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Numerical Experiment for the Formation of the Yellow Sea Cold Water mass

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황해저층냉수의 형성에 관한 수치실험

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A simple three-dimensional cubic model is applied to the formation of the Yellow Sea Cold Water Mass in Summer. We studied how the tidal mixing and the Kuroshio Water Mass affect the formation of the Yellow Sea Cold Water. The tidal mixing effect is parameterized into the vertical diffusion coefficient because of the technical difficulties in the numerical model. In this study, the thermal front along the coast could be formed only by the tidal mixing effect. However, the southern front of the Yellow Sea Cold Water Mass has to consider the warm Kuroshio water. The resultant shows the opposite temperature distribution in upper layer and lower layer. The center of the model is warmer in the upper layer and colder in the lower layer than the coast. The resultant circulation pattern is also reverse, clockwise circulation in the upper layer and counter-clockwise circulation in the lower layer.

하계에 나타나는 황해저층냉수에 간단한 3차원의 육면체 모델을 적용하여, 조석의 혼합작용과 쿠로시오수괴가 황해저층냉수의 형성에 주는 영향을 연구하였다. 본연구에서는 수치모델의 기술적인 문제 때문에 조석의 혼합작용을 연직혼합계수로 매개변수화하였다. 또한 연안을 따라 나타나는 수온전선은 조석의 혼합작용에 의해서 형성되도록 하였으며, 황해저층냉수의 남부에 나타나는 수온전선의 형성에는 고온의 쿠로시오수괴를 고려하였다.
수치실험의 결과, 모델의 상층과 하층에서 수온분포의 경향이 반대로 나타났다. 상층에서는 모델의 중앙부에서, 하층에서는 연안해역에서 각각 상대적으로 고온의 수온분포가 나타났다. 해수의 순환형태 역시 상층과 하층 사이에 반대로서, 상층에는 시계방향이, 하층에는 반시계방향의 순환이 나타났다.

INTRODUCTION

The Yellow Sea is the marginal sea at the north-western part of the Pacific Ocean, surrounded with the Asia continent and the Korean Peninsular. Since the Yellow Sea is shallow water with the mean depth of 44 m, the ocean condition of the Yellow Sea is affected by the tide and the atmospheric condition significantly.

As seen in the Marine Environment Atlas of Korean Waters (Hydrographic Office, 1982), the Yellow Sea Cold Water is located at the central part of the Yellow Sea like a tongue from Spring to Autumn. The characteristic temperature and salinity is below 10℃ and below 33‰(Nakao, 1977; An and Oh, 1984) or 32.0-32.5‰ (Lie, 1984) It is generally thought that the Yellow Sea Cold Water is formed by the surface cooling and the vertical mixing process which are due to the strong cold and dry seasonal wind in mid-Winter. From May to August, the surface water temperature rises rapidly and the strong thermocline is formed at about 30 m depth. The Yellow Sea Bottom Cold Water remain below the thermocline during Summer.

The horizontal feature of the Yellow Sea Cold Water is like tongue toward south because it is bounded on the coastal region and on the south by the strong thermal fronts. An (1986) said that the dynamical mechanism of the coastsl front is active tidal mixing process, and that of the southern front is the frontogenesis by the warm water supply by the western boundary current, Kuroshio.

In this study, the boundary front of the Yellow Sea Cold Water is simulated by the numerical experiment with vertical stratification. In the first place, the square rectangular model basin is used for the tidal front at the coastal water area. In the second model, the southern front is simulated by the consideration of the Kuroshio Water as well as the tidal mixing process.

GOVERNING EQUATION

Under the Boussinesq, hydrostatic and rigid-lid approximation, the model ocean is governd by the following equation

$$\frac{\partial u}{\partial t}+Lu-fv=\frac{-1}{\rho_o}\frac{\partial p}{\partial x}+A_h\nabla_h^2 u+A_v\frac{\partial^2 u}{\partial z^2} \quad (1)$$

$$\frac{\partial u}{\partial t}+Lv+fu=\frac{-1}{\rho_o}\frac{\partial p}{\partial y}+A_h\nabla_h^2 v+A_v\frac{\partial^2 v}{\partial z^2} \quad (2)$$

