

Three-dimensional numerical prediction of vertical temperature structure of the Huanghai and the Bohai Seas

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Abstract—In the paper, the sea is divided into two layers with density jumping, assuming that the physical parameters in each layer are independent of depth. Two-layer flow field with tide and wind currents is calculated with extended ADI method, after the calculation for flow field is stable, coupled with temperature diffusion equations and thermohaline depth prediction equation, a four-day time prediction of the surface, bottom temperature and thermohaline depth of the Huanghai and the Bohai Seas. At the same time, three dimensional temperature field of sea water is predicted through vertical temperature distribution function. The result indicates that the prediction quality of the whole model and the fitting degree between the predicted result and the measured values are satisfactory.

INTRODUCTION

The prediction of sea water temperature plays an important part not only in physical oceanography and air-sea interaction, but also in oceanic fishing, communication, submarine voyage and oceanic exploration. However, the prediction of sea water temperature is related to large scale convection and small scale turbulent mixing, also, to such factors as exchange of energy and mass between air-sea interface and thermol exchange between land and sea, constituting a multi-scale, multi-factor comprehensive research subject. So, the research is helpful to the understanding of all physical parameters and their interaction. Usual prediction methods of sea water temperature are divided mainly into the methods of statistical prediction and solving equations. The method of solving equations is built on the basis of dynamical mechanism, including model of upper mixing layer and predictive model combining vertical temperature self-simulating function. The model of upper mixing layer makes a prediction of such given values of vertical temperature structure as the temperature of the upper and the lower homogeneous layers and the depth of the upper homogeneous layer by using the concept of "entrainment" (Munk, 1948; Stigebrandt, 1981; Wan, 1990). But, these models are mostly one-dimensional. Two and three dimensional models are very little (Hurlbert, 1973; Murakami, 1985; Huang, 1987) and usually simplified

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too much in order to get theoretical solution, so, it can only describe some physical phenomena. The concept of vertical temperature self-simulating function was used firstly by the Soviet Union scholar according to measured data of oceanic water temperature, and used to calculate the water vertical temperature structure of oceanic active layer under the condition of constant bottom water temperature (Kitaigorodskii, 1970; Miropoliskii, 1970). Later, the scholars of China used this method to predict water temperature of the Huanghai and the Bohai Seas under the condition that bottom water temperature varies with time, and established one and two dimensional numerical prediction model of sea water, and got better results (Xu, 1984; Wang, 1991).

The Huanghai and the Bohai Seas belong to the shallow water sea with strong current, complicated shape of bottom and shore, phenomenal nonlinear action, there exists difference or even significant difference between upper and lower layers. So, it is necessary to develop model considering horizontal and vertical comprehensive variation in order to improve prediction accuracy on the basis of existing models. This article is to consider factors of tide, wind current, the sun radiation, thermohaline waving, horizontal convection and diffusion, vertical turbulent mixing etc., and to establish a three dimensional numerical prediction model of vertical temperature structure of sea water.

PHYSICAL MODEL

Vertical temperature self-simulating function of sea water

Vertical temperature of sea water can be described by the following nondimensional variables (Wang, 1991):

$$\eta = \frac{z - h_1}{H - h_1}, \quad (1)$$

$$\theta_T = \frac{T_1 - T_z}{T_1 - T_H}, \quad (2)$$

there, θ_T can be:

$$\theta_T = a_1\eta + a_2\eta^2 + a_3\eta^3, \quad (3)$$

here, a_1, a_2, a_3 are self regression coefficient, T_1 is temperature of upper homogeneous layer, T_H is temperature of bottom layer, T_z is temperature of arbitrary layer.

