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Effect of Shantung Peninsula on the Development of Mean Upwind Flow in the Yellow Sea

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황해의 역풍류 형성에 미치는 산동반도의 영향

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Effect of Shantung Peninsula on the development of mean upwind flow in the Yellow Sea in winter is analysed using a simple model. The results indicate that the disturbances generated by the Shantung Peninsula have a scale much larger than the basin scale whereas disturbances, if any, generated similarly on the other side of the trough has much smaller scale. The effect of Shantung Peninula thus dominates over the whole basin and deflects westward the otherwise northward upwind flow.

간단한 모델을 이용하여 겨울철 황해에서 역풍류 형성시 산동반도가 미치는 영향에 대하여 고찰하였다. 모델 결과, 산동반도의 영향은 만 전체에 걸쳐 나타나는 반면 반대측(한국연안)의 작은 반도들에 의해 생길 수 있는 가능한 영향은 그 규모가 너무 작아서 무시될 수 있는 것으로 나타났다. 산동반도의 영향으로 만의 골을 따라 흐르는 역풍류는 서쪽으로 편향하게 된다.

INTRODUCTION

It has long been suspected, through hydrographic observations (c.f., Fig. 1) and sattelite infrared images (not shown), that there might exist an northward upwind intrusion of warm and saline oceanic water into the Yellow Sea against the northerly wind prevailing in winter in this region. In fact, current observations(Hsueh,1988) reveal that the upwind current occurs near the trough and is due to the southward rise of sea level created by the north wind pulse; downwind current develops over the shallow coastal areas. The current is strongest during the relaxation period of the north wind pulse. The observed current have later been explained in terms of the coastally trapped long waves (Hsueh and Pang, 1989).

Averaged over the season, the current is therefore upwind over the trough under the effect of northerly monsoon in winter in the Yellow Sea. A simple analytic model for this mean upwind current has been attempted (Park, 1986) by assuming the Yellow Sea as an infinitely long uniform channel. This model shows clearly the development of upwind current over the trough and downwind current over the shallow coastal areas. The major force driving the current is northward pressure gradient in the former and wind stress in the latter. Though the model is successful in some degree in explaining the development of upwind current, the Yellow Sea can by no means be thought of as infinitely long uniform channel. The major geometric feature invalidating the assumption of uniform channel is the Shantung Peninsula (Fig. 2). In this study, we thus

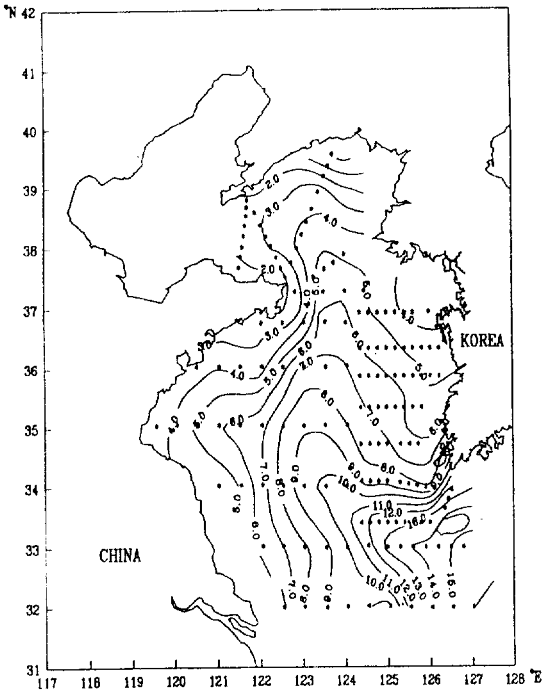

Fig. 1. Climatological mean surface temperature (℃) distribution in February. Data are from NFRDA (1963-1992), Korea for Korean waters and those compiled by Institute of Oceanology, Academia Sinica, Qingdao, China for Chinese waters. Dots are data points.

