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ESTIMATION METHOD FOR RESIDENCE TIME OF BAY WATER

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SYNOPSIS

Tokyo Bay, with its narrow bay mouth, is an inner-bay type sea area having a limited exchange rate of seawater with the open sea. As a result, the quality of water within the bay has deteriorated considerably, and red tide, oxygen-deficient water, etc. have become a problem.

From a standpoint of assessing the environmental impact, it is important to identify the flow of water in the bay, though it seems that the identification of its dynamic behaviour has not been carried out sufficiently.

In this research, a nonlinear programming method was applied to analyze the exchange rate of flow in the bay and to identify the characteristics of flow in the bay area throughout all seasons.

The analytical results revealed the characteristics of flow patterns which have not been expressed by existing simulation analyses. Based on the results of flow analysis, particles were injected into the bay and the tracking of these particles was carried out to evaluate the residence time of water.

INTRODUCTION

In the coastal zone of Tokyo Bay, 90% of the natural coastal area has been lost due to reclamation, and the load of effluent and sewage from the land zone has also increased. Moreover, Tokyo Bay, with its narrow bay mouth, is an inner-bay type sea area that has a limited exchange rate of seawater with the open sea. As a result, the quality of seawater and bottom material in the bay have deteriorated considerably, and the red tide, the oxygen-deficient water, etc. have become a problem, thereby making it necessary to make further efforts not only to improve the polluted seawater but also to restore and revive the coastal environment. At the same time, to make efficient use of seawater and to promote the development and utilization of the sea, it is necessary to assess the marine environment from a long-term standpoint. Although it is important to grasp the characteristics of flow in Tokyo Bay from a standpoint of environmental impact assessment, it seems that the dynamic behavior of such flow has not yet been fully identified.

In this research, Tokyo Bay was divided into arbitrary boxes in which salinity and water temperature were uniform to determine the exchange rate of seawater in such a way that the inflow and outflow quantities of salinity, heat and mass between the boxes were balanced. Based on the results thus obtained, the particles were injected into all boxes in the bay and tracked to estimate residence time of bay water.

DATA PROCESSING

As shown in Table 1, water-temperature and salinity data obtained in the bay area during a 10-year period were processed for each season. The horizontal and vertical exchanges between the total of 215 boxes were calculated by analyzing the movement and exchangeability of seawater using the box model in such a way that the seasonal distribution of respective data could be reproduced.

The layer was divided into eight along vertical directions, taking into consideration the quantity of observation data and the size of horizontal grids. Moreover, from the actual condition of density stratification, grids were divided densely in the upper layer and coarsely in the lower layer.

Data concerning river water flowing into Tokyo Bay were processed on the basis of the chronological table of flows published by the Kanto Regional Construction Bureau of the Ministry of Construction, and the water-quality survey in public waters conducted by the Environment Agency. Discharge loads from the rivers were assigned to the first layer of the boxes located at the mouth of each river (see Fig.1).

Meteorological conditions were based on the data supplied by the meteorological stations located along the coast and items shown in Table 2 were collected as marine conditions.

Table 1 Data Processing Units

Items		Classification of units
Time classification		Season
Space classification		
	Horizontal classification	Every 2.5' latitude, 2.5' longitude
	Vertical classification	Water depths: 0～5m, 5～15m, 15～25m, 25～40m, 40～62.5m, 62.5 ～87.5m, 87.5～125m, 125～175m

Table 2 Data as weather conditions

Acquisition points	Items used	Survey institution	Acquisition period
Tokyo, Yokohama, Chiba, Tateyama	Precipitation, air temperature, all-weather insolation, wind speed, cloudiness, temperature	Weather Station, Meteorological Agency (Monthly Weather Report)	1979～1988

Box Model

In this research, the analytical technique using a box (compartment) model was applied. In the conventional flow analysis, possible use of models is based on the equation of motion and the equation of continuity as well as the equation of diffusion concerning water temperature and salinity. However, the author considered that in such a complicated field as Tokyo Bay where water masses having different densities and the inflow of river waters exist it would be appropriate to apply this technique.

