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Variability of suspended particle concentration due to tidal influences in the shelf sea north of Taiwan

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Abstract: This study investigated the time variation of the concentration of suspended particles in the shelf sea north of Taiwan due to tidal current. Waters from five tidal-cycle stations located on the shelf and the shelfbreak were sampled at various depths at a time interval of 2 hours. Suspended particle concentrations were determined, and currents were measured by a vessel mounted ADCP. It was found that for stations at the continental margin, the variation of particle concentration did not correlated well with the magnitude of the tidal current, but can change with the flow direction. Concentration was higher when the current flowed toward one direction and lower toward the other, which reflected the spatial variation of particle concentration. At the shelf stations, the concentration of the bottom layers increased with the flow velocity regardless of its direction, which may be due to the bottom resuspension and deposition or the convection of particle clouds caused by the tidal current, which in turn maintained a bottom nepheloid layer. The results also showed that the depth average of the ratio of maximum to minimum concentration in a tidal cycle ranged from 1.6 to 2.8, depending on the location, with a mean value of 2.3. That is, there is a factor of two's variation in concentration in a tidal cycle. It was also found that the time and depth mean concentration in the shelf sea was about 0.5 to 2 mg/l while in the shelfbreak region was 0.2 mg/l. The time mean concentration for shelf break station was constant along the depth, while that for shelf stations increased exponentially with depth. By analyzing the disaggregated suspended particles found at a shelf station it was found that 98% of the particle was less than 64 μm with a median diameter about 6 μm. That is, only the fine particles on the sediment surface were involved in the resuspension and deposition cycle.

1. Introduction

Suspended particles consist of terrigeneous minerals and biogeneous particles, which are quite small in size and are light enough to move with the current. To study the transport of suspended particles or geochemical processes associated with particles in water environments, suspended particle concentration (or suspended particulate matter) needs to be investigated. This parameter can be easily measured by sampling the water and then determined gravimetrically or measured electronically using transmissometers or nephenometers. Suspended particle concentration, much like any other marine parameters, varies according to several time sales, such as daily, tidal, seasonal etc. (KRANCK, 1980). Among them, tidal variation has received careful attention for studies carried out in coastal waters such as estuary, bay and inlet (e. g. POSTMA, 1965; KRANCK, 1980; KRANCK and MILLIGAN, 1992), since in these places the resuspension and deposition of the sediment due ot tidal current are prominent. However, for related studies in the shelf, the tidal influences on the suspended particle concentration are often neglected. Particularly, during a survey of continental shelf, stations along one or more transects are often visited sequentially regardless of the tidal phase when the stations are visited. Due to large distance that has to be covered, the mapping of suspended particle by this method can be different from the real synoptic suspended particle distribution. The reasons for this are twofold. One, tidal current on

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the shelf, which are the strongest current in the shelf sea, often traces out a tidal ellipse. Hence, the water sampled at a given location at different time can be different. Moreover, if there is a spatial variation of the particle concentration, the concentration will change with the current direction. Two, at places where depths are shallow enough and where bottom sediments are available for resuspension, the suspended matter would definitely vary with the tidal phase. Hence there is a need to establish the variability of this parameter due to tidal influences.

The objectives of this study are to measure the tidal variation of suspended particle concentration at various stations from the mid-shelf to the shelf edge north of Taiwan. These stations were occupied for 12 hours and current velocity and particle concentration were measured. The current velocity was used to determine the tidal phase. From results of this study, the maximum variability of particle concentration in a tidal cycle in this region was established. It is to note here that although some explanations on the temporal variation of the particle concentration are offered, they may be contested. Further investigation is necessary to clarify the reasons for variations.

2. Sampling locations and methods

The shelf sea north of Taiwan (Fig. 1) is a part of the marginal sea east of Chinese continent. Current field in this region includes Chinese continent coastal water, monsoon driven current, and Kuroshio, and they vary according to the summer and winter seasons (NIINO and EMERY, 1961). Along the coast of Chinese continent, the coastal water flows southward and enter Taiwan Strait in the winter when the northeasterly monsoon prevails. In the summer, the coastal water does not enter the Taiwan Strait, due to the opposing southwesterly monsoon, and turns eastward (THOMAS and PERRY, 1968). In the area north of Taiwan strait (or mid-shelf), the current is mostly monsoon-driven current. In the summer, the wind driven current combines with a branching Kuroshio in the strait flows northward. While in the winter, the current flows southward due to the northeast monsoon. At the lower shelf near the

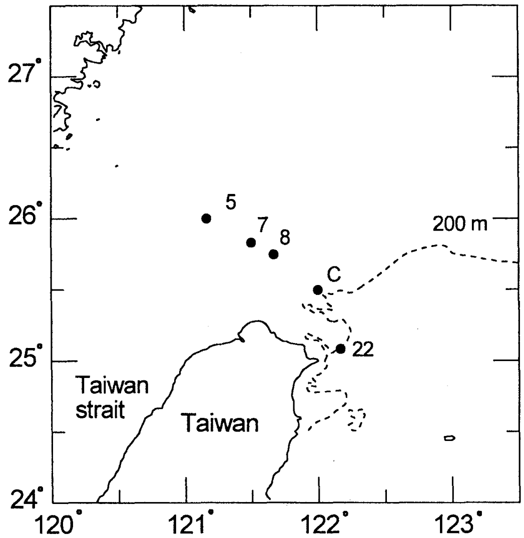

Fig. 1. Stations locations.

