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Tide, Tidal Current and Sediment Transport in Manila Bay

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Abstract: Tide, tidal current and residual flow in Manila Bay are calculated using two-dimensional and three-dimensional numerical models and the mean bottom stress vector is estimated. Mean bottom stress vector expresses the direction of sediment transport. Calculations of the sediment transport direction off Pampanga and along the shoreline of Cavite are in good agreement with the observations by SIRINGAN and RINGOR(1998). The sediment transport in the whole region of Manila Bay can be estimated from the result of model calculation. The bottom sediment does not flow from Manila Bay but is transported into the bay through the bay mouth.

Key words *: Sediment transport, Mean bottom stress, POM, Manila Bay*

1. Introduction

Manila Bay is located along the southern coast of Luzon Island (Fig. 1). There are many industrial factories along its coast. These factories use water of Manila Bay as cooling water or waste disposal system. Manila Bay supplies fish for the people. Recently, water quality in Manila Bay has been deteriorated by drainage from the factories that are distributed along the coast (KATO, 1999). The substance from the land is conveyed through a river and accumulates in the bay. It is important to investigate how suspended substances are transported in the bay. On the basis of the analysis of surface sediment, SIRINGAN and RINGOR (1998) showed that the transport direction of surface sediment is southward off Pampanga and northeastward off Cavite.

In this study, we calculate tidal current and residual flow using numerical model in order to examine the relationship between the current field and the surface sediment transport in Manila Bay. Tide and tide-induced residual current are calculated using a horizontal 2-dimensional barotropic model. The wind-driven current and the density-driven current are calculated using the Princeton Ocean Model (POM). The mean bottom stress vector is estimated using calculated current field and the result is compared with the observed one.

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2. Numerical model

Tide and tidal current

Tidal amplitude spectrum in Manila harbor shows that both K_1 and O_1 constituents have the amplitude of about 30 cm and M_2 and S_2 constituents have 19cm and 6 cm, respectively (Admiralty Tide Tables, 2001). Since the length of Manila Bay is about 18 km, mouth correction coefficient is 1.2 and the mean depth is about 20 m, the co-oscillation period of the bay is about 6.1 hours (UNOKI, 1993). This value is close to M_4 tidal period and M_4 constituent cannot be ignored in Manila Bay although its amplitude 3 is not known.

Along the open boundary, the sea surface elevation is prescribed by linear interpolation using harmonic constants of M_2, S_2, K_1 and O_1 constituents at Mariveles and Puerto Azul. The M_4 constituent is generated by the non-linear effect of M_2 tide.

