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Upwelling and Degree of Nutrient Consumption in Nanwan Bay, Southern Taiwan

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UPWELLING AND DEGREE OF NUTRIENT CONSUMPTION IN NANWAN BAY, SOUTHERN TAIWAN

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Key words: Nanwan Bay, upwelling, dissolved organic nitrogen, degree of nutrient consumption.

ABSTRACT

The newly proposed Degree of Nutrient Consumption (DNC) of upwelled waters was used to evaluate the upwelling process in Nanwan Bay off the southern tip of Taiwan. DNC values were found to be low in subsurface waters or in newly upwelled waters. In general, a low DNC value was detected alongside other traditionally used upwelling indicators such as lower temperature, pH and % oxygen saturation but higher salinity, nutrients and chlorophyll *a*. On the other hand, the DNC value could be several times higher in aged upwelled water found in the surface layer.

INTRODUCTION

Nanwan Bay, located at the southern tip of Taiwan (Fig. 1) adjacent to the Kenting National Park, is in a pristine marine environment with minimum industrial, domestic or agricultural pollution. The Third Nuclear Power Plant northwest of the bay, established before the national park, on the other hand, has been a concern as it draws cooling water from the bay and discharges it back into the bay. Because of the nature of the semi-enclosed bay, whether thermal pollution has harmed the coral community has been an issue. This is because if the warm effluent from the power plant re-circulates within the bay, temperature of the bay water may rise to an intolerable degree for corals.

However, the temperature data in and out of Nanwan Bay does not support a temperature buildup within the bay (Chen *et al.*, 2001). In fact, when compared with sea surface temperature outside of the bay measured during the World Ocean Circulation Experiment (Fig. 2), Sts. 14, 16, 18, 20, 22 and 23 actually have a lower temperaute. This is consistent with the report of a cold eddy inside Nanwan Bay (Chen *et al.*, 1994). In a series of papers Lee *et al.* (1997, 1999a, b) reported tidally induced upwelling, which brings cold water to the surface and may be used to explain the lower temperature in the bay compared with the higher temperature outside. Of note is that St. 24 is near the outlet of the thermal effluent and it has an higher temperature.

Such an upwelling not only helps keeping Nanwan Bay relatively cool despite the power plant, upwelling also has significant biogeochemical implications. This is because upwelled water supplies nutrients to the euphotic zone in the surface oceans and stimulates biological production. Most of the world's major fisheries, like those off Oregon, California, Peru, Namibia, Somalia, Vietnam and East China Sea, are known for their upwelling (Wong *et al.*, 1991; Chen, 1996; Gong *et al.*, 2000; Liu *et al.*, 2000a, b, 2002). In fact, upwelling of nutrient-rich subsurface Kuroshio

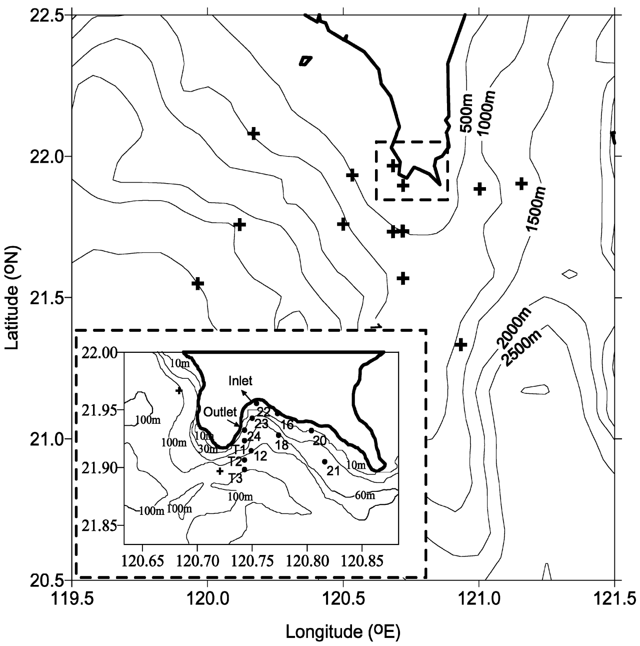

Fig. 1. Sampling stations in Nanwan Bay (•) and WOCE (+) stations nearby.

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waters has been reported (Chen and Wang, 1999) to contribute over 70% of P which is needed to support total new production on the East China Sea continental shelf.