Expressions of vertical temperature section of sea water

$$T_z(x, y, t) = T_1(x, y, t), \quad 0 \leq z \leq h_1 \quad (4)$$

$$T_z(x, y, t) = T_1(x, y, t) - \theta_T[T_1(x, y, t) - T_H(x, y, t)], \quad h_1 < z \leq H \quad (5)$$

Control equations of flow field

Considering rotating incompressible sea with stable stratification, assuming that the sea can be divided into two layers with density and velocity jumping in vertical direction, the first layer is the upper layer when thermohaline is stationary, its depth is h_1 , the second layer is below it

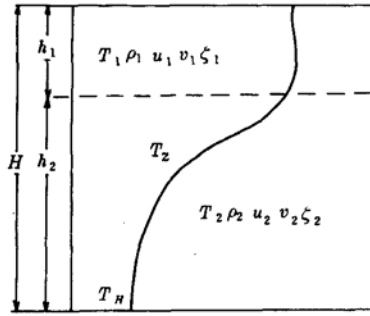


Fig. 1. Schematic diagram of two layer sea. T_1, ρ_1, u_1, v_1 and T_2, ρ_2, u_2, v_2 are vertical average values of the first and second layer, respectively, H is water depth, T_z is temperature of arbitrary layer, T_H is bottom temperature.

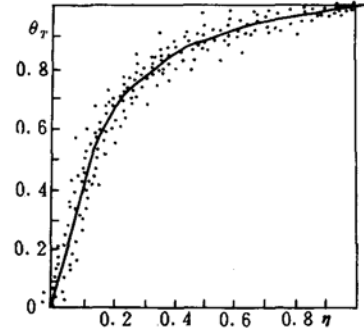


Fig. 2. Self-similing function of vertical temperature section of sea water.

(Fig. 1). To integrate the momentum equations and continuous equations in upper and lower layers, respectively. We yields two-layer fluid kinematic control equations;

$$\begin{aligned} & \frac{\partial \vec{u}_1}{\partial t} + \vec{u}_1 \cdot \nabla \vec{u}_1 + \vec{f} \times \vec{u}_1 \\ & = -g \nabla \zeta_1 + K_v \nabla^2 \vec{u}_1 + \frac{\vec{\tau}_a - \vec{\tau}_I}{\rho_1 (h_1 + \zeta_1 - \zeta_2)} + \vec{S}_1, \end{aligned} \quad (6)$$

$$\begin{aligned} & \frac{\partial \vec{u}_2}{\partial t} + \vec{u}_2 \cdot \nabla \vec{u}_2 + \vec{f}_1 \times \vec{u}_2 \\ & = -\frac{\rho_1}{\rho_2} g \nabla \zeta_1 + g' \nabla h_1 - g' \nabla \zeta_2 + K_v \nabla^2 \vec{u}_2 + \frac{\vec{\tau}_I - \vec{\tau}_b}{\rho_2 (H - h_1 + \zeta_2)} + \vec{S}_2, \end{aligned} \quad (7)$$

$$\frac{\partial \zeta_1}{\partial t} - \frac{\partial \zeta_2}{\partial t} + \frac{\partial h_1}{\partial t} + \nabla \cdot [(h_1 + \zeta_1 - \zeta_2) \vec{u}_1] = 0, \quad (8)$$

$$\frac{\partial \zeta_2}{\partial t} - \frac{\partial h_1}{\partial t} + \nabla \cdot [(H - h_1 + \zeta_2) \vec{u}_2] = 0, \quad (9)$$

where, ρ_1, \vec{u}_1 and ρ_2, \vec{u}_2 are the density and velocity of the upper and the lower layers; g and g' are gravitational acceleration and reduced gravitational acceleration; ζ_1, ζ_2 are the displacement of surface and interface; $\vec{\tau}_a, \vec{\tau}_I$ and $\vec{\tau}_b$ are surface wind stress, interface friction, and bottom friction; \vec{S}_1, \vec{S}_2 are the mass exchange between two layers; \vec{f} is coriolis parameter. The expressions of these parameters are;

$$g' = \frac{\rho_2 - \rho_1}{\rho_2} g, \quad (10)$$

$$\vec{\tau}_a = \rho_a C_D |\vec{W}_{10}| \vec{W}_{10}, \quad (11)$$

$$\vec{\tau}_l = \rho K |\vec{u}_1 - \vec{u}_2| (\vec{u}_1 - \vec{u}_2), \quad (12)$$

