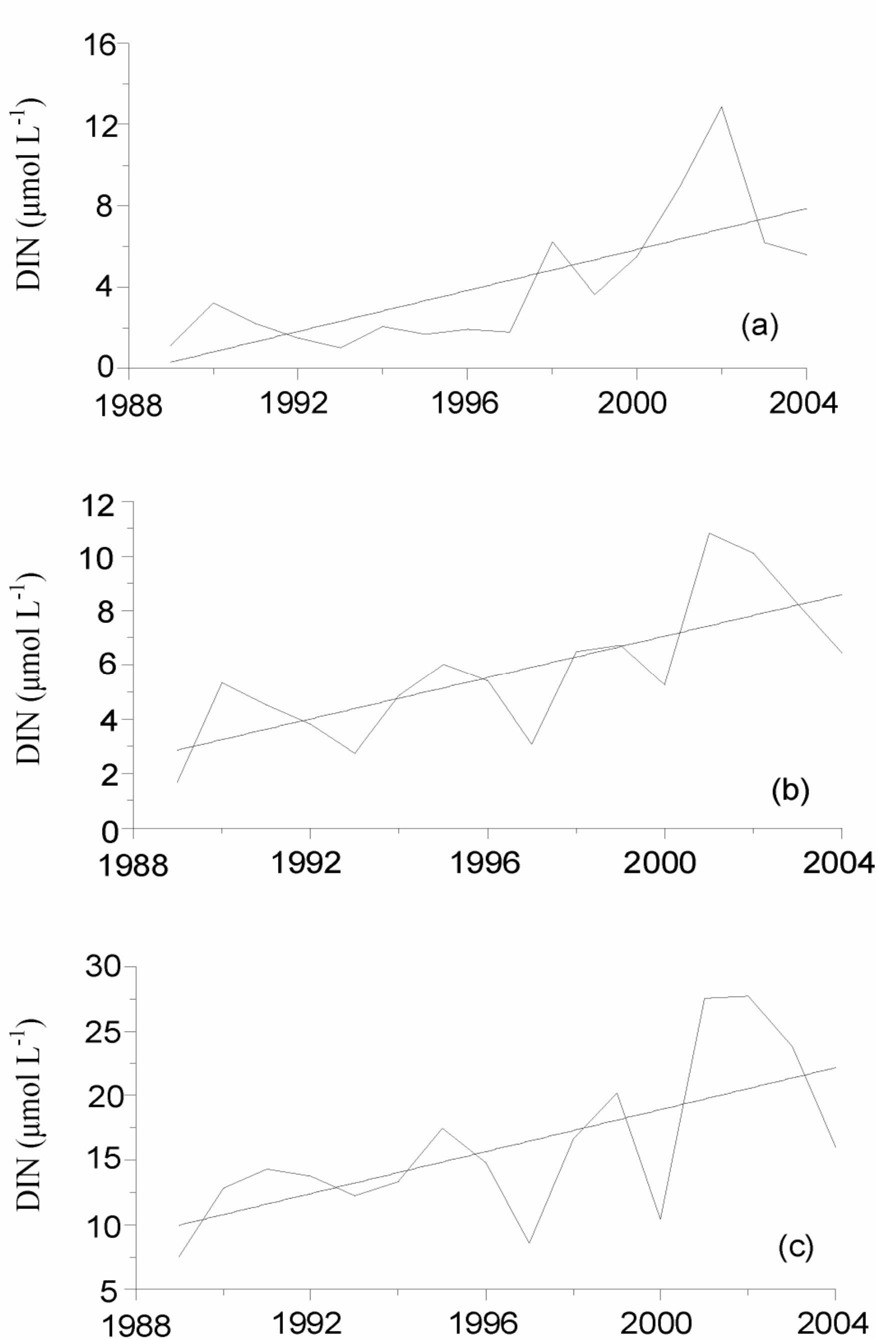


Fig. 7. Similar to Fig. 2, but for DIN concentration:

a) SSDIN, b) DIN_{av}, and (c) DIN_{200}.