$$(L\mu=\frac{\partial \mu u}{\partial x}+\frac{\partial \mu v}{\partial y}+\frac{\partial \mu w}{\partial z} \quad \nabla_h^2\mu=\frac{\partial^2 \mu}{\partial x^2}+\frac{\partial^2 \mu}{\partial^2 y})$$

$$p=-g\int_0^z \rho(z)\, dz \quad (3)$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (4)$$

where (u, v, w) are velocities in the (x, y, z) directions, ρ is the density, ρ_0 is the reference water density, p is the pressure, A_h and A_v are the horizontal and the vertical turbulent eddy coefficients for momentum, f is the Coriolis parameter at latitude Φ as follow,

$$f=2\Omega\ \sin\Phi,\ (\Omega=2\pi/86400\,\text{sec}^{-1})$$

The equations for temperature, salinity and state are followings

$$\frac{\partial T}{\partial t}+LT=\frac{K_v}{\delta}\frac{\partial^2 T}{\partial z^2}+K_h\ \Delta_h^2 T \quad (5)$$

$$\frac{\partial S}{\partial t}+LS=\frac{K_v}{\delta}\frac{\partial^2 S}{\partial z^2}+K_h\ \Delta_h^2 S \quad (6)$$

$$p=p_o+p(S,\ T) \quad (7)$$

where T and S are water temperature and salinity. K_v and K_h are the vertical and horizontal eddy diffusion coefficients. δ is the parameter for the vertical mixing by the vertical density stability as follow.

$$\delta=\begin{cases}1, & \text{when stable state: } \frac{\partial \rho}{\partial z}>0\\ 0, & \text{when unstable state: } \frac{\partial \rho}{\partial z}<0\end{cases} \quad (7)$$

The model basin has the horizontal resolution $\Delta x=\Delta y=20$ km. Fig. 1 shows the model oceans. Model I is the square basin. The depth of this model is 80 m, and both of the east-west and north-south lengths are 360 km

Model II with 360 km width and 600 km length is 80 m depth at the northern part, and 200 m depth at the southern part which is assumed continental slope of the East China Sea.

There are five levels in the vertical direction both in the model I and the model II and the thickness of five layers from above are 20 m, 10 m, 10 m, 10 m and the rest of total depth.

The friction at the bottom is as follow

$$\frac{1}{\rho_o}(\tau_x^B,\ \tau_y^B)=-C_D(u^B,\ v^B) \quad (8)$$

where τ_x^B and τ_y^B are the bottom shear stress, C_D (=0.0026) is the bottom friction coefficient. In the model I there are no wind friction and no heat flux from the surface, and there is no flow through the latteral boundary.

The time step of calculation is assigned to 600 sec from the Courant-Friedrichs-Levy (CFL) condition for computational stability (Haltiner and

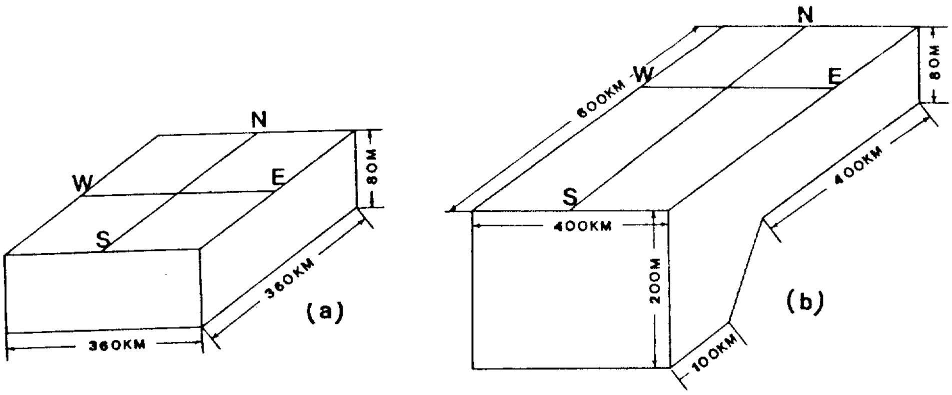

Fig. 1. The schematic views of Model I (a) and Model II (b), E-W line, N-S line are the east-west and the north-south section of Model I and Model II respectively.

Table 1. The depth and the initial temperature and salinity conditions of the vertical distribution in the model I and Model II.