continental margin a complicated exchange process between the shelf water and Kuroshio exists (LIU *et al.*, 1992). Here, Kuroshio, skirting along the east coast of Taiwan, turns toward northeast as it encounters the continental edge located north of Taiwan, following the topography of the edge. Intrusion of Kuroshio water onto the shelf north of Taiwan has been reported by several researchers (e. g. LIU and PAI, 1987; CHERN and WANG, 1989).

Tidal current in the shelf sea north of Taiwan runs in the general direction of WNW and ESE, following the direction of the north coast of Taiwan. During the flood tide, tidal current flows from the offshore area toward the WNW direction and branches into Taiwan Strait. The current direction reverses during the ebb phase. The maximum speed of the current is one to three konts.

The bottom sediment on the shelf in this region has one of the typical distribution patterns on continental shelves as described by MCCAVE (1972). Investigation conducted by BOGGS *et al.* (1974) indicated that close to the Chinese continental coast, the bottom are mainly fine-grained clay and silt particles deposits with traces of sand. This mud belt was suggested to be related to the input of the fine sediments from Chinese rivers (NIINO and EMERY, 1961). The percentage of fine particle deposits decreases and that of sand increases as

Table 1. Locations and depths of sampling stations and the time of sampling.

Station	Latitude	Longitude	Depth(m)	Cruise	Time
5	26°	121°10′	83	389	4–5/6/94
7	25°50′	121°30′	78	352b	22/4/93
8	25°45′	120°40′	115	386	6/5/94
C	25°30′	122°	120	365	29–30/8/93
22	25°5′	122°10′	205	352b	24/4/93

the distance from the continent increases. From the mid-shelf to lower-shelf, seabed changes from sandy mud to mostly sand and shell fragments. Sandy sediments in this area are of relic origin (NIINO and EMERY, 1961). On the continental slope fine-grained particles reappear with its size distribution closely resemble that found near the continental coast. The fine particle distribution pattern in this region seems to conform to the notion that sediment particles are transported from the continental coast toward the offshore water, and deposited on the slope and beyond, passing over the lower shelf (MCCAVE, 1972).

Five tidal-cycle stations (Fig. 1) were occupied in four different cruises (Table 1) during spring and summer seasons. Since the purpose of this study is to look at the changes in the time scale of a tidal cycle, it does not matter whether experiments are conducted in various or in one cruise. Station 5, which has a depth of 83 m, was located at mid-shelf, while stations 7 and 8 at lower mid-shelf with depths of 78 m and 115 m respectively, and stations C and 22 were near the shelf edge with dephs of 120 m and 205 m respectively. Each station was occupied for 12 hours. Since the research vessel was not anchored, it drifted with the tides. Hence, the vessel was always returned to the original position at the sampling time. Water samples from four to five levels, including one from the surface and one from the near bottom were collected every two hours by Go-Flo water bottles on a rosette sampler attached to a CTD. Four to eight liters of water, depending on the concentration, were filtered through preweighted Nuclepore polycarbonate filters for particle concentration determination. Multiple tests showed that the concentration measurements had a coefficient of variation about 10%.

In order to correlate the measured suspended particle concentration with the tidal current, concurrent current data were obtained. The currents were measured by a vessel mounted Acoustic Doppler Current Profiler (from RD Instruments). The ADCP had a frequency of 150 kHz. Ten-minute-average of the ADCP data were obtained. Only the data corresponding to the time when water samples were collected were selected. Due to the limitation of the instrument, the topmost velocity was measured at 12m deep and the lowest layer measured was about 25% of the water depth above the sea bed. Hence, the bottom shear stress created by the current can not determined. The phenomenon of bottom resuspension is often discussed in terms of bottom shear stress. However, in this study only the current velocity is dicussed. This is not really a problem, since this study does not investigate the quantitative relationship between the bottom resuspension and the bed shear stress.

Size distributions of disaggregated bottom sediment and suspended particles were also measured for some stations. Bottom sediments were obtained by a box core and pretreated by sodium hexametaphosphate (GALEHOUSE, 1971) for peptization. Wet sieving was used to separate sands and shells from silts and clays by a 64 μm sieve. Particles larger than 64 μm were then dry-sieved and silts and clays, mixed in DI water suspension, were analyzed by a laser based particle sizer (CIS-1 by Galai). This instrument determines particle size by scanning individual particles with a fine, rotating laser beam. Size information was determined by the time length of light obscuration by the scanned particle (AHARONSON *et al.*, 1986; TSAI and RAU, 1992). Suspended particles were obtained from the filters used for concentration determination by immersing them in DI water and in an ultrasonic bath. Their sizes were also measured by the CIS-1.