The governing equations are expressed by

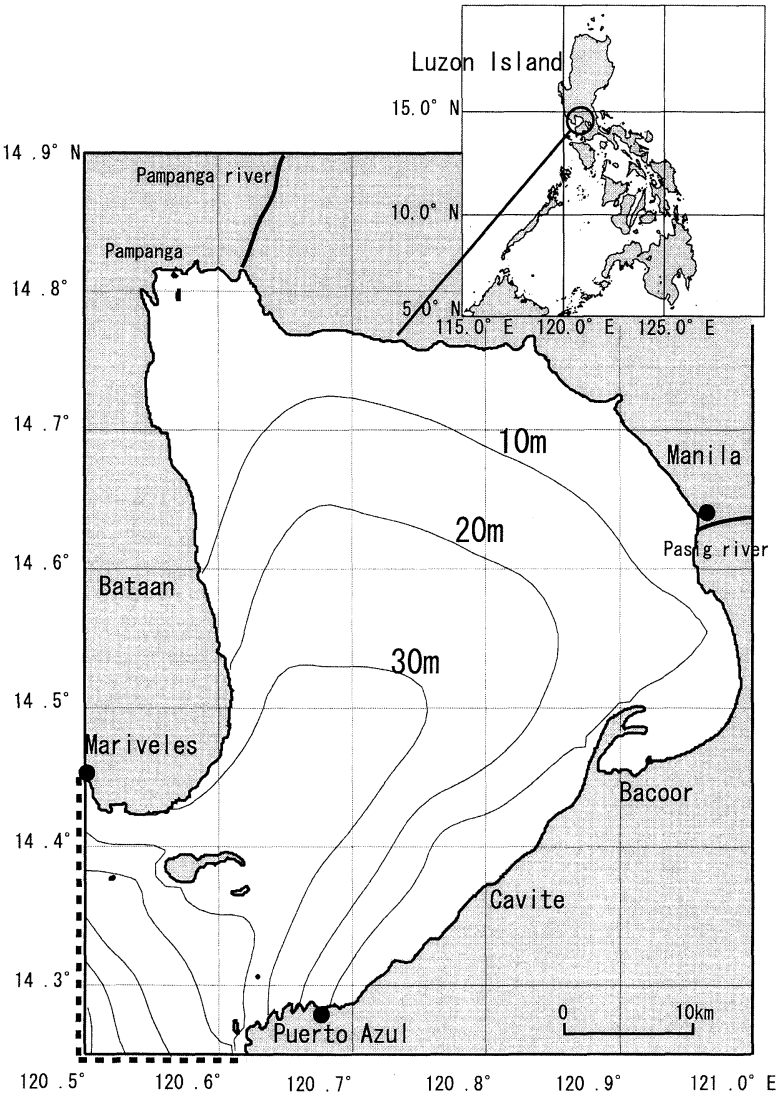


Fig. 1. Model area with bathymetry. Closed circles show the tide gauge stations. Broken line shows the open boundary of the numerical model, and thick lines show rivers flowing into Manila Bay.

$$\frac{\partial \boldsymbol{u}}{\partial t}+(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}+f\boldsymbol{k}\times\boldsymbol{u} = -g\nabla\zeta-\frac{\gamma_b^2\boldsymbol{u}\,|\,\boldsymbol{u}\,|}{H+\zeta}+\upsilon\Delta\boldsymbol{u}, \tag{1}$$

$$\frac{\partial \zeta}{\partial t}+\nabla\cdot\{(H+\zeta)\boldsymbol{u}\}=0, \tag{2}$$

here, $\boldsymbol{u}$ is the depth averaged horizontal velocity vector, ∇ the horizontal differential operator, f the Coriolis parameter ($=3.651\times10^{-5}$ s^{-1}), $\boldsymbol{k}$ the locally vertical unit vector. g the gravitational acceleration ($=9.8$ m sec^{-2}), ζ the sea surface elevation above the mean sea level, γ_b^2 the bottom frictional coefficient ($=2.6\times10^{-3}$), H the local depth, and υ the horizontal eddy viscosity ($=10$ m^2sec^{-1}). The horizontal grid size is 1000 m. Maximum depth is 81.5 m. Time step for the calculation is 2.0 sec. The integration was carried out for 510 hours (21.3 days) in all. Harmonic analysis is carried out using calculated results for last 15 days.

Calculated co-range and co-tidal charts of M_2, S_2, K_1, O_1 and M_4 are shown in Fig. 2. M_2

tidal amplitude is 15.0cm at the mouth of Manila Bay and about 20cm in Pampanga. M_2 tidal wave travels counterclockwise from the mouth of Manila Bay to Pampanga. S_2 tidal amplitude is 4.6 cm at the mouth of Manila Bay. It becomes 6.4 cm in Pampanga. K_1 tidal amplitude is 27.5 cm at the mouth of Manila Bay and 29.0 cm in Pampanga. O_1 tidal amplitude is 25.0 cm at the mouth of the bay and 27.0 cm in Pampanga. M_4 tidal amplitude is 1.5 cm at the mouth of Manila Bay and becomes 6.0 cm in Pampanga.

Table 1 shows the ratio of tidal amplitude at the mouth to that at the head of the bay off Pampanga. Quarter-diurnal tidal amplification is the largest, about 400%, and diurnal tidal one is the smallest, about 110%, because the co-oscillation period of Manila Bay is 6.1 hours.

Figure 3 shows the comparison of observed and calculated results of M_2, S_2, K_1 and O_1 tides at Manila harbor. The root mean squared error is 1.1 cm for tidal amplitude and 2.9° for tidal phase. This calculation of tides well reproduces the observed result in Manila Bay.