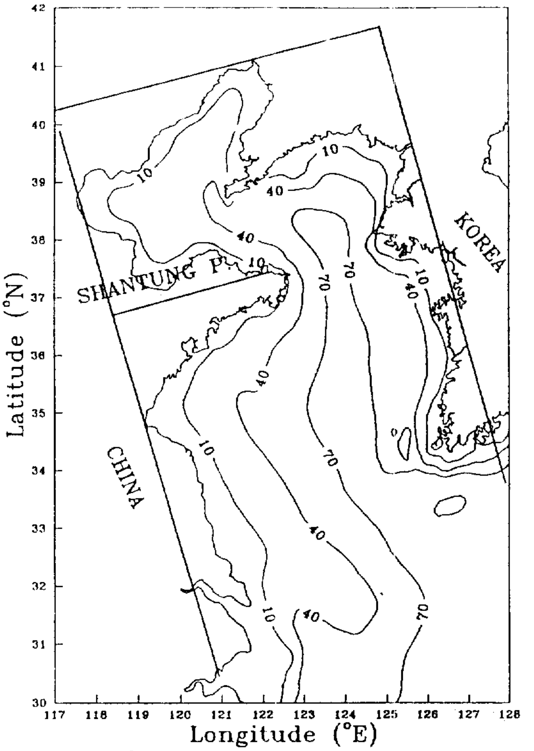

Fig. 2. The Yellow Sea with bottom topography (in meter) and idealized land boundary.

examine the effect of Shantung Peninsula on the developpment of upwind current in the Yellow Sea by idealyzing the Shantung Peninsula as a cross-channel barrier imbedded in otherwise uniform channel. First, the problem is formulated and second, solutions are presented with discussions and finally, some concluding remarks are drawn.

FORMULATION

Idealize the Yellow Sea as a uniform channel partly closed to the north by the Shantung Peninsula (Fig. 2). The effect of northern boundary (north of Shantung Peninsula) is thus neglected. The same idealization of the Yellow Sea has also been made by Kang (1984) in explaining the local tidal system. Except the vicinity of basin head, the bottom topography of the Yellow Sea is approximately uniform along the trough. It is not symmetric , however, with respect to the trough; the trough locates near to the eastern (Korean) coast so that the shelf on the Korean (Chinese) side is narrower (wider) and deeper (shallower). For comparison, we take the same idealized depth configuration (Fig. 3) as that used in the previous study (Park, 1986). Right handed cartesian coordinate system is adapted such that y- axis points northward from the barrier (Shantung Peninsula) along the center line of the channel (Fig. 3). The barirer is assumed occupying the western half (-L/2<x<0; L is the channel width) of the northern boundary (y=0). For comparison, the completely closed boundary, i.e., the cross-channel barrier extending from x=-L/2 up to x=L/2, is also considered.

The governing equations are the steady state, linear shallow water equations

$$-f\psi_x/H = -g\eta_x + r\psi_y/H^2 \tag{1}$$

$$-f\psi_y/H = -g\eta_y - \tau/H\rho - r\psi_x/H^2 \tag{2}$$

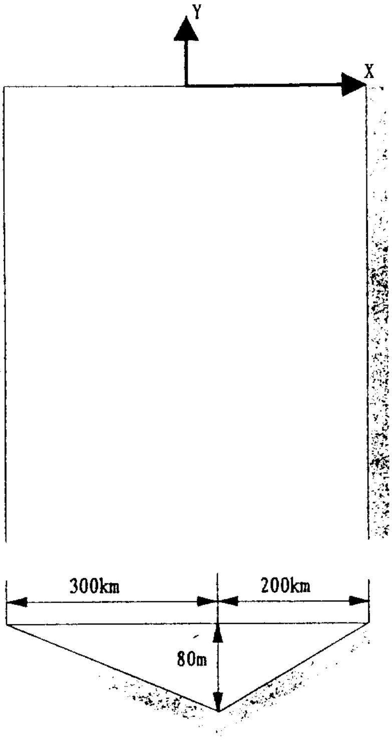

Fig. 3. Horizontal and vertical configuration of model basin (channel) along with horizontal coordinate system.