Reasons of DIN increasing

The increase in DIN in the nSCS 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 (Wei et al., 2003; Qiu et al., 2005). Along with the rapid economic development in China, DIN concentration in the Pearl River estuary and shelf of the China Seas has been dramatically increasing, due to the increasing in urbanization (SOA, 2001). The DIN in waters of the Pearl River Estuary has increased by about 4 times since 1986 (He et al., 2004). Significant inputs of DIN into the nSCS have occurred not only through river discharge, but also 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.

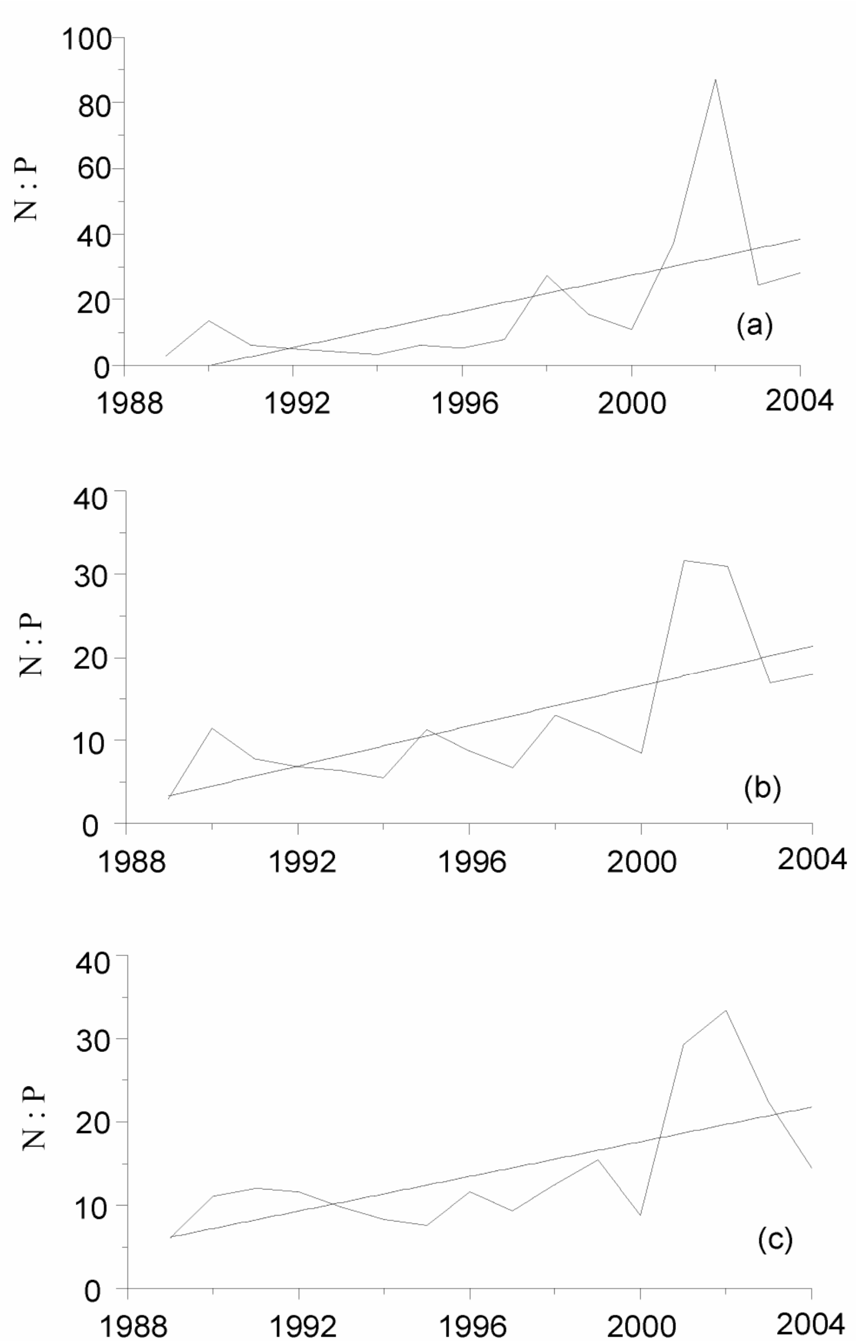


Fig. 8. Similar to Fig. 2, but for N: P ratio: a), SSN: P, b) N: P_{av}, and (c) N: P_{200}.