Calculated tidal currents are shown in Fig. 4. M_2 tidal current amplitude is about 15 cm/s at the mouth of Manila Bay. It flows crossing the mouth of the bay. Off Pampanga, it becomes about 10 cm/s. S_2 tidal current amplitude is about 5 cm/s at the mouth of the bay and 5 cm/s off Pampanga. M_4 tidal current amplitude is about 5 cm/s at the mouth of the bay and becomes 5 cm/s off Pampanga. K_1 tidal current is about 12.0 cm/s at the mouth of the bay and 8.0 cm/s off Pampanga. O_1 tidal current amplitude is about 10.0 cm/s at the mouth and 9.0 cm/s off Pampanga. M_2 tidal current is most dominant in Manila Bay although K_1 and O_1 tidal amplitudes are larger than M_2. The reason is due to the shorter period of M_2 constituent than K_1 and O_1.

Residual flow

According to phase differences between tidal constituents, phases of M_2, S_2, K_1 and O_1 tides will be in agreement every 30 days. Therefore, we have to carry out 30 days calculation in order to estimate the tide-induced residual current by M_2, S_2, K_1, O_1 and M_4 constituents, which is shown in Fig. 5. The speed of tide-induced residual current is less than 1 cm/s, with the exception of 5 cm/s at the mouth of the bay. A clockwise circulation is generated at the mouth of the bay.

We calculate the wind-driven and density-driven currents using Princeton Ocean Model (BLUMBERG and MELLOR, 1987) . Please refer to POM users guide (MELLOR, 1996) about the details of the governing equations. The horizontal grid size is the same as that 5 used for tide and tidal current. The vertical division is 14.

We applied a radiation condition along the open boundary as follows:

$$\frac{\partial \overline{U}}{\partial t} \pm C_e \frac{\partial \overline{U}}{\partial x} = 0, \qquad (3)$$

$$C_e = \sqrt{gH} \qquad (4)$$

Here, $\overline{U}$ is a vertically integrated residual flow velocity, C_e the phase velocity of long wave and H the water depth. Calculation is carried out for 40 days. The time step is 2 seconds for the external mode. As for the internal mode, it is 120 seconds that is 60 times the external mode.

There are 2 major rivers flowing into Manila Bay, Pampanga River in Pampanga and Pasig River in Manila city (Fig. 1). We ignore many small rivers around Pampanga because of their small discharges (Siringan and Ringor, 1998). Average sea surface heat flux in 1993 and 1994 are estimated from ECMWF (European Centre for Medium-Range Weather Forecast).

Figure 6 (a) shows the average wind direction and speed from 1961 to 1995 at Manila. From February to May, wind direction is from southeast. From June to September, wind direction is from southwest. From November to January, wind direction is from northeast. We calculate three types of wind-driven currents, for southeast, southwest and northeast winds. They correspond to April, September and November. Therefore, sea surface heat flux (Fig. 6b) and river discharge (Fig. 6c) in April, September and November are considered as boundary conditions of the model calculation.

Calculated wind-driven and density-driven currents in April, September and November are shown in Fig. 7, respectively. Large variability is seen in the wind-driven and density-driven currents field. Although wind-driven

