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Circulation and biogeochemical processes in the East China Sea and the vicinity of Taiwan: an overview and a brief synthesis

Abstract

The East China Sea shelf (including the Yellow Sea and the Bohai Sea) is a very challenging system for hydrodynamic and biogeochemical studies due to its complicated physical and chemical forcing. It receives much attention because of its capacity for absorbing atmospheric CO_2 in spite of large riverine fluxes of terrigenous carbon. This volume reports field observations and modeling studies during the Kuroshio Edge Exchange Processes and ensuing projects, which are a part of the continental margins study in the Joint Global Ocean Flux Study. A 3-D numerical model has been developed to simulate the climatological circulation in the East China Sea. The model result is supported by observations in the seas around Taiwan. The significance of inflow from the Taiwan Strait is emphasized. Geochemical tracers prove useful in understanding the water and material transport. Biogeochemical studies suggest very efficient recycling of organic carbon by bacterial and protozoan consumption in the shelf water, but a finite amount of particulate organic carbon with a significant terrigenous fraction is exported from the shelf. The fine-grained sediments in the inner shelf appear to be an important source of organic carbon for export. Future studies are needed to improve our understanding of key physical and biogeochemcial processes, to develop coupled physical–biogeochemical models, and to catch and survey the elusive spring algal bloom. A tantalizing goal of our ongoing effort is to document or even to predict future changes in the East China Sea shelf caused by the operation of the Three-Gorge Dam, which is under construction in the middle reach of the Yangtze River.

1. Introduction

The continental shelf of the East China Sea (ECS), together with the Yellow Sea and Bohai Sea, forms a contiguous shelf of about $0.75 \times 10^{12}\,m^2$ in area (Fig. 1). The large shelf is bordered by the Okinawa Trough to the east and connected to the South China Sea through the Taiwan Strait to the south. The Kuroshio flows to the east of Taiwan, enters the Okinawa Trough through the Suao-Yonaguni Pass (Wong et al., 2000), and then flows along the shelf break.

Two of the largest rivers in the world, the Changjiang (Yangtze River) and the Yellow River, empty into the ECS. Despite the substantial riverine flux of carbon discharged to the shelf water, ECS has been found to be a sink rather than a source of atmospheric CO_2 (Peng et al., 1999; Tsunogai et al., 1999; Chen and Wang, 1999). Tsunogai et al. (1999) coined the term "continental shelf pump" to describe this phenomenon. Case studies at several other shelf seas also show similar results as the ECS: that these shelf waters absorb rather than release CO_2 (Liu et al., 2000a). These findings have drawn attention to the role of continental margins in the global carbon cycle (Liu et al., 2000a, b; Yool and Fasham, 2001). However, the mechanism and the capacity of the "continental shelf pump", which is effected by a combination of physical and biogeochemical processes, remain unclear.

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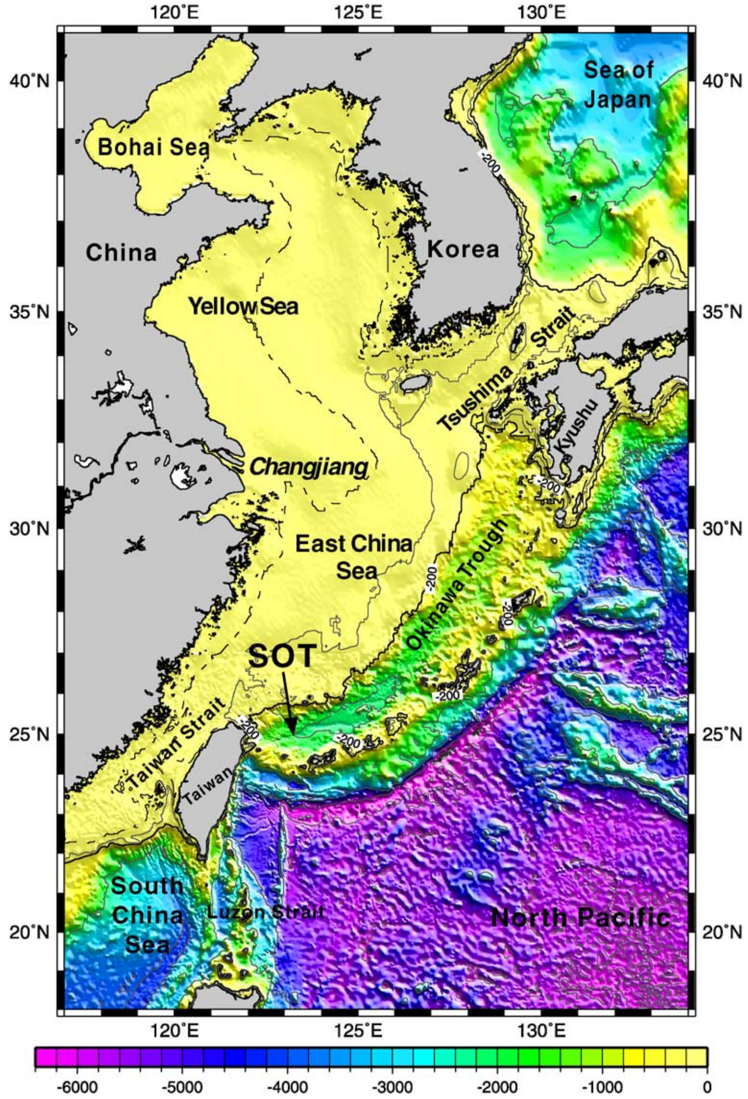