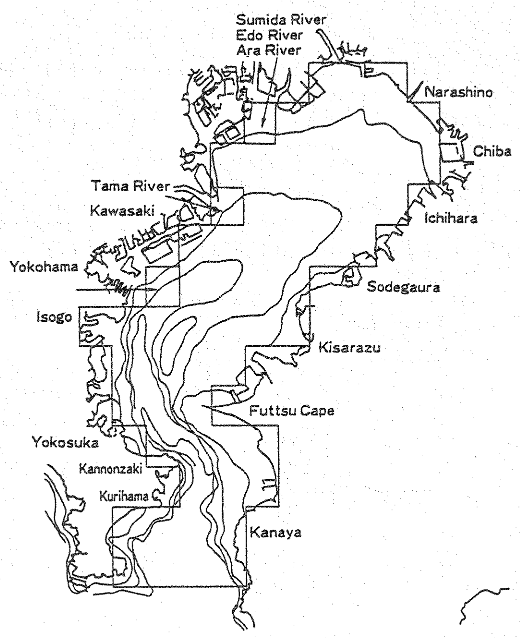

Fig.1 Analysis range

FLOW ANALYSIS BY THE BOX MODEL

This model meets the requirements for carrying out longterm material concentration analysis in which the conservation of mass holds not only in each box but also as a whole system. This technique, which is aimed at determining the field of flow corresponding to the actual field of density, is capable of reproducing the lowering of density mixing (in summer) as well and is situated between the existing box model and the dynamic model.

The goal was to calculate the flow mathematically in such a way that water temperature and salinity observed in each box would be reproduced. As for the method used, the equations of the balance of mass, salinity and heat in each box were formulated, and the exchange rate of seawater between boxes satisfying these equations of the balance were obtained.

For water temperature and salinity, the following three equations were formulated for each box assuming that the exchanges rate of seawater between boxes were unknown.

(1) Equation of the conservation of mass
(2) Equation of the conservation of salinity
(3) Equation of the conservation of heat

These equations are simultaneous linear equations with the exchange flow rate being an unknown quantity. Unfortunately, because of the following problems, these simultaneous linear equations could not be solved in most cases.

Firstly, the number of unknown variables does not always agree with that of the equations, thereby making it difficult to obtain a unique solution. Due to the nature of the model, the exchange flow must be non-negative (positive or zero). As a solution, therefore, simple simultaneous linear equations or a general inverse-matrix method cannot be used, and instead a non-linear programming method with limited conditions (non-negative conditions) must be used. That is to say, an attempt to solve equations (1)~(3) accurately must be given up and instead a solution with least error must be obtained.

Such a solution can be obtained if the non-linear programming method with limited conditions is used, and the exchange flow obtained is non-negative, thereby, minimizing errors in equations (1)~(3).

Box Division

When dividing the sea area into boxes, seawater is considered to be mixed uniformly in both horizontal and vertical directions in each box. In other words, temperature, salinity and density in each box could be regarded as identical.

Equations of Conservation

Three equations of conservation were applied to each box. With attention paid to box i, the following equations of conservation were considered. (see Fig.2)

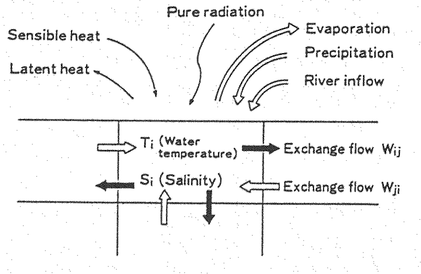

Fig.2 Exchange flows between boxes

(1) Equation of the conservation of mass

$$\sum_{j\neq i} W_{ji}\rho_j - \sum_{j\neq i} W_{ij}\rho_i + \Sigma_i R_{ri}\rho_r' + P_i - E_i = 0 \quad [\mathrm{ton/s}] \quad (W_{ij} \neq W_{ji}) \qquad (1)$$

where, $W_{ij}>0$: Exchange flow rate from box i to box j [m^3/s], ρ_i: Seawater density in box i [ton/m^3], ρ'_r: River-water density of river r [ton/m^3], R_{ri} : Flow rate of river water from river r into box i [m^3/s], P_i : Precipitation into box i [ton/s], E_i : Evaporation from box i into atmosphere [ton/s].