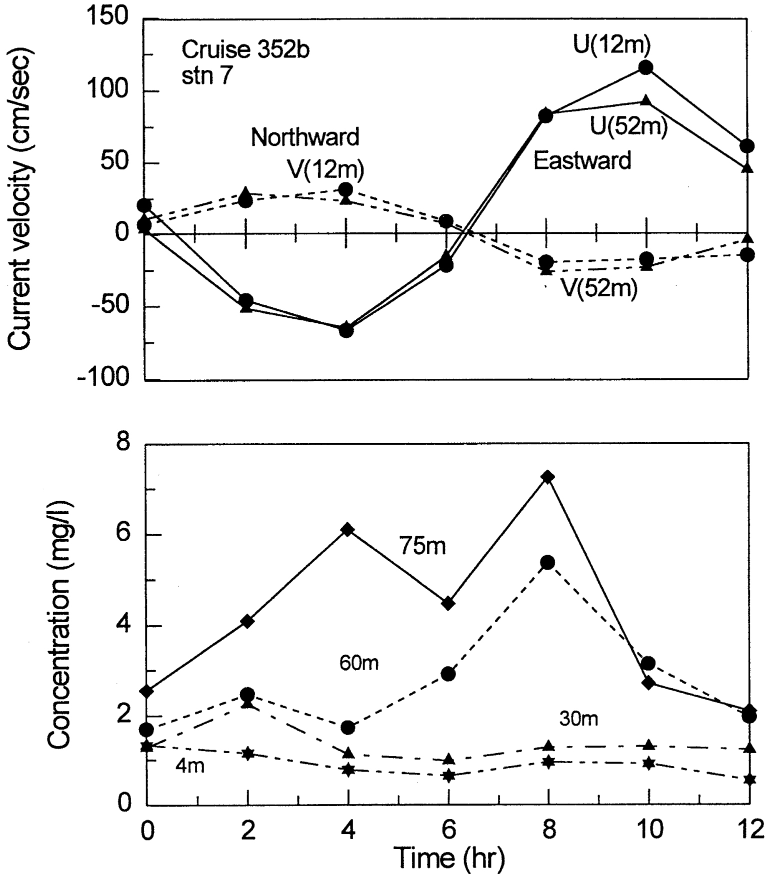

Fig. 2. Temroral variation of current velocity and concentration for the station 7 (U : east-west component and V : north-south component).

3. Results and discussion

3.1 Particle concentration and current velocity

For brevity, two examples are presented here: stations 7 and 22. At the lower-mid shelf station, the tidal current was uniform over the depth and was highly semidiurnal (Fig. 2). In the first half of the observation period, the current was in the direction of WNW and then turned ESE in the later half. The U component was not entirely symmetric between the flood and ebb phases though. The maximum eastward flow was over 100 cm/s while the westward current was only 70 cm/s. The north-south component of the current was, on the other hand, quite symmetric but only reached a maximum speed of 25 cm/sec.

The concentration at the upper layers (4 m and 30 m) was less than 2 mg/l and showed slight increase when the tidal current was in the maximum flood and ebb stages. Since this station was only 78 m deep and the bottom current was quite strong, one would expect that bottom resuspension at the maximum current is important. This phenomenon can be seen from the suspended particle concentration. At 75 m the concentration increased from 2.6 mg/l to 6 mg/l as the current picked up from the slack tide at the hour 0 to maximum flood at the hour 4. At the hour 6 the tide slacked again. The concentration at the bottm decreased to 4.2 mg/l, and then increased to 7.2 mg/l at the hour 8 as the current turned east and accelerated. Then the bottom turbidity dropped sharply to 2.6 mg/l at the 10th hour; equal to its corresponding concentration at hour 0. At the 60 m level, the sediment concentration only

