Journal of the Korean Society of Oceanography
Vol. 37, No. 3, pp. 178 — 186 September 2002

Effects of Upwelling/Downwelling on Suspended Particulate Matter Distributions over Shelf Mud Areas: Numerical Experiments

SHU GAO* AND JIAN-JUN JIA
MOE Key Laboratory for Coast and Island Development, Nanjing University, Nanjing 210093, China

The mud deposit located to the south of Cheju Island, the East China Sea, is characterized by an upwelling system or, on occasions, a combined upwelling-downwelling system. The water mass here is associated with relatively high suspended matter concentrations. In the present study, a vertical 1-D model is used to undertake numerical experiments for evaluating the upwelling and downwelling effects on the suspended particulate matter distribution patterns within the water column. The results show that: (1) because the upwelling or downwelling velocity tends to be of the same order of magnitude as the settling velocity of suspended particles, a number of different patterns of suspended matter concentration distribution are possible, depending on the relative importance of the velocities; (2) the presence of upwelling can enhance the suspended particulate matter concentration; and (3) in an upwelling-downwelling system, maximum concentrations may or may not lie in the middle of the water column, depending on, once again, the interrelationships between the upwelling/downwelling velocities and the settling velocity. Hence, the physical processes associated with upwelling/downwelling appear to be relevant to the suspended material distribution over shelf mud areas.

Key words: Suspended matter, Upwelling-downwelling, Muddeposits, East China Sea

INTRODUCTION

Investigations into the processes and mechanisms of the formation of continental shelf mud deposits are important to shallow sea sediment dynamics, nutrient cycling studies and ecosystem dynamics (Dronkers and Miltenburg, 1996; Lesueur *et al.*, 1996, Friedrich *et al.*, 2000). In the East China Sea region, a distinct feature for suspended particulate matter (SPM) concentration distributions is the formation of high concentration centers that can be observed over a mud deposit. This phenomenon has been observed also by other researchers on different occasions (e.g. Milliman *et al.*, 1989; Guo *et al.*, 1997) and, therefore, is associated with a high frequency of occurrence. For example, during the summer of 1998, on a profile along the 32°N parallel, a concentration maximum was located at 32°N, 126°E, within the mud deposit area to the south of Cheju Island (Gao *et al.*, 2000). Here, maximum concentrations of more than 30 mg L^{-1} were found in the middle layer of the water column (Fig. 1).

It has been proposed that the mud deposits are related to upwelling systems (Hu, 1984) and/or weak tidal currents (Dong *et al.*, 1989). Recently, it has been found that in the mud area to the south of Cheju Island the upper and lower parts of the water column are occasionally (in the summer season) controlled by cyclonic circulation (which is associated with upwelling) and anticyclonic circulation (i.e. downwelling), respectively (Yanagi *et al.*, 1996a). This pattern may be associated with differential tidal mixing over the area, in response to summer heating of the water mass (Xu, 2000). Thus, it is likely that the mud deposit, the high concentration centers and the upwelling-downwelling system are inter-related. One of the resultant problems is: what are influences of the upwelling and downwelling on the suspended matter distribution within the water column over the mud areas? In the present contribution, we intend to deal with this problem using numerical experiments, with special reference to the mud deposit to the south

*Corresponding author: shugao@nju.edu.cn

of Cheju Island.

The mud deposit in consideration covers an area of 15000 km^2, with a maximum deposition rate of 3 mm yr^{-1} (DeMaster *et al.*, 1985). The sediment here is derived from different sources, including the eroded material from the Old Yellow River delta (Milliman *et al.*, 1985) and the modern material input from the Changjiang River (Milliman *et al.*, 1989). *In situ* observations have shown that the SPM concentration is relatively high, forming a secondary high concentration center over the region (Gao *et al.*, 2000). The seabed material here consists of clay (accounting for about 40%) and silt (around 60%); the concentration is higher in the bottom layers than in the surface layers, but bio-generated particles tend to be concentrated in the upper layer of the water column (Lei *et al.*, 2001). It should be noted that, although the secondary high concentration center is present for all the seasons, the patterns of the SPM concentration distribution within the water column vary considerably, as can be shown by a comparison between the different investigations (e.g. Jin, 1992, p.207; Yang *et al.*, 1992; Guo, *et al.*, 1997, 2000; Gao *et al.*, 2000; Lei *et al.*, 2001).