Fig. 1. Bathymetry of the ECS and seas around Taiwan. SOT represents the southern Okinawa Trough. The ECS shelf in this issue is defined as the contiguous shelf including the Yellow Sea and the Bohai Sea. The Changjiang River mouth is labeled in the map. The Yellow River, not shown, discharges to the west end of the Bohai Sea. Contour lines indicate depths of 50 m (dashed), 100, 200, 2000, 4000 and 6000 m. The 200 m contour marks the shelf break.

The purpose of this special issue is to present observational and modeling studies regarding circulation, chemical distribution, biological processes in the lower trophic level and cross-shelf export of materials in the ECS and the vicinity of Taiwan. Most of the work was done during the second (1994–1997) and the third (1997–2000) phases of the Kuroshio Edge Exchange Processes (KEEP) project and the initial stages of the Long-term Observations and Research of the East China Sea (LORECS) and Strait Watch of Environment and Ecosystem with Telemetry (SWEET). Of particular importance are the four cruises conducted in four different seasons between December 1997 and October 1998. These projects, sponsored by the National Science Council of the Republic of

China, have been recognized as a part of continental margins research of the Joint Global Ocean Flux Study (JGOFS). Better knowledge of the physical–biogeochemical processes may allow us to unravel some of the existing mysteries of the ECS, such as the function of the shelf pump, and may help us to detect or even predict environmental changes in the ECS after the operation of the three-Gorge Dam, scheduled to begin in 2009. Earlier work of KEEP has been reported in a previous special volume (Wong et al., 2000). Overviews of the physical, chemical and biological aspects of this special issue are presented, followed by a brief synthesis and future prospectus.

2. Circulation

The Kuroshio, the Changjiang runoff, and the East Asia monsoons are the dominant factors affecting the circulation in the ECS. The Kuroshio enters the region along the east coast of Taiwan and exits along the southern coasts of Japan (Fig. 2). The average transport is 22 Sv ($1\,\mathrm{Sv} = 10^6\,\mathrm{m^3/s}$) east of Taiwan (Lee et al., 2001). Of particular interest to the transport processes in the ECS is the meander in the southern Okinawa Trough and the associated upwelling at the shelf break northeast of Taiwan (Tang et al., 2000). The Changjiang is a major source of fresh water on the ECS shelf. Its annual discharge is about $900\,\mathrm{km^3/yr}$ (Zhang, 1996), maximum in July and minimum in January. Discharge from other rivers, including the Yellow River, are much lower and therefore relatively insignificant in affecting the overall circulation on the shelf. Seasonal variation in the position of the Changjiang plume has a profound influence on the water characteristics on the shelf. Shelf circulation in the region is forced by the strong northeast monsoon from late September to early April and the weaker southwest monsoon from May to August. The monthly climatological circulation in the ECS is given in the numerical results of Lee and Chao (2003). Monsoon winds, Changjiang runoff, volume transports through the Taiwan Strait and the Tsushima Strait, and the Kuroshio current are included in their numerical simulation. The seasonal variation of the inflow in the Taiwan Strait is based on recent direct observations of transport by Wang et al. (2003), Tseng and Shen (2003), and Jan and Chao (2003).