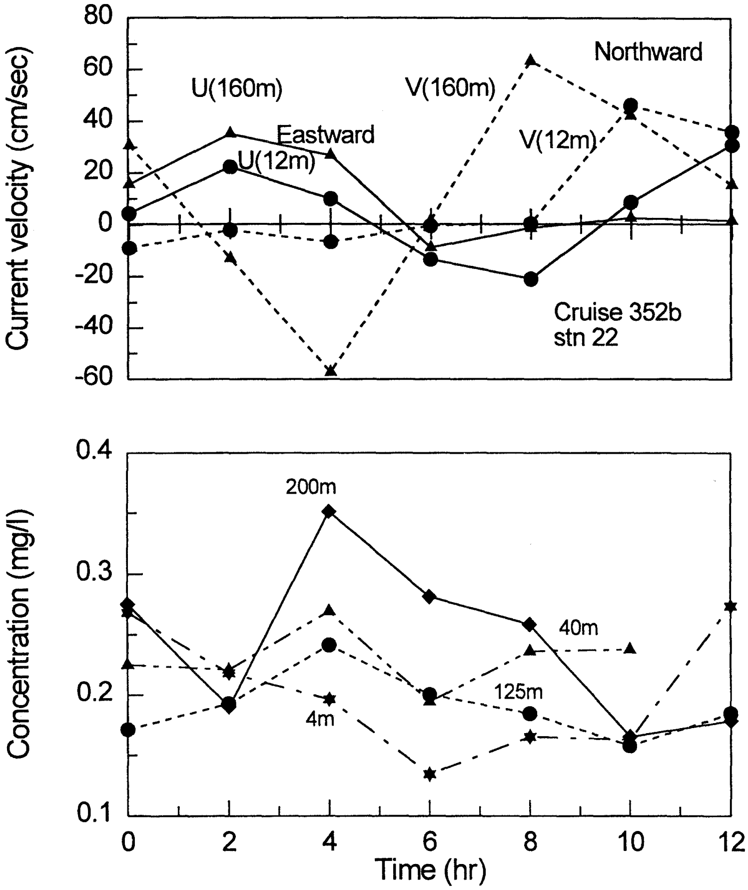

Fig. 3. Temporal variation of current velocity and concentration for the station 22.

increased slightly during the flood tide and then increased significantly as the current turned southeastward when the tide was strong enough to diffuse the particles upward to this level. The asymmetry in the flood and ebb velocity caused the maximum suspended concentration to be higher during the ebb phase than at the flood phase. This and the dip in the bottom concentration at the slack period seem to indicate that the bottom resuspension and deposition were responsible for the fluctuation in the particle concentration. However, the sharp decrease during the peak ebb current at hour 10 contradicts this explanation. This dip may be due to a possible depletion of a limited amount of bottom sediments which the flows are capable to resuspend. The whole temporal fluctuation of concentration may even be attributed to the movement of particle clouds carried by the tidal current, and the sharp decrease of concentration at hour 10 can be explained by the departure of the cloud; or due to both particle clouds and bottom resuspension. Despite this fluctuation, there existed a bottom nepheloid layer at all time with a particle concentration of at least 2 mg/l.

Figure 3 is the current and concentration data obtained from the station 22. The current changed with depth rather significantly at this station. As can be seen from the figure, the magnitude of the surface current was often less than the bottom current, In the surface layer the current flowed towards E and turned towards W and then NE, while in the lower layer the V component exhibited a well defined semidiurnal variation. The east-west component at the 160 m level only showed a eastward flow in the first 6 hours and then it almost

Table 2. Coefficient of variation (CV) and ratio of maximum to minimum values (Cmax/Cmin) for suspended particle concentration for all stations.

Stn 5			Stn 7			Stn 8			Stn C			Stn 22		
Depth (m)	CV (%)	Cmax/Cmin	Depth (m)	CV (%)	Cmax/Cmin	Depth (m)	CV (%)	Cmax/Cmin	Depth (m)	CV (%)	Cmax/Cmin	Depth (m)	CV (%)	Cmax/Cmin
4	25	2.0	4	31	2.5	4	31	2.4	4	33	2.2	4	26	2.0
30	19	1.8	30	31	2.3	40	29	2.2	40	43	3.2	40	11	1.4
55	15	1.7	60	47	3.2	80	30	2.1	90	35	2.6	125	14	1.5
70	34	3.1	75	46	3.5	110	30	2.6	115	17	1.7	200	28	2.1
80	12	1.4												

vanished in the second. Clearly, the current pattern deviates considerably from that of tidal current found at the previous station. By comparing the velocities of the upper and lower levels, one can see that there was large disparity in the flow velocity between the two levels, showing baroclinic effects. This phenomenon may be attributed to the effect of internal tide, generated by the interaction of surface tide and the abrupt change in bottom topography, such as a continental edge (BAINES, 1982). MAEDA (1979) also suggested that internal tide is prevalent in the south East China Sea. The suspended particle concentrations were all quite low, between 0.35 to 0.15 mg/l. At each level, the suspended concentrations also showed variation with time. Noticeably, one can see that during southeastward (ebb) flow, the concentration were higher, and as the flow turned westward, the particle concentration decreased, despite the peaking of the bottom flow speed.

It is clear that there was no discernible bottom resuspension observed at the station near the shelf edge. Although there is no definite increase of concentration as the flow speed reached its peaks, there are indications that suspended particle concentration varies with the flow direction. Hence this phenomenon showed a spatial variation of particle concentration. That is the temporal variation of concentration may de due to convection. In order to clarify the mechanisms which caused the temporal fluctuation of particle concentration, more investigations are warranted. Self-recording transmissometers and current meters tethered on a mooring line or fixed on a tripod for a longer term measurement can be an option.