METHOD

Numerical experiments have been designed for two situations: (1) upwelling throughout the water column; and (2) upwelling for the upper part of the water column and downwelling for the lower part. The model is formulated on the basis of a 3-D advection-dispersion equation for suspended particulate matter, which can be written as:

$$\frac{\partial C}{\partial t}+\frac{\partial(UC)}{\partial x}+\frac{\partial(VC)}{\partial y}+\frac{\partial[(W-W_s)C]}{\partial z}+S = \frac{\partial}{\partial x}\left(A_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(A_y\frac{\partial C}{\partial t}\right)+\frac{\partial}{\partial z}\left(A_z\frac{\partial C}{\partial z}\right) \quad (1)$$

where (U, V, W)=current velocity vector (W=upwelling/downwelling component of the vector), W_s = settling velocity of particles, C = SPM concentration, (A_x, A_y, A_z) = dispersion coefficients for the suspended matter, S = source term from the water column (e.g. organic particles generated by biological activities). Assuming that in the upwelling/downwelling area variations in the SPM concentrations are more significant in the vertical direction than in the horizontal direction, the gradient of horizontal advective transport of suspended material is small, and the source term can be neglected, Equation (1) becomes

$$(W-W_s)C-A_z\frac{\partial C}{\partial z} = 0 \quad (2)$$

or

$$(W-W_s)\frac{C_{i+1}+C_i}{2}-A_z\frac{C_{i+1}-C_i}{Z_{i+1}-z_i} = 0 \quad (3)$$

Equation (3) means that the vertical distribution of suspended material can be determined numerically if the velocity of upwelling/downwelling, particle settling velocity and dispersion coefficient are known. Upwelling (and downwelling) currents tend to be much smaller that horizontal currents, with orders of magnitude of 10^{-3} to 10^{-1} mm s^{-1} (Apel, 1987, p.102). Thus, two values, 0.005 and 0.2 mm s^{-1}, are used in the numerical experiments for the modeling of upwelling effects. In order to compare with the situation of non-upwelling areas, the patterns under the condition of W=0 are also calculated. In the numerical experiments for combined upwelling-downwelling effects, four values i.e. 0.005, 0.05, 0.1 and 0.2 mm s^{-1} for both W_d and W_u were adopted in the calculations, but the sign differs between the upwelling and downwelling currents. It is assumed that upwelling occurs in the upper part and downwelling in the lower part within the water column.

The settling of particles is usually described using the Stokes law, but in marine environments the particles are subjected to flocculation. Observations show that the settling velocity ranges between 0.03 and 0.3 mm s^{-1}, if the SPM concentration is below 40 mg L^{-1} (Eisma *et al.*, 1997). Thus, three values of the settling velocity, i.e. 0.03, 0.1 and 0.3 mm s^{-1}, are used.

The dispersion coefficient for suspended matter has orders of magnitude of 10^{-2} to 10^{-1} m^2 s^{-1} (Shi and Zhou, 2000). In the present study, the coefficient is obtained according to (Dyer, 1986, p.159)

$$A_z = \beta k u_* \cdot \frac{z(H-z)}{H} \quad (4)$$

where β=constant, κ=Karman-Prandtl parameter (=0.4), u_*=friction velocity, z=seabed elevation (with the origin being set at the bed, positive upwards) and H=water depth (taken as 80 m).

The boundary condition, i.e., the SPM concentration at a given level, should be specified. Of course, to maintain such a boundary condition, some source of sediment supply is required. The source can be the near-bed nepheloid layer (McCave, 1983; Yanagi *et al.*, 1996b) in an upwelling system, or the suspended matter input from the mid-water column in a combined upwelling-downwelling system, with the material originated from coastal shallow water masses (e.g.

Milliman *et al.*, 1985; Yanagi and Inoue, 1995; Sun *et al.*, 2000). For the boundary condition for the upwelling situation, the near-bed SPM concentration is taken as a constant; three values i.e. 20, 40 and 80 mg L^{-1} were used for the various experiments. In the situation of combined upwelling and downwelling, the water column is divided into two parts. The upper part (0-40 m) is assumed to be characterized by upwelling, for which the SPM concentration is assumed to be constant at the depth of 40 m, being set to be 40 mg L^{-1}, a representative value based upon field measures (Gao *et al.*, 2000). The lower part is characterized by downwelling; here the suspended matter has two sources i.e. the material settled from the upper part and the material imported from outside at the height where upwelling and downwelling waters separate. Thus, the boundary condition for the lower part is taken as:

$$C' = \frac{2C_0 W_d + C_{40} W_s}{W_s + W_d} \tag{5}$$

where C'=the concentration at the top of the lower water column, C_{40}=the concentration at H=40 m for different experiments, W_d=velocity of downwelling, and C_0=the concentration of the imported material from surrounding waters, taken as 5 mg L^{-1}.

In order to evaluate the cross-sectional distribution (passing through the core of the upwelling system over the mud area), the horizontal distribution of the upwelling (or downwelling) velocity is defined as:

$$W = W_{max}\left(\frac{1+\cos\alpha}{2}\right) \tag{6}$$

where W_{max} = maximum upwelling (or downwelling) speed at the core. With an interval of $\pi/10$, 21 vertical profiles of the concentration can be plotted between the domain $(-\pi, \pi)$ so that the cross-sectional distribution can be obtained.

In the numerical experiments, the spatial step $(z_{i+1}-z_i)$ is taken as 1 m.

It should be noted that these numerical experiments do not represent a simulation of the natural pattern observed over the mud area; rather, because the real upwelling and/or downwelling field is not known, they should be viewed as a preliminary investigation into the controlling factors for suspended matter distributions.

