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Temporal and Spatial Distribution of Dissolved Oxygen in the Pearl River Estuary and Adjacent Coastal Waters

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Abstract

The Pearl River is one of the large rivers in the world and it discharges to the northern part of the South China Sea. There has been a concern about the deterioration of dissolved oxygen conditions in the Pearl River estuary and adjacent coastal waters. In this study, historical data on dissolved oxygen (DO) from 1980, recent data from a summer cruise in 1999, and a 10-year time series in DO for 1990-2000 were used to examine spatial and temporal distribution of DO in the Pearl River estuary and adjacent coastal waters near Hong Kong. In the adjacent coastal waters, low oxygen waters <4 mg l^{-1} occurred in large areas during the summer of 1981, but DO rarely dropped to <3 mg l^{-1}. In the Pearl River estuary, DO was 3.5-4 mg l^{-1} in the eastern part, but was >4 mg l^{-1} in the western part in August 1984. In July 1999, DO was < 4 mg l^{-1} in a near bottom 2 m layer in a large area of the estuary and was <2.5 mg l^{-1} in the eastern section, just inside the entrance of the estuary. In the coastal waters adjacent to Hong Kong, DO was > 4 mg l^{-1}. The 10-year time series showed that DO decreased periodically in summer, but rarely dropped to <3 mg l^{-1}. There was no apparent trend of decreasing DO between 1990 and 2000. Compared to August 1984, DO decreased significantly during the summer of 1999 in the Pearl River estuary, although large scale hypoxia (<2 mg l^{-1}) was not observed. The spatial distribution of low oxygen waters may be controlled by estuarine circulation because DO was significantly correlated with salinity in the summers of 1981 and 1984. Furthermore, the spatial distribution of DO in the bottom layer was parallel to the topography of the bottom, indicating the importance of benthic consumption of DO in the sediment and the subsequent flux of low DO waters from the sediment-water interface resuspended by physical mixing. Relative to the high loading of nitrogen from the Pearl River, the present PO_4 concentration is still low. It is possible that the lack of large areas of hypoxia in the region may be linked to phosphorus limitation as shown in the previous study. Phosphorus may also be a limiting factor for bacterial decomposition which has a strong control on total oxygen consumption in the water column and sediments.

Key words: Pearl River estuary, dissolved oxygen, hypoxia, phosphorus, Hong Kong

Introduction

Eutrophication has become a major concern in shallow coastal waters (NRC, 2000). Hypoxia (dissolved oxygen < 2 mg l^{-1}) is one of the problematic symptoms of eutrophication. Hypoxia not only causes mortality of organisms, but it also affects living resources, and habitat carrying capacity (Diaz and Solow, 1999). Specifically, hypoxia or anoxia can reduce the recruitment of demersal fish stocks (Bagge et al., 1990), and cause the disappearance of marine organisms (Baden et al., 1990) and the mortality of aquatic organisms such as oysters (Lenihan and Peterson, 1995) and fish (Paerl et al., 1998). Prolonged oxygen depletion can disrupt benthic communities (Rosenberg et al., 1992; Modig and Olafsson, 1998; Flemer et al., 1999) and demersal communities (Keister et al., 2000; Diaz et al., 1995). Hypoxia can alter the ecosystem energy flow along the food chain via prey-predator interactions related to species tolerance to low oxygen (Diaz et al., 1992; Keister et al., 2000; Nestlerode and Diaz, 1998). Depletion of oxygen may also result in changes in biogeochemical cycling (Naqvi et al., 2000).

Hypoxia occurs in many coastal areas in the world, and hypoxic and anoxic (oxygen-deprived) waters have existed throughout geologic time (Diaz and Rosenberg, 1995). However, their occurrence in shallow coastal and estuarine areas appears to be increasing, most likely accelerated by human activities (NRC, 2000; Cloern, 2001). An alarming example is the “dead zone”, in the northern Gulf of Mexico on the Louisiana–Texas continental shelf. It is the largest zone of oxygen-depleted coastal waters in the United States. From 1993 to 1997, the size of the Gulf of Mexico hypoxic zone was consistently greater than 16,000 km^2 in mid-summer (Rabalais et al., 1998). This zone ranks third in area behind the northwestern shelf of the Black Sea and the Baltic basins (Boesch and Rabalais, 1991). The historical trend showing decreasing DO is more apparent in Chesapeake Bay (Cooper, 1995, Boynton and Kemp 2000). Other areas of hypoxia included the York River (Diaz et al., 1992) and Virginia estuaries (Kuo and Neilson, 1987), New York Bight (Waldhauer et al., 1985), Long Island Sound (Welsh and Eller, 1991), Pamlico River Estuary (Stanley, 1994), Florida Keys (Lapointe and Matzie, 1996), Erka estuary in the Adriatic Sea (Legovic et al., 1991), and northern Adriatic Sea (Justić et al., 1993).

The Pearl River estuary is situated on the south coast of China and flows into the northern part of the South China Sea. Hong Kong is part of its western shores. The Pearl River is the second largest river in China next to the Yangtze River and is ranked the 13th in the world in terms of discharge. The Pearl River stretches for 2,214 km and drains an area of 452,000 km^2 (Zhao, 1990). The Pearl River flows into the Pearl River estuary through eight entrances, four of which enter the Ling Ding Yang estuary, a sub-estuary of the Pearl River estuary, between Hong Kong and Macao (Fig. 1). The annual average river discharge is 10,524 m^3 s^{-1}, with 20% occurring during the dry season in October-March and 80% during the wet season in April-September (Zhao, 1990). The Pearl River estuarine waters are subjected to three water sources: the Pearl River discharge, oceanic waters from the South China Sea and coastal waters from the South China Coastal Current (Chau and Abesser, 1958; Chau and Wong, 1960; Watts 1971a; b; 1973; Williamson, 1970; Morton and Wu, 1975). These water regimes are driven by two seasonal monsoons. In winter, the northeast monsoon prevails and the South China Coastal Current dominates the coastal waters of Hong Kong. In summer, the interaction of the estuarine plume and oceanic waters dominates due to the southwest monsoon. Therefore, the coastal waters of Hong Kong become very dynamic.

In recent years, the Pearl River has a high load of anthropogenic nutrients from increased agricultural activities (Neller and Lam, 1994), fish dike farming (Ruddle and Zhong, 1988) and wastewater (Hills et al., 1998) due to the population increase and economic development in southern China and the Pearl River delta region (Lin, 1997). This increase in nutrients in the Pearl River is likely to result in an increase in algal biomass and a subsequent decrease in oxygen concentration in the estuary and coastal waters when the algal biomass is decomposed. However, there is little information in the literature about the spatial and temporal distribution of oxygen for this large important estuary. In this study, we used data from various sources to characterize the spatial and temporal distribution of low oxygen waters in the Pearl River estuary and adjacent coastal waters near Hong Kong.

Materials and Methods

The data on dissolved oxygen (DO) include historical data from October 1980, January, April and July 1981 in the adjacent coastal waters and during April, August, October 1984 and January 1985 in the Pearl River estuary, recent data from a summer cruise in 1999 and a 9 year time series of DO for 1990-2000 in the adjacent waters around Hong Kong from the Environmental Protection Department (EPD), Hong Kong government.

1980-81, 1984-85 Cruises were conducted in coastal waters adjacent to the Pearl River estuary during October 1980, January, April and July 1981 (Fig. 1A), and in the Pearl River estuary during April, August, October 1984 and January 1985 (Fig. 1B). A CTD instrument was used to take readings of salinity and temperature in the water column. Water samples were collected with Niskin bottles at the surface and near-bottom (1 m above the sediment). Dissolved oxygen was determined by the Winkler titration method, as outlined by Parsons et al. (1984).

Summer 1999 A cruise was conducted during the summer of 1999 in the Pearl River estuary and adjacent coastal waters (Fig. 1A) on the research vessel Haijiang 74. A YSI®6600 instrument was used to measure salinity, temperature and dissolved oxygen (DO) in the water column. The DO was calibrated against the saturation level each time before a vertical profile was taken.

EPD Time Series The Environmental Protection Department (EPD) of the Hong Kong Government has maintained a comprehensive sampling program to monitor water quality in the territorial waters for over 10 years from 1990 to 2000. There are 86 monitoring stations over the marine territorial waters (EPD 1998). In this study, 4 stations representing different geographical regions were selected. They were located in the Pearl River Estuary (NM6), in southern (SM17 and SM19) and southeastern waters of Hong Kong (MM11) (Fig. 1B). Therefore, these 4 stations are representative of the estuary (NM6), the coastal plume (SM17 and 19) and oceanic conditions (MM11), based on the classification of Hong Kong waters by Morton and Morton (1983). The cruises were conducted monthly or bi-monthly on the government vessel 'Catherine Lam'. A SEACAT19 CTD was used to take vertical profiles of salinity, temperature and dissolved oxygen. Data for DO were collected at 3 depths: surface, middle and bottom (1 m above the bottom). If the water depth was < 4-5 m, the mid-depth was omitted.

Results

Spatial variations in DO are presented using the historical data for 1980-81 and 1984-85 and data for 1999 in the Pearl River estuary and adjacent coastal waters, while temporal variations are based on the 9 year time series from 1990 to 2000. Effects of the tidal cycle are based on the 24 h time series of DO in 1981 at stations in the coastal waters and at 2 stations C1 and C2 in the estuary in 1999.

Spatial Distribution

In the adjacent coastal waters, DO remained saturated above 5.75 mg l^{-1} (Normal Atmospheric Equilibrium Concentration=5.478 mg l^{-1} at S=30 and T=16^{O}C) at both the surface and bottom in January 1981 (Fig. 2). In April, DO at the surface were distributed parallel to the shore, like a plume. DO was the highest (7.8 mg l^{-1}) near the entrance of the estuary, but decreased offshore to <5 mg l^{-1}. DO at the bottom was lower than at the surface and formed a minimum zone < 4.0 mg l^{-1} near Stn 302. In July, DO in the surface was lower than in April and formed two maximum zones: one near the right side of the estuary entrance at Stn 101 and the other at Stn 108. Note that DO in waters south of Hong Kong appeared like a plume spreading towards the east. DO at the bottom was <4 mg l^{-1} in a large area of the region, particularly in the eastern part, and was near 3 mg l^{-1} at Stn 101 where the maximum concentration of DO was present at the surface. In October, DO was distributed like an estuarine plume again with small differences between the surface and bottom (Fig. 2).

DO in the Pearl River estuary was saturated above 6 mg l^{-1} in January at both the surface and bottom (Fig. 3). In April, DO was lower than in January, but there were small differences (<1 mg l^{-1}) between the surface and bottom. By August, DO at the surface was lower than in April and DO at the bottom decreased to <4 mg l^{-1} in the lower half of the estuary. The distribution of DO near the bottom reflected an intrusion of the salt wedge. In October, contour lines of DO were distributed along the axis of the estuary (Fig. 3), showing strong lateral variation.

Surface DO was ca. 7.0 mg l^{-1} along the estuary in July 1999 and decreased with depth (Fig. 4). There was a bottom 1.5 m layer where DO was below 4 mg l^{-1} covering a distance of 70 km from Stn 3 to 19 along the estuary (Fig. 4). Across the coastal plume (from Stn 21 to 30), there was a surface maximum of DO above 7.0 mg l^{-1}, between Stns 39 and 28 (Fig. 4), corresponding to the chl *a* maximum zone (Yin et al., this volume). Bottom DO was rarely <4 mg l^{-1} (Fig. 4) underneath the coastal plume. An interesting feature in the DO distribution was that contour lines of DO were parallel to the bottom topography of the estuary and the adjacent coastal waters under the coastal plume (Fig. 4).