	Model I			Model II				
					central area		southern area	
level	depth	T(℃)	S(‰)	depth	T(℃)	S(‰)	T(℃)	S(‰)
1st	20 m	27	31	20 m	27	31	29	31
2nd	10 m	14	32	10 m	14	32	27	33
3rd	10 m	10	32.5	10 m	10	32.5	23	34
4th	10 m	9	32.5	10 m	9	32.5	20	34.5
5th	30 m	5	32.5	30-150 m	5	32.5	20	34.5

Williams, 1980). The Euler backward scheme is used once in every elliminate of the computational implicit seperation of the preceding scheme each eight step.

Table 1 shows the initial vertical distribution of temperature and salinity. This would be very similar to hydrographical state of the Yellow Sea in Summer. To clarify the formation of the bottom cold water mass, the temperature of 5th level is less than the real temperature.

In the model II, all boundary conditions are equal to that of the model I, and the initial T and S distributions of shallow part is also the same as in Table 1. However the southern region's T, S distributions is allocated 29-20℃ and 31-34.5 ‰, which is assumed to represent the Kuroshio Water Mass in the same season.

In these models, tidal mixing effect is not considered directly but parameterized by the vertical diffusion coefficient, K_v

Bowers and Simpson(1987) showed that tidal fronts induced by the tidal mixing process, should parallel to contours of u^3/h, where u is the maximum tidal current velocity, and h is water depth. Therefore, the value of the vertical diffusion coefficient, K_v which implicitly include the tidal mixing effect is increasing with decreasing water depth, and increasing the tidal current velocity.

Fig 2 shows the K_v distribution that varies from 1 cm^2sec in less tidal area to 100 cm^2sec in the coast. So that K_v in the model I is distributed in symmetric circles . In the model II, the central and the southern regions are taken the value of K_v to 1 cm^2sec.

At the coastal region ($K_v=100$ cm^2/sec), the typical mixing time scale, $[h]^2 \cdot [K_z]^{-1}$, is 7.4 days. Therefore the model run time is more than seven days when the vertical mixing fully operates at

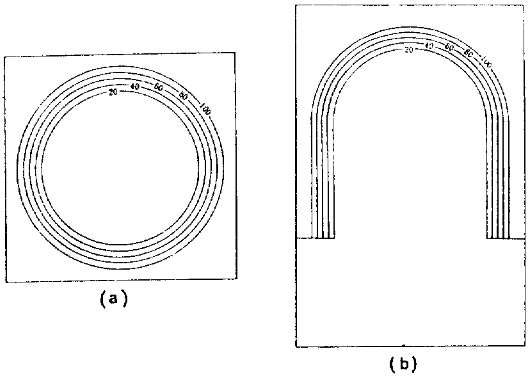

Fig. 2. The horizontal distribution of the vertical diffusion coefficient K_v (cm^2/sec) in Model I (a) and Model II(b).

the coastal region, and makes the water column vertically homogeneous.

RESULTS

Model I

Fig. 3. shows the horizontal temperature and velocity distributions of the model I after seven days run time. At the first layer, there is the warm water at the center of the model basin, and the water temperature is decreasing with approaching the coast.

In 2nd layer and 3rd layer, the temperature difference between the center and the coast is lower than that of the 1st layer.

But in 4th layer and 5th layer, the temperature difference between center and coast is reversed. The circular cold water is formed in the central basin where the temperature of water is colder than that of the coast. The vertical mixing by the vertical diffusion coefficient will make the water of the coastal area vertically homogeneous. Therefore the central water is warmer than the coastal water in upper layer and in lower layer vice versa.

In the upper layer, because of the colder and denser water at the coastal area, the clockwise circulation appears. On the contrary, in the lower layer, the circulation is counter clockwise direction.

Fig. 4. shows the vertical temperature distribution of the model I. Due to the symmetric condition of the model, there is no difference between the north-south section and east-west section. At the central area, the thermocline is formed in about 30 m water depth and the cold water mass appear under it. The isothermal line radially spreads out near the coast due to the vertically homogeneous temperature.