The importance of upwelling notwithstanding, it is not yet possible to measure upwelling directly. Traditionally, lower temperature, dissolved oxygen content and pH, but higher salinity, nutrients and chlorophyll a have been used to identify upwelled water. However, solar heating, evaporation, precipitation, as well as river input and groundwater seepage tend to blur the temperature, salinity, and nutrient signals. Further, biological consumption may reduce nutrients while chlorophyll a is increasing. As a result, the upwelling center may actually have a negative correlation between nutrient content and chlorophyll *a*.

DEGREE OF NUTRIENT CONSUMPTION

Further clouding the relationships among nutrients, chlorophyll a and upwelling is that when the later process is intensive, the nutrient-rich subsurface waters may be diverged from the upwelling center before phytoplankton has a change to fully grow. Consequently, the chlorophyll *a* concentration may actually be higher at the perimeter of the upwelling center. On the other hand, if the upwelling process is slow, phytoplankton can grow fully near the upwelling center, hence making

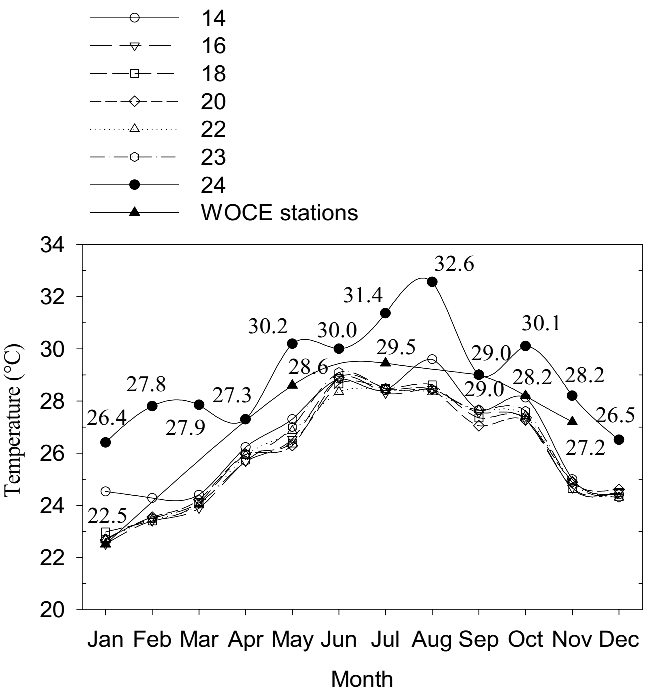

Fig. 2. Comparison of average sea surface temperature at seven stations within nanwan bay (1986-2003) and at WOCE stations nearby.

the chlorophyll *a* concentration high near the center. In the meantime, nutrient concentrations may be low near the center because of consumption (Chen *et al*., 2004).

In order to express the aging status of a given upwelled water mass, Takahashi *et al*. (1986) took into account the relative percentages of chlorophyll *a* and nitrite plus nitrate. Chen *et al*. (2004) renamed the aging index of upwelling as Degree of Nutrient Consumption (DNC):

$$DNC_c = \frac{0.7 \times chlorophyll\ \text{a}}{NO_3^- + NO_2^- + 0.7 \times chlorophyll\ \text{a}} \qquad (1)$$

where subscript c refers to DNC based on chlorophyll *a*. A similar equation based on *P* was proposed by Chen (2000):

$$DNC_P = \frac{DOP + PP}{DIP + DOP + PP} \qquad (2)$$

where *DOP*, *DIP* and *PP* refer to dissolved organic *P*, dissolved inorganic *P* and particulate *P*, respectively. Recently, Chen *et al*. (2004) proposed a similar equation based on *N*:

$$DNC_N = \frac{DON + PON}{DIN + DON + PON} \qquad (3)$$

where *DON*, *PON* and *DIN* are, respectively, dissolved organic *N*, particulate organic *N* and dissolved inorganic *N*.