$$\vec{\tau}_b = \rho_2 K_b |\vec{u}_2| \vec{u}_2, \quad (13)$$

$$\vec{S}_1 = \rho_2 W_{e1} \frac{\vec{u}_2 - \vec{u}_1}{\rho_1 h_1}, \quad (14)$$

$$\vec{S}_2 = \rho_1 W_{e2} \frac{\vec{u}_1 - \vec{u}_2}{\rho_2 h_2}, \quad (15)$$

$$\vec{f} = 2\vec{\Omega} \sin \varphi, \quad (16)$$

here, ρ_a is air density; $C_0 = (0.8719 + 0.000704 |\bar{W}_{10}|) \times 10^3$, is sea-surface dragging coefficient; W_{10} is wind speed 10 m high above sea surface; $\rho = (\rho_1 + \rho_2)/2$, K is frictional coefficient between interface; $K_b = \frac{1}{M} \bar{H}^{-1/6}$ is bottom frictional coefficient, M is manning coefficient; W_{e1} and W_{e2} are entrainment velocities upward and downward crossing interface, respectively. Their expressions are (Stigebrandt, 1981):

$$W_{e1} = 2m_{ow} u_{*w}^3 / [g\alpha(T_1 - T_2)h_1] - Q_s / [\rho_1 c_p (T_1 - T_2)], \quad (17)$$

$$W_{e2} = 2m_{ob} u_{*b}^3 / [g\alpha(T_1 - T_2)h_2], \quad (18)$$

here, m_{ow} and m_{ob} are experiential parameters; α is heat expanding coefficient; c_p is specific heat of constant pressure; $u_{*w} = (\tau_a / \rho_1)^{1/2}$, $u_{*b} = (\tau_b / \rho_2)^{1/2}$ are frictional velocities of sea surface and bottom; T_2 is average temperature below the upper homogeneous layer:

$$T_2 = \frac{1}{H - h_1} \int_{-H}^{-h_1} T dz = T_1 - \frac{1}{H - h_1} \int_{-h_1}^{-H} \theta_T dz (T_1 - T_H). \quad (19)$$

Q_s is heat input of sea surface, its expression is (Wang, 1983):

$$Q_s = f[Q_0, (T_1 - T_a)] / (c_p \rho_1), \quad (20)$$

here, Q_0 is total radiation of the sun when it is clear, T_a is air temperature.

Prediction equations of temperature structure

The heat equation is usually as follows:

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + W \frac{\partial T}{\partial z} - A_T \nabla^2 T = - \frac{\partial(\bar{W}T) + R}{\partial z}. \quad (21)$$

To integrate Eq. (21) in upper, lower layers along vertical direction, respectively, under the condition of not considering molecular effect and assuming that the heat to sea surface is absorbed by a thin layer of sea-surface, the following is obtained:

$$\frac{\partial T_1}{\partial t} + u_1 \frac{\partial T_1}{\partial x} + v_1 \frac{\partial T_1}{\partial y} + A_T \nabla^2 T_1 = \frac{Q_s - Q_l}{h_1 + \xi_1 - \xi_2}, \quad (22)$$

$$\frac{\partial T_2}{\partial t} + u_2 \frac{\partial T_2}{\partial x} + v_2 \frac{\partial T_2}{\partial y} + A_T \nabla^2 T_2 = \frac{Q_l}{H - h_1 + \xi_2}, \quad (23)$$

here, A_T is horizontal heat transition coefficient; Q_l is vertical heat exchange at interface. Along the interface (Niiler, 1977), $\bar{W}T + W_e \Delta T = 0$, so,

$$Q_1 = (W_{e1} - W_{e2})(T_1 - T_2). \tag{24}$$

The prediction of the upper homogeneous layer thickness h_1 is based on the definition of "entrainment" velocity (Phillips, 1977)—mean flow normal to interface on unit area (or normal velocity of mean position of interface):

$$W_e = W_{e1} - W_{e2} = \frac{dh_1}{dt}, \tag{25}$$

that is,

$$\frac{\partial h_1}{\partial t} + u_1 \frac{\partial h_1}{\partial x} + v_1 \frac{\partial h_1}{\partial y} = W_{e1} - W_{e2}. \tag{26}$$

So, Equations (4) ~ (9), (19), (22), (23) and (25) constitute the physical model of this numerical prediction.