where: f is the Coriolis parameter; ψ, the transport stream function increasing to the right of the current direction; H, the bottom depth; g, the gravity constant; η, the surface elevation; r, the linear friction coefficient; τ, the value of northerly wind stress; ρ, the density of sea water. The subscripts x and y denote partial differentiation. Cross-differentiation of Eqs. (1) and (2) leads to the vorticity equation. Non-dimensionalyzing (x, y) by the channel width L, bottom depth H, by the depth of trough H_o and stream function ψ, by $\dfrac{\tau H_o L}{\rho r}$, the resulting equation becomes

$$\psi_y (1/H)_x/\varepsilon - (1/H)_x - [(\psi_x/H^2)_x + \psi_{yy}/H^2] = 0 \quad (3)$$

where $\varepsilon = r/H_o f$ is the ratio of inertial period to frictional decay time, which is usually much smaller than unity; we take 1/16 as the typical value of ε as done by Park(1986). In Eq. (3), and hereafter, all variables are assumed non-dimensionalized unless otherwise mentioned. In Eq. (3) the first term is the vortex stretching(shrinking) by down-(up-) slope current, the second term is torquė by wind stress and the last two terms are torque by friction. For convenience, we separate the stream function into two parts: one for uniform channel without barrier, ψ_∞, and the other for disturbances created by the cross-channel barrier, ψ', i.e., $\psi = \psi_\infty + \psi'$. The undisturbed stream function, ψ_∞, is independent of y and the disturbance stream function, ψ', is a function of both x and y. When introduced into Eq. (3), these stream functions satisfy the following equations:

$$(1/H)_x + (\psi_{\infty x}/H^2)_x = 0 \quad (4)$$

$$\psi'_{xx} + \psi'_{yy} - 2H_x \psi'_x/H + H_x \psi'_y/\varepsilon = 0 \quad (5)$$

The undisturbed current, solution to Eq. (4), has no cross-channel component and vorticity balance is made between wind stress and friction. With boundary condition

$$\psi_\infty = 0 \quad \text{along} \quad x = -1/2 \quad \text{and} 1/2 \quad (6)$$

The solution is given by

$$\psi_\infty = \int_{-1/2}^{x} H^2\,dx \cdot \left(\int_{-1/2}^{1/2} H\,dx \Big/ \int_{-1/2}^{1/2} H^2\,dx \right) - \int_{-1/2}^{x} H\,dx \quad (7)$$

as shown by Park(1986). As mentioned earlier, the disturbances satisfying Eq. (5) have cross-channel component of current and vorticity balance is between friction and vortex stretching (shrinking). Boundary conditions are

$$\psi' = 0 \quad \text{along} \quad x = -1/2 \quad \text{and} \quad 1/2 \quad (8)$$

$$\psi' \to 0 \quad \text{as} \quad y \to -\infty \quad (9)$$

Along the northern boundary, conditions are different depending on wheather it is closed or open. Along the closed part,

$$\psi' = -\psi_\infty \quad (10)$$

and along the open part,

$$\psi'_y = 0 \quad (11)$$

Eq. (11) assumes that flows through the open part of boundary are in along-channel direction.

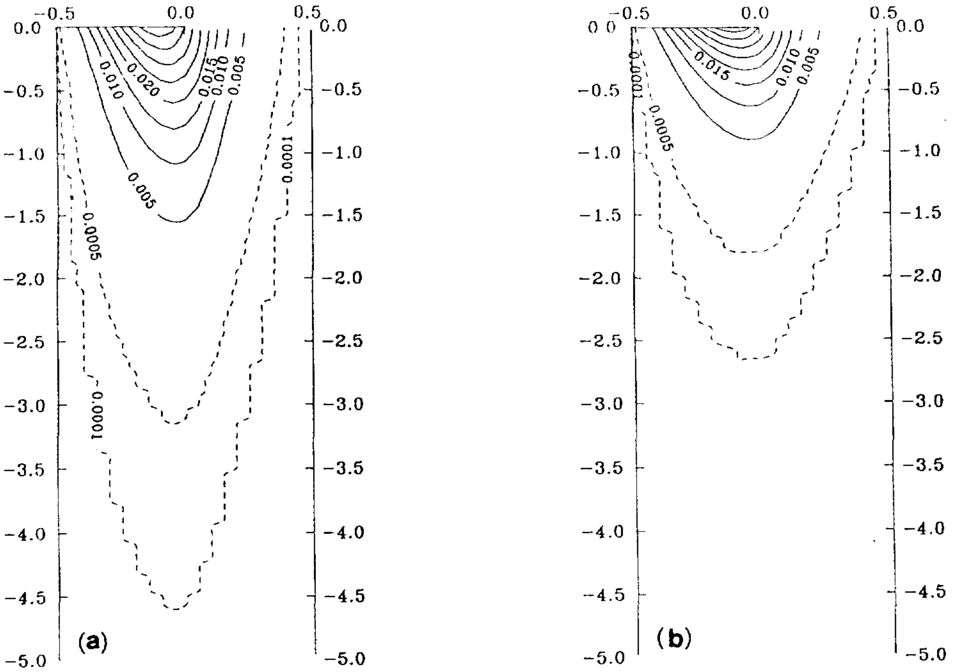

Fig. 4. Distributions of disturbance stream function for $\varepsilon=1/16$ (a) and $\varepsilon=1/8$ (b) in case where only the western half of the channel is closed. All values are normalized (see text).