The rationale behind the above equations are that the subsurface waters contain high amounts of DIN and DIP but low amounts of chlorophyll *a*, DON, DOP, PP and DON. As a result, before upwelling the DNC is low. On the other hand, the DNC is high after most nutrients are converted to organic form in the euphotic zone. Chen *et al*. (2004) was the first to show that based on data in the literature, DNC_N can be used not only to identify the upwelling phenomenon in Nanwan Bay, but also its strength. Because of the limitation in the available data, which were two decades old (Su *et al*., 1985), Chen *et al*. (2004) were able to show only the average value for the 25 m-thick upper water column, hence no vertical resolution. It is the purpose of this manuscript to show the upwelling phenomenon and DNC_N in Nanwan Bay based on spatially and vertically distributed data. In addition, examples based on DNC_C are also presented below.

SAMPLING LOCATIONS AND ANALYTICAL METHODS

The sampling locations are plotted in Fig. 1. Temperature and salinity were determined at 11 stations with a Sea-Bird 19 CTD (Conductivity-Temperature-

Depth/Pressure) unit, and discrete samples were collected from eight stations using a Niskin bottle. Salinity in discrete samples was determined by measuring conductivity using an AUTOSAL salinometer 8400B calibrated with IAPSO standard seawater (batch no. P128) for a precision of 0.003. Dissolved oxygen (DO) in discrete samples was measured by direct spectrophotometry (Pai *et al*., 1993). The precision of the measurement was about 0.32% at the 190 μmol kg^{-1} level. The apparent oxygen utilization (AOU) was calculated based on the oxygen solubility equation of Chen (1981). pH was measured at 25 ± 0.05°C with a Radiometer PHM-85 pH meter using a GK-2401C combination electrode. A Tris seawater buffer was used to calibrate the electrode. The precision was better than ± 0.003 pH unit.

Nitrate (NO_3^-) was measured by reducing nitrate to nitrite (NO_2^-) and then determining the nitrite employing the pink azo dye method by using a flow injection analyzer with an on-line Cd coil. The precision of this method was about ± 0.08 μmol L^{-1} for NO_3^- and ± 0.02 μmol L^{-1} for NO_2^-. Phosphate (PO_4^{3-}) was determined by the molybdenum blue method using a flow injection analyzer. The precision of the measurement was about ± 0.05 μmol L^{-1}. Silicate (SiO_2) was measured by the method of Fanning and Pilson (1973), also using a flow injection analyzer. The precision of the method was ± 0.1 μmol L^{-1}. CSK standards in artificial seawater (Wako, Japan) were used for calibration (Pai *et al*., 1990; Chen *et al*., 2004).

DOP, DON and PON samples were collected by filtration through a precombusted 0.7 μm Whatmann GF/F fiberglass filter. Total suspended matter and chlorophyll *a* samples were collected by filtration through a 0.45 μm diameter Millipore polycarbonate filter. A Turner Designs model 10-AU fluorometer was used to measure chlorophyll *a* after extraction by 90% acetone (Strickland and Parsons, 1972). A LECO CHN-932 Elemental Analyzer was used to measure total particulate nitrogen (PN) at 950°C, with 11 pure and mixtures of NIST SRM-2704, LECO EDTA standard and sulfa-methazine used to calibrate the analyzer. A separate sample was burned at 450°C for 3 hours to remove organic matter and then remeasured with the Elemental Analyzer to obtain the value of particulate inorganic nitrogen. The difference between this value and PN determined PON. The method of Valderrama (1981) was followed to oxidize DOP and DON to PO_4^{3-} and NO_3^-. Duplicate samples were run and the precision for DOP and DON was 24 and 8%, respectively. Glycol and ATP (Sigma ultrapure) were used to prepare running standards.

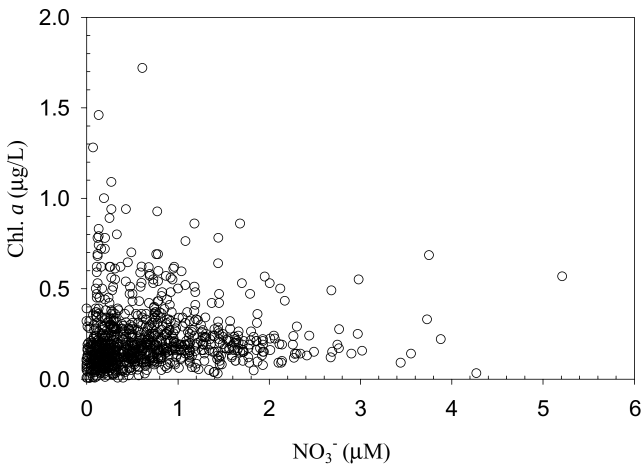

Fig. 3. Relationship between chlorophyll *a* and nitrate (July, 1983-Dec., 2003).