NUMERICAL MODEL

Diferencial method

There already exists ADI method for numerical solution of two-dimensional depth-integrated equations, in order to solve the two-layer flow field of our model, we use the alternative implicit method of splitting operation. This method is an expansion of ADI method, its accuracy and stability are the same as ADI method. HN method is used for temperature prediction equations, variables of flow field are implicit and others are explicit.

Platzman staggered grid is used in calculation. The directions of x -axis, y -axis and z -axis are eastward, northward and upward, respectively, the positions of variables on grid points are shown in Fig. 3. The spacial distance between grid points is $\Delta x = \Delta y = 20$ km, time step is $\Delta t = 1\ 200$ s.

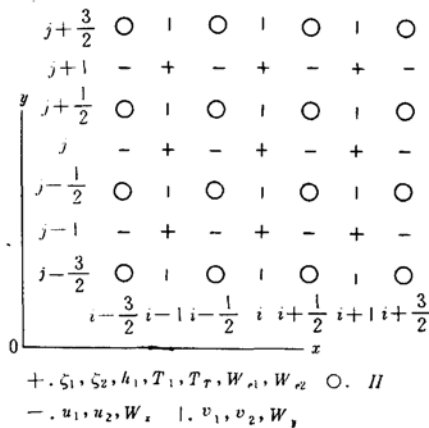


Fig. 3. Definition of grid and variables.

Conditions for solving equations

Boundary conditions. Along close boundary, let normal velocities be zero, that is $\vec{u} \cdot \vec{n} = 0$; along open boundary, let $\partial u / \partial x = \partial v / \partial y = 0$, tidal wave is inputted on sea face:

$$\zeta_1 = \sum_{i=1}^N [f_i H_i \cos(\sigma_i t + v_{oi} + u_i - G_i)], \quad (27)$$

where, N is the number of tidal constituents (four are taken in the paper: M_2, S_2, O_1, K_1); H, G are harmonic constants; f, σ_i are nodal factor and angular velocity; $v_{oi} + u_i$ is astronomical phase angle. On the interface of two-layer ocean along open boundary, when interface balance position and sea bottom are horizontal, ignoring convection, diffusion, friction and without considering Coriolis force, we can yield interface wave from flow field equations corresponding that when the surface wave is tidal wave (Adrian, 1982), its expression is

$$\zeta_2 = \frac{H - h_1}{H} \zeta_1. \quad (28)$$

Also, along all horizontal boundaries, let $\vec{n} \cdot \nabla T = 0$, $\vec{n} \cdot \nabla h_1 = 0$. Along close boundaries, this condition means that land does not affect the thermohaline of the ocean.

Initial conditions.

When $t = 0$, $\vec{u}_1 = \vec{u}_2 = 0$, $\zeta_1 = \zeta_2 = 0$, $h_1 = h_{10}$, $T_1 = T_{10}$, $T_2 = T_{20}$.

Selections of various parameters. The values of each parameters are in Table 1.