RESULTS

Distributions of SPM concentration in response to upwelling

The vertical distributions of SPM concentration at

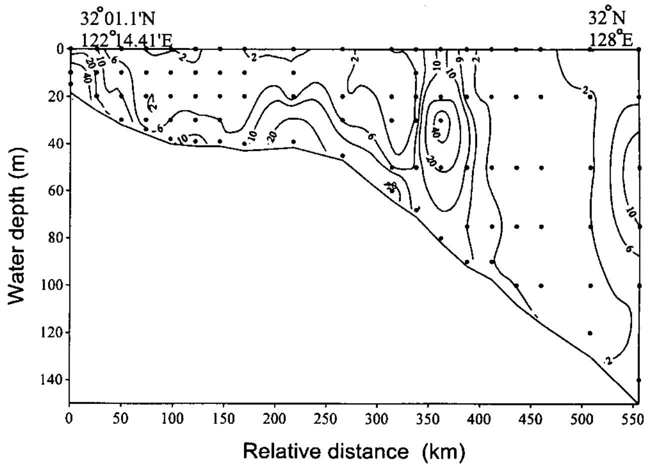

Fig. 1. Vertical distributions patterns of SPM concentrations (in mg L^{-1}) across the continental shelf (along the 32°N parallel), observed in the summer of 1998 (after Gao *et al.*, 2001)

Table 1. Results of numerical experiments for the cases of the absence and presence of upwelling (the concentration at bottom is set to be constant)

Experiment Number	W_s (mm s^{-1})	W_u (mm s^{-1})	C (mg L^{-1}) Surface	Middle	Bottom
1	0.03	0	17	19	20
2	0.03	0	35	39	40
3	0.03	0	71	78	80
4	0.03	0.005	18	19	20
5	0.03	0.005	36	39	40
6	0.03	0.005	73	78	80
7	0.03	0.2	36	22	20
8	0.03	0.2	73	45	40
9	0.03	0.2	147	90	80
10	0.1	0	13	18	20
11	0.1	0	27	37	40
12	0.1	0	55	74	80
13	0.1	0.005	14	18	20
14	0.1	0.005	28	37	40
15	0.1	0.005	56	74	80
16	0.1	0.2	28	21	20
17	0.1	0.2	57	42	40
18	0.1	0.2	114	85	80
19	0.3	0	6	16	20
20	0.3	0	13	32	40
21	0.3	0	26	64	80
22	0.3	0.005	6	16	20
23	0.3	0.005	13	32	40
24	0.3	0.005	27	64	80
25	0.3	0.2	13	18	20
26	0.3	0.2	27	37	40
27	0.3	0.2	55	74	80

the center of the upwelling system, in the case of the absence and presence of upwelling, derived from the numerical experiments are listed in Table 1. The results show that: (1) the concentration is enhanced in the upper and middle layers, with the presence of upwelling, indicating that upwelling is able to concentrate the suspended material; (2) with the presence of upwelling, if the upwelling velocity is smaller than the settling velocity of particles, then a maximum concentration occurs at the bottom of the water column; and (3) if the upwelling velocity is larger than the settling velocity, then the maximum concentration occurs at the water surface.

Using the data sets obtained, the cross-sectional distributions of the concentration for Experiments 5, 8, 17 and 26 are shown in Fig. 2. These patterns indicate that: (1) if the upwelling velocity is smaller than the particle settling velocity, and both of the velocities are small, then there is an insignificant effect of upwelling in the central area (Fig. 2a) (2) if the upwelling velocity is larger than the settling velocity, then a relatively turbid water mass occurs at the water surface (Fig. 2b, 2c), which would be shown on a remotely sensed image as a high concentration center; and (3) if the upwelling velocity is smaller than the settling velocity, but the velocities are both relatively large, then there is a significant effect of upwelling in the central area (Fig. 2d).

Because the upwelling velocity and the particle settling velocity are often of the same order of magnitude, the frequency of occurrence of the former being larger than the latter, and *vice versa*, may not be small. Thus, there would be many possible patterns of the concentration distribution within the water column. The exact form will depend upon the relative importance of, and the difference between, the two velocities. In a real world, both velocities can vary considerably according to the physical factors (the intensity of anticyclonic circulation, water temperature, salinity, etc.); therefore, even without taking the biological and biochemical factors into account, complex concentration distribution patterns may be generated.

