On the Origin of the Tsushima Current (I) : Barotropic Case

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The Tsushima Current has been known to branch out from the Kuroshio west of Kyushu and to flow north to the Korea Strait. Then, it has to flow across the isobaths and so needs some driving forces. As the forces, sea level difference between the Korea and Tsugaru Straits, Reynolds stress west of Kyushu and density differences have been suggested, In this paper, their roles have been numerically studied in the barotropic case.

Model results show that the Tsushima Current is possible without any above force. The flows just follow isobaths over the East China Sea. They seem to be driven by their own dynamics without any external force. The mechanism is just like outflows from a gap.

Model results also show that the flows in this area could be significantly affected by the external forces such as Reynolds Stress. Then the dynamics and flows in real ocean might be complicated. However, the barotropic study tells us that the Tsuahima Currents is basically driven by geostrophic adjustment.

Introduction

There is no doubt about the fact that the warm and saline Tsushima Waters come from the Kuroshio Waters, but their flow pattern has not been clarified yet. Uda(1934) has first suggested that the Tsushima Waters branch out from the Kuroshio Waters west of Kyushu and flow northward(dotted path in Fig. 13). However, current observations do not support Uda's idea. The mean surface currents observed in 1924 to 1934, which is presented by Nitani(1972), do not show such a branching flow, but the general northeast flows over the East China Sea as shown in Fig. 1(A). GEK data shown in Fig. 1(B), presented by Rikishi etc.(1986), show rather southwest mean surface flows west of Kyushu. Other GEK data, for example, presented by Qiu and Imasato(1990), show more irregular flow patterns.

Such results make us confused about the origin of the Tsushima Current. The above observation data may by contaminated by tide or wind, so that they might not represent the Tsushima Current. Nevertheless, they show at least that the origin of the Tsushima Current could not be like Uda's idea. This has been pointed out by many researchers (Beardsley 1985, etc.).

About the mechanism of the Tsushima Current, a couple of theories have been suggested so far, as will be mentioned in the next section. However, none of them seems to explain clearly yet. Each theory explain some phenomena, but not others. It might not be possible to explain everything, since the flow patterns, which have been known to us, are not consistent themselves. We still have some problem in describing the flows of the Tsushima Current.

The problem comes from not only insufficient observations, but also lack of our understanding. Above all, we are still not sure of its basic mechanism. We need to understand it to describe the flows reasonabley. It is also necessary for a better

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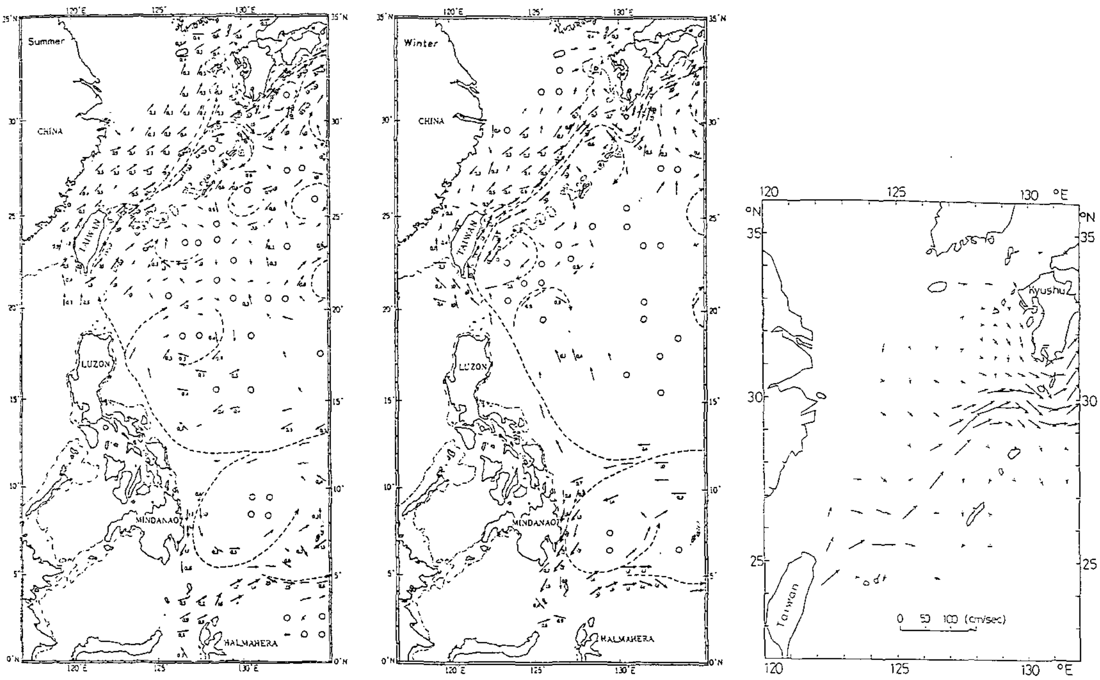