Across the estuary, low DO <4 mg l^{-1} was present in the deeper channels, upstream from Stn 5 to 9, while downstream, the bottom layer of <4 mg l^{-1} was 2 m thick across the entrance of the estuary (Fig. 5). On the western half of this cross-section, DO reached 2.5 mg l^{-1} in a layer 1.5 m above the bottom (Fig. 5). The feature of the parallel distribution with the bottom topography was evident, particularly in the lower layer, was evident.

Temporal Distribution

In January 1981, DO was similar between the surface and bottom and did not change over the 24 h time series (Fig. 6). In April, DO at depth decreased but it was > 4 mg l^{-1} at Stns 101, 201, and 402. At Stn 601, DO at the surface fluctuated between 5.5 and 8.5 mg l^{-1}, but near the bottom it was usually < 4 mg l^{-1} (Fig. 6). By July, low DO (<4 mg l^{-1}) occurred at the bottom depths at all the stations. Bottom DO frequently decreased to <3 mg l^{-1} at Stns 201, 301, 402, and 501, and reached <2 mg l^{-1} at Stn 601. In July 1999, DO at the bottom remained at < 3 mg l^{-1} at C1 in the middle of the estuary, but was >3 mg l^{-1} at a downstream station C2 near the entrance of the estuary throughout most of the time series (Fig. 7). At both stations, vertical gradients of DO were strong and the contour lines of DO fluctuated vertically during the time series, reflecting the influence of mixing in the water column with the tidal cycles (Fig. 7).

There were strong seasonal variations in DO in the waters around Hong Kong (Fig. 8). Over 10 years, at NM6, DO at the surface increased in winter and early spring and decreased in summer in the estuary with a slight decrease at the bottom depth. At SM17 and SM19 in waters south of Hong Kong, the seasonal fluctuation in DO at the surface seen at NM6 was not so clear. However, DO near the bottom fluctuated regularly with lower values (<4 mg/L) in summer. The fluctuation in DO was synchronized between the two stations. At MM11, a station in the eastern waters of Hong Kong, DO also fluctuated with peak values in winter-spring and lower values in summer-late fall. Only at SM19, did the lower values in DO periodically decrease to 3 mg l^{-1} (Fig. 8). The 9 year time series at 4 stations around Hong Kong did not appear to show a clear decreasing trend of DO.

Correlation of DO with other variables

Low DO waters (<4 mg l^{-1}) occurred largely in summer in both the estuary and adjacent coastal waters. There were significant correlations between DO and salinity during July 1981 in coastal waters and during August 1984 in the estuary (Fig. 9). However, there were no significant correlations between DO and temperature during the same time period (data not shown). The significant correlation between DO and salinity, and temperature was found during the 24 h time series at some coastal stations during April 1981 and at all the coastal stations during July 1981 (Table 1). The correlation was negative for DO-salinity and positive for DO-temperature. In July 1999, T-S diagrams showed two straight lines at most stations along the estuary (Fig. 10), indicating that the water column mainly consisted of two water masses. The near-bottom water mass (the line of high salinity-low temperature segment) was the salt wedge. DO-salinity diagrams closely resembled the T-S diagrams (Fig. 10). The resemblance between T-S diagrams and DO-salinity diagrams held true at stations across the estuary (S5-S9, S13-S16) and across the coastal plume (S25-S30) (Fig. 10) as well as at C1 and C2 during the time series (Fig. 11), indicating the dominant role of vertical mixing in the DO distribution.

Discussion

DO and Nutrients

The increasing occurrence of hypoxia in estuaries is believed to be related to an increase in the nutrient loading in rivers (NRC, 2000; Cloern, 2001). For example, considerable evidence indicates that nutrient loading from the Mississippi River system is the dominant factor in controlling the extent and degree of hypoxia (Rabalais et al., 1998). Low DO waters were a common phenomenon in the bottom layer in the Pearl River estuary and adjacent coastal waters in summer. However, it appears that hypoxia during summer of 1999 was limited to a very small area downstream of the turbidity maximum (Pang et al., this volume). The differences in DO were surprisingly small between 1984 and 1999, given the fact that the coastal population and economic activities in the Pearl River delta and Hong Kong have dramatically expanded since 1984 (Lin, 1997). The 9-year time series in coastal waters around Hong Kong did not show an apparent decreasing trend in DO, either. During the season of high river discharge, NO_3 concentrations upstream of the Pearl

River estuary were high (>100 µM, Yin et al., 2000). NO_3 is certainly higher than in other large rivers such as the Amazon River (10-15 µM, Edmond et al., 1981) and the Sacramento and San Joaquin Rivers (<25 µM) which discharge into San Francisco Bay (Schemel and Hager, 1986) and even higher than the largest Chinese river to the north, the Yangtze River (Shen, 1993). NO_3 concentrations in the Pearl River are lower than the Rhine River (4 mg NO_3-N l^{-1} or 270 µM, Schaub and Gieskes, 1991) and comparable to those of the Mississippi River (60-120 µM, Dortch & Whitledge, 1992; Rabalais et al., 1998), and to Chesapeake Bay where NO_3 in the freshwater region ranged between 70-120 µM (Fisher et al., 1988; Ward and Twilley, 1986). NH_4 in the Pearl River estuary (<4 µM) was similar to the Mississippi River estuary (Dortch and Whitledge, 1992; Rabalais et al., 1998), in which there was hypoxia, or anoxia in the northern Gulf of Mexico (Rabalais et al., 1992; Dortch et al., 1994) and Chesapeake Bay (Breitburg, 1990; Malone et al., 1988).

In contrast to temperate coastal waters where N is considered to be the most limiting nutrient, in the Pearl River estuary and adjacent coastal waters, PO_4 concentration was low (<1 µM) and P was found to be the most limiting nutrient (Yin et al., 2000; Yin et al., 2001; Zhang et al., 1999). The PO_4 concentration of the Pearl River is similar to that of the Amazon River (Edmond et al., 1981), and the Yangtze River (Shen, 1993) where no hypoxia has been reported. PO_4 in the Pearl River estuary was definitely much lower than in the Rhine River (0.35 PO_4-P mg l^{-1} or 11 µM, Schaub and Gieskes, 1991), and lower than the Mississippi and Sacramento Rivers where PO_4 concentrations were 3 µM (Dortch and Whitledge, 1992; Rabalais et al., 1998), and 4 µM (Schemel and Hager, 1986), respectively. It is possible that particulate organic phosphorus eventually limits oxygen consumption in the water column, if phosphorus in particulate organic matter in the water column is assumed to be 1 µM. Based on the oxygen requirement for decomposition of organic matter: 106C: 16N: 1P + $138O_2$, 138 µM O_2 would be consumed during the decomposition of 1 µM particulate organic phosphorus. If 224 µM O_2 (7 mg O_2 l^{-1}) is common in the water column, 86 µM O_2 (2.69 mg O_2 l^{-1}) would be left even after the complete decomposition of 1 µM particulate organic phosphorus (POP). Therefore, DO levels have rarely dropped to below 3 mg l^{-1} in the region over the 20 year period between 1980-1999 and phosphorus remains low now. However, if DO in the deep waters that are transported onto the near-shore is already low, e.g., 5 mg l^{-1}, the complete decomposition of 1 μM (POP) would reduce DO to 0.58 mg l^{-1}. However, not all of the organic matter produced at the surface sinks. If only 0.5 μM POP sinks, DO would remain at 2.79 mg l^{-1}. In fact, chl *a* concentrations near the bottom layer were lower than those in the surface layer in the estuary (Yin et al., this volume A) and adjacent coastal waters (Yin 2002). In contrast, in Chesapeake Bay, the bottom chl *a* is much higher than in the surface layer and anoxia occurs every summer (Malone et al., 1988). The parallel distribution of DO to the bottom topography which was observed during the July cruise of 1999, indicates that low DO concentrations near the bottom were due to the consumption of DO by the sediments and subsequent benthic flux of low DO from the sediment-water interface by the bottom water flow.

DO and Physical Processes

The estuarine circulation and stratification are important in determining the residence time of the bottom layer and consequently the DO in the bottom layer below the euphotic zone. As anthropogenic nutrient loading increases, stratification becomes increasingly important in the consumption of DO and the formation of hypoxia in coastal waters, as observed in the New York Bight (Waldhauer et al. 1985) and more so in the Neuse River estuary, North Carolina (Buzzelli et al. 2002). Therefore, not all estuaries receiving high nutrient loading show hypoxia/anoxia due to short residence times or rapid flushing of the bottom layer, for example, in James River, a tributary of Chesapeake Bay (USA) (Kuo and Neilson, 1987), and in Hudson River (USA) (Leslie, 1988) and in the Bay of Brest (France) (Le Pape and Menesguen, 1997). The Pearl River estuary is shallow in most areas, except for two deeper channels. It belongs to the category of microtidal estuaries (tidal range < 2 m) (Mao et al., this volume). There is a salt wedge estuarine circulation in the Pearl River estuary with freshwater flowing outwards in the upper layer and saline water flowing inwards in the bottom layer. In summer, the southwest monsoon prevails and moves the surface water offshore due to the Coriolis effect, resulting in upwelling circulation in the coastal area beyond the estuary (Chau and Wong, 1960). In spite of high nutrients carried in the Pearl River in summer, the volume of river discharge is so high that it flushes through the estuary in a few days (Yin et al., 2000). The shallow euphotic zone due to high turbidity relative to the halocline (Yin et al., this volume A), causes light limitation for phytoplankton in the estuary and as a result, much of the riverine nutrients are not utilized (Yin et al., 2000; Yin et al., 2001). At the edge of the coastal plume, particles settle out, and water transparency and phytoplankton biomass increase (Yin et al., 2000; Yin et al., this volume A). Some of the phytoplankton biomass may sink to the near bottom waters and be carried onshore or back into the estuary, although little is known about the fate of phytoplankton production in the coastal plume. The more saline and colder the near-bottom water mass is, the more time the water mass has to receive organic matter from sedimentation as it moves towards the estuary as a result of the estuarine circulation. More organic matter may cause more oxygen consumption. The negative DO-salinity and positive DO-temperature correlations during the 24 h time series in July 1981 demonstrated the influence of the estuarine circulation on the DO distribution. Significant correlations between DO and salinity, DO and temperature were found at all the stations in July 1981, but only at some stations in January when the vertical mixing is strong due to winds. The freshwater-induced estuarine circulation is weak during January, but strong during July. Parallel lines of DO-salinity and T-S in these diagrams (Figs. 10 and 11) provided convincing evidence for the dominant role of estuarine circulation and vertical mixing in the DO distribution.