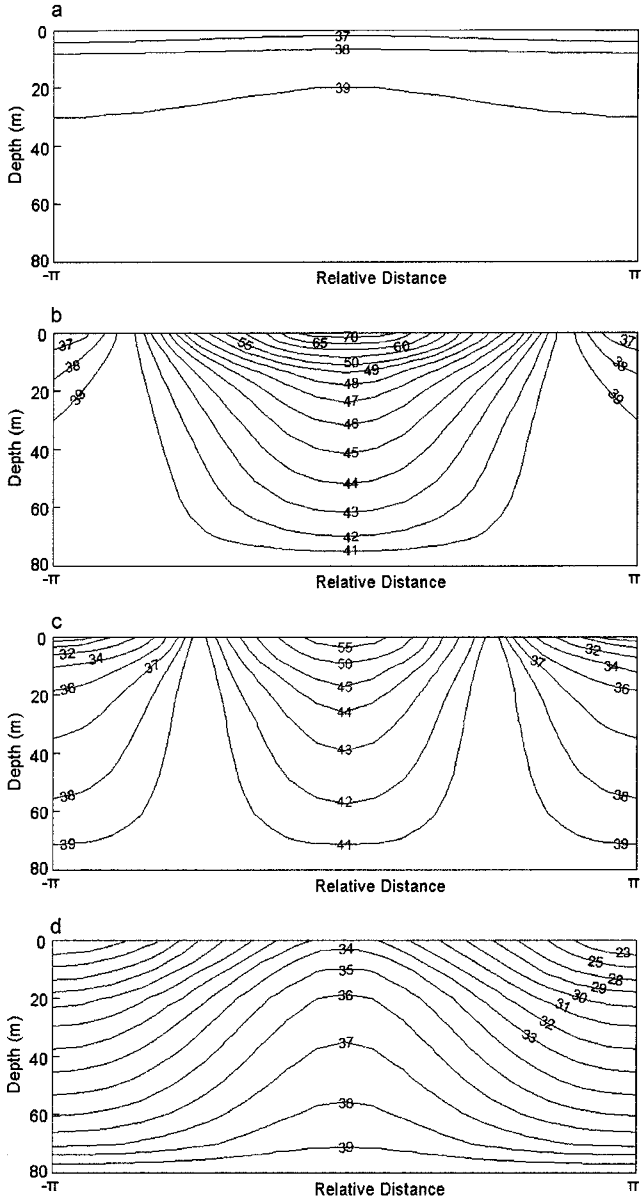

Fig. 2. Calculated SPM concentration (in mg L^{-1}) distributions in response to upwelling for (a) W_s = 0.03 mm s^{-1}, W_u = 0.005 mm s^{-1}; (b) W_s = 0.03 mm s^{-1}, W_u = 0.2 mm s^{-1}; (c) W_s = 0.1 mm s^{-1}, W_u = 0.2 mm s^{-1}; and (d) W_s = 0.3 mm s^{-1}, W_u = 0.2 mm s^{-1}

Distributions of SPM concentration due to combined upwelling and downwelling

The distribution patterns of SPM concentrations, for the various combinations of the particle settling velocity and the upwelling and downwelling velocities, are listed in Table 2. The results indicate that: (1) minimum concentrations occur near the bottom; and (2) in the upper part of the water column, if the particle settling velocity is larger than the upwelling velocity, then a maximum concentration occurs in the middle of the water column (e.g. Experiments 1-4, 17–24 and 33–48), otherwise maximum values occur at the water surface (e.g. Experiments 5–16 and 25–32).

To illustrate the influences of the settling velocity

Table 2. Results of numerical experiments for the combined effect of upwelling and downwelling (the concentration at the middle is set as 40 mg L^{-1})

Experiment Number	W_s (mm s^{-1})	W_u (mm s^{1})	W_d (mm s^{-1})	SSC (mg L^{-1}) Surface	Bottom
1	0.03	0.005	0.005	37.2	33.3
2	0.03	0.005	0.05	37.2	22.5
3	0.03	0.005	0.1	37.2	20.7
4	0.03	0.005	0.2	37.2	22.8
5	0.03	0.05	0.005	42.4	33.3
6	0.03	0.05	0.05	42.4	22.5
7	0.03	0.05	0.1	42.4	20.7
8	0.03	0.05	0.2	42.4	22.8
9	0.03	0.1	0.005	48.9	33.3
10	0.03	0.1	0.05	48.9	22.5
11	0.03	0.1	0.1	48.9	20.7
12	0.03	0.1	0.2	48.9	22.8
13	0.03	0.2	0.005	65.4	33.3
14	0.03	0.2	0.05	65.4	22.5
15	0.03	0.2	0.1	65.4	20.7
16	0.03	0.2	0.2	65.4	22.8
17	0.1	0.005	0.005	30.5	29.4
18	0.1	0.005	0.05	30.5	26.0
19	0.1	0.005	0.1	30.5	25.0
20	0.1	0.005	0.2	30.5	26.7
21	0.1	0.05	0.005	34.7	29.4
22	0.1	0.05	0.05	34.7	26.0
23	0.1	0.05	0.1	34.7	25.0
24	0.1	0.05	0.2	34.7	26.7
25	0.1	0.1	0.005	40.0	29.4
26	0.1	0.1	0.05	40.0	26.0
27	0.1	0.1	0.1	40.0	25.0
28	0.1	0.1	0.2	40.0	26.7
29	0.1	0.2	0.005	53.3	29.4
30	0.1	0.2	0.05	53.3	26.0
31	0.1	0.2	0.1	53.3	25.0
32	0.1	0.2	0.2	53.3	26.7
33	0.3	0.005	0.005	16.7	16.5
34	0.3	0.005	0.05	16.7	17.2
35	0.3	0.005	0.1	16.7	18.2
36	0.3	0.005	0.2	16.7	21.0
37	0.3	0.05	0.005	19.2	16.5
38	0.3	0.05	0.05	19.2	17.2
39	0.3	0.05	0.1	19.2	18.2
40	0.3	0.05	0.2	19.2	21.0
41	0.3	0.1	0.005	22.4	16.5
42	0.3	0.1	0.05	22.4	17.2
43	0.3	0.1	0.1	22.4	18.2
44	0.3	0.1	0.2	22.4	21.0
45	0.3	0.2	0.005	30.0	16.5
46	0.3	0.2	0.05	30.0	17.2
47	0.3	0.2	0.1	30.0	18.2
48	0.3	0.2	0.2	30.0	21.0