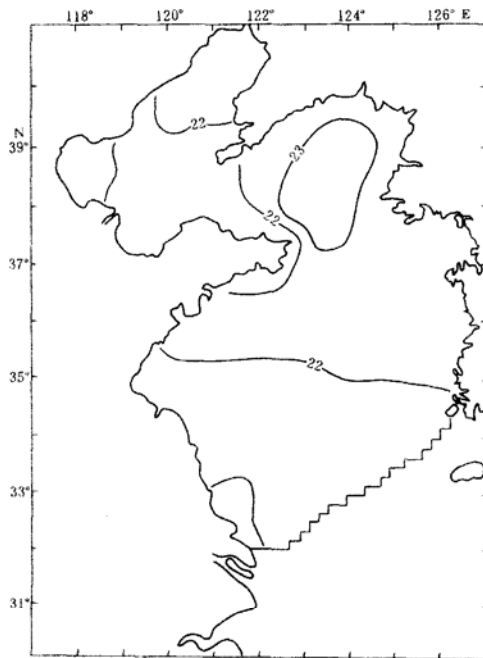


Fig. 4. Predicted surface temperature of the Huanghai and the Bohai Seas (July 9, 1979).

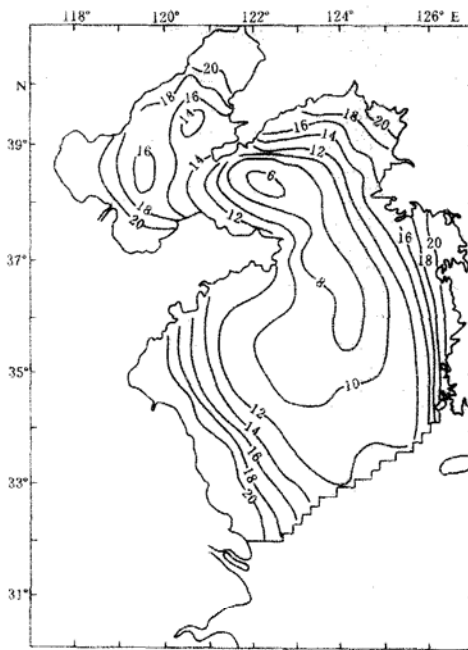


Fig. 5. Predicted bottom temperature of the Huanghai and the Bohai Seas (July 9, 1979).

Table 1. Corresponding parameters of the model

ρ_1	1.022 5	α	3×10^{-4}	K_v	10^7
ρ_2	1.025 5	c_p	0.938	K_b	$\frac{1}{N} H^{\frac{1}{2}}, N=0.01$
ρ_a	1.23×10^{-3}	c_D	$(0.871 9 + 0.000 7 W_{10}) \times 10^{-3}$	K	3.7×10^{-4}
g	980	A_T	10^{-6}	$\Delta X, \Delta Y$	2×10^6
m_{*w}	1.6	m_{*b}	0.2	Δt	1.2×10^3

RESULTS AND DISCUSSION

When prediction is carried out, tide current is firstly calculated. After several tidal periods, the flow field reaches stable dynamically. Then, wind field is inputted, and later coupling with

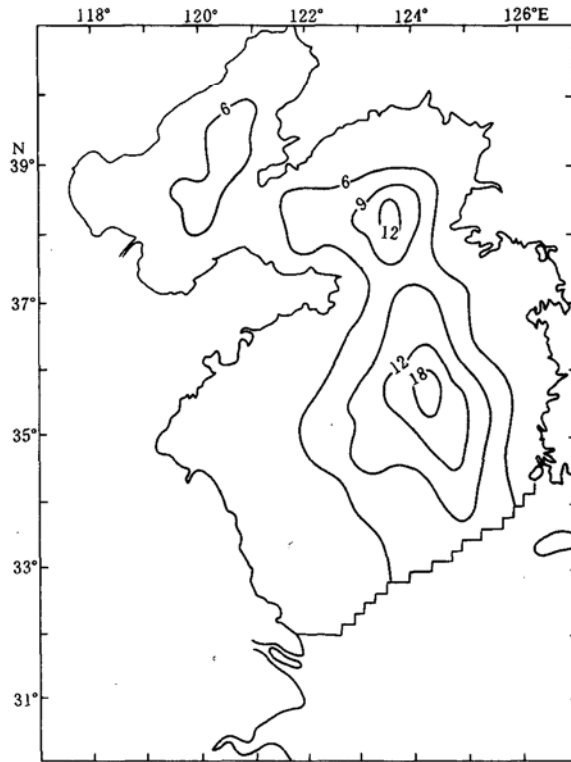


Fig. 6. Predicted thermohaline depth of the Huanghai and the Bohai Seas (July 9, 1979).