Hypoxia in estuaries can be periodic due to wind events (Stanley and Nixon, 1992), spring-neap tidal cycles (Diaz et al., 1992; Montani et al., 1998; Uncles et al., 1998) and other events such as rainfall (Lapointe and Matzie, 1996, Paerl et al., 1998), storms (Wilson et al., 1991; Glasgow and Burkholder, 2000). Winds are periodically strong in summer in the region (HKO data). During July 2000, when there was a strong easterly wind event, the coastal plume was held back and the water column was almost homogeneously mixed (Yin et al., this volume B). Hurricanes have been reported to exert large impacts on hypoxia on the US's largest lagoonal estuary (Paerl et al., 1998; 2001, Mallin et al., 1999). Consequently, the low DO waters in the bottom layer as observed in other years disappeared except near the water-sediment boundary layer (data not shown). Tidal mixing in the region did not appear to be strong enough to destroy the stratification and elevate the oxygen based on the two times series, at C1 and C2. There is a rainy season in summer for the region, but torrential rains are often accompanied with strong winds or typhoons. The rain favors the development of hypoxia (Portnoy, 1991; Lapointe and Matzie, 1996), but winds destroy the hypoxia due to vertical mixing as a result of the storm (Paerl et al., 1998; 2001, Stanley and Nixon, 1992).

In summary, low oxygen waters occur in summer, but hypoxia appears to occur over a limited spatial scale in the Pearl River estuary and adjacent coastal waters. Concentrations of inorganic nitrogen are very high in the Pearl River, but concentrations of phosphorus are low (e.g. N: P ratio >100:1). It is possible that phosphorus limitation to phytoplankton biomass and subsequent limitation to bacterial decomposition may control the total oxygen consumption in the water column. Seasonal southwest monsoons and high river discharge increase the flushing of the bottom waters, and occasional wind events in summer may interrupt the development of hypoxia in the bottom waters of the estuary and adjacent coastal waters due to vertical mixing processes. These physical and biological processes may set up a buffering system (Cloern, 1996) for limiting hypoxia in the region. How large is the buffering capacity, is an important question to address. A change in climate may change the filter capacity of the coastal ecosystem for DO in the future. For example, if the southwest monsoon weakens, vertical mixing would decrease and the renewal of DO in the near bottom waters would be slower. A decrease may be associated with climate change in the Pearl River discharge in summer. This may result in a slower flushing of the estuary and consequently, high primary production inside the estuary, and the increased phytoplankton biomass may end up in the bottom water and result in hypoxia. If the phosphorus concentration in the Pearl River increases due to an increase in P loading, more organic matter would be produced and the subsequent decomposition could cause hypoxia in the Pearl River estuary. These possibilities may result in a long-term alteration of estuarine and coastal ecosystems in the region.

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References

Baden, S.P., Loo, L.O., Pihl, L., Rosenberg, R., 1990. Effects of eutrophication on benthic communities including fish: Swedish west coast. *Ambio* 19, 113-122.

Bagge, O., Nielsen, E., Mellergaard, S., Dalsgaard, I., 1990. Hypoxia and the demersal fish stock in the Kattegat (IIIa) and Subdivision 22. ICES Council Meeting 1990 (Collected papers), ICES, Copenhagen (Denmark), p. 52.

Boesch, D.E., 1985. Effects on benthos of oxygen depletion in estuarine and coastal waters. *Estuaries* 8 (2B) p. 43A.

Boesch, D.F., Rabalais, N.N., 1991. Effects of hypoxia on continental shelf benthos: Comparisons between the New York Bight and the northern Gulf of Mexico. In: Tyson, R.V., Pearson, T.H. (Eds.), Modern and ancient continental shelf anoxia, Geological Society Special Publication no. 58. London, England: The Geological Society. pp. 27-34.

Boynton, W.R., Kemp, W.M., 2000. Influence of river flow and nutrient loads on selected ecosystem processes: a synthesis of Chesapeake Bay data. In: Hobbie, J.E. (ed), Estuarine Science: A Synthetic Approach to Research and Practice. Washington, DC: Island Press, pp. 269-298.

Breitburg, D.L., 1990. Near-shore hypoxia in the Chesapeake Bay: patterns and relationships among physical factors. *Estuarine Coastal Shelf Science* 30, 593-609.

Buzzelli, C.P., Powers, S.P., Luettich Jr., R.A., McNinch, J.E., Peterson, C.H., Pinckney, J.L., Paerl, H.W., 2002. Estimating the spatial extent of bottom water hypoxia and benthic fishery habitat degradation in the Neuse River Estuary, NC. *Marine Ecology Progress Series* 230: 103-112.

Chau,Y.K., Abesser, R., 1958. A preliminary study of the hydrology of Hong Kong territorial waters. *Hong Kong University Fisheries Journal* 2, 37-42.

Chau, Y.K., Wong, C.S., 1960. Oceanographic investigations in the northern region of the South China Sea off Hong Kong. *Hong Kong University Fisheries Journal* 3, 1-25.

Cloern, J.E., 1996. Phytoplankton bloom dynamics in coastal ecosystems: a review with some general lessons from sustained investigation of San Francisco Bay, California. *Reviews of Geophysics* 34, 127-168.

Cloern, J.E., 2001. Our evolving conceptual model of the coastal eutrophication problem. *Marine Ecology Progress Series* 210, 223-253.

Cooper, S.R., Brush, G.S., 1991. Long-term history of Chesapeake Bay anoxia. *Science* 254, 992-96.

Cooper, S.R., 1995. Chesapeake Bay watershed historical land use: impact on water quality and diatom communities. *Ecological Application* 5: 703-723.

Diaz, R.J., Neubauer, R.J., Schaffner, L.C., Pihl, L., Baden, S.P., 1992. Continuous monitoring of dissolved oxygen in an estuary experiencing periodic hypoxia and the effect of hypoxia on macrobenthos and fish. *Marine Coastal Eutrophicaton*, 1992, *Science of the Total Environment* (Suppliment) pp. 1055-1068.

Diaz, R.J., Rosenberg, R. 1995. Marine benthic hypoxia: A review of its ecological effects and the behavioural responses of benthic macrofauna. *Oceanography and Marine Biology: Annual Review* 33, 245-303.

Diaz, R.J., Solow, A., 1999. Ecological and economic consequences of hypoxia: Topic 2 report for the integrated assessment on hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series No. 16. Silver Spring, MD: National Oceanic and Atmospheric Administration, Coastal Ocean Office.

Dortch, Q., Whitledge, T.E., 1992. Does nitrogen or silicon limit phytoplankton production in the Mississippi River plume and nearby regions? *Continental Shelf Research* 12, 1293-1309.

Dortch, Q., Rabalais, N.N., Turner, R.E., Rowe, G.T., 1994. Respiration rates and hypoxia on the Louisiana shelf. *Estuaries* 17, 862-72.

Edmond, J.M., Boyle, E.A., Grant, B.C., Stallard, R.F., 1981. The chemical mass balance in the Amazon plume I: the nutrients. *Deep-Sea Research* 28A, 1339-1374.

Flemer, D.A., Kruczynski, W.L., Ruth, B.F., Bundrick, C.M., 1999. The relative influence of hypoxia, anoxia, and associated environmental factors as determinants of macrobenthic community structure in a northern Gulf of Mexico estuary. *Journal of Aquatic Ecosystems*, *Stress Recovery* 6, 311-328.

Glasgow Jr., H.B., Burkholder, J.M., 2000. Water quality trends and management implications from a five-year study of a eutrophic estuary. *Ecological Applications* 10, 1024-1046.

Hills, P., Zhang, L., Liu, J., 1998. Transboundary pollution between Guangdong Province and Hong Kong: Threats to water quality of the Pearl River Estuary and their implications for environmental policy planning. *Journal of Environmental Plan and Management* 41, 375-396.

Justić, D., Rabalais, N.N., Turner, R.E., Wiseman, W.J., 1993. Seasonal coupling between riverborne nutrients, net productivity, and hypoxia. *Marine Pollution Bulletin* 26, 184-189.

Keister, J.E., Houde, E.D., Breitburg, D.L., 2000. Effects of bottom-layer hypoxia on abundances and depth distributions of organisms in Patuxent River, Chesapeake Bay. *Marine Ecology Progress Series* 205, 43-59.

Kuo, A.Y., Neilson, B.J., 1987. Hypoxia and Salinity in Virginia Estuaries. *Estuaries* 10, 277-283.

Lapointe, B.E., Matzie, W.R., 1996. Effects of stormwater nutrient discharges on eutrophication processes in nearshore waters of the Florida Keys. *Estuaries* 19(2B), 422-435.

Le Pape, O., Menesguen, A., 1997. Hydrodynamics prevention of eutrophication in the Bay of Brest (France), a modeling approach. *Journal of Marine Systems* 12, 171-186.

Legovic, T., Petricioli, D., Zutic, V., 1991. Hypoxia in a pristine stratified estuary (Krka, Adriatic Sea). Physical, chemical and biological processes in stratified estuaries. *Marine Chemistry* 32, 347-359, Lenihan, H., Peterson, C.S., 1995. Mass mortality of oysters, *Crassostrea virginica*, in a wind-driven estuary: Prolonged hypoxia and the restoration of a declining fishery. *Twenty-Third Benthic Ecology Meeting, 1995*.

Leslie, J.A., Abood, K.A., Maikish, E.A., Keeser, P.J., 1988. Recent dissolved oxygen trends in the Hudson River. *Fisheries Research in the Hudson River*, State University of New York Press Albany, pp. 287-303.

Lin, G.C.S., 1997. Red capitalism in south China: growth and development of the Pearl River Delta. UBC Press, Vancouver, Canada.

Mallin, M.A., Posey, M.H., Shank, G.C., McIver, M.R., Ensign, S.H., Alphin, T.D., 1999. Hurricane effects on water quality and benthos in the Cape Fear watershed: Natural and anthropogenic impacts. *Ecological Applications* 9, 350-362.

Malone, T.C., Crocker, L.H., Pike, S.E., Wendler, B.W., 1988. Influences of river flow on the dynamics of phytoplankton production in a partially stratified estuary. *Marine Ecology Progress Series* 48, 235-249.

Modig, H., Olafsson, E., 1998. Responses of Baltic benthic invertebrates to hypoxic events. *Journal of Experimental Marine Biology and Ecology* 229(1), 133-148.

Montani, S., Magni, P., Shimamoto, M., Abe, N., Okutani, K., 1998. The effect of a tidal cycle on the dynamics of nutrients in a tidal estuary in the Seto Inland Sea, Japan. *Journal of Oceanography* 54, 65-76.

Morton, B., Wu, S.S., 1975. The hydrology of the coastal waters of Hong Kong. *Environment Research* 10, 319-347.

Morton, B., Morton J., 1983. The sea shore ecology of Hong Kong. Hong Kong University Press, Hong Kong, 350 p.

Naqvi, S.W.A., Jayakumar, D.A., Narvekar, P.V., Naik, H., Sarma, V.V.S.S., D'Souza, W., Joseph, S., George, M.D., 2000. Increased marine production of N_2O due to intensifying anoxia on the Indian continental shelf. *Nature* 408, 346-349.

Neller, R.J., Lam, K.C., 1994. The Environment. In: Yeung, Y.M., Chu, D.K.Y., (Eds.), Guangdong: Survey of a province undergoing rapid change. The Chinese University of Hong Kong Press, Hong Kong.

Nestlerode, J.A., Diaz, R.J., 1998. Effects of periodic environmental hypoxia on predation of a tethered polychaete, *Glycera americana*: implications for trophic dynamics. *Marine Ecology Progress Series* 172, 185-195.

NRC (National Research Council), 2000. Clean coastal waters: understanding and reducing the effects of nutrient pollution. National Academy Press, Washington, D.C., USA, p. 405.