(A) (B)

Fig. 1. (A) Current charts in knots in summer(left panel) and winter(right panel) from Nitani(1972) and (B) *Mean surface currents determined from GEK data from Rikishi(1984) in the East China Sea.*

design of observations. The purpose of this paper is therefore to try to understand the basic mechanism. As a preliminary work, we are going to first find from the previous theories what the present problem is in the following section and thereafter, try to solve theoretically the problem using the GCM model of Semtner(1974).

Previous Theories

The theories on the mechanism of the Tsushima Current are largely classified into two groups. One is the sea level difference between the Korea and Tsugaru Straits to pull waters into the East Sea (Minato and Kimura, 1980). The other is the Reynolds stress west of Kyushu to push waters over to the East China Sea(Ichiye, 1984).

Fig. 2 shows the schematic model domain used by Minato and Kimura(1980) and the results. The model domain (A) is composed of the North Pacific, a marginal sea and two straits. the usual winds shown in (A) drive an anti-cyclonic gyre (C), and some waters penetrate into the marginal sea. This penetration is driven by sea level difference between two straits (B), which is caused by the North Pacific Gyre.

However, the geography(the location of two straits) and topography are too simplified in the model. So, the sea level difference between two straits may be overestimated. Ichiye(1984) pointed out that the wind stress curl of North Pacific ocean, which causes the sea level difference in the model, is stronger in winter than in summer, while the sea level difference in the real ocean is just out of phase. It means that the simplification of geometry and topography is not adequate. Bottom topography could be crucial in this problem.

Using more realistic geography and topography, many researchers including Ichiye and Li(1984) and Yuan and Su(1984) have been nuberically studied on the Tsushima Flows over the East China

Sea. However, the works should be classified in the same group as Minato and Kimura's, because they have used the forced boundary conditions on the Korea Strait. The forced boundary condition on the Korea Strait pulls waters from the model domain, so it is basically the same kind of forcing as that of sea level difference. By the forced boundary condition, waters have to flow through the Korea Strait even with realistic geography and topography. Therefore, the question has not been solved yet.

Instead, Ichiye(1984) showed that some of Kuroshio Waters can be pushed to the Korea Strait by the Ryenolds Stress west of Kyushu. He calculated Reynolds Stress from the current data. However, he made a mistake in numerical conforming the effect. He chose some model results in his another paper(Ichiye and Li, 1984), in which a forced boundary condition is also used. With forced boundary condition, Reynolds Stress can not make any contribution. To see the effect, a free boundary condition should be used.

Besides the above two theories, there is another suggestion that the Tsushima Current is a density flow. It interpretes the Tsushima flows along the shelf edge as a result of lateral mixing. On the viewpoint of water mass distributions over the East China Sea(Miyazaki and Abe, 1960; Lim, 1971; Sewara and Hanzawa, 1979), it seems to be quite plausible if there is no other driving forces. Therefore, we want to first check what is the primary force of the Tsushima Current.

As alluded, the present problems from the previous theories are as follows: (1) We do not have any clear answer to the force by the sea level difference. Numberical modelling with a forced boundary condition is not proper. (2) In spite of its possibility, the effect of Reynolds Stress should be checked in some way. (3) Density distribution may be important, but we should have an answer to the other forces before we can say that it is a major force.

The first one can be solved by using a free boundary condition. If there are still flows in the Korea Strait with a free boundary condition, the sea level difference is not the major force. The second one can be also solved by using a free boundary condition. With boundary condition, the Reynolds stress can make contribution to push waters to the Korea Strait. The third one will be done indirectly with a homogeneous ocean to check if the flows can be driven without density distributions.