model II

Fig. 5. shows the horizontal temperature and ve-

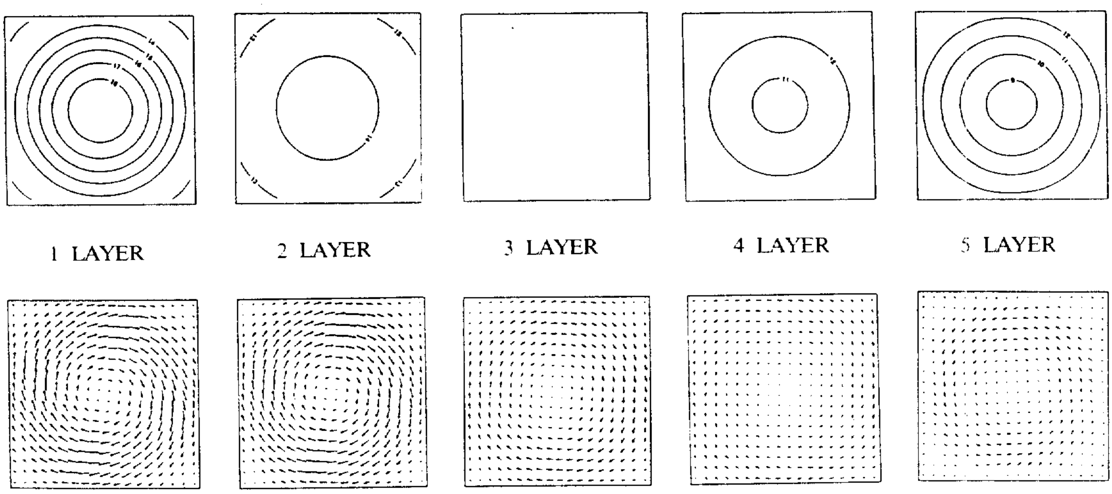

Fig. 3. The horizontal temperature and velocity distribution of Model I.

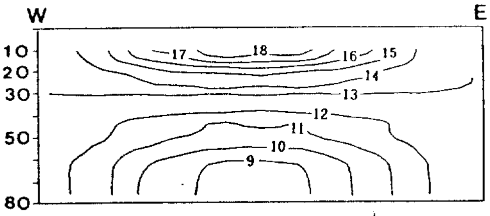

Fig. 4. The vertical temperature distribution of model I along E-W line, east-west section.

locity distribution of the model II. In the initial state, the Kuroshio Water Mass is considerd at the southern part of the model basin. As seen in this figure, the isothermal line goes up to the north at the central basin in the 1st layer. The water temperature patterns of the 2nd and 3rd layer is similar to that of the 1st layer. In the lower layer, the thermal front appear between the central part and the southern part. In 5th layer, the cold water below 14℃ appear at the central part with circulation pattern. This cold water is form by the vertical diffusion mixing of the coastal area like the results of the model I. The velocity field is only governed by the geostrophic balance like the model I. The clockwise circulation appears in the upper layer of the model II (1st and 3rd layers).