Paerl, H.W., Pinckney, J.L., Fear, J.M., Peierls, B.L., 1998. Ecosystem responses to internal and watershed organic matter loading: consequences for hypoxia in the eutrophying Neuse River Estuary, North Carolina, USA. *Marine Ecology Progress Series* 166, 17-25.

Paerl, H.W., Bales, J.D., Ausley, L.W., Buzzelli, C.P., Crowder, L.B., Eby, L.A., Fear, J.M., Go, M., Peierls, B.L., Richardson, T.L., Ramus, J.S., 2001.

Ecosystem impacts of 3 sequential hurricanes (Dennis, Floyd and Irene) on the US's largest lagoonal estuary, Pamlico Sound, NC. Proc. Natl. Acad. Sci. USA. 98(10): 5655-5660.

Parsons, T.R., Maita, Y., Lalli, C.M. 1984. A Manual of Chemical and Biological Methods for Seawater Analysis. Pergamon Press, Oxford, 173 p

Portnoy, J.W., 1991. Summer oxygen depletion in a diked New England estuary, *Estuaries* 14(2), 122-129.

Rabalais, N.N., Turner, R.E., Wiseman Jr., W.J., 1992. Distribution and characteristics of hypoxia on the Louisiana shelf in 1990 and 1991. *Proceedings, nutrient enhanced coastal ocean productivity worksho*p, 15–20. Publication no. TAMU-SG-92-109. College Station, TX: Texas A&M University, Texas Sea Grant College Program.

Rabalais, N.N., Turner, R.E., Justić, D., Dortch, Q., Wiseman, W.J., 1998. Charaterization of hypoxia: Topic 1 Report for the Integrated Assessment of Hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series No. 15. NOAA Coastal Ocean Program, Silver Spring, MD pp. 167.

Rosenberg, R., Loo, L.O., Moeller, P., 1992. Hypoxia, salinity and temperature as structuring factors for marine benthic communities in a eutrophic area. Proceedings of the 26th European Marine Biology Symposium. Biological Effects of Disturbances on Estuarine and Coastal Marine Environments 1992, *Netherlands Journal of Sea Research* 30, 121-129.

Ruddle, K., Zhong, G., 1988. Integrated agriculture-aquaculture in South China : the dike-pond system of the Zhujiang Delta. Cambridge University Press, Cambridge, pp.173.

Schaub, B.E.M., Gieskes, W.W.C., 1991. Eutrophication of the North Sea: the relation between Rhine river discharge and chlorophyll a concentration in Dutch coastal waters. In: Elliot, M., Ducrotoy, J.P., (Eds.), Estuaries and coasts: spatial and temporal intercomparisons. pp. 85-90.

Schemel, L.E., Hager, S.W., 1986. Chemical variability in the Sacramento River and in Northern San Francisco Bay. *Estuaries* 9, 270-283.

Shen, Z., 1993. A study on the relationships of the nutrients near the Changjiang River estuary with the flow of the Changjiang River water. *Chinese Journal Oceanology and Limnology* 11, 260-284.

Stanley, D.W., 1994. Regulation of primary productivity and hypoxia in the Pamlico River estuary, NC, by factors other than nutrients: Implications for management strategies to control eutrophication. *37th Conference of the International Association for Great Lakes Research and Estuarine Research* Federation: Program and Abstracts, IAGLR, Buffalo, NY (USA), p. 165.

Stanley, D.W., Nixon, S.W., 1992. Stratification and bottom-water hypoxia in the Pamlico River Estuary. *Estuaries* 15, 270-281.

Tippie, V.K., 1984. Environmental Characterization of Chesapeake Bay and a Framework for Action. The Estuary as a Filter, Academic Press, Orlando FL. P 467-487.

Uncles, R.J., Joint, I., Stephens, J.A., 1998. Transport and retention of suspended particulate matter and bacteria in the Humber-Ouse Estuary, United Kingdom, and their relationship to hypoxia and anoxia, *Estuaries* 21(4A), 597-612.

Waldhauer, R., Draxler, A.F.J., McMillan, D.G., Zetlin, C.A., Leftwich, S., Matte, A., O'Reilly, J.E., 1985. Biological, physical and chemical dynamics along a New York Bight transect and their relation to hypoxia. *Estuaries* 8(2B), 129A.

Ward, L.G.; Twilley, R.R., 1986. Seasonal distributions of suspended particulate material and dissolved nutrients in a coastal plain estuary. *Estuaries* 9(3), 156-168.

Watts, J.C.D., 1971a. The hydrology of the continental shelf area south of Hong Kong. 1. Oceanographic observation for the year 1969. *Hong Kong Fisheries Bulletin* 2, 51-57.

Watts, J.C.D., 1971b. A general review of the oceanography of the northern sector of the South China Sea. *Hong Kong Fisheries Bulletin* 2, 41-50.

Watts, J.C.D., 1973. Further observation on the hydrology of the Hong Kong territorial waters. *Hong Kong Fisheries Bulletin* 3: 9-35.

Welsh, B.L., Eller, F.C., 1991. Mechanisms controlling summertime oxygen depletion in western Long Island Sound. *Estuaries* 14(3), 265-278.

Williamson, G.R., 1970. The hydrography and weather of the Hong Kong fishing grounds. *Hong Kong Fisheries Bulletin* 1, 43-49.

Wilson, J.G., Brennan, M., Brennan, B., 1991. Horizontal and vertical gradients in sediment nutrients on mudflats in the Shannon Estuary, Ireland. Marine and Estuarine Gradients, 1993, *Netherlands Journal of Aquatic Ecology* 27(2-4), 173-180.

Yin, K., Qian, P.Y., Chen, J.C., Hsieh, D.P.H., Harrison, P.J., 2000. Dynamics of nutrients and phytoplankton biomass in the Pearl River estuary and adjacent waters of Hong Kong during summer: preliminary evidence for phosphorus and silicon limitation. *Marine Ecology Progress Series* 194, 295-305.

Yin, K., Qian, P.Y., Wu, M.C.S., Chen, J.C., Huang, L., Song, X., Jian, W., 2001. Shift from P to N limitation of phytoplankton biomass across the Pearl River estuarine plume during summer. *Marine Ecology Progress Series* 221: 17-28.

Yin, K., 2002. Monsoonal influence on seasonal variations in nutrients and phytoplankton biomass in coastal waters of Hong Kong in the vicinity of the Pearl River estuary. *Marine Ecology Progress Series 245: 111-122*

Yin, K., Qian, P.Y., Zhang, J., Jian, W., Huang, L., Chen, J.[3], Wu, M.C.S., this volume A. Effect of wind events on phytoplankton blooms in the Pearl River estuary during summer. *Continental Shelf Research.*

Yin, K.D., Sun, J., Song, X.X., Wu, M.C.S., this volume B. Potential P Limitation Leads to Excess N in the Pearl River Estuarine Coastal Plume. *Continental Shelf Research.*

Zhang, J., Yu, Z.G., Wang, J.T., Ren, J.L., Chen, H.T., Xiong, H., Dong, L.X., Xu, W.Y., 1999. The subtropical Zhujiang (Pearl River) Estuary: nutrient, trace species and their relationship to photosynthesis. *Estuarine Coastal Shelf Science* 49, 385-400.

Zhao, H., 1990. Evolution of the Pearl River Estuary. Ocean Press, Beijing, China pp. 358. (in Chinese)

Table 1. Correlation coefficient, r, between DO and salnity and temperature during 24 h time series at coastal stations near the entrances of each sub-estuary during 1981. n = the total number of samples taken at multiple depths every 2 hour. The asterisk * indicates that r is significant at $p<0.05$ using the critical values for r from Zar (1999).

	January		April		July	
Stations	O_2-S	O_2-T	O_2-S	O_2-T	O_2-S	O_2-T
102	-0.038 (n=77)	0.109 (n=77)	-0.024 (n=64)	-0.012 (n=64)	-0.978* (n=64)	0.974* (n=64)
201			-0.516* (n=25)	0.626* (n=25)	-0.875* (n=38)	0.799* (n=38)
301	-0.390* (n=38)	-0.26 (n=38)	-0.281 (n=25)	-0.263 (n=25)	-0.972* (n=37)	0.895* (n=37)
402	-0.044 (n=51)	-0.097 (n=51)			-0.916* (n=38)	0.970* (n=38)
501	-0.713* (n=38)	-0.715* (n=38)	-0.593* (n=25)	0.394* (n=25)	-0.680* (n=34)	0.847* (n=34)
601			-0.811* (n=25)	0.880* (n=25)	-0.924* (n=38)	0.847* (n=38)

Figure Legend

Figure 1. Map of the Pearl River estuary and sampling stations: A) stations in coastal waters for 1980-81 are represented by numbers 101-604 and stations in the Pearl River estuary for 1984-85 are indicated by (Δ), and B) stations for summer 1999 are indicated by (●) and stations for EPD time series from 1990-98 by (♦).

Figure 2. Contours of DO at the surface and bottom during October 1980, January, April and July 1981 in adjacent coastal waters of the Pearl River estuary.

Figure 3. Contours of DO at the surface and bottom during April, August, October 1984, and January 1985 in the Pearl River estuary.

Figure 4. Contours of the vertical distribution of DO along A) the estuary (Stns 1-31) and B) across the coastal plume (Stns 21-30) in summer 1999.

Figure 5. Contours of the vertical distribution of DO along the two lateral transects across the estuary: A) Stns 5, 6, 7, 8 and 9 and B) Stns 13, 14, 15 and 16 during summer 1999.

Figure 6. Variations in DO at the surface and bottom during a 24 h time series at stations along the coast in January, April and July 1981.

Figure 7. Contours of the vertical distribution of DO during 24 h time series at C1 and C2 in the estuary during summer 1999. The water level indicates the tidal cycle at the same vertical scale.

Figure 8. A 9 year time series of DO at the surface and bottom during 1990-1998 for NM6, SM17, SM19 and MM11.

Figure 9. DO vs salinity for October 1980, January, April and July 1981 and April, August, October 1984, and January 1985.

Figure 10. T-S diagrams and DO-salinity diagrams at selected stations along the estuary (Stns 10-31) from north to south, across the coastal plume (Stns 25-30) and across the estuary upstream (Stns 5-9) and downstream (Stns 13-16) for summer 1999. The across the estuary direction is from west to east.

Figure 11. T-S diagrams and DO-salinity diagrams at selected sampling times of 6 h intervals during the 24 h time series at C1 and C2 in Fig. 7.