To study these points, we are going to run a barotropic model with free open boundary and the Reynolds Stresses calulated by Ichiye(1984).

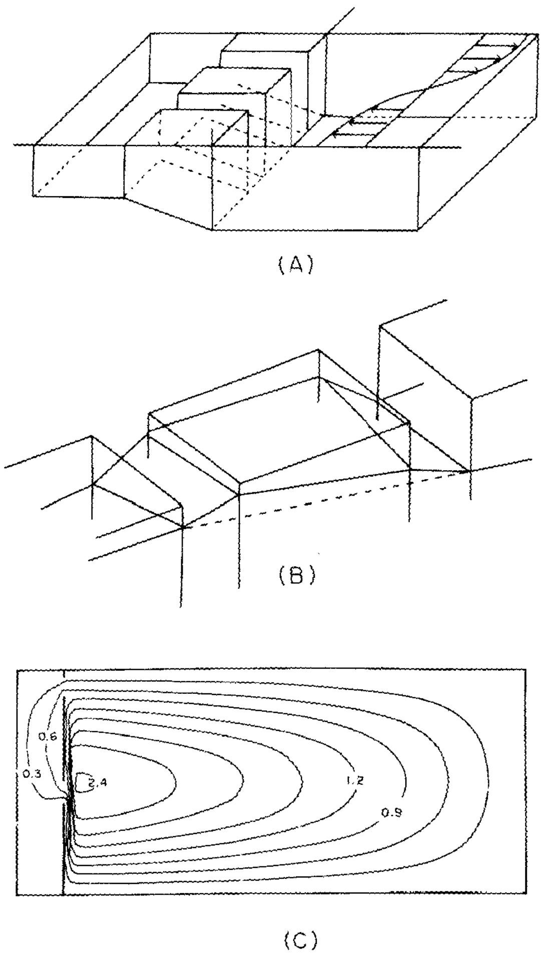

Fig. 2. (A) Model ocean and wind stress, (B) Sketch of the sea-surface topography near the channels and (C) Typical stream lines, in Minato and Kimura(1980).

Model Setting with Free Boundary Condition

In this section, we first want to see, in a barotropic model with a free boundary, what happens in the East China Sea without any driving force. Fig. 3 shows the model domain and bottom topography. The grid length is 15′, Water is forced to flow in through the southern boundary and free to flow out through the eastern boundaries.

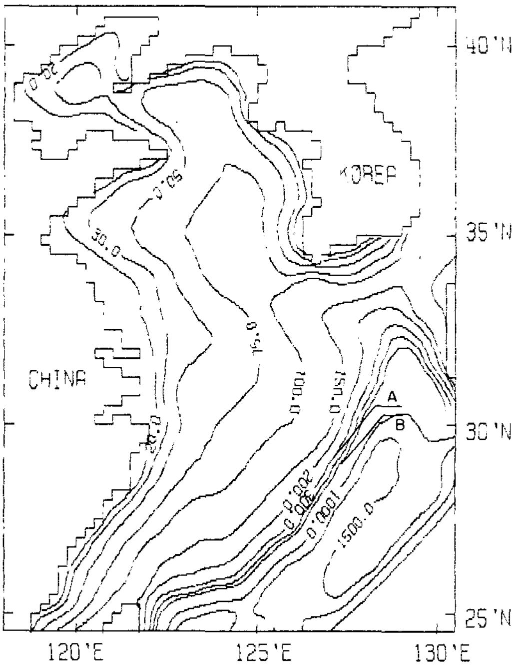

Fig. 3. Model domain and bottom topography. Ichiye (1984) calculated Reynolds stresses along lines A and B. The same Reynolds stresses are applied along the same lines in this paper.