and upwelling/downwelling velocities on the concentration distribution patters, using the data sets from Table 2, the cross-sectional distributions of the concentration for Experiments 5, 8 and 14 are shown in Fig. 3, and those for Experiments 38, 40 and 46 are shown in Fig. 4.

The patterns in Fig. 3 represent the situation that the settling velocity is relatively small, which shows that: (1) if the upwelling velocity is equal to, or smaller than, the downwelling velocity, then a maximum concentration occurs in the upper part of the water column, and a minimum occurs in the lower part; and (2) if the upwelling velocity is larger that the downwelling velocity, then a maximum concentration occurs at the water surface, with an increasing trend for the concentration from the lower part towards the upper part of the water column.

The patterns in Fig. 4 represent the situation that the settling velocity is relatively large, which shows that for the different relationships between the upwelling and downwelling velocities, a maximum concentration occurs in the middle paer of the water column. The patterns shown by Fig. 4, which represent the situations of the core area of the upwelling/downwelling system, and the pattern over the mud area (water depth 60–80 m) in Fig. 1 are comparable in that maximum concentrations are placed in the middle water column.

As a summary of the experimental results outlined above, conceptual models of the effects of upwelling and combined upwelling-downwelling on the distribution of SPM concentrations can be formulated. Generally, complex concentration distribution patterns may be present, simply because the interrelationships between the upwelling/downweling velocities and the particle settling velocity are highly variable. For instance, if the upwelling velocity is smaller than the settling velocity, then suspended material will be concentrated in upwelling areas; likewise, in an upwelling-downwelling system, the suspended material can be concentrated in the middle layer within the water column. These results provide an explanation for the complex concentration patterns observed in the East China Sea shelves. It is worth pointing out that the experimental results are based upon some physical processes only, and the distribution of SPM is also influenced by other processes. A full understanding of the patterns requires knowledge about not only the physical processes, but also biological and biogeochemical processes involved.