(2) Equation of the conservation of salinity

$$\sum_{j\neq i} W_{ji}\rho_j S_j - \sum_{j\neq i} W_{ij}\rho_i S_i + \Sigma_i R_{ri}\rho_i'(S'_r - S_i) = 0 \quad [\mathrm{ton/s}] \qquad (2)$$

S_i : Salinity in box i [‰], S'_r : Salinity in river r [‰],

(3) Equation of the conservation of heat

$$\sum_{j\neq i} W_{ji}\rho_j T_j C - \sum_{j\neq i} W_{ij}\rho_i T_i C + H_i = 0 \quad [\mathrm{Mcal/s}] \qquad (3)$$

T_i : Water temperature in box i [℃], H_i : Heat flux from the atmosphere into box i [Mcal/s], C: Specific heat of seawater [cal/g · ℃].

Conversion into Non-Linear Programming Problem

The simultaneous linear equations with non-negative condition are converted into a least-error problem with non-negative conditions.

Definition is made as follows:

$\varepsilon = \Sigma_i$ { α_i (left side of equation of the conservation of mass (1) in box i)^2
+ β_i (left side of equation of the conservation of salinity in box i)^2
+ γ_i (left side of equation of the conservation of heat in box i)^2}

Then, ε is a function of exchange flow, and is the square sum of errors in the equations of conservation.

Exchange flow rates W_{12}, W_{13}, ... may be obtained as W_{12}, W_{13}, ... which make error function $\varepsilon = \varepsilon(W_{12}, W_{13}, \ldots)$ least under non-negative condition $W_{12}, W_{13}, \ldots \geq 0$.

This problem is generally called NNLS (non-negative least squares).

ANALYTICAL RESULTS

Available information[1)2)]

Although there is no clear view of the characteristics of the residual current in Tokyo Bay, the following study results are available.

(a) Residual-current patterns are dominated by wind patterns, and a clockwise current is recognized in autumn and winter. It is not clear in summer.

(b) In the upper layer on the Kanagawa Prefecture side within the bay, there is a narrow current advancing southward.

(c) It can be considered that the surface-layer current is mainly caused by a wind-induced current with speed of 2～3% of wind velocity.

(d) The distributions of water-temperature (T) and salinity (S) may be generally classified into either a convection period or a stratification period. The distributions of T and S during the convection period tends to become uniform in the vertical direction, though in the bottom layer the temperature and salinity are high and a temperature inversion takes place. As a result, the isoline of temperature and salinity is narrow in the neighborhood of the bay mouth, and thermohaline front is formed. In the stratification period, a thermohaline is formed near the surface layer. Salinity in the surface layer around this time of the year (late spring to early autumn) is low and the isoline is horizontal, with high-temperature and low-salinity water covering the surface-layer water.

Results of Flow Analysis

(a) Winter (see Figs.3 and 4; vertical current component is shown by an oblique arrow)

As a flow pattern in winter, the convective action is strong, and a large complicated flow is recognized in the horizontal and vertical directions in the bay. Also, the water mass which goes up north from the bottom layer of the open sea becomes an ascending current and flows into the bay from the second layer (5～15 m). In the surface layer (0～5 m) of the bay-mouth area, a southward current which passes over the bay is recognized. In the area deeper than the third layer (15～25 m), the horizontal exchange with water in the bay is small. This is considered attributable to the fact that the inflow of open-sea water from the bottom layer is impeded due to the effect of thermohaline front at the bay mouth in winter.

According to previous research, there were many descriptions of a predominant clockwise circulation in the bay in the winter time.

Our present analytical results indicate the counterclockwise circulation is recognized in the south of the bay, though the circulation is not simple. In the north of the bay, a current which goes up north along the eastern coast is recognized, contrary to the past research, though the circulation of a small scale is produced on the whole. The movement of the circulation, inversion of flow direction, etc., which are seen in the north of the bay agree with previous research. Likewise, the strong southward current in the surface layer along the western coast and the northward current in its bottom layer also are both in agreement with existing data.