RESULTS

First of all we looked at the relationship between chlorophyll *a* concentration and nitrate based on data collected for this study and some of our unpublished data (Fig. 3). There seems to be a negative correlation which suggests that the study area is nutrient limited and the phytoplankton growth is out of phase with the nutrient supply. That is, phytoplankton starts to flourish when nutrient contents becomes high, and reaches the highest phytoplankton (chlorophyll *a*) stock while nutrients are near depletion. Subsequently, biological productivity is reduced to an extent when nutrient contents start to build up again, perhaps by upwelling. This indicates that upwelled waters do not necessarily contain higher NO_3^- or chlorophyll *a*. This is when DNC becomes useful because it indicates whether the upwelled water is new (lower DNC) or has been aged (higher DNC).

The spatial distributions of T, S, pH, DO (%), NO_3^-, SiO_2, chlorophyll *a* and DNC_C in the surface layer in Oct. 2000 are given in Fig. 4-1. It is noted that near the center of the bay T, pH and DO (%) reveal a minimum whereas S, NO_3^- and SiO_2 are high. Indeed, DNC_C also shows a minimum near the center. This is a clear indication that upwelling near the center of the bay was strong so that a rather low DNC_C value was maintained. Fig. 4-2 shows pretty much the same information at 10 m depth. Of note is that chlorophyll *a* did not show either a maximum nor a minimum in the surface layer at the upwelling center (Fig. 4-1). At 10 m depth, chlorophyll *a* was actually low near the upwelling center, perhaps because phytoplankton did not have enough time to fully grow. Chlorophyll *a* values are higher at 10 m then at surface, a common phenomenon found in the oceans, especially in the tropics (Chen, 1994).

Fig. 4 was based on data in the fall when upwelling appears to be the strongest and the most frequent. The upwelling signal seems to be the weakest and the occurrence the least frequent in winter and early spring. Fig. 5-1 shows such a phenomenon detected in Jan. 1997. In this case, the upwelled water seems to have moved toward Sts. 16 and 22, rather than near the center of the bay (St. 18). Indeed, rapid temperature drops have been detected nearshore based on a recent continuous temperature record (Fig. 6). Upwelling becomes more apparent and increases in frequency in late May, shown as an example in Fig. 5-2. In this case, as most often

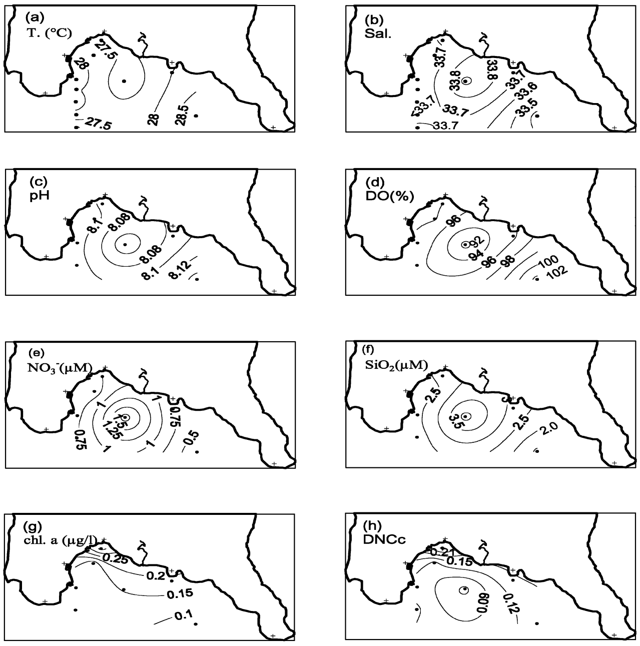

Fig. 4-1. (a) Temperature, (b) salinity, (c) pH, (d) DO (%), (e) NO_3^-, (f) SiO_2, (g) chl. *a* and (h) DNC_C in the surface layer in Oct. 2000.