3.2 Range of variation of particle concentration

Since the suspended particle concentration varied with time, one can examine its range of variation within a tidal cycle. Listed in Table 2 are the statistics of the particle concentration for each depth level for all stations. The table includes : the coefficients of variation (CV), computed by dividing the standard deviation of concentration by the time mean concentration, and the ratios of maximum to minimum concentration measured in the tidal period. The CV value represents the variability relative to the time mean value, while the ratio stands for the maximum variability within the tidal cycle. Among all stations, the coefficient of variation ranged from 11% to 47%; all are larger than the variation due to the measurement itself. The ratio of maximum to minimum concentration varied between 1.4 and 3.5. As can be seen, these two parameters also varies with depth at each station. At the station 7, the CV and Cmax/Cmin increased towards the bottom, as there was large concentration variability due to resuspension and deposition. The variability for stations 5, C, and 22 also differed significantly with the depth, while that for station 8 was uniform with depth. Figure 4 plotted the envelopes of minimum and maximum concentration for all stations. The envelopes represent the band within which the concentration in the tidal cycle fall. By integrating the CV and the maximum to minimum concentration ratio with depth, their depth mean values for each station were obtained (Table 3). Among these five places, the depth mean CV changed from 17% to 37% and maximum to minimum ratio was in the interval of 1.6 to 2.8. As can be seen from the table, station 7 has the largest variability with station C the second, while

Table 3. Comparison of depth mean value of CV and the ratio of maximum to minimum value of particle concentration with that of water temperature and salinity.

	Stn 5		Stn 7		Stn 8		Stn C		Stn 22		Mean	
	CV (%)	max/min	CV (%)	max/min	CV (%)	max/min	CV (%)	maX/min	CV (%)	max/min	CV (%)	max/min
Conc.	21	2.0	37	2.8	30	2.3	35	2.6	17	1.6	28	2.3
Temp.	0.61	1.02	5.56	1.19	2.78	1.07	7.28	1.23	7.16	1.21	4.68	1.14
Sal.	0.03	1.001	1.04	1.031	0.04	1.001	0.38	1.011	0.07	1.002	0.31	1.009

station 22 has the least. On average, the CV value for all stations was 28% and the ratio of maximum to minimum concentration was 2.3. The latter value is significant; It indicates that the maximum variability of particle concentration in a tidal cycles is at least 2.

It is well known that the suspended particle concentration is independent of the temperature and salinity of the water. However, for the purpose of comparison, the variability of the latter two parameters within a tidal cycle was investigated. Also listed in the Table 3 are depth mean of CV and maximum to minimum ratio for water temperature and salinity. It shows that their variability was quite small compared with that for the particle concentration. The highest variability for temperature was 7.3% and 1.23 for CV and maximum to minimum ratio, respectively, which occurred at the station C. The average among stations was 4.7% for CV and 1.14 for maximum to minimum ratio. Correspondingly, the largest variability for salinity occurred at the station 7 with a 1.04% for CV value and 1.03 for maximum to minimum ratio. The variability for salinity averaged among stations was only 0.31% for CV and 1.009 for maximum to minimum ratio.

3.3 Particle concentration profile

Also plotted in Fig. 4 are the time mean concentration profiles for all stations. As can be seen, the time mean surface concentrations were very close for all stations (between 0.2 and 0.3 mg/l) except at station 7, whose value was 0.9 mg/l. For stations on the shelf (5, 7 and 8), where there existed a bottom nepheloid layer, their time mean concentration exhibited an increasing trend towards the bottom. On the other hand, there was no definite trend for time mean concentration change over depth for stations C and 22, where there was no bottom resus-pension. Their profiles of time mean concentration can be approximated by a constant value. The depth averages of the time mean values were 0.5 mg/l for stations 5 and 8, 2 mg/l for station 7 and 0.2 mg/l for shelf edge stations C and 22. For the former three stations, their mean concentration correlate with their maximum tidal current speed, which is 70 cm/s for stations 5 and 8 and 100 cm/s for station 7. The low concentration for stations C and 22 can be attributed to no resuspension and their proximity to the deep ocean.

Sediment resuspended by the tidal current will diffuse upward by turbulence while the gravity will pull them downward. The net results is an exponential increase of sediment concentration toward the bottom (McCave, 1972). This type of concentration profile has been demonstrated by many measurements. For example, the temporal variation of particle concentration measured by Postma (1965) in the Guerrero Negro lagoon, Baja California, which is about 10 m deep, fits the exponential distribution very well. Lick *et al.* (1992) also showed this by solving the conservation of mass equation for vertical particle transport for steady state solution. The equation is

$$\frac{\partial}{\partial z}(w_s C) = \frac{\partial}{\partial z}\left(A_V \frac{\partial C}{\partial z}\right) \qquad (1)$$

where z is the vertical distance measured from the water surface. C the concentration, w_s the settling velocity and A_v the eddy diffusivity. For an idealized case, assuming that w_s and A_v are independent of z, then the concentration C has the form

$$C = C_o \exp(z_o z) + F/w_s \qquad (2)$$

where C_o is a reference concentration, $z_o = w_s/A_v$, and F an integration constant corresponding to the flux w_sC specified at a large negative z distance. If the flux is set zero, the concentration profile bercame

$$C = C_o \exp(z_o z) \qquad (3)$$

Which is an exponential function with C_o represents the surface concentration, and z_o is an coefficient indicating the degree of increase of the concentration with respect to depth.