(b) Summer (see Figs.5 and 6)

The flow in summer is much more affected by stratification than in spring, and the scale of the flow becomes small on the whole, especially in the top layer, where the vertical flow in the bay is hardly recognized. Also, in the horizontal direction, a southward current which is considered attributable to the effect of rivers is recognized in the surface layer (0～5 m) on the west coast. In the bay-mouth zone, different from the top-layer zone, an upward current is seen from the fourth and fifth layers (25～60 m) to the third layer (15～25 m).

According to previous research, in the top layer there are counterclockwise circulations in the north and center of the bay, and a clockwise circulation in the south of the bay. In the west coast of the bay, it is said that there is a southward current in the top layer and bottom layer as well, which heads from the inner part of the bay toward the bay mouth. It is also said that the counterclockwise circulation in the north corresponds to the seasonal wind in summer. Both the circulation and southward current which were reproduced during our experiment match each other in almost every instance. On the west coast, however,

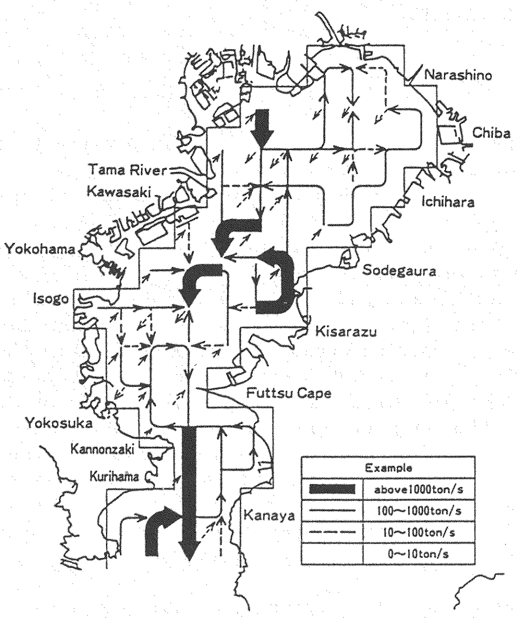

Fig.3 Flow patterns
[Winter, first layer (0 ~ 5m)]

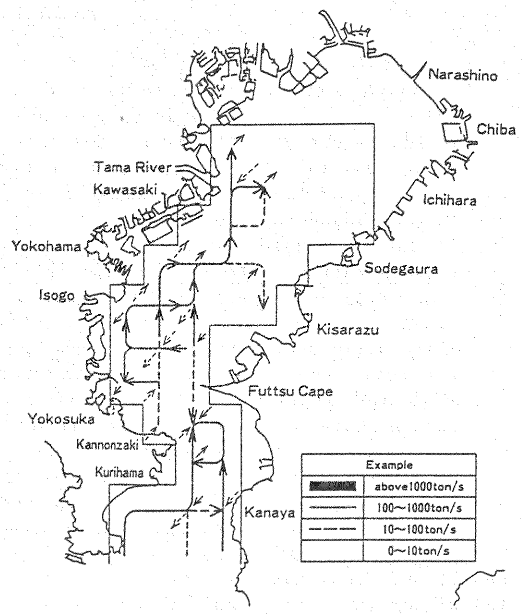

Fig.4 Flow patterns
[Winter, third layer (15~ 25m)]

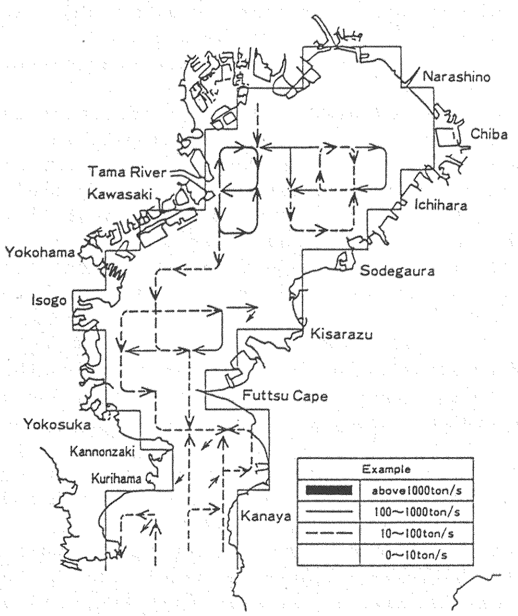

Fig.5 Flow patterns [Summer,
first layer (0~ 5m)].