Tseng and Shen (2003) demonstrate the presence of a continuous northward flow through the Taiwan Strait in fall in the trajectories of two surface drifters. The speed of the drifters is between 30 and 50 cm/s in the strait. When reaching the shelf north of the Taiwan Strait, the drifters move slower. The trajectories show oscillations at the period of the semi-diurnal tides. The onset of the northeast monsoon results in one drifter's southward movement and entrainment by the Kuroshio at the shelf break northeast of Taiwan, where the trajectory shows cyclonic rotation in a cold dome.

Based on time-series of shipboard acoustic doppler current profiler (ADCP) data from eight repeated cruises, Jan and Chao (2003) demonstrate the seasonal variation of the flow through the Penghu Channel, where the major transport through the Taiwan Strait occurs. The transport is northward, varying from a maximum of 1.5 Sv during the southwest monsoon to zero at the peak of the northeast monsoon in winter. The maximum flow speed reaches 1 m/s in summer. The diminishing transport in winter implies that a northward warm current against the wind in the Penghu Channel is not likely in winter.

Liang et al. (2003) have compiled the shipboard ADCP measurements in the seas surrounding Taiwan to provide information on surface currents in the Taiwan Strait and the Kuroshio east of Taiwan. The meander of the Kuroshio in the Luzon Strait and the intrusion onto the shelf at the shelf break northeast of Taiwan are shown in the composite flow field (Fig. 2). The northward flow through the Taiwan Strait onto the shelf north of Taiwan is demonstrated in summer. Whether the flow in the Taiwan Strait continues northward, stops altogether or even reverses under the northeast monsoon in winter is not resolved because of the gap in data and lack of water mass information.

Lee and Chao (2003) present numerical model results with focus on the dispersal of the Changjiang plume and the mesoscale features along the