Governing Equations

In model calculation, we use finite-difference method and a spherical polar coordinates(λ, ϕ, z), rotating with angular speed Ω, λ, ϕ, and z represent longitude, latitude and height, respectively. The ocean is contained between the surface $z=0$ and the bottom $z=-H(\lambda, \phi)$. To make the bottom topography shown in Fig. 3, 13 layers are used. The thicknesses of each layer are 10, 10, 10, 20, 25, 25, 50, 50, 300, 500, 1000, 1000, 1000 meters. With Boussinesq approximation and hydrostatic approximation, the governing equations(momentum and continuity equations) are as follows;

$$\frac{\partial u}{\partial u}+Lu+\frac{uv\tan\phi}{a}-fv=-\frac{1}{\rho a\cos\phi}\frac{\partial p}{\partial\lambda}+k\frac{\partial^2 u}{\partial z^2}+A_h\{\nabla^2 u+\frac{(1-\tan^2\phi)u}{a^2}-\frac{2\sin\phi}{a^2\cos^2\phi}\frac{\partial v}{e\lambda}\} \quad (1)$$

$$\frac{\partial v}{\partial t}+Lv+\frac{u^2\tan\phi}{a}+fu=-\frac{1}{\rho a}\frac{\partial p}{\partial\phi}+k\frac{\partial^2 v}{\partial z^2}+A_h\{\nabla^2 v+\frac{(1-\tan^2\phi)v}{a^2}-\frac{2\sin\phi}{a^2\cos^2\phi}\frac{\partial u}{\partial\lambda}\} \quad (2)$$

$$\frac{\partial p}{\partial z}=\rho g \quad (3)$$

$$\frac{1}{a\cos\phi}\frac{\partial u}{\partial\lambda}+\frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}(v\cos\phi)+\frac{\partial w}{\partial z}=10 \quad (4)$$

In the above we have advection operator L and horizontal Laplacian Operater ∇^2.

$$L=\frac{1}{a\cos\phi}\frac{\partial}{\partial\lambda}u+\frac{1}{a\cos\phi}\frac{\partial}{\partial\lambda}\cos\phi\ v+\frac{\partial}{\partial z}w$$

$$\nabla^2=\frac{1}{a^2\cos^2\phi}\frac{\partial^2}{\partial\lambda^2}+\frac{1}{a^2\cos\phi}\frac{\partial}{\partial\phi}(\cos\phi\frac{\partial}{\partial\phi})$$

Here, u, v, w, ρ, a, A_h, k, g, f are, respectively, velocity components in λ, ϕ and z, water density, earth radius(6370km), horizontal and vertical eddy viscosity coefficients, gravitational acceleration, Coriolis parameter($2\Omega\sin\phi$).

Boundary Conditions

The momentum flux is taken to be zero at the ocean bottom and given by wind stress at the ocean surface if there is. At lateral walls, a no-slip condition is imposed. The ocean surface is assumed to be a horizontal rigid lid so that high frequency surface gravity waves are filltered out. Along the ocean bottom, flow is required to parallel the slope.

$$\rho k\frac{\partial}{\partial z}(u, v)=0 \qquad \text{at } z=-H(\lambda, \phi)$$

$$\rho k\frac{\partial}{\partial z}(u, v)=(\tau_\lambda, \tau_\phi) \qquad \text{at } z=0$$

$$(u, v)=0 \qquad \text{at lateranl walls}$$

$$w=0 \qquad \text{at } z=0$$

$$w=-\frac{u}{a\cos\phi}\frac{\partial H}{\partial\lambda}-\frac{v}{a}\frac{\partial H}{\lambda,\ \phi} \qquad \text{at } z=-H(\lambda, \phi)$$

Along the southern boundary, (Kuroshio) water flux of 30Sv is prescribed by stream function. Along the eastern boundary, a free boundary condition is used so that water fluxes in the Korea Strait(Tsushima Water) and the Tokara Strait south of Kyushu(Kuroshio Water) are calculated.

Prognostic Equations

Due to rigid lid approximation, we do not know ocean surface elevations and thus barotropic velocity from the above governing equations. Because pressure at any depth z is composed of pressure P_s at the the rigid lid and hydrostatic part, i. e., $P(z)=P_s+\int_z^0 \rho\, g dz$, from the equation (3) and no prediction equation for P_s at $z=0$ is available.