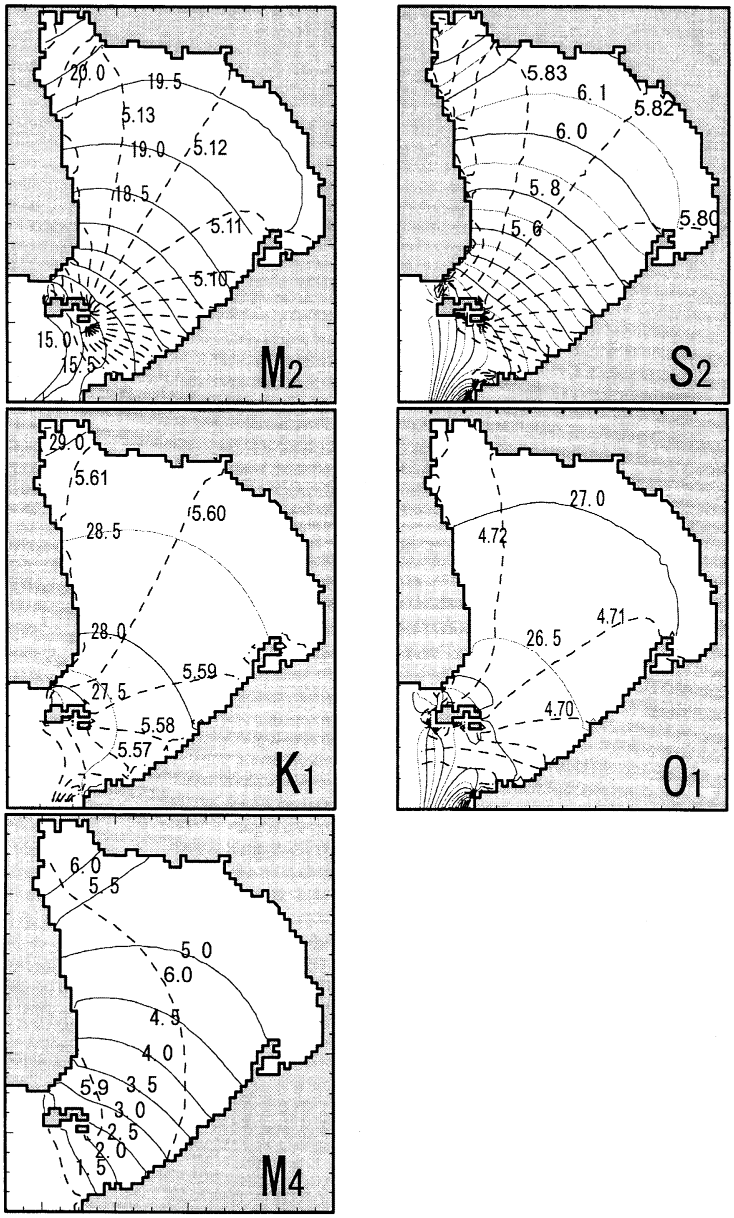


Fig. 2. Calculated co-range (thin line, unit in cm) and co-tidal (dashed line, unit in radian) charts of M_2, S_2, K_1, O_1 and M_4 constituents.

Table 1 Tidal amplification ratio of each constituent from the mouth to the bay head in Manila Bay.

Constituent	M_2	S_2	K_1	O_1	M_4
Amplification ratio(%)	130	133	107	110	400

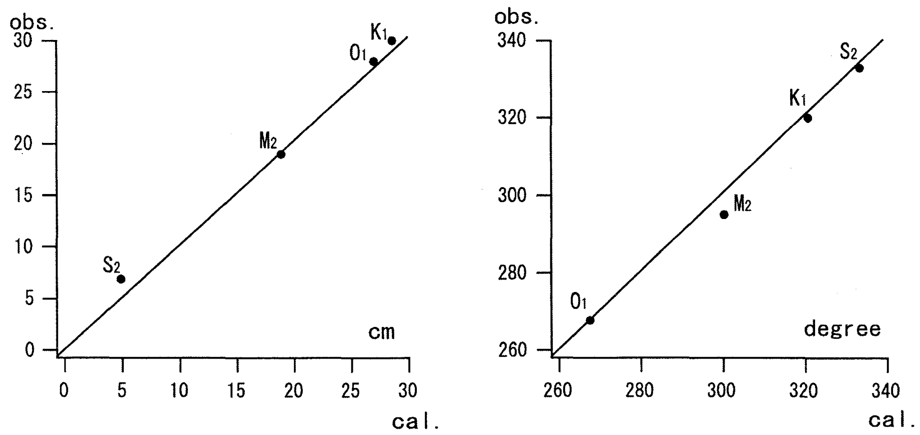


Fig. 3. Comparison of observed and calculated results of tidal amplitude and phase at Manila harbor.

current predominates in the surface layer, its influence is small in the bottom layer. Wind-driven and density-driven currents speed is about 5 cm/s above the bottom. Near the head of the bay, they flow along the wind direction. In the place where depth is large, the compensated flow is dominant.