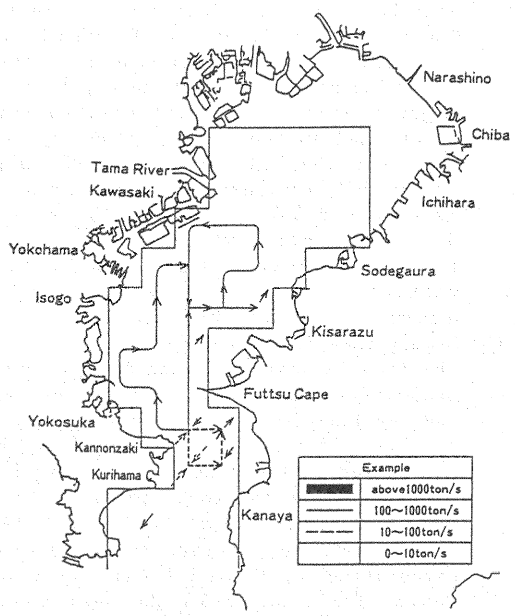

Fig.6 Flow patterns [Summer,
third layer (15~ 25m)].

there is a southward current in the top layer and a northward current in the bottom layer, which represent the concept of a gravitational circulation expected from the usual dynamic aspects.

EVALUATION OF FLOW CALCULATION RESULTS

In the conventional elucidation of the marine environment of bay water, two-dimensional or three-dimensional numerical models are used. In Tokyo Bay, a tidal current is generally predominant. However, if flow velocities observed at certain points are averaged at 24 hours and 50 minutes, the mean current component called residual current would remain. This mean current is mainly composed of a tidal residual current, a density current and a wind induced current.

In the prediction of changes in the marine environment, these mean current components have a large effect on the diffusion of material, so an emphasis has been placed on the method of calculating the mean current components. As a result, it is necessary to carry out analysis by considering the tidal residual current, the change in density due to the inflow of river water, and the wind induced current, using the three-dimensional model based on the equations of motion and continuity of a fluid, and the diffusion equations concerning water temperature and salinity concentration.

Although similar attempts were made in Tokyo Bay, there was difficulty in conducting a quantitative assessment, thereby making it impossible to attain fully satisfactory modelling.

The results of these analyses revealed the flow patterns which could not be expressed by the conventional simulation analyses and also showed seasonal characteristics. It can be considered that these results have made it possible to discuss the environmental values provided in each box.

RESIDENCE TIME OF WATER

Based on the so-called Lagrangian consideration on flow velocities obtained from exchange flows in the box model, particles in all boxes in Tokyo Bay as well as particles from the major river mouths were tracked, and the stagnation of seawater particles was examined from a standpoint of seasonal transition and space scale.

The particles were injected into the center of each box in the inner bay area. Time classification refers to the seasonal classification used in examining the characteristics of water-temperature and salinity distributions in Tokyo Bay, hence the particle tracking time is assumed to be divided into 90-days. However, the particles which do not reach the open sea after the lapse of more than 90 days are judged to be stagnant.

The results of these analyses are as follows:

Assuming that the residence time of seawater particles refers to the seawater exchange in the whole bay, then it can be divided into seawater exchange periods (autumn and winter) and stagnant periods (spring and summer).