Figure 4 shows that the time mean concentration profiles fit equation (3) well. Regression analysis showed the profiles fit exponential functions with correlation coefficient (R^2) better than 88%. A more closer examination also showed that the concentration profile for station 7 at each time step also fits the exponential profile well (Table 4). It is to note that the changes of C_o value with time correspond well with the time variation of measured surface concentration. The z_o value also varies in-step with resuspension activities.

3.4 Particle size distributions

Suspended particles exist in water as a flocculated particles, and they continue to aggregate and disaggregate due to particle collision and shear. In order to investigate the size of constituent particle (or so called primary particle) of these suspended particles, they have to be disaggregated. The size distributions of disaggregeted suspended particles from the station 7 were analyzed, since this station exhibited the most active bottom resuspension. Shown in Fig. 5 are four suspended samples from various depth at different tidal phases. The figure indicates that these distributions are almost identical ; although the largest median size is 6.2 μm obtained at the 75 meter depth during the highest resuspending activity and the smallest median diameter is 5.4 μm for the surface sample at hour 12. It can also be seen that 95% of the particles are fine-grained. This indicates that only the fine-grained portion of the sediments are being resupended and deposited by the tidal current.

The stations on the shelf showed possible occurrence of resuspension, while the continental edge stations did not. The resuspension of bottom sediment depends on the magnitude of the current and the availability of sediment. Thus, it is of interest to determine the type of the sea bed. Shown in Fig. 6 are the sizes of sediments from stations 5, 7 and 22. As can be seen, at station 5 (in mid-shelf), its bottom sediment contains about 30% mud and 70% of sand. The median size at this place is 90 μm. Further outward, the median size at station 7 is 190 μm and only 1% is fine-grained. Although there was more mud found at station 5 than at station 7, since the maximum tidal current for the former station was 30% smaller than the latter, the former location had less suspended particles than the latter. The sediment at the station 22, located on the shelf edge, is coarser than that of stations 5 and 7. Its bottom sediment had a median diameter of 210 μm and contained a large percentage (about 30%) of particle larger than 500 μm, which was observed to be shell fragments, while there was only 3% for the sediment found at the station 7. In general this size analysis conforms to the distribution of bottom sediment reported by BOGGS *et al.* (1974)

4. Summary

Water samples were obtained from five stations on the shelf and near the shelfbreak north of Taiwan. The particle concentrations were measured from various levels and their variation with time in a tidal cycle was examined. The current velocity ws also measured concurrently. It was found that on the shelf particle concentrations were influenced by the speed of the current through bottom resuspension or convection of particle clouds, while near the continental margin the concentration was generally insensitive to the current speed, but can vary with the direction of the flow. This is an evidence that there is a spatial variation of particle concentration, and this causes the changes of concentration due to the tidal current. Within a tidal cycle, the highest particle concentration was 1.4 to 3.5 times as large as the lowest concentration, depending on the depth and location. In the bottom layer of the shelf station, where bottom resuspension was significant, the maximum to minimum concentration ratio was the highest. Taking average on this ratio over the water depth, it varied from 1.6 to 2.8 for various stations. On average, it can be said that the suspended particle concentration in a tidal cycle varied with a factor of no less than two. This is the error that can be expected