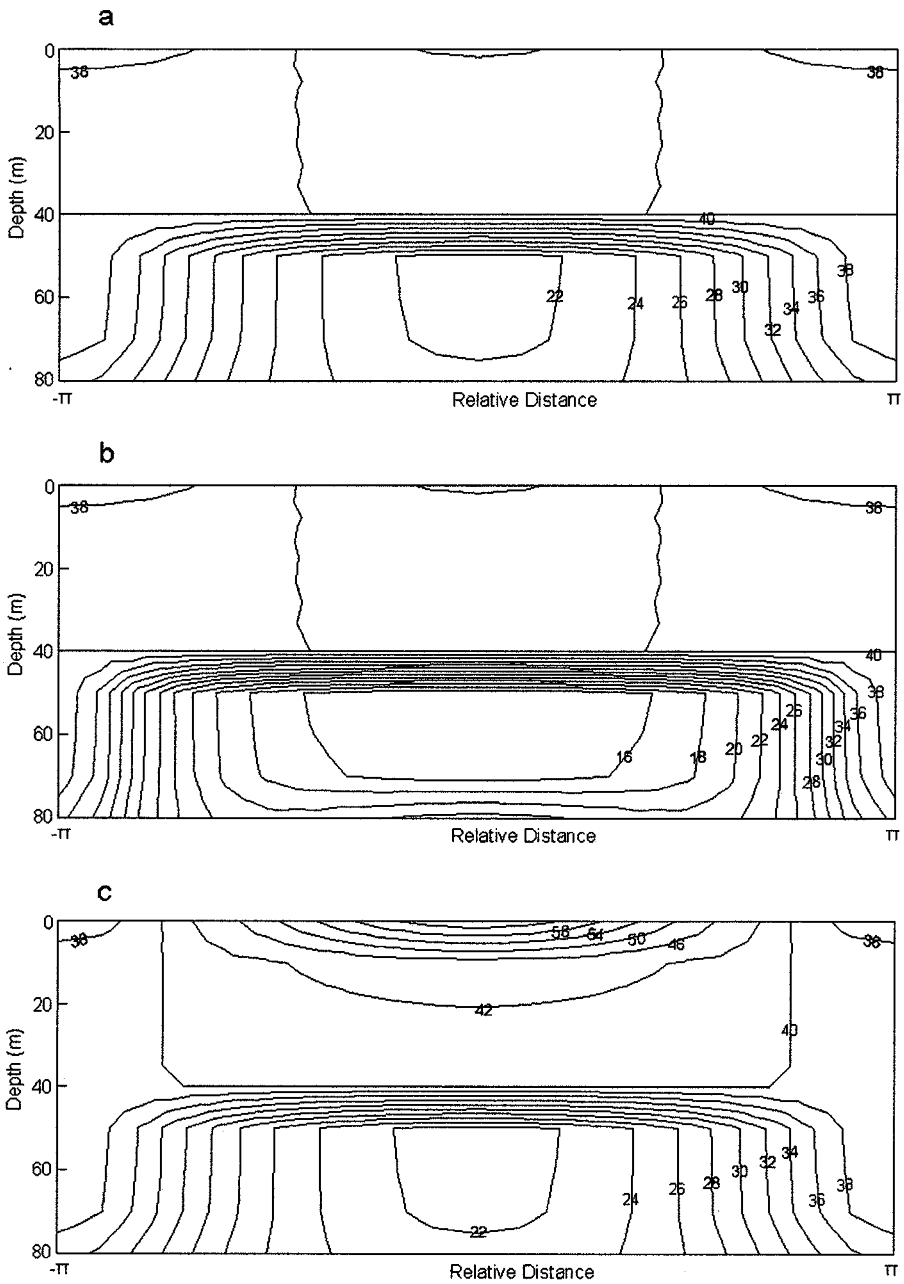

Fig. 3. Calculated SPM concentration (in mg L^{-1}) distributions in a combined upwelling and downwelling system in which W_s=0.03 mm s^{-1}: (a) W_u=W_d=0.05 mm s^{-1}; (b) W_u=0.05 mm s^{-1}, W_d=0.2 mm s^{-1}; and (c) W_u=0.2 mm s^{-1}, W_d=0.05 mm s^{-1}

DISCUSSION: MUD AREA SEDIMENT FLUXES

If suspended material can be concentrated by upwelling, then the following question arises: in this case can the vertical sediment fluxes be enhanced near the seabed? In order to answer this question, first of all we may need to consider the definition of the vertical flux. Without upwelling or downwelling, the flux can be expressed as:

$$F = W_s C - A_z \frac{\partial C}{\partial z} \qquad (7)$$

Apparently, if the parameters W_s and A_z are fixed, then the flux depends upon the magnitude and the vertical gradient of the concentration. In calm water, with the settling of the suspended particles, both the magnitude and the vertical gradient of the concentration will be progressively reduced. When the water mass eventually becomes clear, no further accumulation of material will occur. However, with the presence of upwelling, the flux will be modified:

$$F = (W_u + W_s)C - A_z \frac{\partial C}{\partial z} \qquad (8)$$

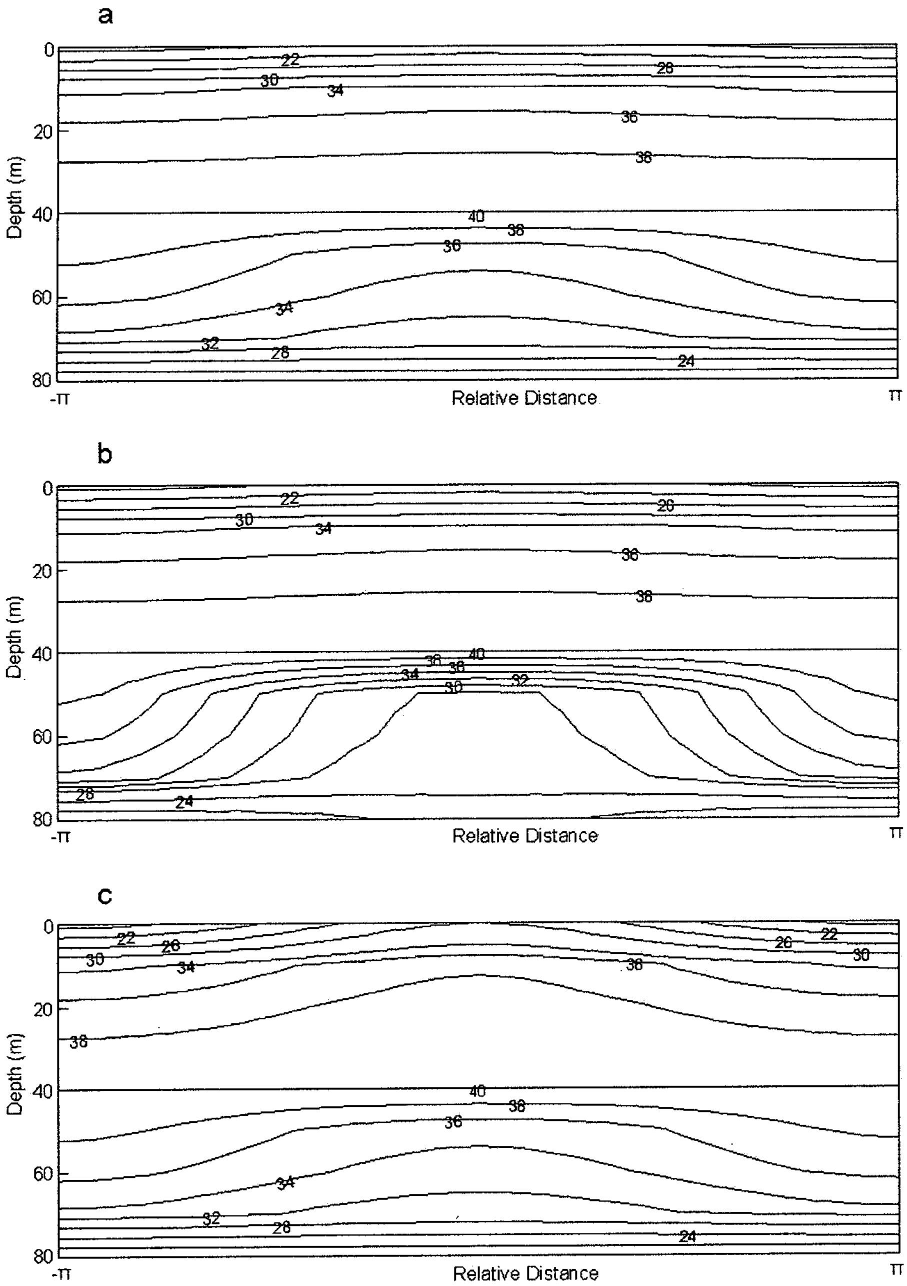

Fig. 4. Calculated SPM concentration (in mg L^{-1}) distributions in a combined upwelling and downwelling system in which W_s=0.3 mm s^{-1}: (a) W_u=W_d=0.05 mm s^{-1}; (b) W_u=0.05 mm s^{-1}, W_d=0.2 mm s^{-1}; and (c) W_u =0.2 mm s^{-1}, W_d=0.05 mm s^{-1}

In this case, as indicated by the experimental results from the present study, when $W_s < W_u$, no downward net flux will occur, but with the occurrence of $W_s > W_u$ net downward flux will take place. Furthermore, the water mass will be constantly exchanged with the surrounding water masses through the lower layer of the water column, providing the central upwelling area with continuous material supply. As a result, the accumulation of suspended matter will be in a sustainable manner and, therefore, the presence of upwelling can enhance the settling flux.

In a combined upwelling/downwelling system, within the lower part of the water column, W_u in Equation (8) should be replaced by W_d. In such a system, because the suspended matter can be concentrated in the core area and material is supplied by the middle layers of the water column, continuous accumulation will occur.

There is also an indirect effect of upwelling on the flux. Upwelling brings with it nutrients, which enhance biological productivity and the content of bio-generated particles in sediment. This has been observed for the Cheju Island mud area (Milliman, *et al.*, 1989; Lei *et al.*, 2000). The addition of the bio-matter should enhance the vertical flux and the content of particulate organic carbon over the mud area. It has been found that the organic carbon is relatively high in the central part of the Cheju Island mud (Zhao and Yan, 1994); this may be related to the upwelling system.

SUMMARY

The numerical experiments undertaken in the present study show that, because of the highly variable interrelationships between the settling velocity and the upwelling/downwelling velocities, there are many possible patterns the concentration distribution within the water column. Thus, if the upwelling velocity over a mud deposit area is smaller than the settling velocity of suspended particles, then the suspended particulate matter will be concentrated at the core of upwelling. Likewise, in an upwelling-downwelling system and under the condition that the upwelling velocity is smaller than the settling velocity, the suspended material will be concentrated at the middle of the water column.

The presence of upwelling or combined upwelling/downwelling drives continuous water exchange with the surrounding waters and tends to concentrate suspended materials. These processes provide a constant material source for the seabed underneath. As a result, net accumulation of fine-grained material at the seabed is enhanced.

ACKNOWLEDGEMENTS

The study was supported financially by the National Natural Science Foundation of China, through a grant from the "Outstanding Young Scientists Program" (No.49725612), and the Chinese Academy of Sciences, through the program "Land-ocean interaction over the Chinas seas and its impact on the environment" (KZ951-B1-403). Professor Hu Dun-xin is thanked for his valuable comments and suggestions. Finally, the authors wish to thank the anonymous reviewer who made constructive comments on the original manuscript.

REFERENCES

Apel, J.R., 1987. Principles of Ocean Physics. Academic Press, London, 631pp.

DeMaster, D.J., B.A. McKee, C.A. Nittrouer, J.C. Qian and G.D. Cheng, 1985. Rates of sediment accumulation and particle reworking based on radiochemical measurements from continental shelf deposits in the East China Sea. *Cont. Shelf Res.*, **4**: 143–158.

Dong, L.X., J.L. Su and K.S. Wang, 1989. Relationship between tidal current field and sediment transport in the Yellow and Bohai Seas (in Chinese with English abstract). *Acta Oceanologica Sinica*, **11**(1): 102–114.

Dronkers, J. and A.G. Miltenburg, 1996. Fine sediment deposits in shelf seas. *J. Mar. Sys.*, **7**: 119–131.

Dyer, K. R., 1986. Coastal and estuarine sediment dynamics. John Wiley, Chichester, 342pp.