To obtain barotropic velocity, the vertically averaged velocity components $(\bar{u},\bar{v})$ can be written in terms of a volume transport function φ as follows:

$$\bar{u}=\frac{1}{H}\int_{-H}^{0} u dz=-\frac{1}{Ha}\frac{\partial\varphi}{\partial\phi}$$

$$\bar{v}=\frac{1}{H}\int_{-H}^{0} v dz=-\frac{1}{Ha\cos\phi}\frac{\partial\varphi}{\partial\lambda}$$

With the above definition, the equation of stream function can be obtained from the equations (1) and (2) by cross differentiating to eliminate P_s.

$$\left[\frac{\partial}{\partial\lambda}\left(\frac{1}{H\cos\phi}\frac{\partial^2\varphi}{\partial\lambda\partial t}\right)+\frac{\partial}{\partial\phi}\left(\frac{\cos\phi}{H}\frac{\partial^2\varphi}{\partial\phi\partial t}\right)\right]$$
$$-\left[\frac{\partial}{\partial\lambda}\left(\frac{f}{H}\frac{\partial\varphi}{\partial\phi}\right)-\frac{\partial}{\partial\phi}\left(\frac{f}{H}\frac{\partial\varphi}{\partial\lambda}\right)\right]$$
$$=-\left[\frac{\partial}{\partial\lambda}\left(\frac{g}{\rho H}\int_{-H}^{0}\int_{z}^{0}\frac{\partial\rho}{\partial\phi}dz'dz\right)\right.$$
$$\left.-\frac{\partial}{\partial\phi}\left(\frac{g}{\rho H}\int_{-H}^{0}\int_{z}^{0}\frac{\partial\rho}{\partial\lambda}dz'dz\right)\right]$$
$$+\left[\frac{\partial}{\partial\lambda}\left(\frac{a}{H}\int_{-H}^{0}G^{\phi}dz\right)-\frac{\partial}{\partial\lambda}\left(\frac{a\cos\phi}{H}\int_{-H}^{0}G^{\lambda}dz\right)\right] \quad (5)$$

where G^{λ} and G^{ϕ} and as follows:

$$G^{\lambda}=-Lu+\frac{uv\tan\phi}{a}+k\frac{\partial^2 u}{\partial z^2}$$
$$+A_h\left(\nabla^2 u+\frac{(1-\tan^2\phi)u}{a^2}-\frac{2\sin\phi}{a^2\cos^2\phi}\frac{\partial v}{\partial\lambda}\right)$$

$$G^{\phi}=-Lu-\frac{u^2\tan\phi}{a}+k\frac{\partial^2 v}{\partial z^2}$$
$$+A_h\left(\nabla^2 v+\frac{(1-\tan^2\phi)v}{a^2}+\frac{2\sin\phi}{a^2\cos^2\phi}\frac{\partial u}{\partial\lambda}\right)$$

Equation (5) is a prognostic equation for stream functions, which requires inversion of a second order differential operator to obtain the functions. It is necessary to specify boundary condition for this inversion. along the coast line of continent, ϕ is specified as a constant(zero). On the Islands, ϕ is generally caluculated by the method of Takano (1974). However, on Kyushu Island which is on the middle of the open boundary, φ is set as the mean of φ's for the surrounded grids.

We use β-plane and 4.5×10^8 and 1.0(cm²/sec) horizontal and vertical eddy viscosity coefficients. Time interval of calculation is 1,800 sec. φ is calculated by the method of successive over relaxation and used to calculate velocity field.

Model Results

Only with Free Boundary Condition

Fig. 4 shows a model result in the case of total input water of 30Sv through a 300km-width section east of Taiwan(27Sv) and the Taiwan Strait(3Sv). Lines shows stream lines and numbers are values of stream functions in Sv unit. Most(about 9/10) of total input water flows out through the Tokara Strait south of Kyushu and the rest(about 1/10)

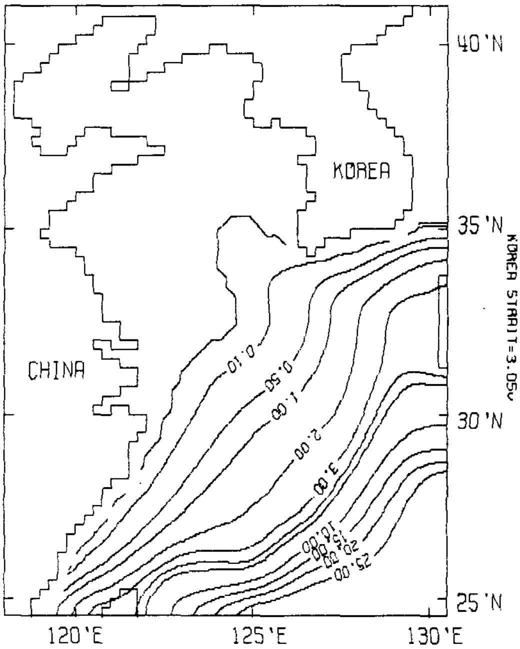

Fig. 4. Stream lines(in Sv unit) for the input waters of 3Sv and 27Sv(total 30Sv input flux) throught the Taiwan Strait and a 300km-width section east of Taiwan, respectively. Waters freely flow out through the eastern boundaries.