Sediment transport

The mean bottom stress vector is calculated using obtained results of M_2, S_2, K_1, O_1 and M_4 tidal currents, tide-induced residual current, wind-driven and density-driven currents. The mean bottom stress $\overline{\tau_B}$ is calculated by the following equation (Yanagi and Fuji-ie, 2001).

$$\overline{\tau_B} = \rho_W C_D \frac{1}{T} \int_0^T u\sqrt{u^2}\,dt, \tag{5}$$

$$u = u_{M_2} + u_{S_2} + u_{K_1} + u_{O_1} + u_{M_4} + u_T + u_r, \tag{6}$$

where $\rho_w (=1.022\ \mathrm{kg/m^3})$ denotes the water density, $C_D(=0.0024)$ the bottom drag coefficient, $T(=30\ \mathrm{days})$ the averaging period, each of $u_{M_2}+u_{S_2}+u_{K_1}+u_{O_1}$ and u_{M_4} is tidal current velocity vector, u_T is tide-induced residual current, and u_r is velocity vector of residual flow whose components are density-driven and wind-driven currents. Here over bar means the average in 30 days.

Horizontal distributions of calculated mean bottom stress vector in April, September and November are shown in Fig. 8. Mean bottom stress toward northeast is common at the mouth of the bay in April, September and November. The sediment transport direction is toward west along the shoreline at the northeastern head of the bay in April and November. Off Cavite, although the transport direction in September is toward northeast, it is toward southwest in November. In April, it is toward southeast. Such variation is due to the seasonal variation of wind-driven current.

Figure 9 (a) shows averaged sediment transport vector in April, September and November and Fig. 9 (b) the sediment transport path estimated by the field observation of Siringan and Ringor (1998). From the calculation off Pampanga, the sediment transport is toward southeast. Off Bataan, the sediment transport is toward north. Off Cavite, the sediment transport is toward northeast (Fig. 9a). These calculation results agree with the observation results by SIRINGAN and RINGOR (1998). From the calculation result, there is a convergence of sediment transport in the center of Manila Bay and sediment transport is into the bay at the mouth of the bay.

3. Conclusion

The average sediment transport direction in Manila Bay is calculated by averaging the mean bottom stress vector in April, September and November. The results are in agreement with the results of field observation by SIRINGAN and RINGOR (1998). Therefore, the result of this study can explain the sediment transport in a long time scale.