Eisma, D., K.R. Dyer and W. van Leussen, 1997. The in-situ determination of the settling velocities of Suspended fine-grained sediment: a review. In: Cohesive Sediments, edited by Burt, N., R. Parker and J. Watts, John Wiley, Chichester, pp. 17–44.

Friedrich, C.T., L.D. Wright, D.A. Hepworth and S.C. Kim, 2000. Bottom-boundary-layer processes associated with fine sediment accumulation in coastal seas and bays. *Cont. Shelf Res.*, **20**: 807–841.

Gao, S, P. Cheng, Y.P. Wang and Q.Y. Cao, 2000. Characteristics of suspended sediment concentrations over the areas adjacent to the Changjiang River estuary, the summer of 1998. *Marine Science Bulletin* (English Version), **2**(1): 14–24.

Gao S., Y.P. Wang and W.H. Zhao, 2001. Suspended sediment and nutrient concentrations over East China Sea continental shelf, summer 1998. *J. Sea Res.*, submitted.

Guo, Z.G., Z.S. Yang, D.X. Hu and H. Bai, 1997. Suspended matter of the northern East China Sea in the springs: its distribution structure and effect on sedimentation (in Chinese with English abstract). *Oceanologia et Limnologia Sinica*, **28**: Supplement Issue, 66–72.

Guo, Z.G., Z.S. Yang, Y.H. Qu and D.J. Fan, 2000. Study on comparison sedimentary geochemistry of mud area on East China Sea continental shelf (in Chinese with English abstract). *Acta Sedimentologica Sinica*, **18**: 284-289.

Hu, D.-X., 1984. Upwelling and sedimentation dynamics. I. The role of upwelling in sedimentation in the Huanghai Sea and East China Sea-a description of general features. *Chinese Journal of Oceanology and Limnology*, **2**: 12-19.

Jin, X.L. (editior), 1992. The Marine Geology of the East China Sea (in Chinese). China Ocean Press, Beijing, 524pp.

Lei, K., Z.S. Yang, Z.G. Guo, and H. Bai, 2001. Suspended sediment fluxes in spring on the East China Sea shelf with different surface sediment types (in Chinese with English abstract). *Oceanologia et Limnologia Sinica*, **32**: 50–57.

Lesueur, P., J.P. Tastet and L. Marambat, 1996. Shelf mud fields formulation within historical times: examples from offshore the Gironde estuary, France. *Cont. Shelf Res.*, **16**: 149–170.

McCave, I.N., 1983. Particulate size spectra, behavior, and origin of nepheloid layers over the Nova Scotia continental rise. *J. Geophys. Res.*, **88**: 7647–7666.

Milliman, J.D., R.C. Beardsley, Z.S. Yang and R. Limeburner, 1985. Modern Huanghe-derived muds on the outer shelf of the East China Sea: Identification and potential transport mechanisms. *Cont. Shelf Res.*, **4**: 175–188.

Milliman, J.D., Y.-S. Qin and Y.A. Park, 1989. Sediments and sedimentary processes in the Yellow and East China Sea. In: Sedimentary Facies in the Active Plate Margin, edited by Taira, A. and F. Masuda, Terra Scientific Publishing Company, Tokyo, pp. 233–249.

Shi, Z. and H.Q. Zhou, 2000. Numerical modeling of vertical distribution of suspended sediment concentrations, North Channel, Changjiang Estuary (in Chinese with English abstract). *China Ocean Engineering*, **18**(3): 57–62.

Sun, X.G., M. Fang and W. Huang, 2000. Spatial and temporal variations in suspended particulate matter transport on the Yellow and East China Sea shelf (in Chinese with English abstract). *Oceanologia et Limnologia Sinica*, **31**: 581–587.

Xu, D.F., 2000. Northwestern Pacific Ocean circulation patterns and their influence on the circulation in China seas (in Chinese with English abstract). Unpublished Ph.D. Thesis, Institute of Oceanology (CAS), Qingdao, 91pp.

Yanagi T. and K.-I. Inoue, 1995. A numerical experiment on the sediment processes in the Yellow Sea and the East China Sea. *J. Oceanogr.*, **51**: 537–552.

Yanagi, T., T. Shimizu and T. Matsuno, 1996a. Baroclinic eddies south of Cheju Island in the East China Sea. *J. Oceanogr.*, **52**: 763–769.

Yanagi, T., S. Takahashi, A. Hoshira and T. Tanimoto, 1996b. Seasonal variation in the transport of suspended matter in the East China Sea. *J. Oceanogr.*, **52**: 539–552.

Yang, Z.-S., Z.-G. Guo, Z.-X. Wang, J.-P. Xu and W.-B.Gao, 1992. Basic pattern of transportation of suspended mater from the Yellow Sea and East China Sea to the east deep seas (in Chinese, with English abstract). *Acta Oceanologica Sinica*, **23**(2): 222–227.

Zhao, Y.-Y. and M.-C. Yan, 1994. Geochemistry (in Chinese). China Science Press, Beijing, 203pp.

Manuscript received April 11, 2001
Revision accepted August 30, 2002
Editorial handling: Jae Hak Lee