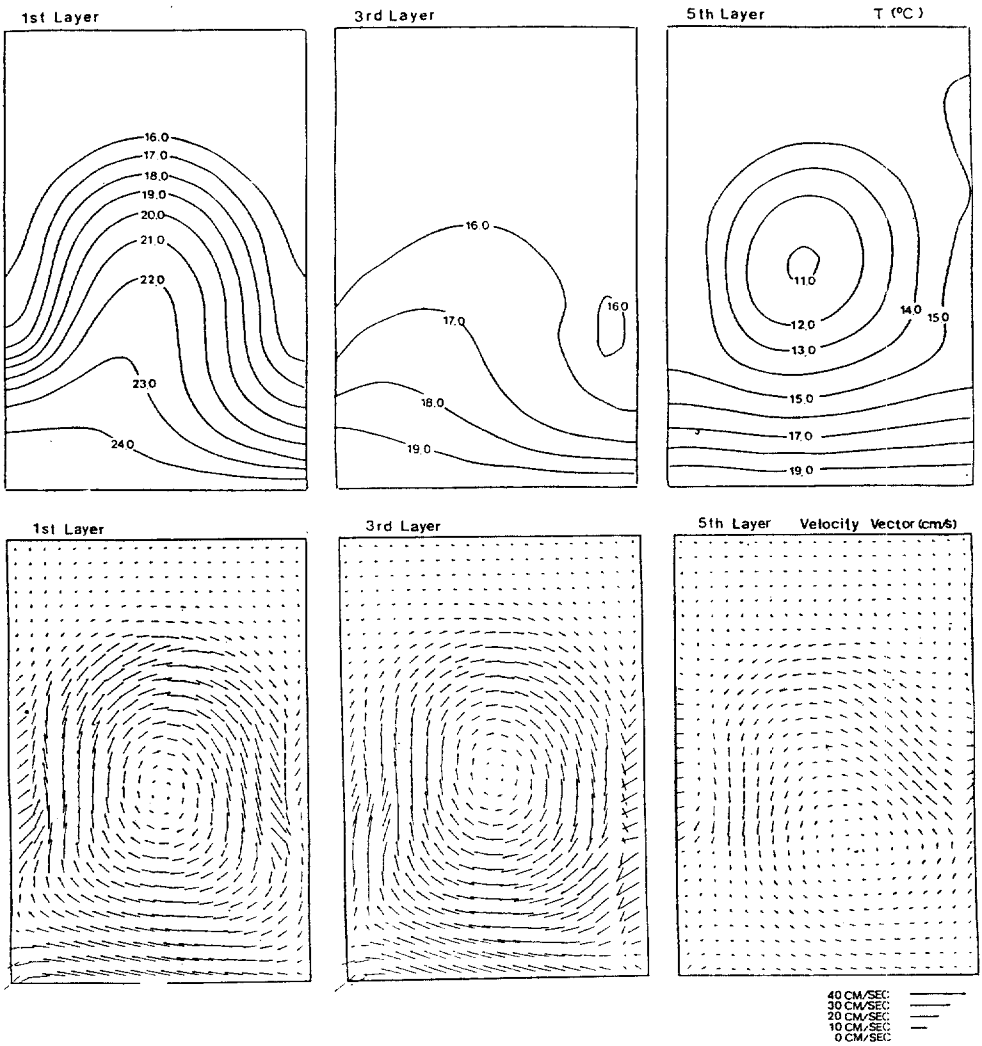

Fig. 5. The horizontal temperature and velocity distribution of Model II.

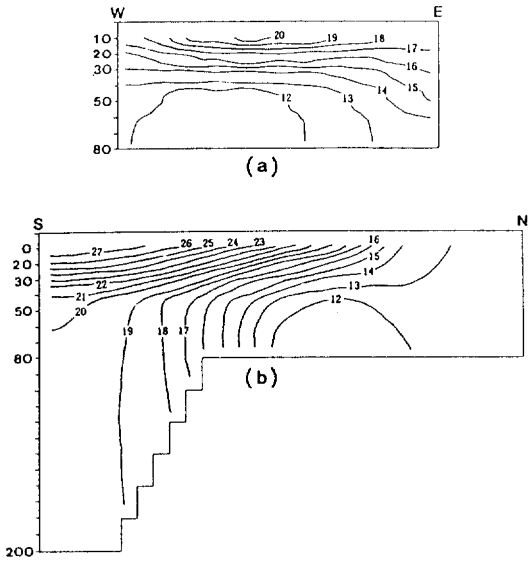

Fig. 6. The vertical temperature distribution of Model II along E-W line (a) and N-S line (b).

This pattern is due to the cold and dense water which is formed by the vertical mixing near the coastel region.

The 5th layers has the counter-clockwise circulation contrary to the upper layer pattern. The advection effect of circulation makes the horizontal temperature distribution unsymmetric in the east-west direction. In the upper layer, the Korean coastal water is 1-2℃ colder than the China coastal water. On the contrary, in the lower layer the Korean coastal water is quite warmer than the China coastal water.

Fig. 6. shows the vertical temperature section of the model II. In the east west section, the isothermal line spread out radially toward the coast. In the central region the cold water mass is preserved under the thermocline. In the north south temperature section, the southern thermal front appear on the slop of the model basin. The isothermal line is declining toward the south.

CONCLUSIONS

Using the 3-D numerical model, we formulated the Yellow Sea Bottom Cold Water on Summer under condition of the tidal mixing effect and the thermal boundary effect.

(1) The Yellow Sea Cold Water Mass could be formulated by the tidal mixing effect along the coastal area, and the contact with the Kuroshio Water Mass in the southern area.

(2) Due to the resultant density field, the circulation of the upper layer is clockwise direction and that of the lower layer is counter-clockwise direction.

(3) For the advection effect, the Korean coastal water is colder than the China coastal water on surface layer, and the Korean coastal water is warmer than the China coastal water on the lower layer.

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