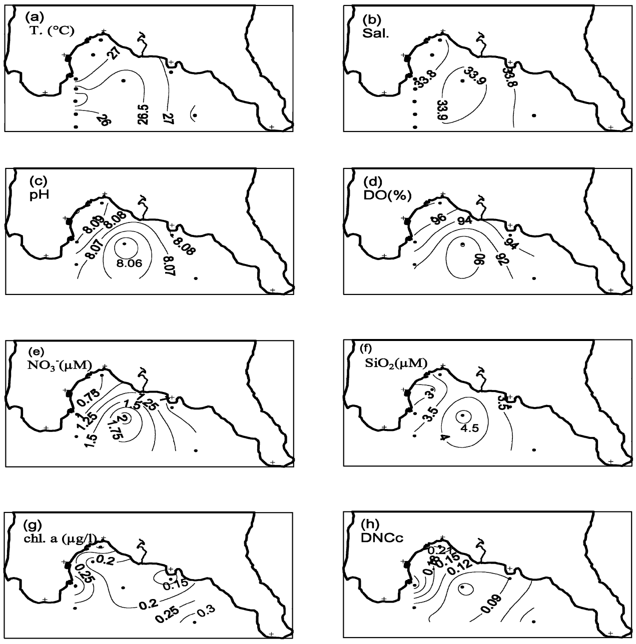

Fig. 4-2. (a) Temperature, (b) salinity, (c) pH, (d) DO (%), (e) NO_3^-, (f) SiO_2, (g) chl. *a* and (h) DNC_C in the 10-m depth layer in Oct. 2000.

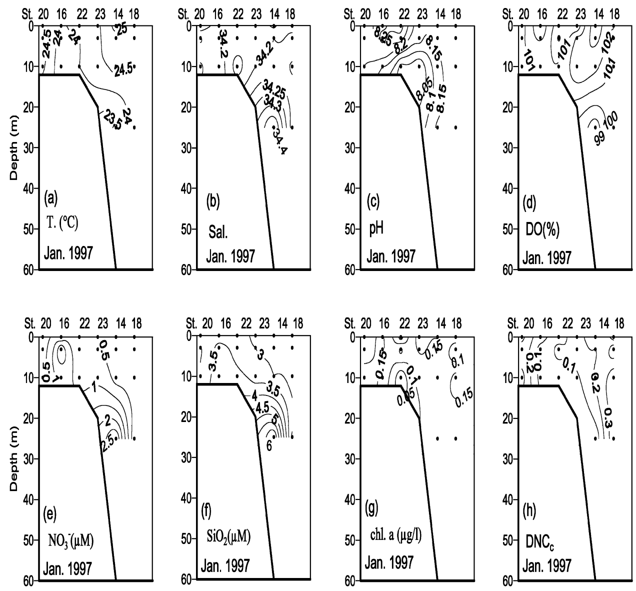

Fig. 5-1. Cross-sections of (a) temperature, (b) salinity, (c) pH, (d) DO (%), (e) NO_3^-, (f) SiO_2, (g) chl. *a* and (h) DNC_C for Nawan Bay in Jan., 1997.

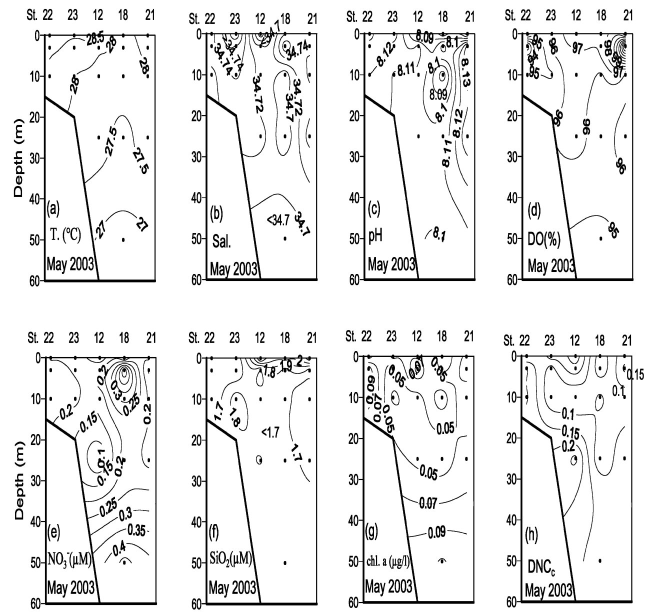

Fig. 5-2. Cross-sections of (a) temperature, (b) salinity, (c) pH, (d) DO (%), (e) NO_3^-, (f) SiO_2, (g) chl. *a* and (h) DNC_C for Nawan Bay in May, 2003.