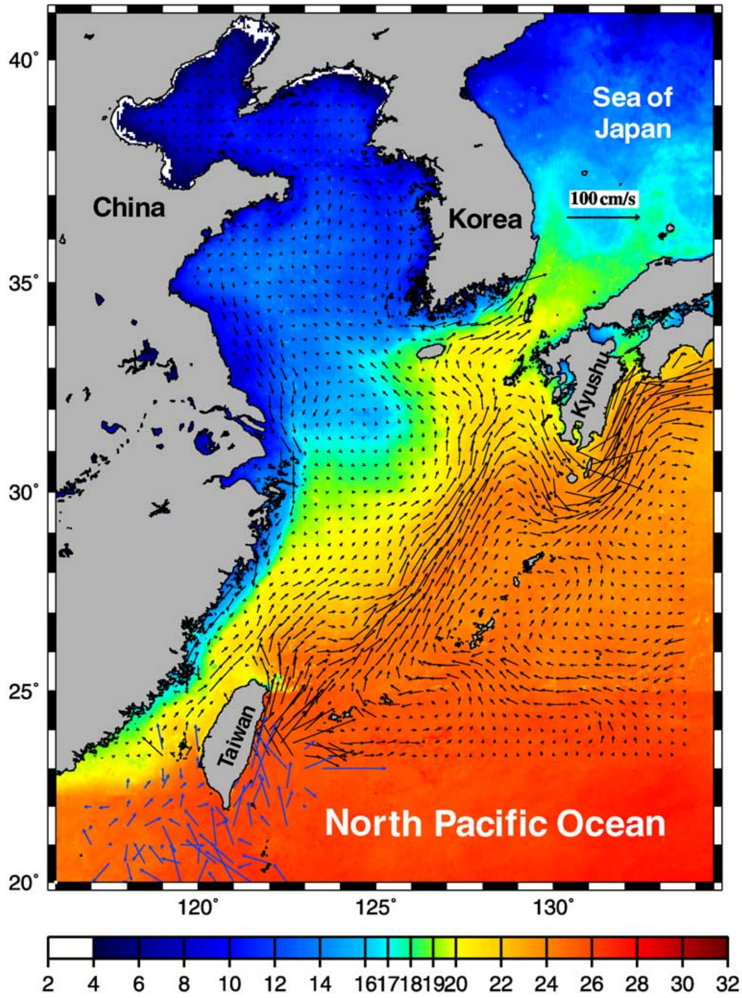

Fig. 2. Distribution of mean sea surface temperature (SST) in December in the ECS and seas around Taiwan overlaid with observed (blue vectors, south of 23°N) and modeled (black vectors, north of 23°N) surface currents. The SST data in °C are averaged from stacked data of December in 1999–2001 obtained by AVHRR onboard NOAA satellites. The observed currents represent the long-term average at 30 m measured by the ship-board acoustic doppler current profiler (Liang et al., 2003) under northeast monsoon (November–April). For clarity only those south of 23°N are shown for the observed currents. The modeled currents (Lee and Chao, 2003) are averages in the upper 50 m. The flow field agrees with the thermal field well.

shelf break of the ECS. On the shelf of the ECS, the southward coastal current in fall and winter and the northward expansion of the flow from the Taiwan Strait in spring and summer are reproduced. The Changjiang plume is greatly influenced by this circulation pattern. The plume forms a narrow band flowing southward along the coast of China in winter (Fig. 2), but disperses toward north and east in summer. The model reproduces anticyclonic meanders of the Kuroshio northeast of Taiwan and southwest of Kyushu and upwelling and downwelling areas at the shelf break, but the cyclonic cold eddy off northeast coast of Taiwan is too small to be resolved by their model. The modeled meander of the Kuroshio as it encounters the shelf break of the ECS near Taiwan agrees with the observed composite flow of Liang et al. (2003). The model shows persistent upwelling east of the Okinawa Island although verification by observations is needed.

3. Geochemistry and material transport

It has been demonstrated that the Kuroshio strongly influences not only the circulation in the ECS shelf but also its chemistry (e.g., Gong et al., 1996; Liu et al., 2000c) through water mass exchanges, which are yet to be fully explored. Wong and Zhang (2003) illustrate the two major species of dissolved iodine, namely, iodate (IO_3^-) and iodide (I^-), as a pair of novel tracers to indicate origin of water masses and biogeochemical processes in the southern ECS. Their survey results show the composition of the upwelling Kuroshio subsurface water with elevated concentration of iodate and depressed concentration of iodide. In contrast, the variations in the concentration of iodate and iodide among other surface water masses are relatively small. They conclude that within the shelf system, iodate is consumed and iodide is produced. The frontal exchanges between the shelf system and the Kuroshio result in a net export of iodide from the shelf system to the Kuroshio, implying the ocean margins are a significant net source of iodide to the ocean interior.

The "continental shelf pump" is facilitated by the cross-shelf exchange of water masses and materials. Using a global general circulation model, Yool and Fasham (2001) show that the shelf pump is capable of absorbing more than 0.5 Pg C annually if the shelf pump functions similarly in all margins. They also demonstrate that the shelf pump would be more efficient if the carbon export is in the organic form. Several papers in this issue address the export of dissolved and particulate organic matter from the shelf.

There are many studies of dissolved organic matter (DOM) in the open ocean, but relatively few studies are carried out in the marginal seas. Hung et al. (2003) describe the distributions of dissolved organic carbon (DOC) and stoichiometric patterns (namely, relative abundance of nitrogen and phosphorus in the dissolved organic form) in the ECS. Their results give evidence to the efficient recycling of DOM in the ECS shelf; the dissolved organic phosphorus (DOP) is especially labile. Because the intruding Kuroshio surface water is enriched in DOC, the DOC export via water mass exchange roughly balances the input. This makes the ECS shelf not an important source nor sink of DOC.

On the other hand, the ECS shelf is definitely an important source of particulate matter to the deep sea. The southern Okinawa Trough (SOT) is noted as an important sink of particulate matter from the shelf. A direct observation of shelf export is provided by Chung et al. (2003), who deployed time-series sediment traps and current meters in the slope area of the southern ECS and the western SOT (Fig. 1) to collect and study the settling particulate matter. They measured particulate mass fluxes, the associated currents, size distributions, chemical compositions, and particle-active radioisotopes. The time-series collection scheme and the many sampling sites distributed in the SOT region throughout the second and third stages of KEEP provided information on the spatial and temporal variation of the settling particulate matter. These results are used to evaluate the mixing and transport of the particulates in the KEEP study area. They find that the near-bottom traps collected much higher fluxes of radioactive nuclides (i.e., ^{210}Pb) than those derived from the inventories of radioactivity in the underlying sediments. They suggest the large fluxes of particulate matter observed near bottom are not the flux of deposition but a flux in transit.