The seasonal variation in the direction of

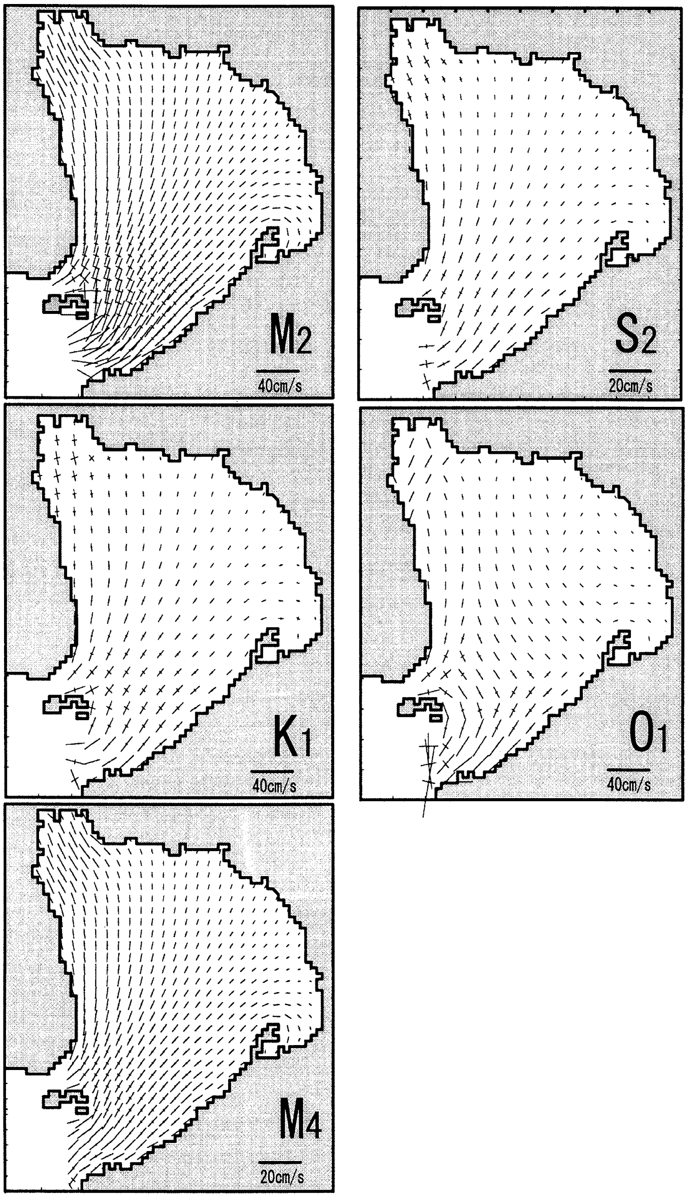


Fig. 4. Calculated long and short axes of M_2, S_2, K_1, O_1 and M_4 tidal current ellipses.

sediment transport in Manila Bay, mainly seen at the shallow area, depends on the variability of wind-driven and density-driven currents.

It is very interesting that transport vector is directed into the bay at the mouth of Manila Bay. This result suggests that bottom sediments are always transported from the bay mouth into the bay and sediments do not flow from Manila Bay. Therefore, the prevention of contamination from the land is very important in Manila Bay in order to preserve the sediment environment there.

Next, we will calculate the transport direction of various substances such as suspended matter.

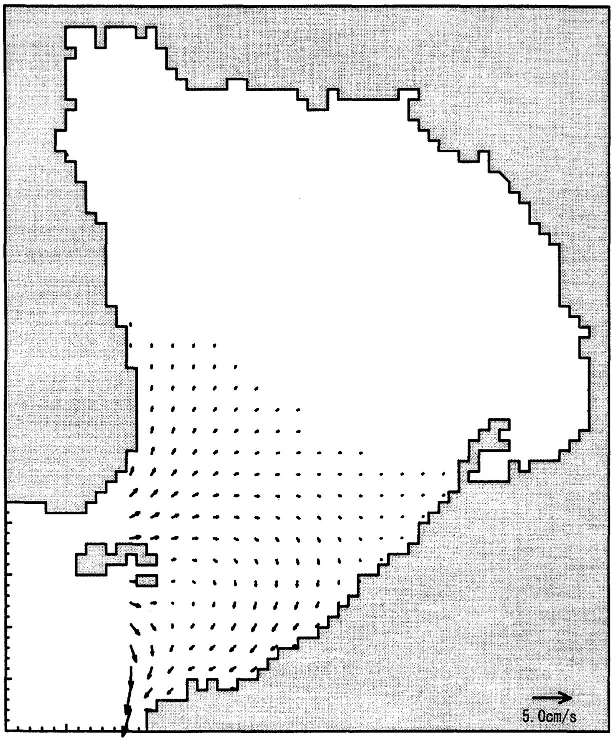
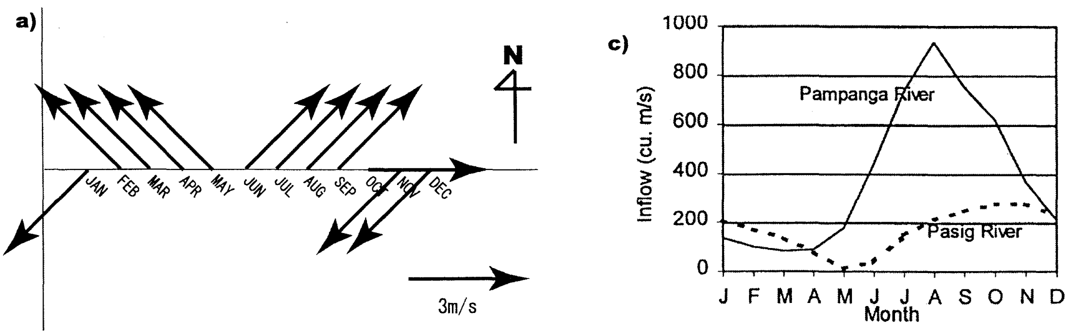


Fig. 5. Calculated tide-induced residual current by M_2, S_2, K_1, O_1 and M_4 constituents. Only the flow velocities larger than 0.5cm/s are shown.