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. 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; Jiang and Yao, 1999).

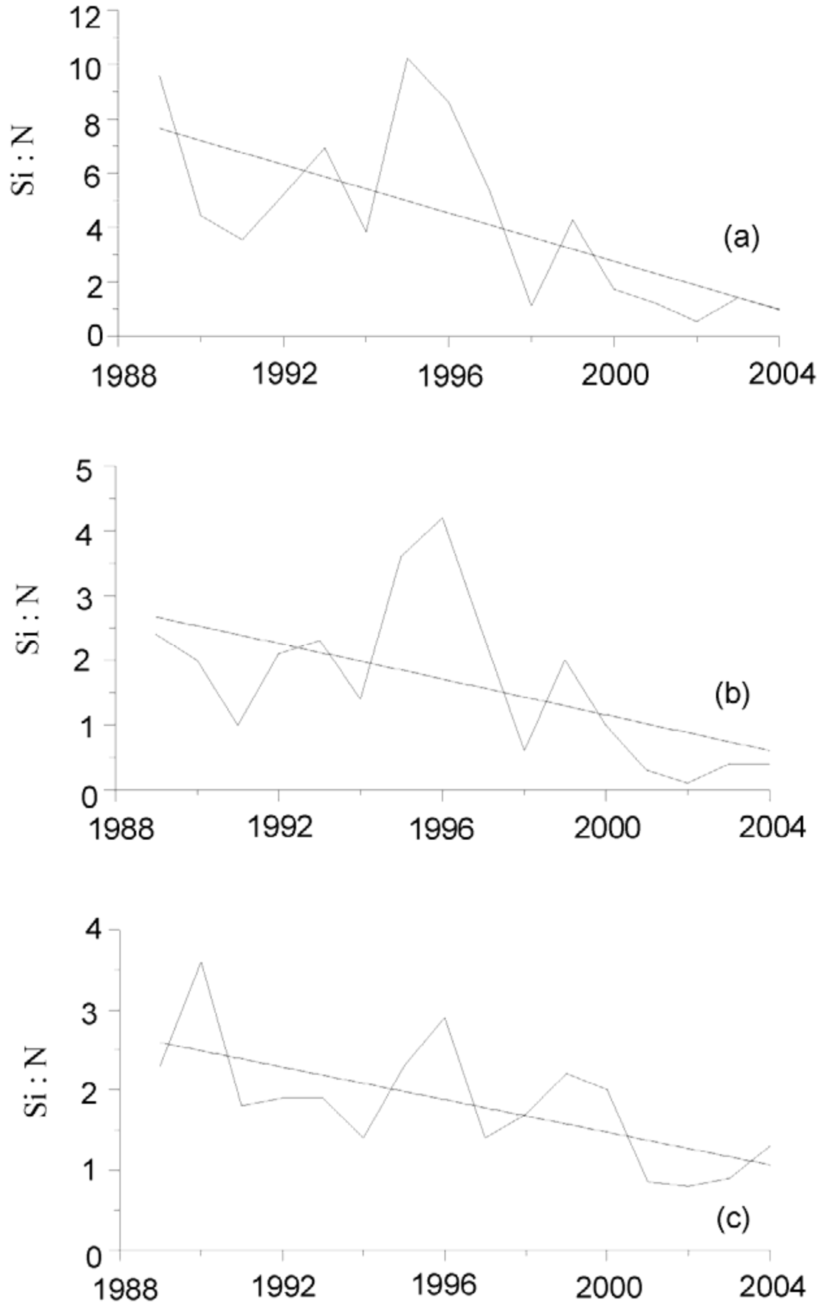
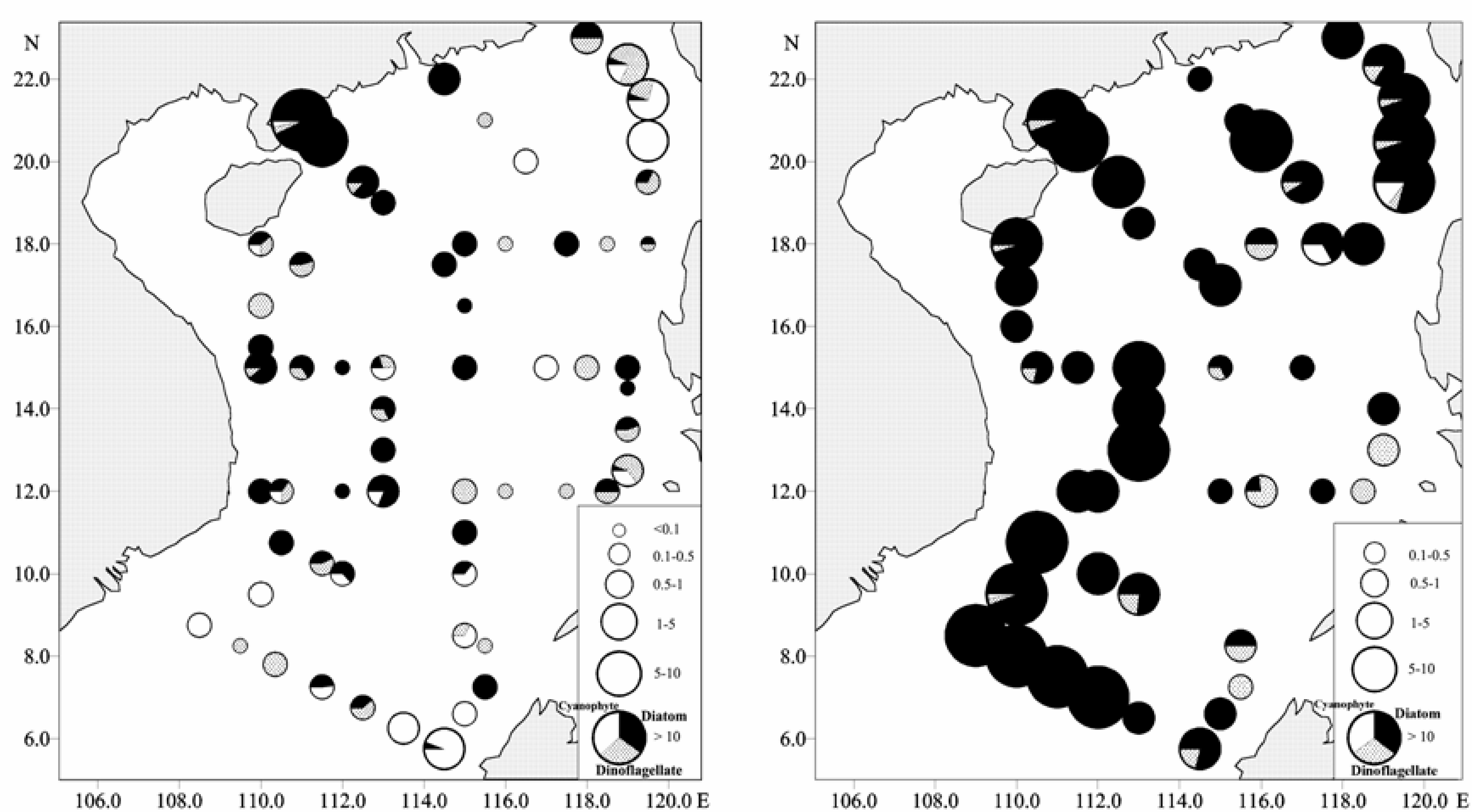