SOLUTIONS

Eq. (5), with boundary conditions (8) through (11), is solved numerically. Before solving it, it may have to be mentioned about the length scale of disturbances in y- direction, L', though, in Eq (5), it was treated the same as the channel width L. The length scale in y-direction should necessarily be known in advance in order to ensure sufficiently large numerical domain. Two length scales are possible: either larger ($L' \gg L$) or smaller ($L' \ll L$) than the channel width. For disturbances with smaller scale, the second and last terms in Eq. (5) balance each other. L' is thus of the same order as ε. For disturbances with larger scale, the last term should be of order unity. L' is thus of order ε^{-1}. With distance variables normalized by the channel width L, the model domain has width 1.0. The length is taken as 5.0 considering the scale of disturbances discussed above. It is reminded that the stream function value is already normalized in Eq. (3) by using the wind stress. In solving Eq (5) numerically, grid size is taken as 0.05.

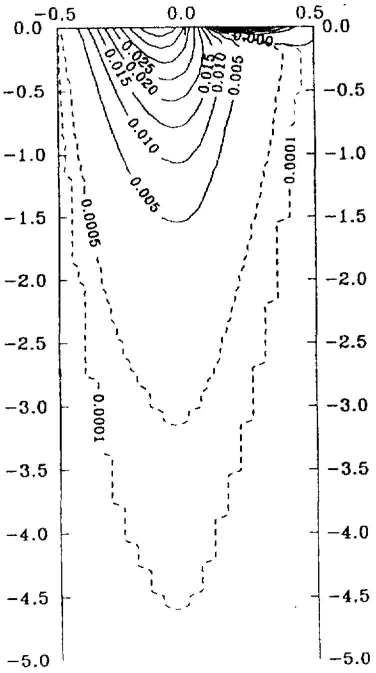

Fig. 5. Distribution of disturbance stream function for $\varepsilon=1/16$ in case where the channel is completely closed. Note the small area with negative values near the eastern barrier (y=0 , x>0).

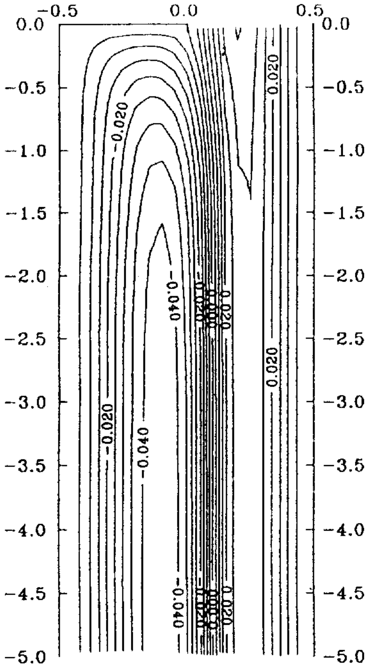

Fig. 6. Distribution of total stream function for $\varepsilon=1/16$ in case where the channel is partly closed on the western half.

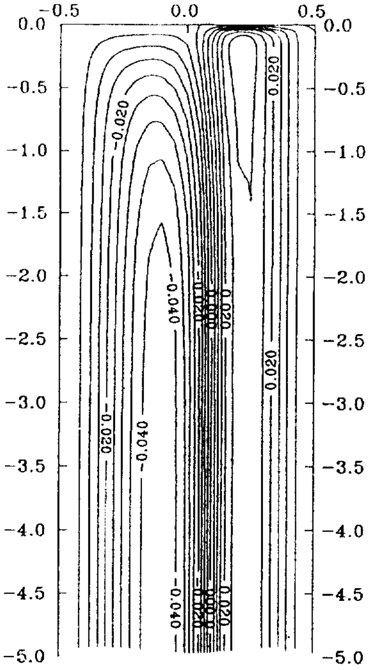

Fig. 7. Distribution of total stream function for $\varepsilon=1/16$ in case where the channel is completely closed.