Fig. 1

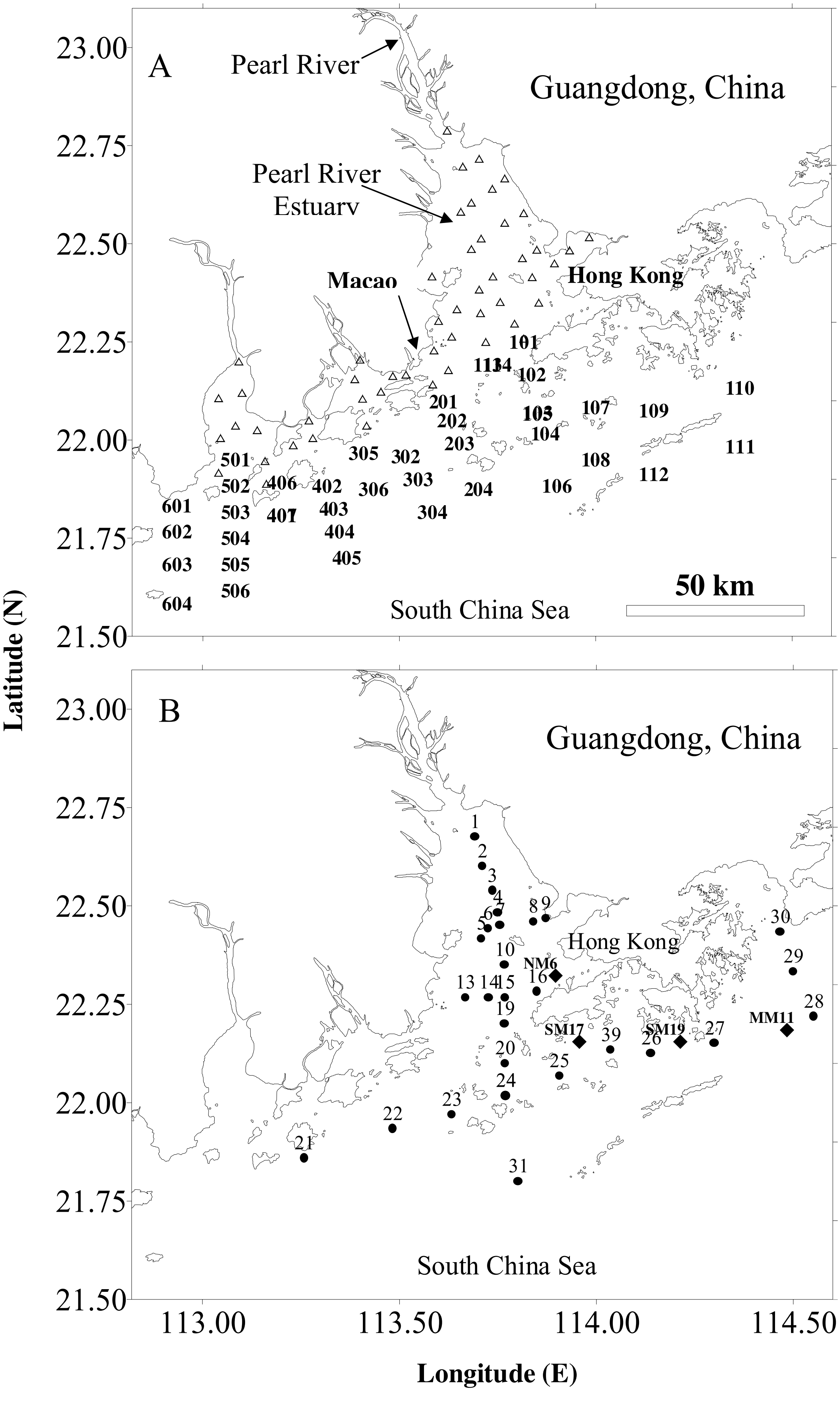

A
Pearl River
Pearl River
Estuarv
Guangdong, China
Macao
Hong Kong
101
113
114
102
201
202
203
103
105
104
107
109
110
111
108
112
106
204
305
302
303
304
306
501
502
503
504
505
506
406
401
407
402
403
404
405
601
602
603
604
50 km
South China Sea
B
Guangdong, China
Hong Kong
1
2
3
4
5
6
7
8
9
10
NM6
13
14
15
16
19
SM17
39
26
SM19
27
MM11
28
29
30
20
25
24
23
22
21
31
South China Sea
23.00
22.75
22.50
22.25
22.00
21.75
21.50
113.00
113.50
114.00
114.50
Latitude (N)
Longitude (E)

Fig. 2

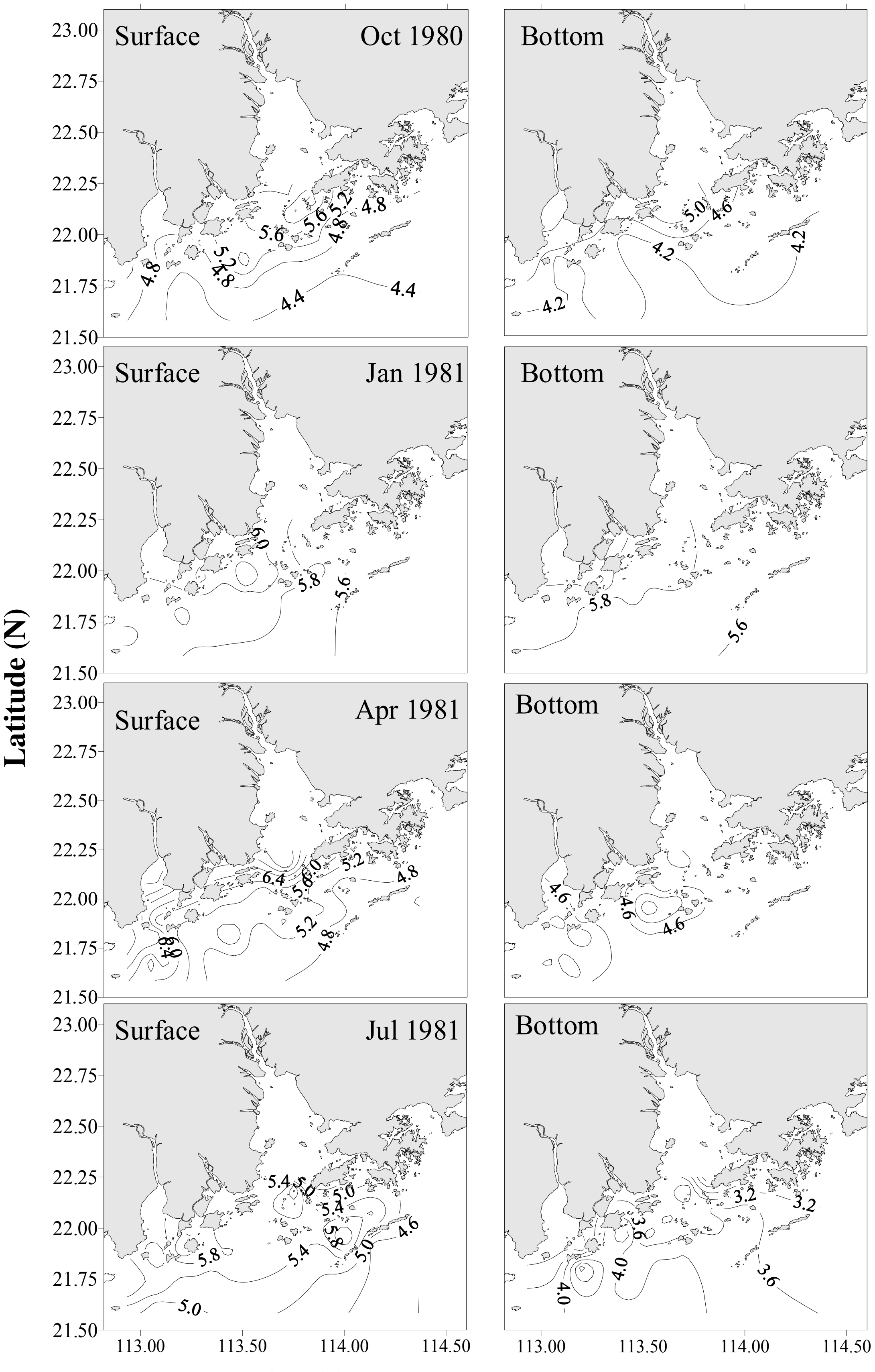

Latitude (N)
23.00
22.75
22.50
22.25
22.00
21.75
21.50
Surface
Oct 1980
5.6
5.6
5.2
4.8
4.8
5.2
4.8
4.8
4.4
4.4
Bottom
5.0
4.6
4.2
4.2
4.2
Surface
Jan 1981
6.0
5.8
5.6
Bottom
5.8
5.6
Surface
Apr 1981
6.4
5.6
6.0
5.2
4.8
5.2
4.8
6.0
Bottom
4.6
4.6
4.6
Surface
Jul 1981
5.4
5.0
5.0
5.4
5.8
4.6
5.8
5.4
5.0
5.0
Bottom
3.2
3.2
3.6
4.0
4.0
3.6
113.00
113.50
114.00
114.50
Longitude (E)
113.00
113.50
114.00
114.50
Longitude (E)

Fig. 3

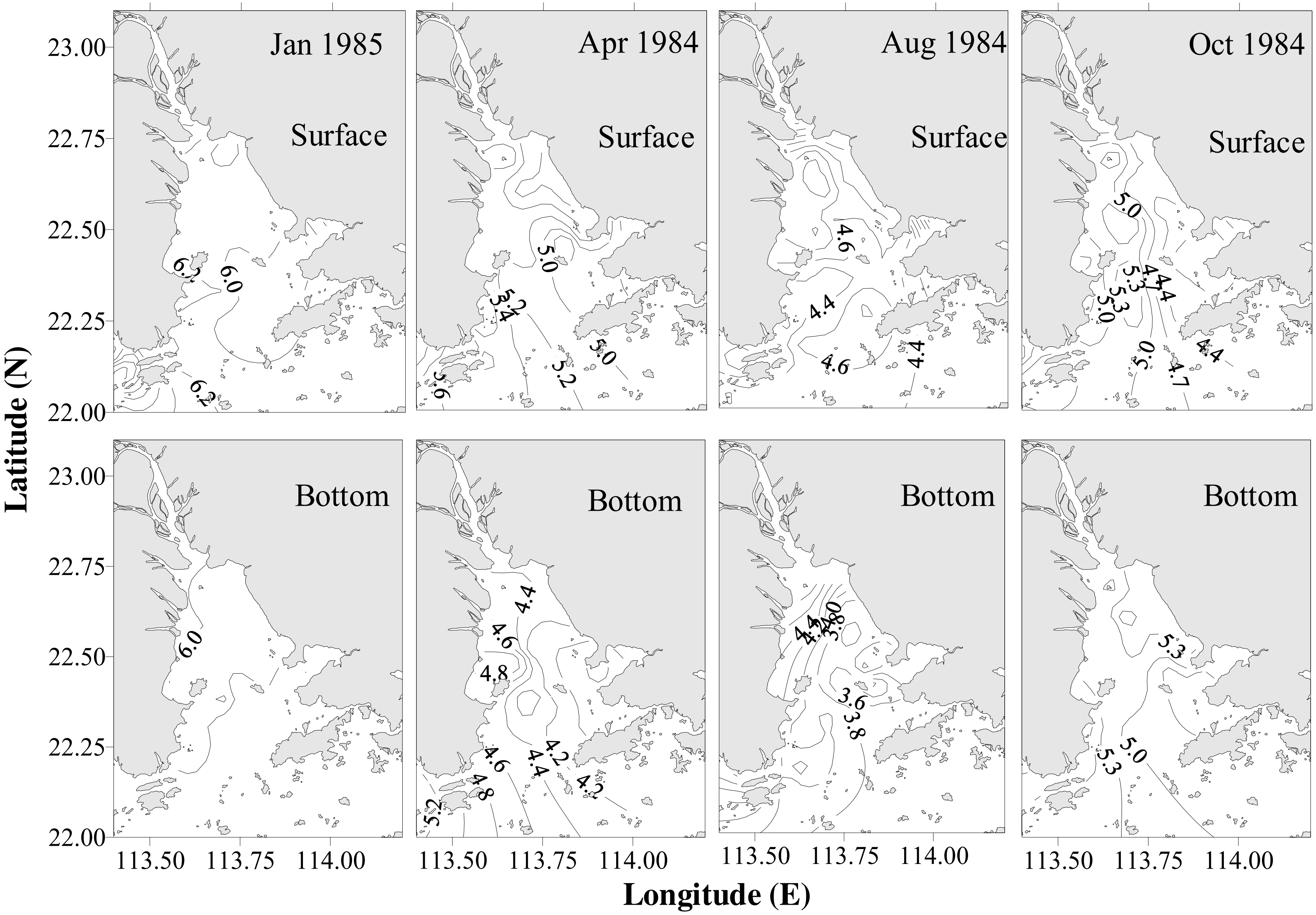

Jan 1985
Apr 1984
Aug 1984
Oct 1984
Surface
Bottom
6.2
6.0
6.2
5.0
5.2
3.4
5.2
5.0
5.6
4.6
4.4
4.6
4.4
5.0
4.7
4.4
5.3
5.3
5.0
5.0
4.4
4.7
6.0
4.4
4.6
4.8
4.6
4.8
4.4
4.2
4.2
5.2
4.4
4.4
4.0
3.8
3.6
3.8
5.3
5.0
5.3
Latitude (N)
23.00
22.75
22.50
22.25
22.00
Longitude (E)
113.50
113.75
114.00