temperature prediction equations calculation is carried out. Because the limitation of wind and air temperature data, we use the data of July 4~8, 1977 (FGGE) to make 4-day tidal prediction. Figures 4~6 are predicted sea water temperature of the upper and the lower layers and thermohaline depth of July 8, 1979. From the figures, we can see that the surface temperature is homoge-

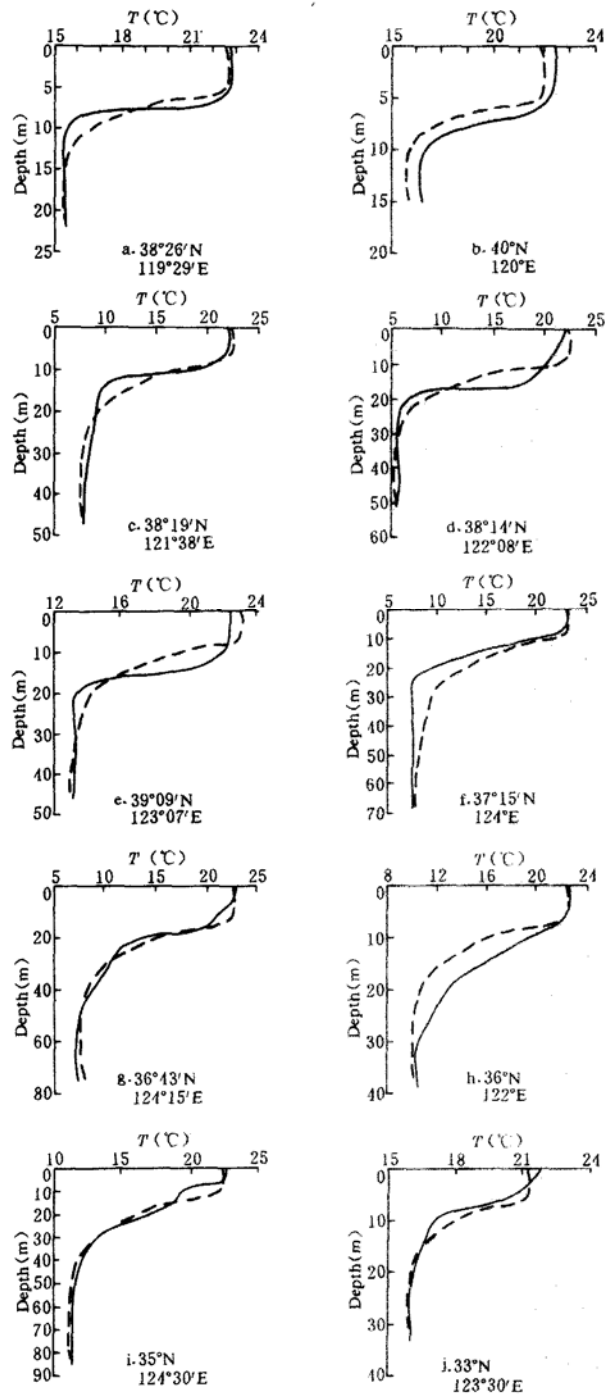


Fig. 7. Predicted (dashed) and measured (solid) vertical temperature distribution at ten stations over the Huanghai and the Bohai Seas.

neous, generally between 21~23°C. An important character of the Huanghai and the Bohai Seas is the existence of cold water mass. The predicted bottom temperature distribution shows that the position of cold water mass and the minimum value of water temperature are well in agreement with the measured data; the character of thermohaline depth is: there are no thermohaline along the Bohai Sea shore, thermohaline depth in the middle area of the Bohai Sea is between 5~10 m; in the Huanghai Sea, thermohaline depth is 5~20 m and with two centers in deeper depth, one