The particulate organic matter (POM) exported to the SOT off northeastern Taiwan may come from plankton produced in the overlying water column, from the ECS shelf, from the runoff of the Lanyang River in northeastern Taiwan, or from other rivers farther south on the east coast of Taiwan. In order to trace the origin of POM, there are two different approaches reported in this issue: employing either organic compounds or isotopic signature to indicate the sources. Jeng et al. (2003) use hydrocarbon distribution to identify the source of organic matters. They examine *n*-alkanes, *n*-fatty alcohols and sterols in the sediments from SOT and conclude that most of the extracted lipids were of terrestrial origin.

Alternatively, Kao et al. (2003) use carbon and nitrogen isotopes as tracers to track down the elusive export flux of organic matter from the shelf to the deep sea. Comparing isotopic characteristics of sedimentary organic matter all over the ECS and the adjacent Okinawa Trough, they find uncanny similarity ($\delta^{13}C = -23‰$ to $-21‰$, $\delta^{15}N = 3.5‰$ to $4.5‰$) between sediments from the inner shelf near the China coast and from the Trough. They report that the coastal belt of elevated total organic carbon content extends southward from Changjiang mouth and veers offshore towards SOT just north of Taiwan, indicating a pathway for channeling fine-grained sediments from the inner shelf to SOT.

4. Biology and carbon cycling

It is remarkable that the ECS shelf waters are undersaturated with respect to atmospheric CO_2 both in the warm and the cold seasons (e.g., Peng et al., 1999; Tsunogai et al., 1999). As the sea-surface temperature of the shelf water increases markedly ($>27°C$) in mid-summer (Gong et al., 1996), fairly efficient autotrophic uptake of carbon must be in action to keep the fugacity of CO_2 in the surface water below saturation. In this special issue, four papers deal with the autotrophic processes in the ECS, while three other papers deal with heterotrophic processes that convert organic carbon into CO_2 during respiration. These studies put constraints on how the biological processes may contribute to the shelf pump.

Gong et al. (2003) show that biological fixation of carbon (i.e. primary productivity) is the highest in summer. The favorable temperatures, higher light intensities, and copious supply of inorganic nutrients (from the Changjiang runoff and coastal upwelling under the southwest monsoon) in summer lead to the maximal growth of autotrophs within the plume of Changjiang diluted water and the adjacent coastal zone. Due to the phosphate poor condition of the Changjiang runoff, Gong et al. propose that the supply of dissolved inorganic phosphorus from the coastal upwelling and, perhaps, organic and particulate phosphorus, which is enriched in the Changjiang discharge and may be readily hydrolyzable, fuel the high primary production in summer. Their estimated annual mean of primary productivity is $155\,gC/m^{-2}\,yr^{-1}$ for the coastal waters and $144 \pm 27\,gC/m^{-2}\,yr^{-1}$ for the outer shelf. The two mean values are statistically indistinguishable. It is counter-intuitive that the eutrophic coastal zone is not more productive than the oligotrophic waters in the outer shelf on the annual basis. This is mainly due to the rather low primary production under the northeast monsoon, which prevails from October to April. Independently, Gong et al. (2003) Chen and Chen (2003) reach the same conclusion that light limitation caused by high turbidity of the coastal water under strong wind prevents high primary production in the coastal waters.

The papers by Chang et al. (2003a, b) and by Chen and Chen provide important attributes of the phytoplankton community. Using the volume of the phytoplankton cells to estimate the biomass in terms of carbon unit, Chang et al. (2003b) determined the carbon to chlorophyll ratios in three typical environments of the ECS shelf, namely, the coastal zone, the middle shelf and Kuroshio upwelling zone. The large variation of the C:Chl ratio, ranging from 18 in the coastal zone to 94 in the outer shelf, points to the environmental control of the phytoplankton physiology. The range is considerably larger than that (32–80) considered in existing biogeochemical modeling (Doney et al., 1996; Liu et al., 2002). Using the ^{15}N uptake data, Chen and Chen report that on average, 40% of the primary production in the ECS shelf is supported by nitrate uptake. Chang et al. (2003a) report that *Synechococcus*, one of the major primary producers in the ECS, contribute 5–63% of the total primary production. They also report that more than 37% of the *Synechococcus* production is not consumed by grazers (i.e. flagellates and ciliates) in spring and summer.