In the seawater exchange periods, the vertical circulation is active as compared with the stagnant period, and this vertical circulation plays a major role in the seawater exchange in Tokyo Bay. Notably, the seawater exchange in autumn is the largest of all seasons, though this is not shown here. The behavior of particles is complicated as a whole. In the tracking of particles, a counterclockwise circulation current was recognized in the surface layer in the inner part of the bay. (See Figs.7 and 8)

Regarding the bottom-layer inflow and the surface-layer outflow, the results obtained agreed with those shown in past research. As is clear from the tracking of particles from the major rivers, it was consequently shown that the southward current along the west coast of Yokohama～Kannonzaki in the first and second layers had made a major contribution to the discharge of bay water out of the bay. As for the movement of particles in the neighborhood of the bay mouth in winter, a vertical circulation which headed toward the inner bay in the third layer and toward the outside of the bay in the fourth layer was recognized in the north of Kannonzaki～Futtu Point. This flow pattern is due to the gravitational circulation which is considered attributable to difference in the heat storage capacity driven from disparity in water depths in and outside the bay. Based on this movement, given that the thermohaline front is basically caused by

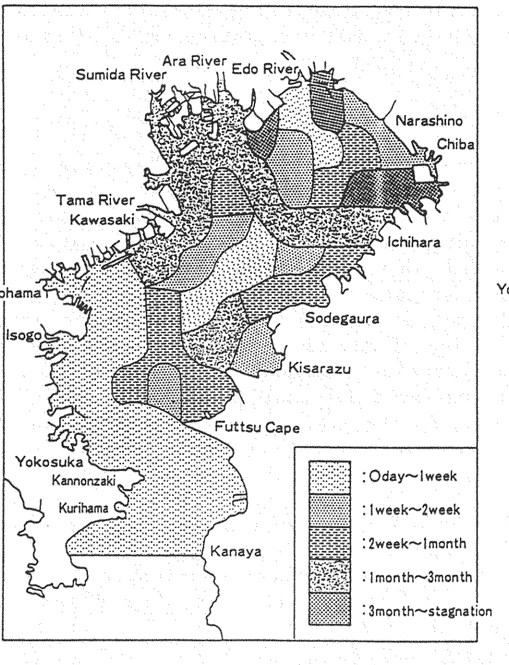

Fig.7 Retention time water mass in the first Layer (0～5m) <Winter>

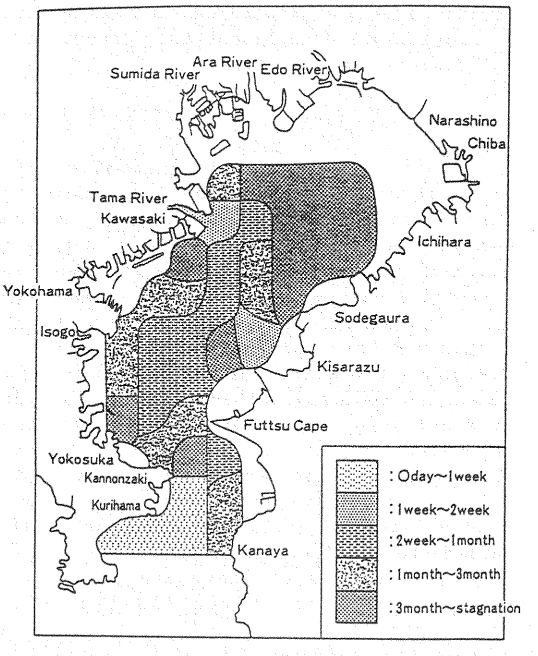

Fig.8 Retention time water mass in the third Layer (15～25m) <Winter>

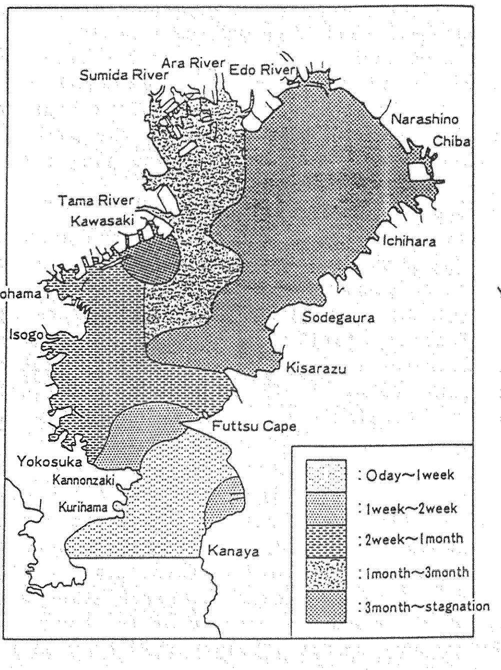

Fig.9 Retention time water mass in the first Layer (0～5m) <Summer>

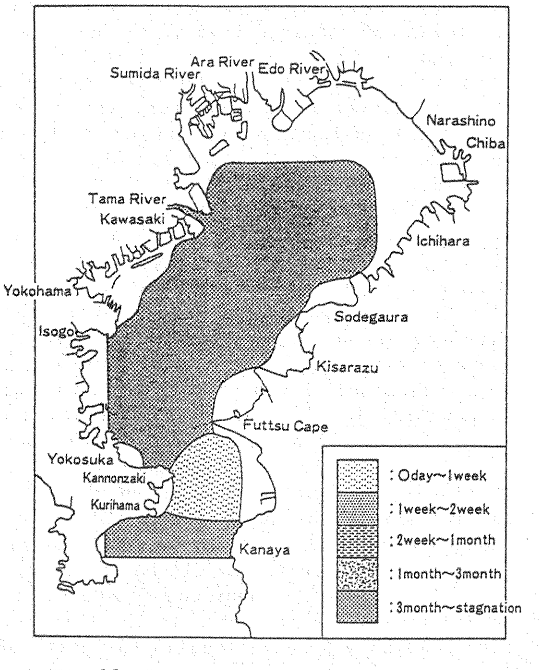

Fig.10 Retention time water mass in the third Layer (15～25m) <Summer>

the water-temperature difference in and outside the bay due to sea-surface cooling and by the salinity difference due to the inflow of river water; this matches well with the result that the distributions of water temperature and salinity stand in a dense and vertical manner at the bay mouth in winter.