The dependence of solutions on L' (thus ε) is seen in Fig. 4 where solutions with two different values of ε are compared. In Fig. 4, disturbances having smaller scale ($L' \ll L$) are not seen because, as seen in Fig. 5, it is generated only by the barrier east of the trough, i.e., over the eastern shelf. The total stream functions are obtained by adding ψ_∞, given by Eq (7), to ψ' obtained above (Fig. 6 and 7). It is again confirmed that length scales of disturbances are different depending on where they are generated. This can be understood well by considering the vorticity dynamics over the eastern and western shelves.

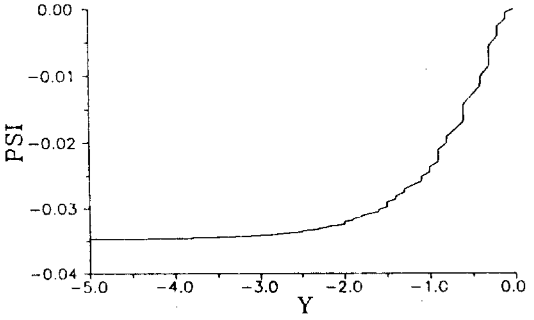

Fig. 8. Distribution of stream function along the center line of the channel (x=0).

Due to the presence of barriers, the water transported northward by the upwind flow should turn back southward and join to the downwind flow in coastal regions. The major component of disturbances is therefore up-slope current carrying waters from near the trough to the coastal regions. This up-slope current produces negative vorticity by vortex shinking on both sides of the trough. On the other hand, the wind stress acting over the surface of variable bottom depth, generates positive and negative vorticities, respectively, over the western and eastern shelves. Over the western shelf, vorticity balance can therefore be made between wind stress and vortex shinking. This is not the case on the eastern shelf. The only process that can produce the positive vorticity which can counterbalance the negative vorticities by wind and vortex shrinking is the friction. A narrow boundary layer thus develops along the barrier. Outside the boundary layer, over the broad region, weak down- slope return currents directing from the coast toward the trough are formed. These return currents create positive vorticity which then counterbalance the negative vorticity created by wind stress torque.

The north-south dimension of the Yellow Sea is comparable to the channel width (east-west dimension). The disturbances generated by the Shantung Peninsula may therfore dominate over the whole basin. On the contrary, disturbances generated by smaller peninsulas on the Korean (eastern) coast, if any, may only be trapped near the locations of generation. The disturbances so generated by the Shantung Peninsula over the western shelf may induce across- trough transport over the whole basin thus invalidating the assumption of uniform upwind transport along the trough; distribution of stream function in along- channel direction (Fig. 8) indicates significant cross -channel current at distance L from the barrier. In fact, historical observations (e. g. Fig. 1) seem to suggest westward deflection of otherwise along-trough warm water intrusion.

CONCLUDING REMARKS

Effect of the Shantung Peninsula on the development of upwind flow in the Yellow Sea is examined by idealizing basin geometry and using simple dynamics. The disturbances generated by the Shantung Peninsula may have sufficiently large length scale to dominate over the whole basin. These disturbances may induce across- trough component of current toward Chinese coast thus deflecting westward the otherwise northward intrusion of warm and saline oceanic water. On the contrary, disturbances created by smaller peninsulas (barriers) over the Korean (eastern) shelf, if any, may have much smaller scales so that their effects are not felt far from the barriers. The different behavior of disturbances between west and east of the trough can be explained in terms of the vorticity balance among the effects of wind, vortex shrinking by upslope current and friction. Over the western shelf, wind stress torque and vortex shrinking balance each other. Whereas over the eastern shelf, both these two processes generate negative vorticity and strong fricton is needed to counterbalance them. A narrow boundary layer thus develops along the barrier with broad region of weak down-slope current.

This study considers very simple dynamics. Especially, it relies on linear dynamics by assuming that climatological mean motion is coupled with climatological mean wind. In reality, the motion is fundamentally transient and it is not known how well the dynamics of mean motion above is valid. The Yellow Sea is also idealized as a semi-infinitely long uniform channel. However, the north-south oriented Korean coastline ends at the southwestern tip of Korean Peninsula and it is not known to what extent the above results are applicable. These remained problems are left as next research tasks.

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