Fig. 9. Similar to Fig. 2, but for Si: N ratio: a) SSSi: N, b) Si: N_{av}, and (c) Si: N_{200}.



a. In summer **b.** In winter

Fig. 10. Phytoplankton abundance ($\times 10^3$ cell·L^{-1}) and distribution at the surface of the SCS (Ning et al., 2004)

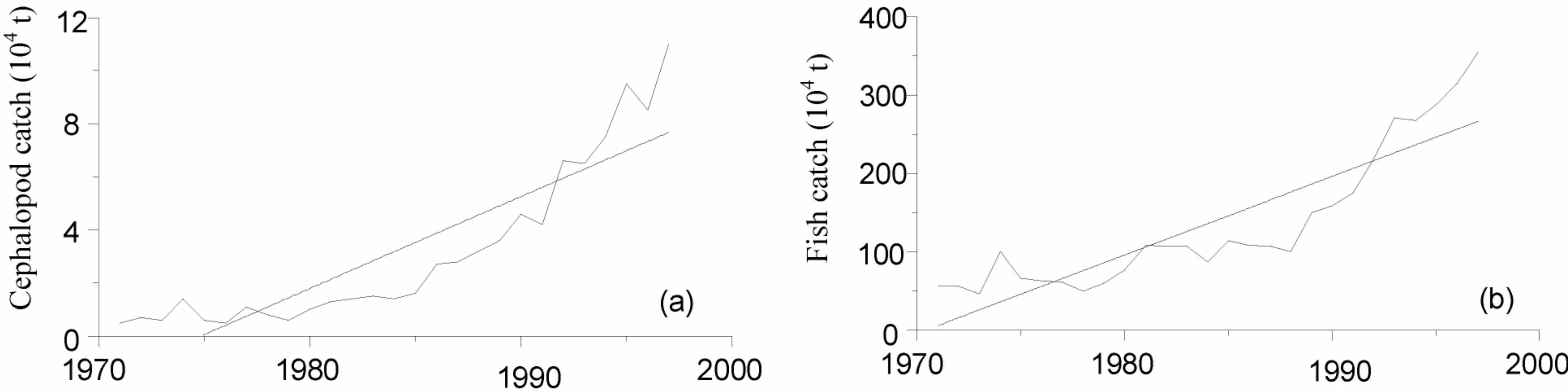


Fig. 13. Variation trends of the catches of cephalopod and fishes in the nSCS. (a) Catches of cephalopod; (b) Catches of fishes (Data from Guo and Chen 2000)

Response of ecological environment to ENSO events

During the observation period at the S4, 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) happened (Wang and Gong, 1999; Qin, 2003; Mcphaden, 2004; Levimson, 2005). In general, whenever El Nino/La Nina happens, SST and Tav was low/high in the nSCS (Figs. 2 and 10a; Table 4).