Fig. 4

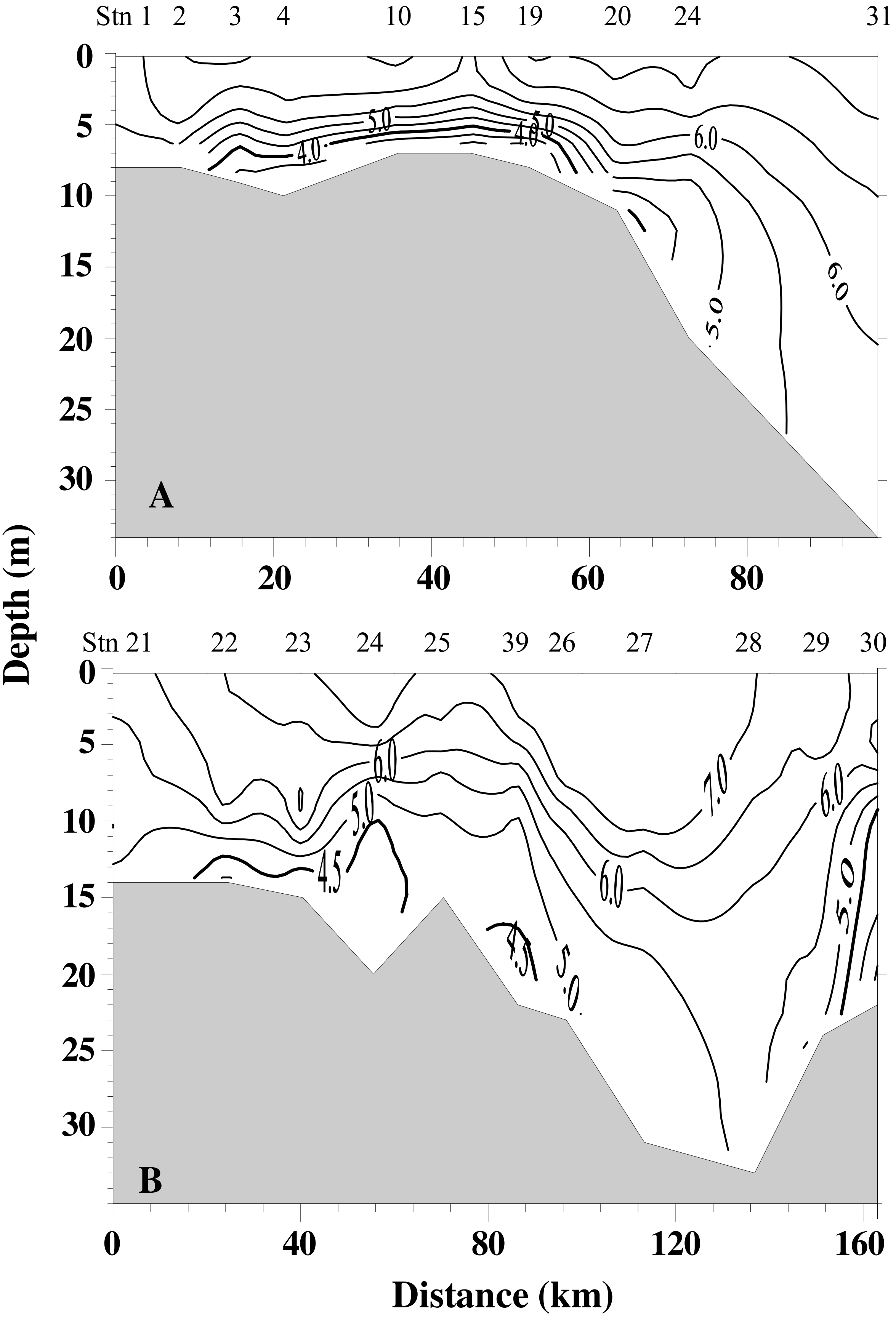

Stn 1 2 3 4 10 15 19 20 24 31
0
5
10
15
20
25
30
4.0
5.0
4.0
5.0
6.0
5.0
6.0
A
0
20
40
60
80
Depth (m)
Stn 21 22 23 24 25 39 26 27 28 29 30
0
5
10
15
20
25
30
6.0
5.0
4.5
4.5
5.0
6.0
7.0
6.0
5.0
B
0
40
80
120
160
Distance (km)

Fig. 5

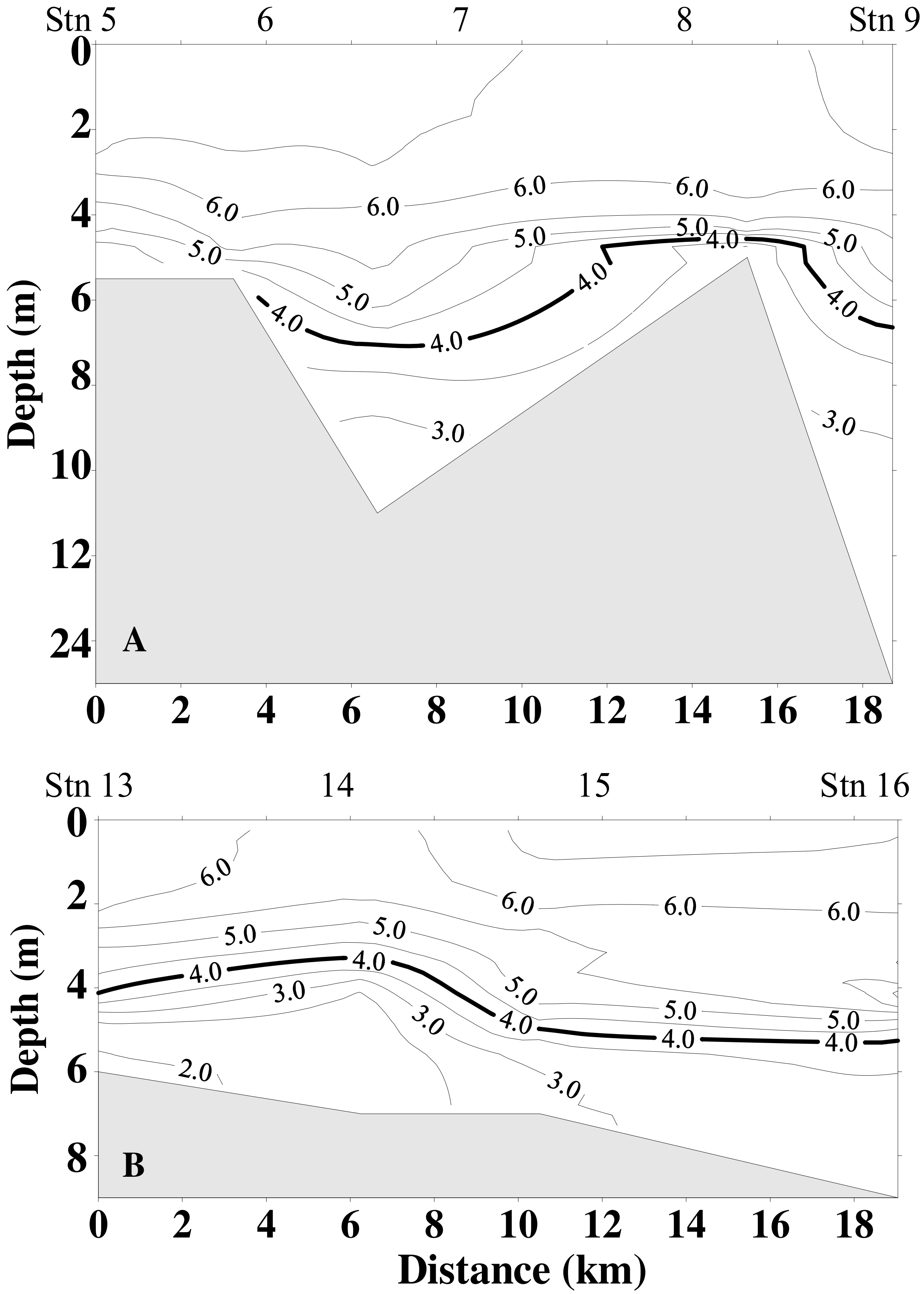

Stn 5
6
7
8
Stn 9
Depth (m)
0
2
4
6
8
10
12
24
6.0
6.0
6.0
6.0
6.0
5.0
5.0
5.0
5.0
5.0
4.0
4.0
4.0
4.0
4.0
3.0
3.0
A
0
2
4
6
8
10
12
14
16
18
Stn 13
14
15
Stn 16
Depth (m)
0
2
4
6
8
6.0
6.0
6.0
6.0
5.0
5.0
5.0
5.0
5.0
4.0
4.0
4.0
4.0
4.0
3.0
3.0
3.0
2.0
B
0
2
4
6
8
10
12
14
16
18
Distance (km)