through the Korea Strait. Therefore, in this input situation, most of input water through the Taiwan Strait flows along the isobaths up to the Korea Strait. It is possble because the isobaths are linked between two straits and the water fluxes in the two straits are almost equal.

However, the output flux ratio of the Korea Strait to the total flux(about 1/10) is maintained for different input flux ratios. Fig. 5 shows the results of 20Sv input flux east of Taiwan and 10Sv input flux in the Taiwan Strait. When the input flux in the Taiwan Strait exceeds the output flux in the Korea Strait, the excess immediately moves to Kuroshio area and flows out south of Kyushu. The flows are quickly adjusted as soon as they are input to the model domain and thereafter, waters follow isobasths so that the flow pattern beyond the adjustment looks similar to that in Fig. 4. Thus, the output flux ratio is maintained.

The adjustment is also done for no input flux through the Taiwan Strait and even for no input flux through the normal Kuroshio area. Fig. 6 shows the model results of the two cases. Waters are input through a 300km-width section just east of Taiwan in (A) and another 300km-width section east of the previous section in (B). The total input fluxes are 30Sv. In these cases, the same amount of water as the output flux in the Korea Strait moves over to the East China Sea Shelf and follows isobaths to the Korea Strait. Therefore, beyond the adjustment the flow patterns are similar to the previous ones and the output flux ratios are maintained.

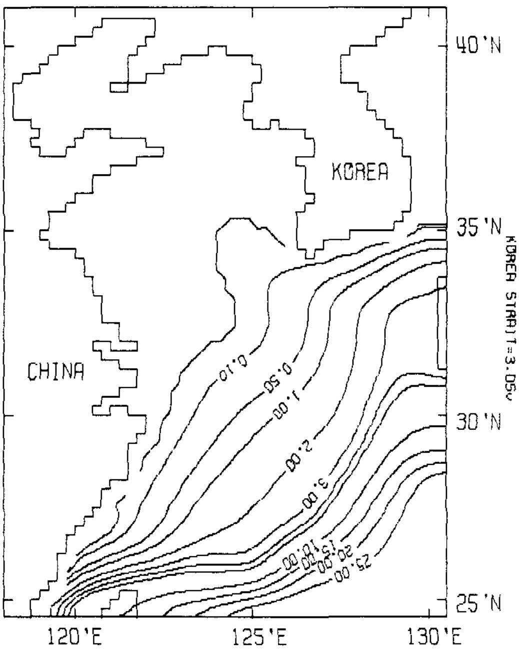

Fig. 5. Stream lines(in Sv unit) for the input waters of 10Sv and 20Sv(total 30Sv input flux) throught the Taiwan Strait and a 300km-width section east of Taiwan, respectively. Waters freely flow out through the eastern boundaries.

These results motivate us to make an experiment to block waters not to flow over the East China shelf as in Fig 7. The input situation is the same as in Fig. 6 (A) (30Sv input flux through a 300km-width section east of Taiwan). By the barrier, waters are forced to flow east, but after the end of barrier, they are quickly adjusted and follow isobaths, too. So the flow patterns after the adjustment are still the same and the output flux through the Korea Strait is almost maintained. The adjustment looks like outflow from a gap as shown in Fig. 8(Nof, 1983, 1987, 1988; Nof and Im, 1985). In Northern Hemisphere, waters from a gap flow with the wall on the right hand side over a Rossby Deformation Radius (A). Even if the width of a gap is smaller than the Rossby Deformation Radius, it is adjusted to have the same formation (B). It can explain why flow patterns on the East China Sea are maintained in any input circumstances. So, the output flux ratio in the Korea Strait can be maintained.