In the stagnant period, the growth of stratification is conspicuous, and the outflow of particles is dependent on the southward current along the west coast, which is affected by river water. It should, therefore, be considered that the exchange of seawater takes place in the surface layer only, as evidenced particularly in the surface layer in the west of the bay in summer (see Figs.9 and 10). It can be observed that in the vertical distribution structure there is a tendency toward stratification even in spring; in summer, the growth of a stratification becomes conspicuous in the top layer.

CONCLUSION

The repetition of the stagnant period and exchange period throughout the year in Tokyo Bay has a large effect on the distribution of the marine environment in the bay, consequently bringing about conspicuous seasonal changes.

Based on the flow of particles and the spread of stagnant water mass, the correlation with marine environmental problems may be evaluated as follows:

1) The flow obtained by the box model method agrees with the condition of flow based on available information. In this method, processing is carried out in such a way that the conservation of mass holds not only in each calculation box but also as a whole system, thus making it possible to determine a realistic flow.
   It is also indicated that the realistic density distribution has a large effect on the flow in Tokyo Bay.
2) The method of analysis used in this research is aimed at determining the field of flow based on observation data such as water temperature, salinity, etc. Accordingly, the quality of data to be used (accuracy, spatial and time fineness) will have a direct effect on the quality of a solution. In the future, further acquisition of data and research on the effect of box sizes on the behavior of flow will be necessary.

ACKNOWLEDGMENT

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APPENDIX - NOTATION

The following symbols are used in this paper :

- C = Specific heat of seawater ;
- E_i = Evaporation from box i into atmosphere ;
- H_i = Quantity of heat flowing from the atmosphere into box i ;
- P_i = Precipitation in to box i ;
- R_{ri} = Flow of river water from river r into box i ;
- S_i = Salinity density in box i ;
- S'_r = Salinity density in river r ;
- T_i = Water temperature in box i ;
- W_{ij} = Exchange flow from box i to box j ;
- ρ_i = Seawater density in box i ;
- ρ'_r = River-water density of river r ;
- ε = Square sum of errors in the equation of preservation.

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