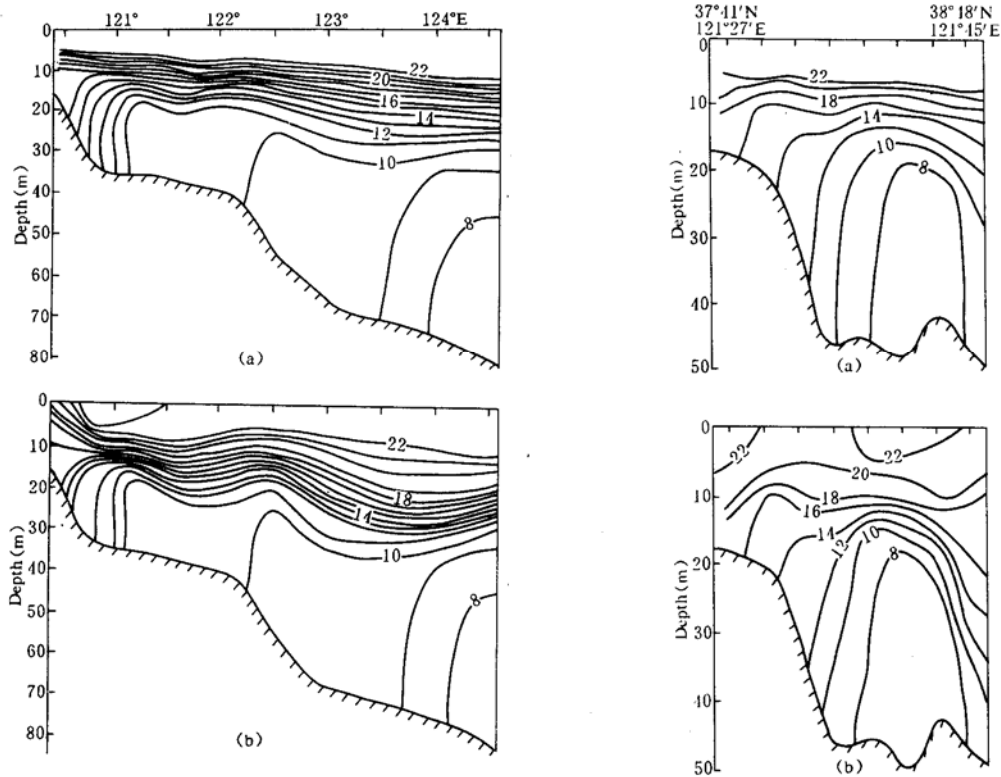


Fig. 8. Predicted(a) and measured(b) results of temperature section profile along 36° N.

Fig. 9. Predicted (a) and measured (b) results in section of the Bohai Strait.

is at 38. 2°N, 124°E (>12 m) and the other at 35. 8°N , 124. 5°E (> 18m). Figure 7 is a comparison between predicted sea water temperature vertical distribution and the measured one. It is shown that the results well reflect the vertical temperature structure of the Huanghai and the Bohai Seas in summer and the majorities of absolute error of temperature are less than 0. 5°C , reach the error demanded by theoretical analysis of vertical temperature self-simulation function. This indicates that the assumption in analysis is reasonable (this work will be published in other articles). Figures 8 and 9 are two predicted and measured water temperature section profiles . We can see from the figures that predicted surface, bottom temperature values well fit measured values, the upper homogeneous depth, thermohaline character and the position of cold water mass under thermohaline also fit the measured well. Especially, because the sea is divided into two lay-

ers in our model, the upwelling phenomena of bottom cold water is partly reflected in the section profile (shown in Fig. 8). This has improved our previous works.

But in Fig. 8, the predicted results cannot reflect the phenomena that measured isothermal lines lift up and form thermal front. However, thermohaline turns to extinguish in the upper 10 m west of 121° E. This mainly attributes to using ideal boundary conditions as the linking up conditions from areas with thermohaline to areas without thermohaline in prediction. This is to be improved in the future work.

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