It means that the amount of output flux through the Korea Strait is determined only by the total amount of input flux. Fig. 9 shows two cases of total input flux of 20Sv (A) and 40Sv (B). The waters are input through a 300km-width section east of Taiwan as in Fig. 6 (A). The output fluxes in the Korea Strait are, respectively, about 2.1Sv and 4.0Sv, of which the ratios to the total fluxes are about 1/10 as in the previous cases. Their flow patterns are also the same as in the previous cases (note that the selected values of stream lines drawn in the figures are different).

The above model results with a free boundary

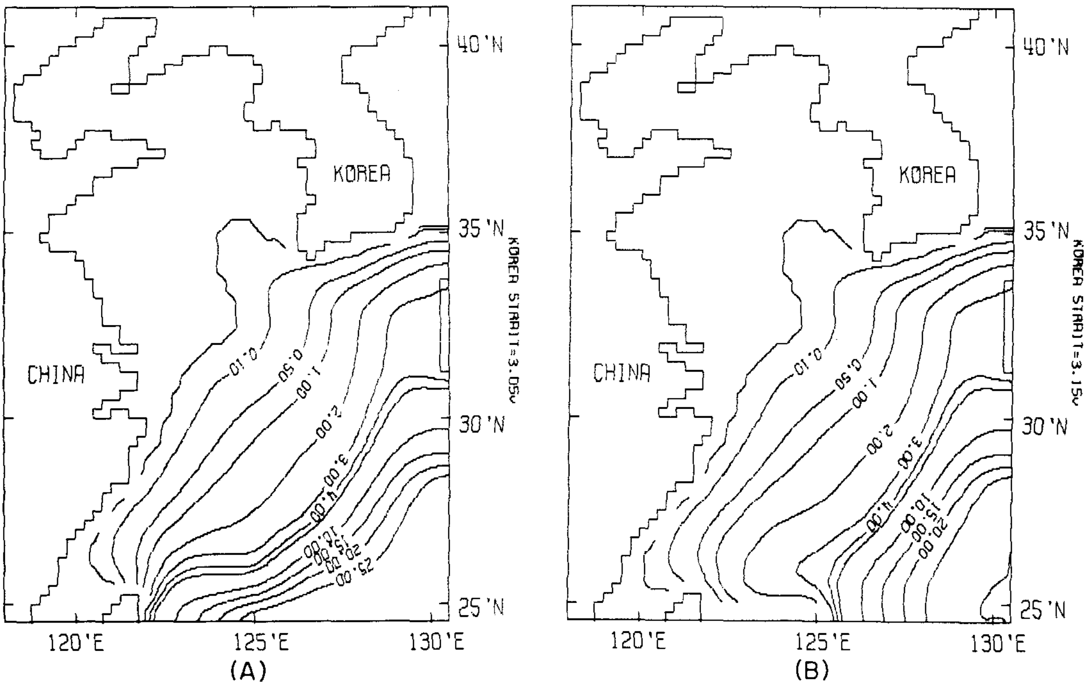

Fig. 6. Stream lines(in Sv unit) for the input waters of 30Sv through (A) a 300km-width section east of Taiwan and (B) another 300km-width section east of the previous section. Waters freely flow out through the eastern boundaries.

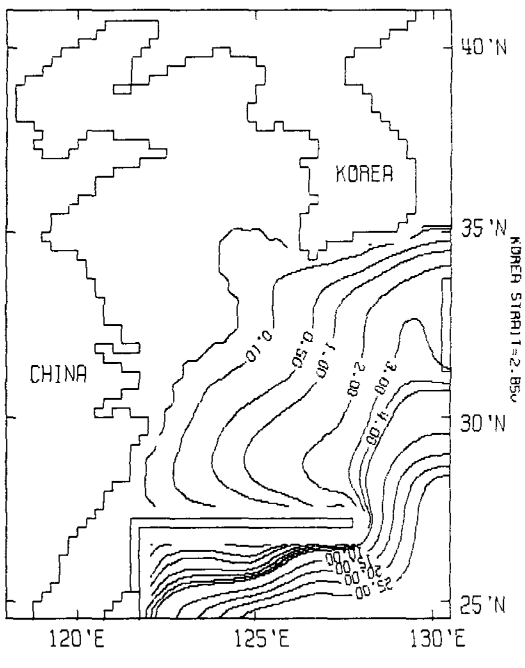

Fig. 7. Stream lines(in Sv unit) for the input waters of 30Sv through a 300km-with section east of Taiwan, in the case of blocking waters not to flow over the East China Sea. Waters freely flow out through the eastern boundaries.