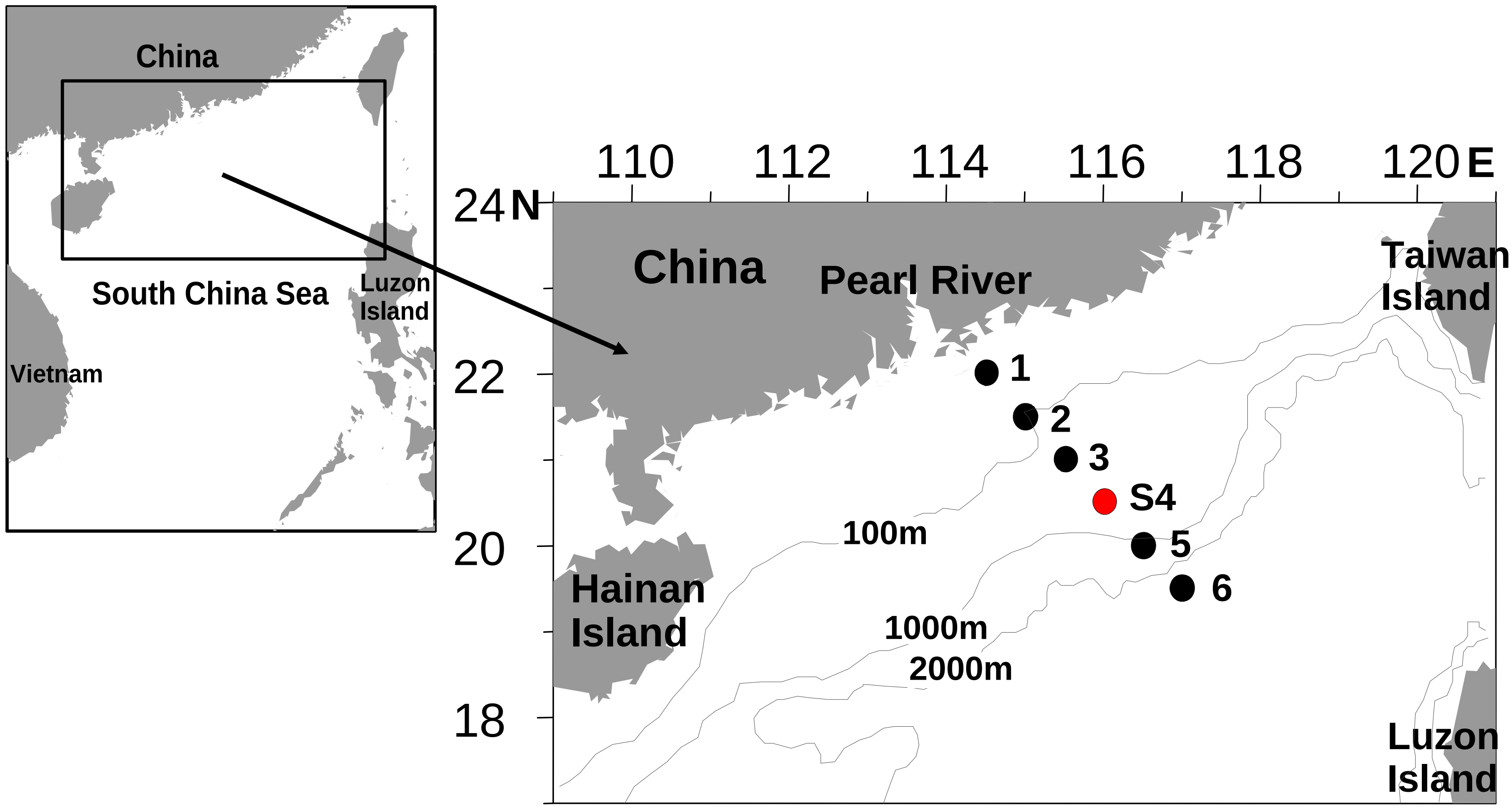


Fig. 11. Geographical locations of the long term oceanographic monitoring station (S4, 19-20ºN, 116-117ºE) in the nSCS.