Fig. 6

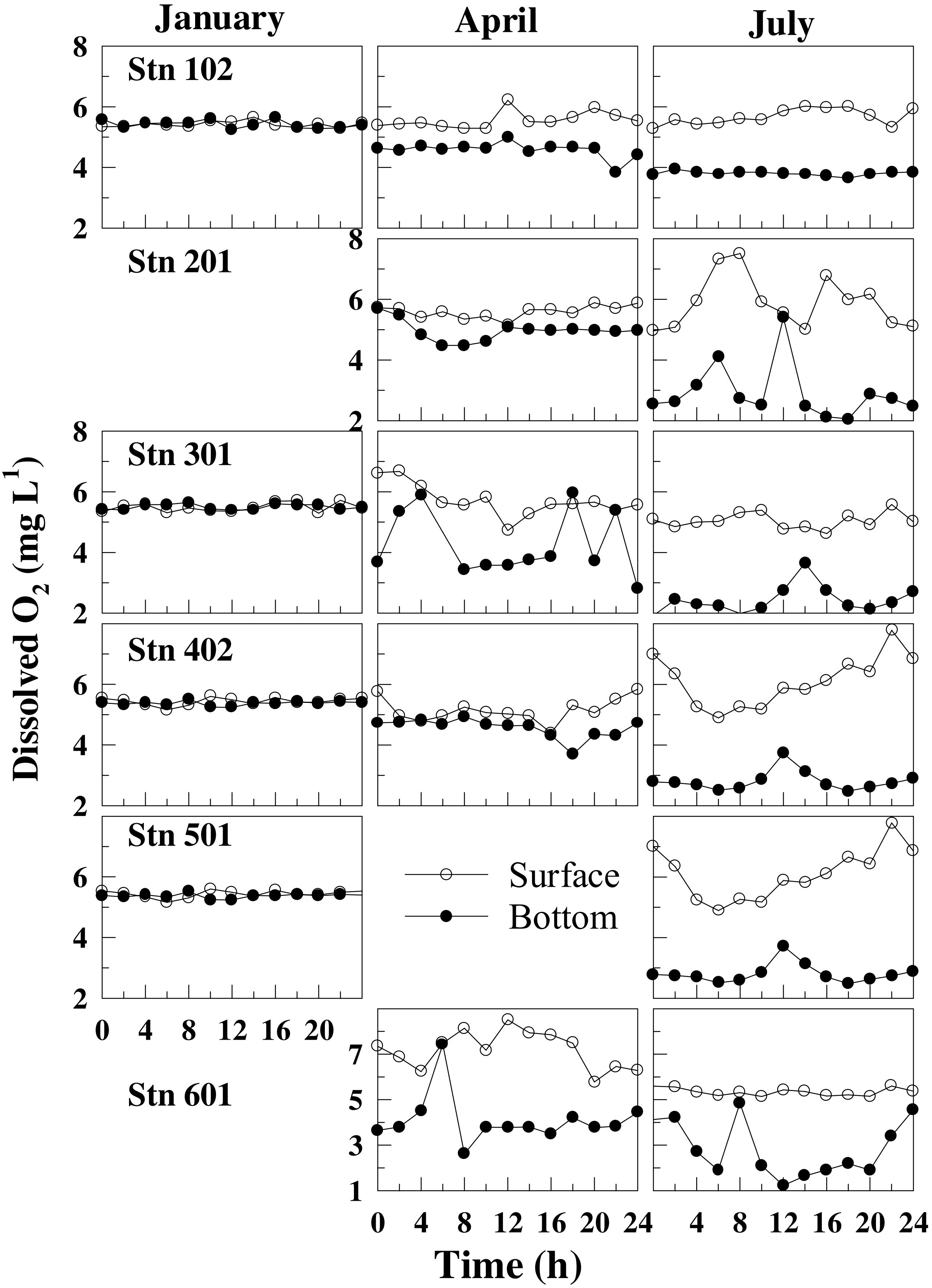

January
April
July
Stn 102
Stn 201
Stn 301
Stn 402
Stn 501
Stn 601
Dissolved O$_2$ (mg L^{-1})
Time (h)
Surface
Bottom
8
6
4
2
7
5
3
1
0
4
8
12
16
20
24

Fig. 7

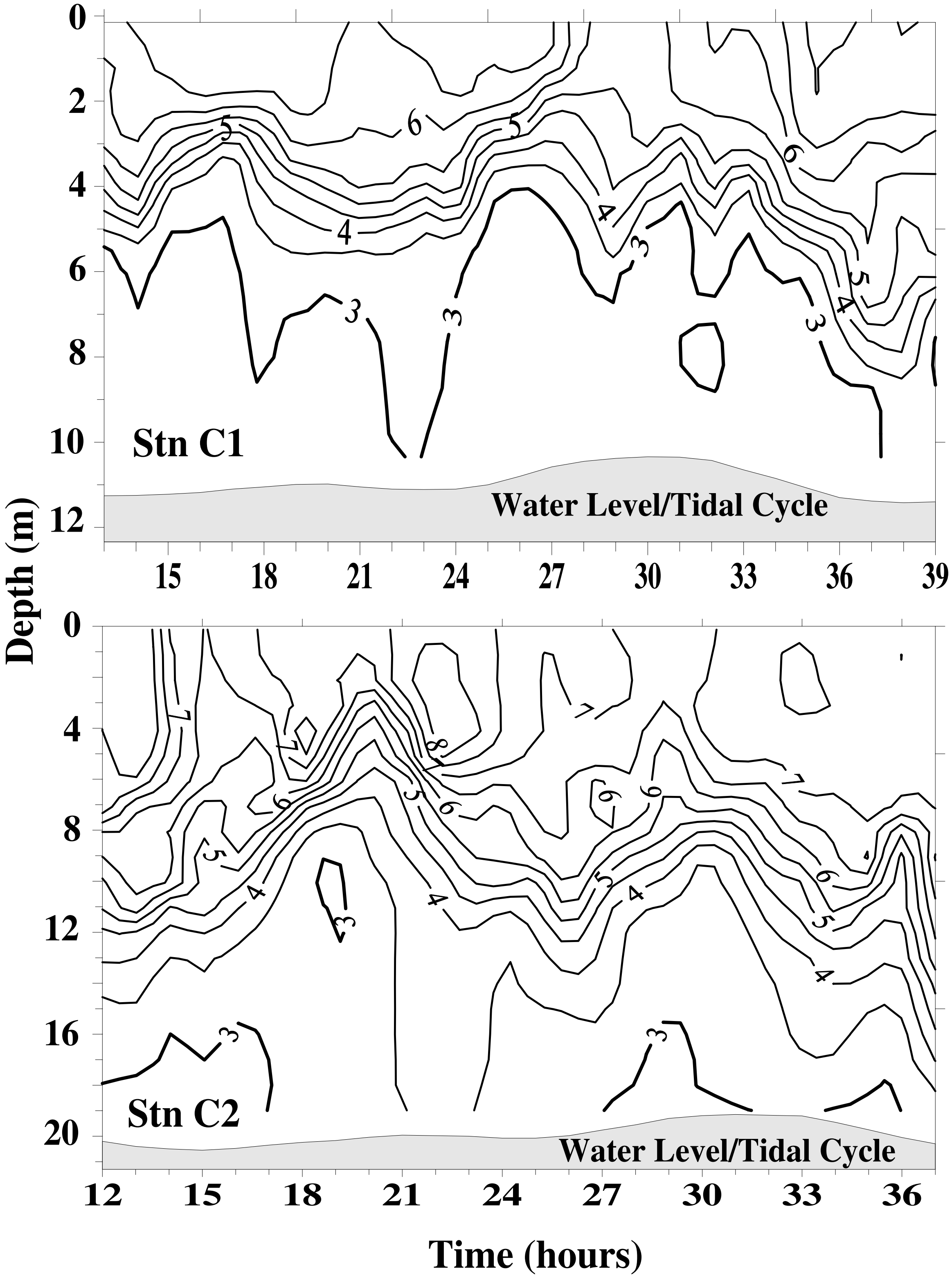

Stn C1
Water Level/Tidal Cycle
0
2
4
6
8
10
12
15
18
21
24
27
30
33
36
39
3
4
5
6
Depth (m)
Stn C2
Water Level/Tidal Cycle
0
4
8
12
16
20
12
15
18
21
24
27
30
33
36
3
4
5
6
7
8
Time (hours)

Fig. 8

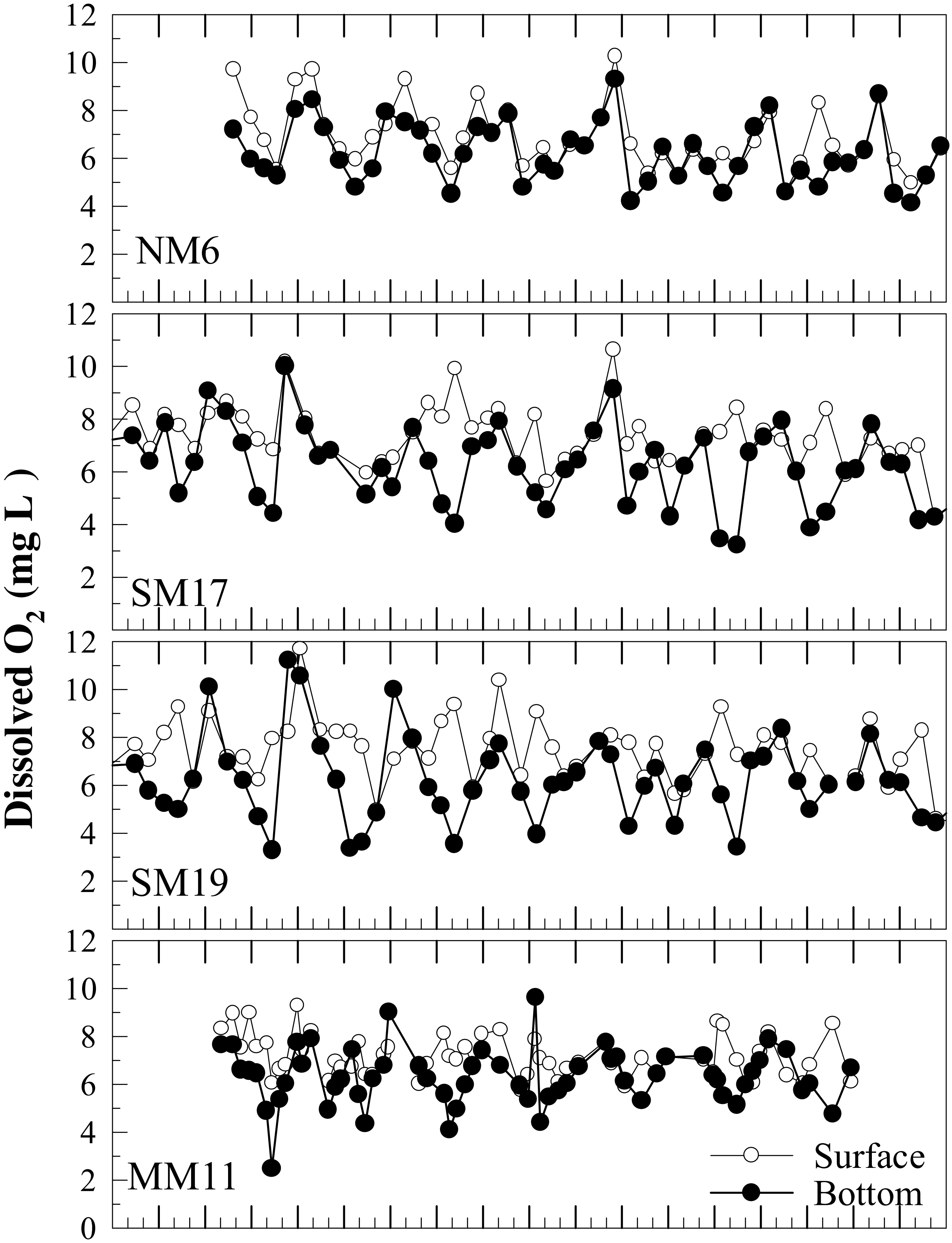

Dissolved O$_2$ (mg L^{-1})
NM6
SM17
SM19
MM11
Surface
Bottom
0
2
4
6
8
10
12
1 7 1 7 1 7 1 7 1 7 1 7 1 7 1 7 1 7
1990 91 92 93 94 95 96 97 98