The high primary production in summer does not necessarily lead to higher organic carbon export. The favorable conditions in summer not only make autotrophs flourish but also enhance heterotrophic activities. Chiang et al. (2003) report highest ciliates abundance in summer, and ascribe it to the rich supply of food in the Changjiang plume during the highest runoff of the year. Shiah et al. (2003) report maximal bacterial growth rate in summer. The summer carbon demand of ciliates could reach as high as

108% of primary production, while the annual average is only 40%. The combined carbon demand by ciliates and bacteria could reach as high as ~200% of the measured primary production in summer. On the annual cycle, bacterial growth inside the mid-shelf during cold (winter and spring) and warm (summer and autumn) seasons is regulated by temperature and organic substrate supply, respectively; the estimated bacterial carbon demand could be as high as the annual primary production. In autumn, the planktonic community respiration demands a carbon supply three times the primary production (Chen et al., 2003), implying that any leftover of fixed carbon from summer would be effectively consumed in autumn. The strong carbon demand is attributed mainly to bacterial respiration in the mesotrophic inner/mid-shelf waters and mainly to the protozoan respiration in the oligotrophic outer shelf waters. The strong heterotrophic activities may be partially induced by organic matter discharged from the Changjiang, especially in summer when the runoff reaches maximum.

The physical conditions in summer do not favor seaward export either. The prevailing southwest monsoon in summer favors upwelling, which may prevent sinking particles, especially the organic-rich fine particles, from settling (Hu, 1984) and make them more susceptible to bacterial degradation in the water column. Strong stratification may retain the biogenic DOM in the surface water, where bacterial degradation or photolysis may consume DOM easily. In the less productive outer shelf, the higher bacterial production/primary production ratios observed by Shiah et al. (2003) also makes organic carbon export unfavorable.

5. A brief synthesis and future prospectus

Findings in this issue have shed new light on the biogeochemical cycles in the ECS and illuminate how the shelf pump may function. Based on nutrient and carbon budgeting, Chen (2003) suggests that the new production:primary production ratio or *f* ratio (0.4) based on $^{15}NO_3^-$ uptake is considerably higher than the fraction of exported primary production, which is more likely in the range of 0.12–0.15. The apparently higher *f*-ratio is attributed to the nitrate regenerated on the shelf, which is manifested by the nitrate-enriched, oxygen-depleted bottom water observed by Gong et al. (1996). On the other hand, the enhanced nitrate uptake agrees well with the implication that the ECS shelf is a preferred site for iodide production, because the reduction of iodate is closely associated with nitrate uptake (Wong and Hung, 2001).

The strong northward flow observed in the Taiwan Strait places the annual mean volume transport at 0.86 Sv or higher (Wang et al., 2003; Jan and Chao, 2003), which is considerably larger than those (0.36 Sv or less) employed in the box models for water budgeting (e.g., Chen and Wang, 1999). This calls for new estimates on the turnover rate of shelf waters in the ECS, and consequently, warrants revision of the nutrient and carbon budgets. This new finding appears to exacerbate the existing discrepancy between estimates of residence time of the ECS shelf water: more than 2 years vs. less than 1 year. The former came from Nozaki et al. (1989), who based their calculation on supply and inventory of radium isotopes in shelf waters; the latter was derived from the water budget generated by box models of water and salt balance (e.g., Chen and Wang, 1999). Higher inflow from the Taiwan Strait will drive the already low estimate from water budget even smaller. The model results of Lee and Chao (2003) show a possibility of reconciliation between the two contradicting estimates. Their flow fields show that most of the outflow from the Taiwan Strait veers seaward in the southern ECS shelf and merge with the Kuroshio south of 28°N. Based on such a scenario, Liu and Chen (2002) separate the ECS shelf into two regimes, the southern ECS shelf that has fast turnover of shelf water and the northern ECS shelf (including the Yellow Sea and the Bohai Sea) that shows considerably longer residence time. Most of the data of Nozaki et al. (1989) were obtained in the northern regime, and hence, produced a rather long residence time.