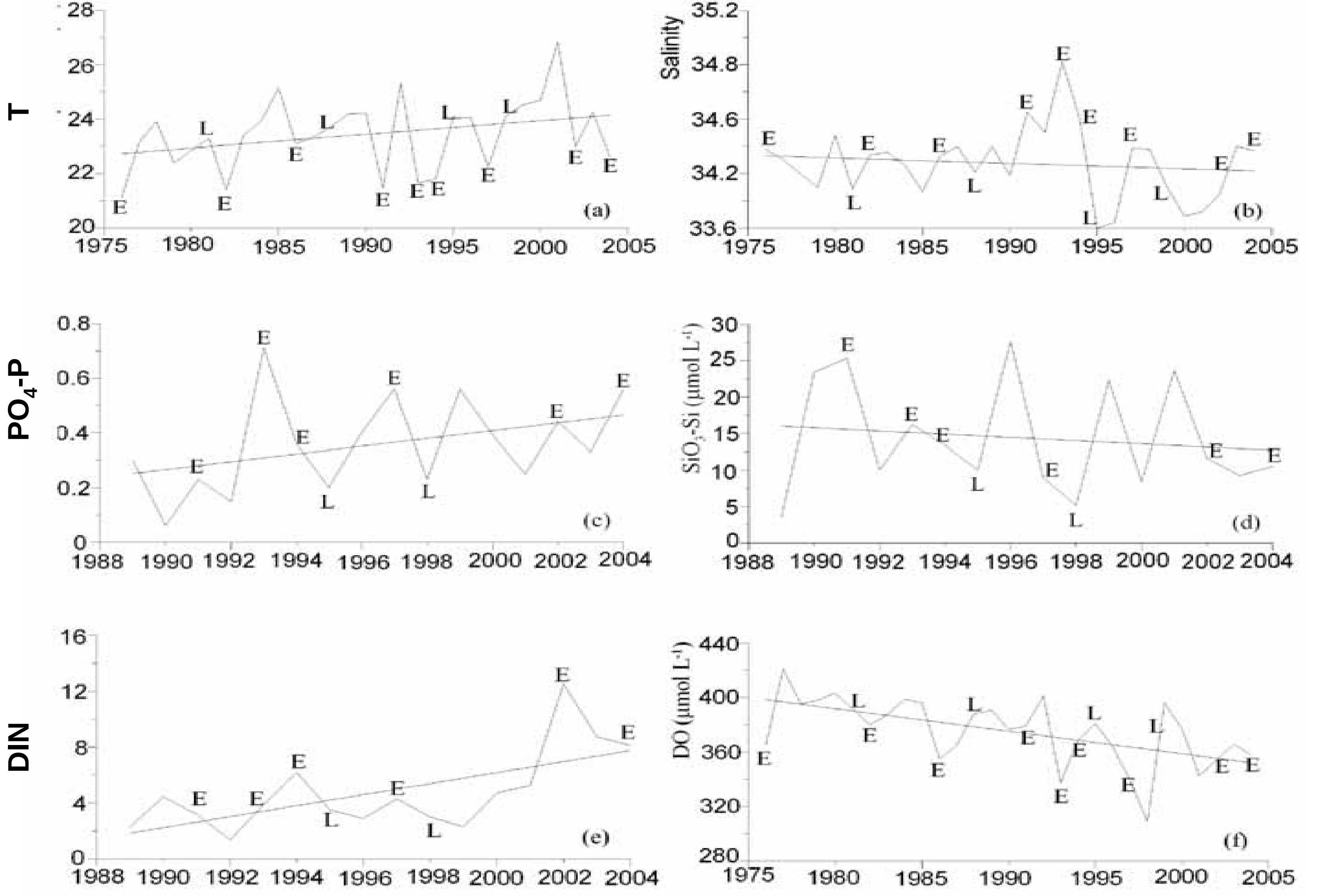


Fig. 12. The interannual changes of the water column average values of temperature a), b) salinity, c) PO_4-P , d) SiO_3-Si, e) DIN and f) DO at the S4 of the nSCS in summer during the observation period.

Comparing fluctuations of T_{av}, S_{av}, DO_{av}, PO_4-P_{av} , SiO_3-Si_{av}, DIN_{av} and sea surface Chl *a* at the S4 of the nSCS in summer during the observation period with the relative ENSO events happened, pronouncedly responsive relationships between these parameters and ENSO could be found (Figs. 12). In general, each peak/valley values of Tav and DOav were corresponding to La Nina/El Nino events, and each peak/valley values of S_{av}, and nutrients (PO_4-P_{av}, SiO_3-Si_{av} and DIN_{av}) were corresponding to El Nino/La Nina events (Fig. 12).

There is a cyclonic eddy in the sea area around S4 (near Dongshan Islands) in summer. Whenever medium and strong El Nino phenomena happen, summer monsoon is weak (Zhang et al., 2003; Zhu et al., 2000,), the cyclonic eddy strengthens, leading to strong upwelling, resulting low T_{av} and DO_{av}, and high S_{av}, nutrients and Chl *a* induced by phytoplankton growth; whenever La Nina events happen, vice versa.

CONCLUSION

- During 1976-2004 the annual rates of SST, T_{av}, S_{av} and S_{200}), DIN and N: P increased, while those of DO, Si: N, SSS and T200 decreased in the nSCS. The climate trend coefficients, R_{xt} of these time series were significant;
- The increasing trends in SST and T_{av} were consistent with the rise of the mean air temperature (AT) in the northern Hemisphere and the southern China;
- SSS decreased along the northern coast of the SCS, which led to strengthening of thermocline and decreasing in the P supply from deep waters;

CONCLUSION

- The increasing trend in DIN may have been influenced by the Pearl River discharge, atmospheric dry and wet deposition, which are related to anthropogenic activities, coastal upwelling and cyclonic eddies;
- Pronounced responses of the environmental features to ENSO have been observed. The effects of climate change on the nSCS were mainly through changes in monsoon, and physical-biological oceanography coupling processes;
- The nSCS was always experienced limitation of N before 1997, it has been mitigated since 1998, the evolving nutrient environment, may be related to the observed ecosystem changes, such as increase in biological productivity.