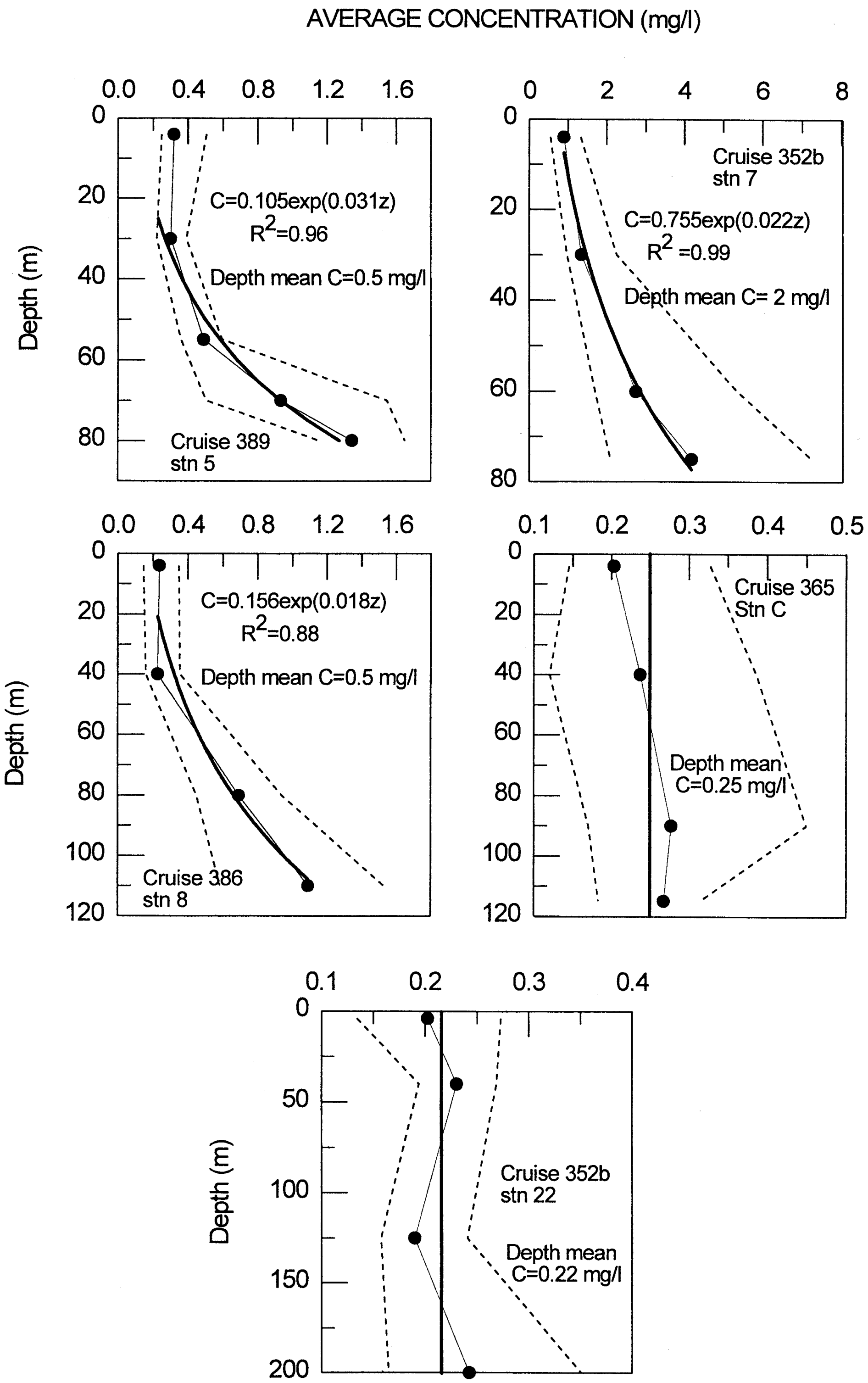

Fig. 4. Time averaged depth profiles of particle concentation (including the minimum and maximum envelopes) for all stations.

Table 4. Parameters of the concentration profile, $C=C_o\exp(z_oz)$, and correlation coefficient R^2 for the station 7 at various sampling times.

	0h	2H	4h	6h	8h	10h	12h
C_o(mg/l)	1.00	1.07	0.46	0.49	0.64	0.76	0.54
z_o(1/m)	0.012	0.018	0.031	0.029	0.033	0.020	0.020
R^2	0.75	0.90	0.82	0.98	0.95	0.90	0.93

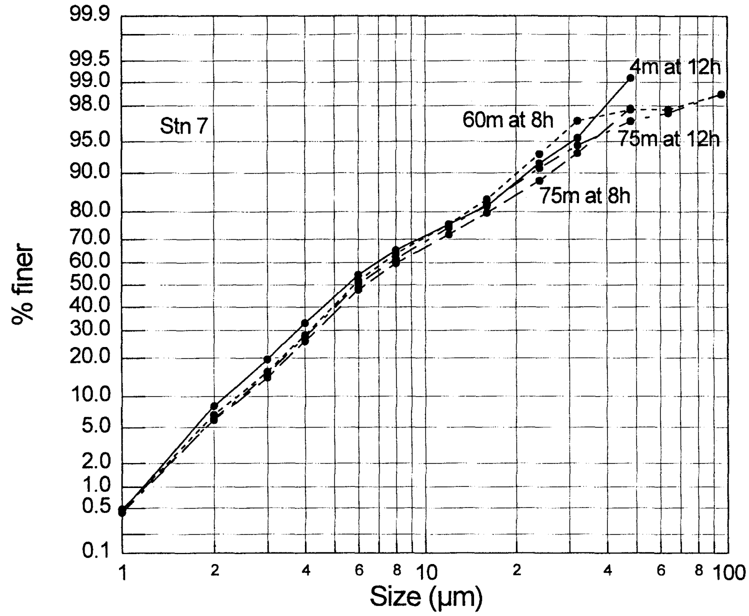

Fig. 5. Size distributions for disaggregated suspended particles obtained at various depths and times at the station 7 (in log-normal probability).