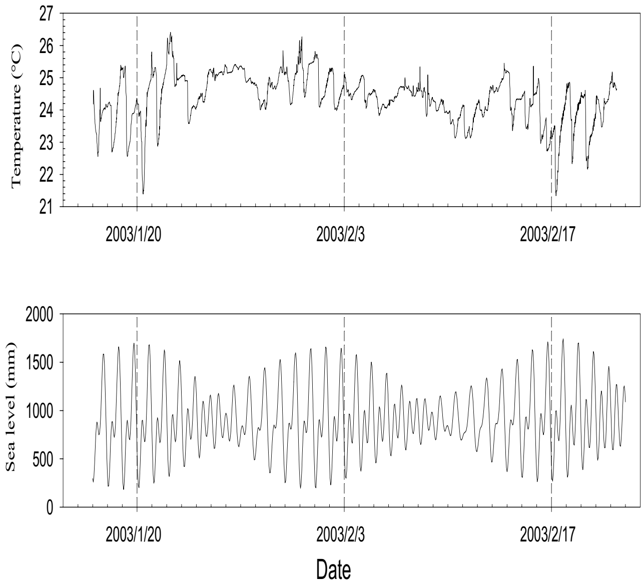

Fig. 6. Continuous temperature and tide record at St. 24 between 17 Jan and 21 Feb 2003.

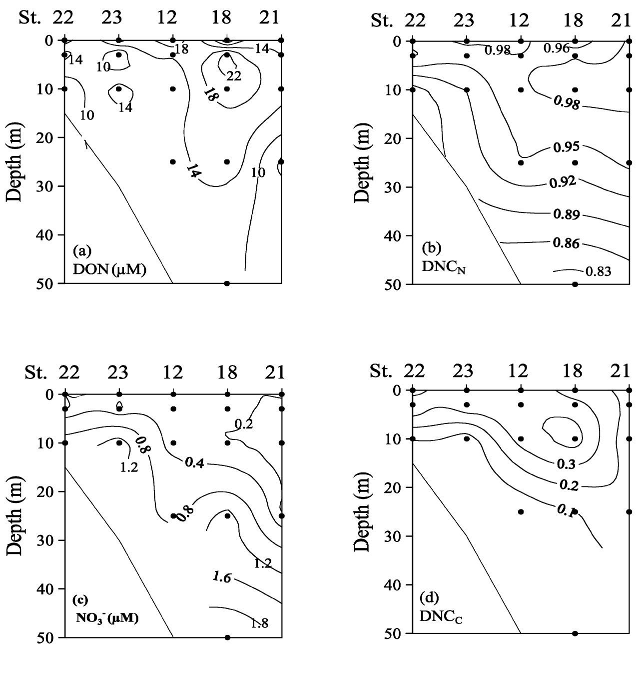

Fig. 7. Cross-sections of (a) DON, (b) DNC_N (c) NO_3^- and (d) DNC_C for Nanwan Bay.

found, the upwelling center is near St. 18 near the center of the bay.

DISCUSSION

Coastal processes are generally complicated with a lot of temporal and spatial variability. Topographical features, internal waves, winds and tides further complicate the upwelling issue even in a small bay such as Nanwan. It is shown that the DNC signal agrees qualitatively with the commonly used upwelling signals based on T, S, pH, % oxygen saturation, chlorophyll *a* and nutrients. The absolute values of DNC_N and DNC_C differ (Fig. 7). Nevertheless, both do show the same upwelling feature. More importantly, both provide a semi-quantitative way to indicate whether an upwelling water is new or aged.

CONCLUSIONS

In order to supplement the use of temperature and salinity as upwelling indicators, and to obtain a semi-quantitative measure of the intensity of upwelling, the Degree of Nutrient Consumption was used to evaluate the upwelling process in Nanwan Bay. Upwelling seems to be the strongest and the most frequent in the fall, and the weakest and the least frequent in winter and early spring. It was found that when the upwelling was strong, chlorophyll *a* was actually low near the upwelling center, perhaps because phytoplankton did not have enough time to fully grow.

ACKNOWLEDGEMENTS

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