Fig. 9

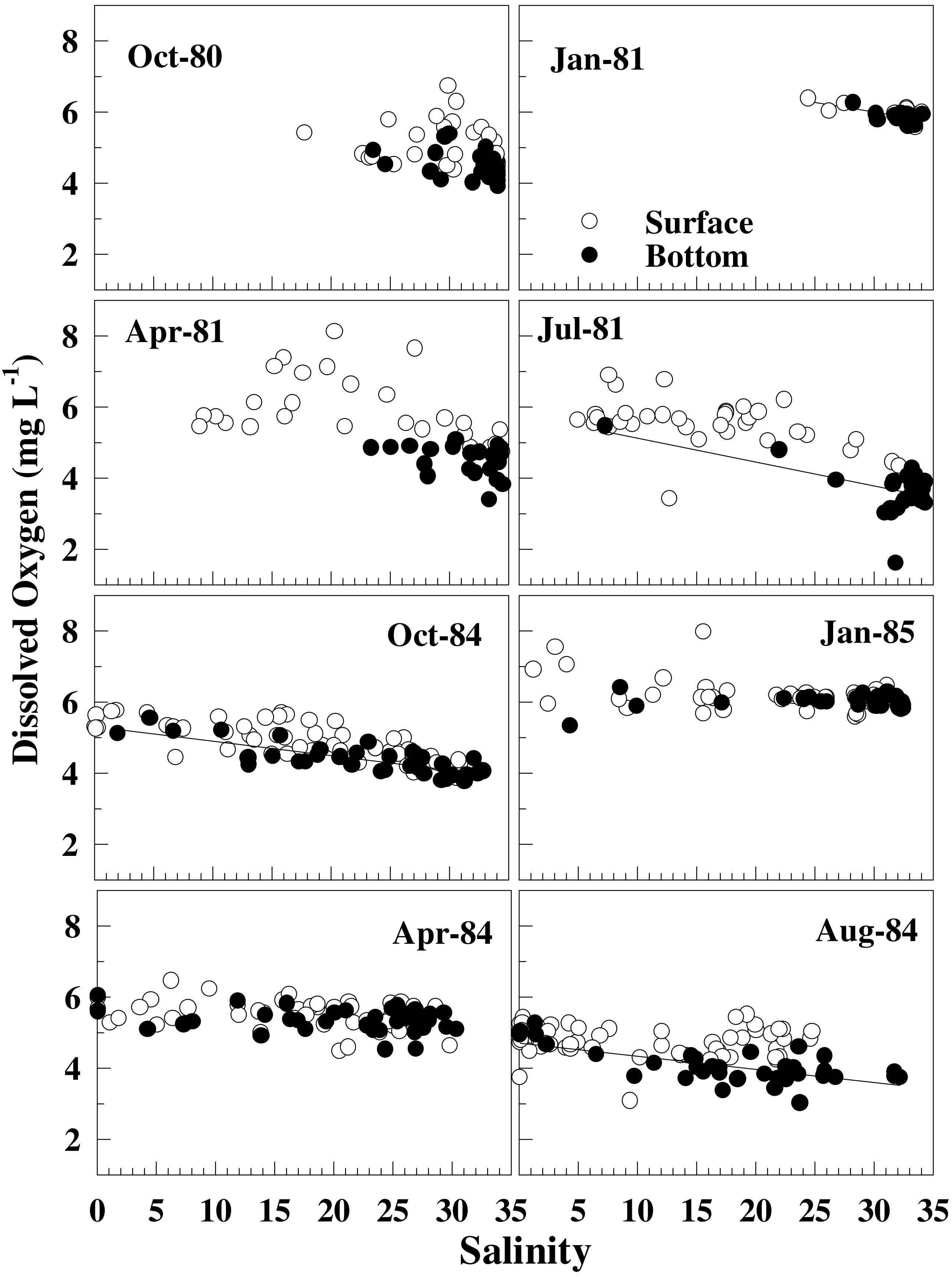

Oct-80
Jan-81
Surface
Bottom
Apr-81
Jul-81
Oct-84
Jan-85
Apr-84
Aug-84
Dissolved Oxygen (mg L^{-1})
2
4
6
8
0
5
10
15
20
25
30
35
Salinity

Fig. 10

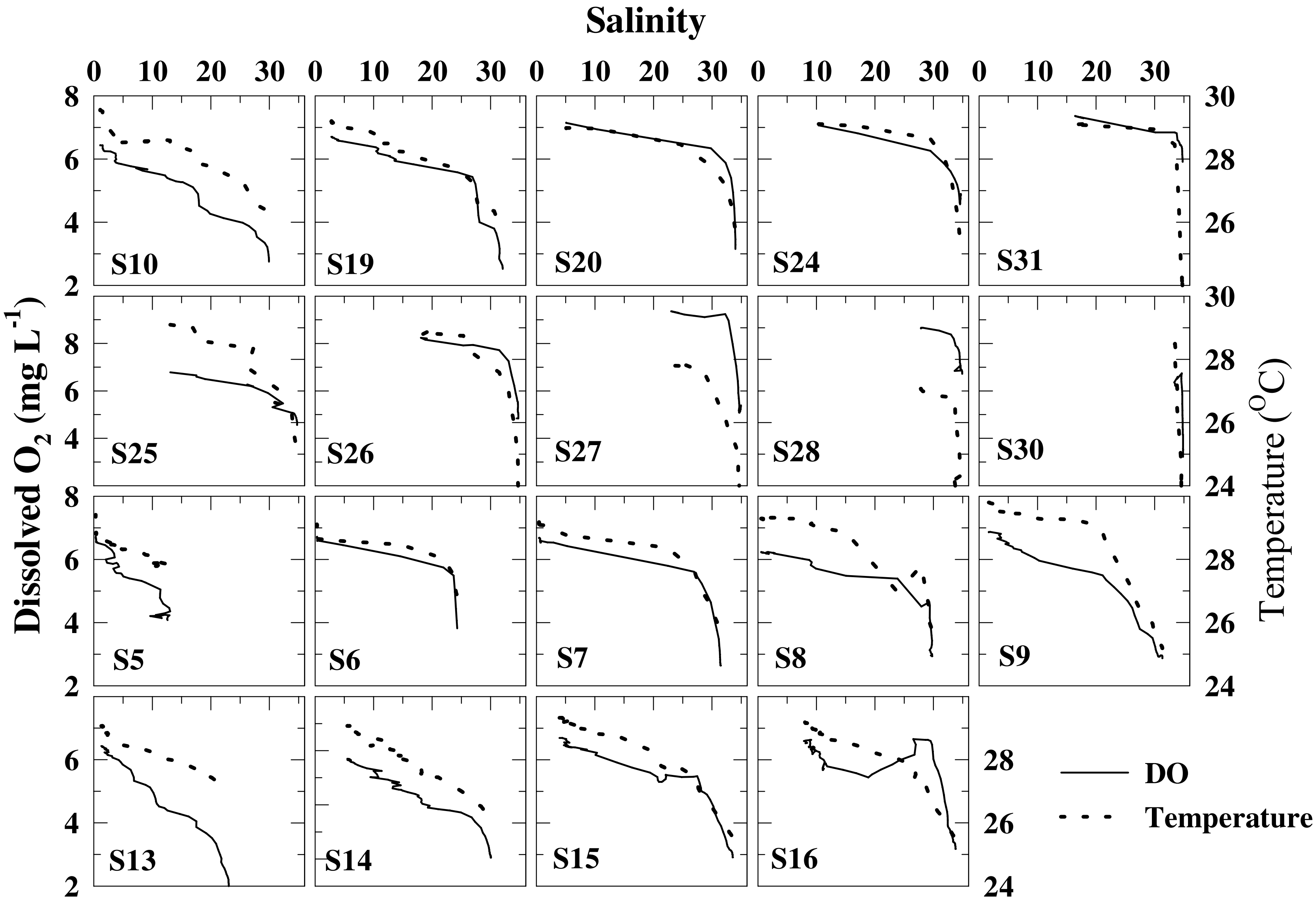
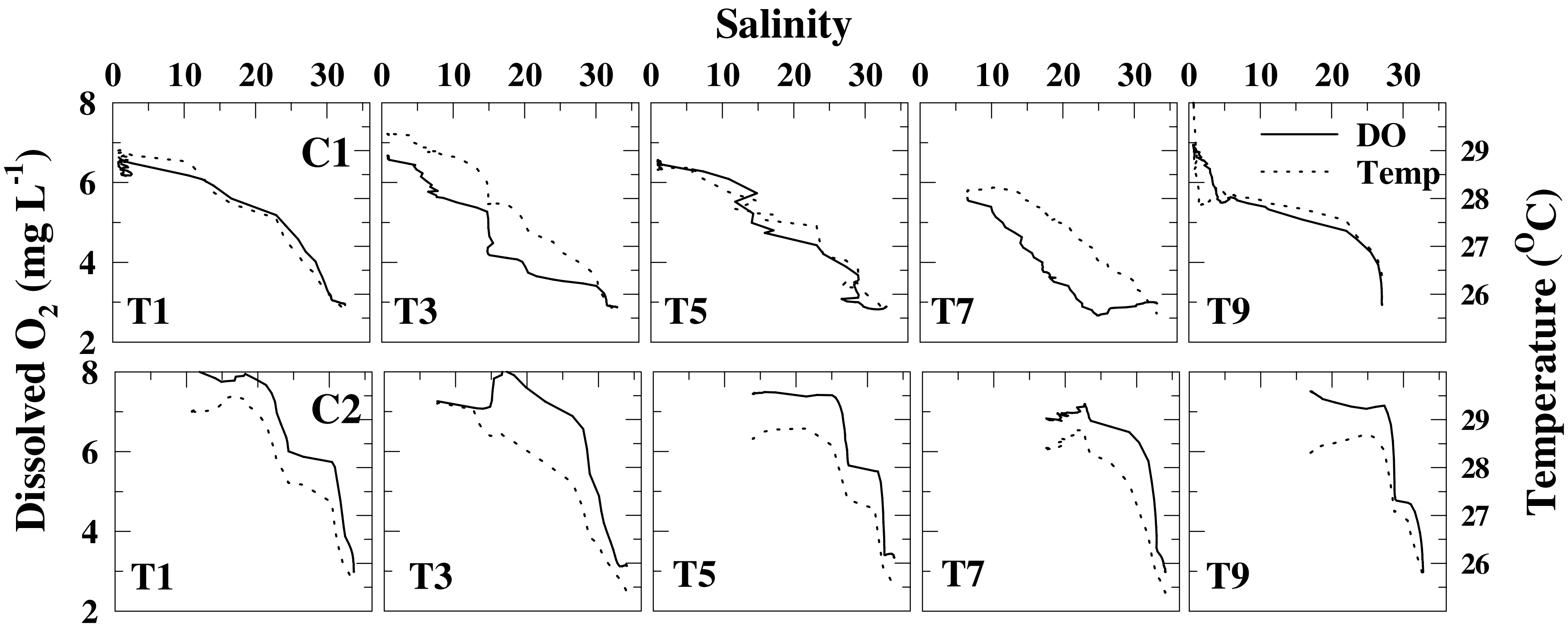

Salinity
0
10
20
30
Dissolved O$_2$ (mg L^{-1})
Temperature (^{O}C)
8
6
4
2
30
28
26
24
S10
S19
S20
S24
S31
S25
S26
S27
S28
S30
S5
S6
S7
S8
S9
S13
S14
S15
S16
DO
Temperature

Fig. 11


Salinity
0
10
20
30
8
6
4
2
Dissolved O$_2$ (mg L^{-1})
Temperature (^{O}C)
29
28
27
26
C1
C2
T1
T3
T5
T7
T9
DO
Temp