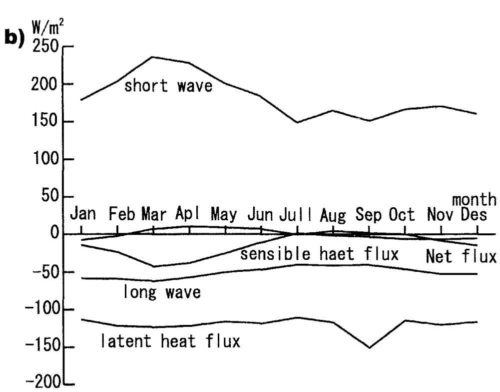


Fig. 6. Wind speed and direction at Manila. (average in 1961–1995, Philippine Atomospheric, Geophysical and Astronomical Services Administration) (a). Heat flux in Manila Bay (average over 1993–1994, ECMWF). Positive value represents downward heat flux(b). River discharge from Pampanga and Pasig rivers(SIRINGAN and RINGOR, 1998)(c).

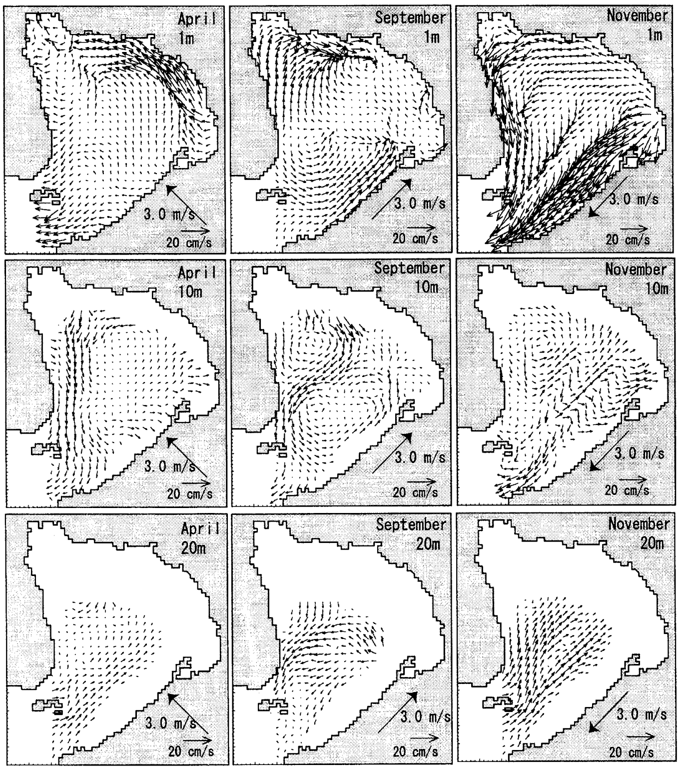


Fig. 7. Wind-driven and density-driven currents calculated for April, September and November.

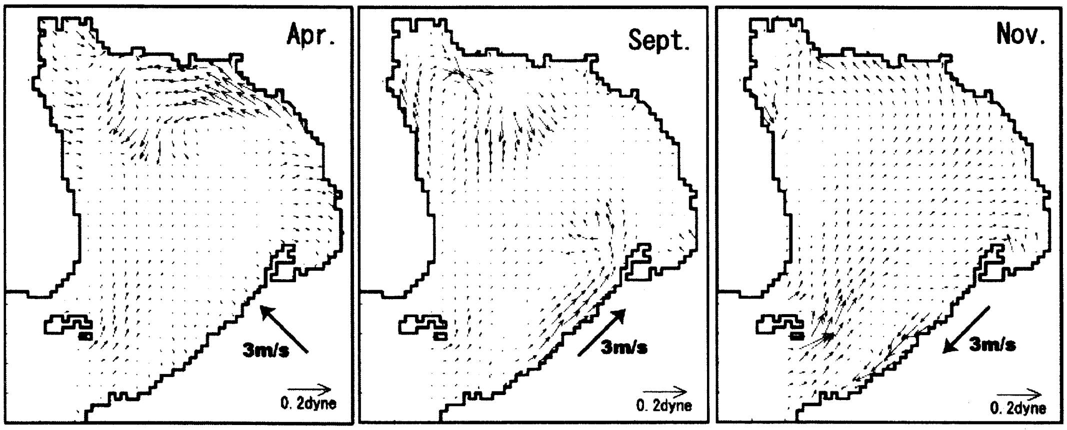


Fig. 8. Horizontal distribution of mean bottom stress vector during 30 days in Manila Bay in April, September and November.