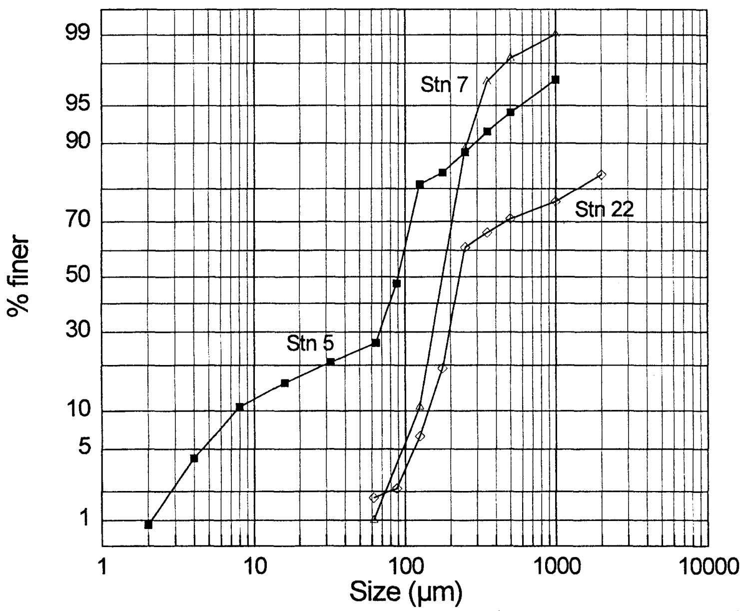

Fig. 6. Size distributions for bottom sediments (in log-normal probality).

in this region if the tidal phase is ignored when studying suspended particle distribution.

On the shelf the time mean (over a tidal period) concentration increased exponentially with depth. The depth mean value of the time mean concentration varied from 0.5mg/l to 2 mg/l, depending on the magnitude of tidal current. At two locations close to the continental margin no bottom resuspension was observed. Their depth profile of the time mean concentration can be approximated by a constant value of 0.2 mg/l. Particle size analysis perfomed on the resuspended particles revealed that the primary suspended particles were predominantly fine-grained particles with a median diameter of 6 μm. This means that only the fine-grained particles are continuously being resuspended and settled on the shelf. Some of the resuspended particles are then transported to the deep ocean.

Acknowledgments

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References

AHARONSON, E. F., N. KARASIKOV, M. ROITBERG, and J. SHAMIR (1986): Galai-CIS-1: a novel approach to aerosol particle size analysis. J. Aeros. Sci., **17**, 530–536.

BAINES, P. G. (1982): On internal tide generation models. Deep Sea Res., **29**, 307–338.

BOGGS, S. Jr., W. C. WANG and J. C. CHEN (1974): Textural and compositional patterns of Taiwan shelf sediment. Acta Oceanogr. Taiwan., **4**, 13–56.

CHERN, C. S. and J. WANG (1989): On the water masses at northern offshore area of Taiwan. Acta Oceanogr. Taiwan. **22**, 14–32.

GALEHOUSE, J. S. (1971): Sedimentation snalysis. in Procedures in Sedimentary Petrology. Carver, R. E. (ed.), Wiley-Interscience, New York, 69–94.

KRANCK, K. (1980): Variability of particulate matter in a small coastal Inlet. Can. J. Fisheries and Aquatic Sci., **37**, 8, 1209–1215.

KRANCK, K. and T. G. MILLIGAN (1992): Characteristics of suspended particles at an 11-hour anchor station in San Francisco Bay, California. J. Geophys. Res., **97**, C7, 11373–11382.

LICK, W., J. LICK and C. K. ZIEGLER (1992): Flocculation and its effect on the vertical transport of fine-grained sediments. Hydrobiologia, **235/236**, 1–16.

LIU, C. T. and S. C. PAI (1987): As the Kuroshio turns, II, The oceanic front north of Taiwan, Acta Oceanogr. Taiwan., **18**, 49–61.

LIU, K. K., G. C. GONG, C. Z. SHYU, S. C. PAI, C. L. WEI and S. Y. CHAO (1992): Response of Kuroshio upwelling to the onset of the northeast monsoon in the sea north of Taiwan: Observations and a numerical simulation. J. Geophys. Res., **97**, C8, 12511–12526.

MCCAVE, I. N. (1972): Transport and escape of fine-grained sediment from shelf areas, in Shelf Sediment Transport: Process and Pattern. SWIFT, D. J. P. D. B. DUANE and O. H. PILKEY, (eds.), Dowden, Hutchinson and Ross, Pennsylvania, 225–248.

MAEDA, A. (1979): Short internal waves on the margin of the continental shelf of the East China Sea. La mer, **17**, 18–27.

NIINO, H. and K. O. EMERY (1961): Sediments of shallow portions of East China Sea and South China Sea. Geol. Soc. America Bull., **72**, 731–762.

POSTMA, H. (1965): Water circulation and suspended matter in Baja California lagoons. Netherlands J. Sea Res. **2**, 566–604.

THOMAS, H. E. and W. L. PERRY (1968): Historical environmental data: East China Sea-Yellow Sea, Area 16. Naval Oceanographic Office, Washington, D. C., 213 pp.

TSAI, C. H. and S. R. RAU (1992): Evaluation of Galai CIS-1 for measuring size distribution of suspended primary particles in the ocean. TAO, 3, 2, 147–163 (Chinese Geoscience Union: Taipei, Taiwan).

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