Both the budgeting of DOC (Hung et al., 2003) and estimates of carbon demand by heterotrophic processes (Shiah et al., 2003; Chen et al., 2003) suggest little, if any, organic carbon from primary production is available for export. This seems difficult to reconcile with the rather strong shelf pump implied by air–sea CO_2 fluxes (Tsunogai et al., 1999; Peng et al., 1999) and carbon budgeting (e.g., Chen and Wang, 1999). It may be premature to jump into conclusion based on biological observations, because the spring algal bloom, which is not reported in this volume, could account for as much as 1/3 of the annual primary production in some cases and may result in significant export. However, rather high chlorophyll concentrations (Ning et al., 1998) and production (Jiao et al., 1998) approaching bloom conditions in the mid-shelf have been reported, but its extent is yet to be determined. When a large-scale spring bloom does occur, primary production may outpace bacterial consumption as indicated by the observation of Shiah et al. (2003) that the ratio of bacterial production vs. primary production decreases with increasing primary production. Consequently, a surplus of organic carbon is likely to survive for export.

A finite amount of particulate organic carbon must be exported from the shelf as indicated by direct and indirect evidence (Chung et al., 2003; Jeng et al., 2003; Kao et al., 2003). Kao et al. (2003) infer from carbon and nitrogen isotopic results that the inner shelf may be an important source of the exported sedimentary organic, which is transported via the seaward flow off northeastern coast of Taiwan to the SOT. Their inference is supported by the model results of Lee and Chao (2003) that such a seaward transport is likely to happen under the northeast monsoon. On the other hand, the voluminous sediment production on Taiwan is certainly important to the sedimentation in the SOT. Especially notable is the Lanyang Hsi (Kao and Liu, 2002), which discharges to the landward end of SOT with an average annual load of about 9 Mt. Chung et al. (2003) suggest a near-bottom sediment movement as an important mode of lateral transport from the continental shelf to the bottom of the Okinawa Trough, which may correspond to the density driven flow observed elsewhere (e.g., Ogston et al., 2000).

As shown above, substantial amount of field work has been conducted in the ECS, but our understanding of the physical and biogeochemical processes is not yet sufficient for us to fully comprehend the operation of the shelf pump. Relative to the findings we had established a few years earlier (Wong et al., 2000), we have gained more insight of the relative significance of different biological processes and their relationships with environmental conditions; we have established better geochemical tracers suitable to trace the origin of various biogeochemical substances; most of all, we have established a numerical hydrodynamic model supported by field observations.

In the future, the numerical model can be used as a tool to explore biogeochemical processes, to delineate carbon transport and transformation in the ECS shelf and to verify the hypotheses raised in this volume. In order to develop a coupled physical–biogeochemical model, we need to formulate all essential biogeochemical processes in terms of state variables and relevant parameters. The latter may be derived from field observations, such as the C:Chl ratios observed by Chang et al. (2003b), or from on board mechanistic experiments. More physical and biogeochemical observations are needed to constrain and verify the model. Most needed are simultaneous observations of biogeochemical variables (e.g., CO_2 fugacity in surface seawater and overlying air, nutrient concentrations, autotrophic and heterotrophic activities, isotopic signatures and biomarkers in sediments and particulate matter, etc.), and environmental factors (e.g., water column stratification, hydrography, wind, river discharge, etc.).

Although ocean color data obtained by satellite remote sensing is routinely used to determine chlorophyll concentrations in surface seawater, from which primary productivity may be estimated, application of ocean color algorithm in the ECS shelf is problematic due to severe interference from suspended particulate matter and colored dissolved organic matter from river runoffs (Gong et al., 1998). In order to fully utilize the remotely sensed ocean color, we need to develop the algorithm for Case II waters in the ECS. It will prove most essential to the future research and monitoring of the ECS (IOCCG, 2000).

For the ECS shelf, an unprecedented change may occur in the near future as the Three-Gauge Dam begins to interrupt and regulate the flow of the Changjiang. We hope that our effort will allow us to use the current observations as the baseline, against which future changes may be detected. We also hope to be able to assess impacts upon the ecosystem of the changed environment using tools yet to be fully developed.

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