References

ADMIRALTY Tide TABLES (2001) : Indian Ocean and South China Sea (Including tidal stream tables): The hydrographer of the Navy: 3, 416p.

BLUMBERG, A. F. and G. L. MELLOR (1987) : A description of a three dimensional coastal ocean circulation model. Three-Dimensional Coastal Ocean Models, Coastal and Estuarine Sciences, Vol. 4, N. Heaps, ed., Amer. Geophys. Union, 1–16.

KATO, S. (1999) : Current Status of Water Quality in Philippines: Public Health and Environment Research Division, Mie Pref. Science & Technology

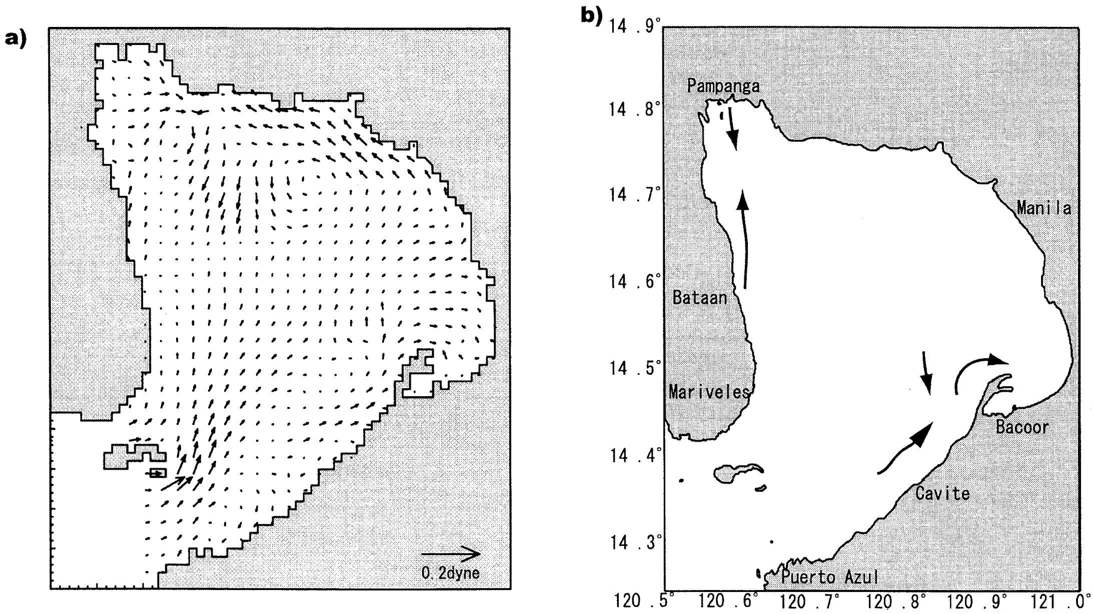


Fig. 9. (a)Calculated horizontal distribution of average mean bottom stress vector throughout the year. (b)Observed pattern of sediment transport path by SIRINGAN and RINGOR(1998).

Promotion Center Report, **19**, 23–33.

UNOKI, S. (1993) : Coastal physical oceanography, Tokai Univ. Press. 674pp. (in Japanese).

MELLOR, G. L. (1996) : Users guide for a three-dimensional, primitive equation, numerical model. Princeton University, 38pp.

SIRINGAN, F. P. and L. RINGOR (1998) : Changes in bathymetry and their implications to sediment dispersal and rates of sedimentation in Manila Bay. Science Diliman, **2**, 12–26.

YANAGI, T. and W. FUJI-IE (2001) : Transport of bottom sediment in the coastal sea of Okinawa, Umi-no-kenkyu, **10** (6), 485–494 (in Japanese).

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