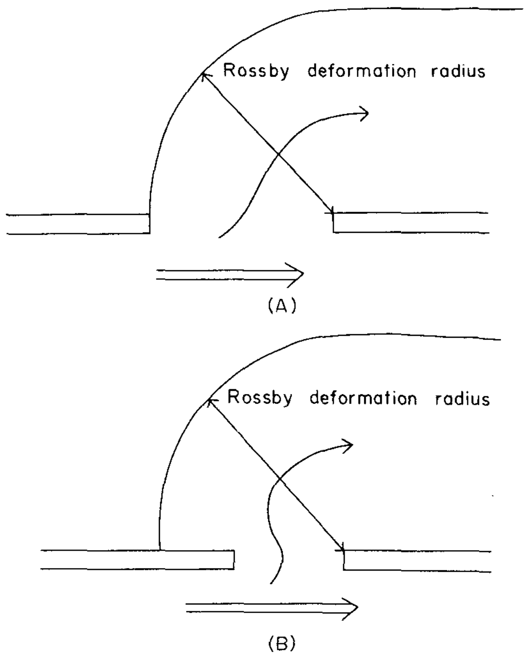

Fig. 8. Schematic representations of a gap flow. (A) In Northern Hemisphere, waters from a gap flow with the wall on the right hand side over a Rossby Deformation Radius. (B) Even if the width of a gap is smaller than the Rossby Deformation Radius, it is adjusted to have the same formation.

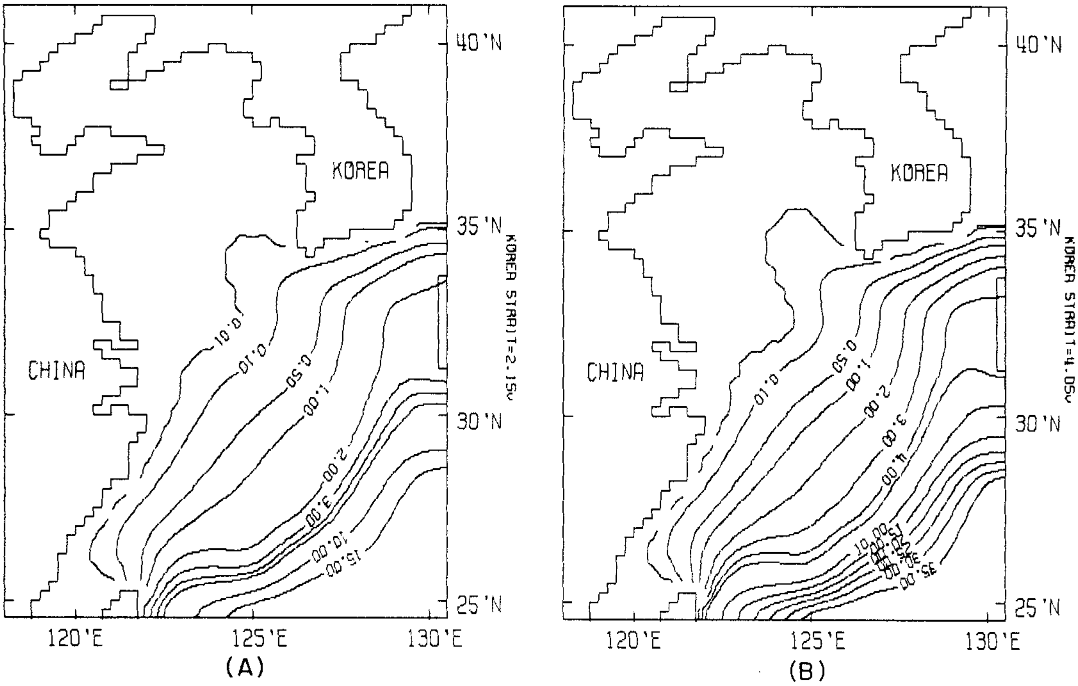

Fig. 9. Stream lines(in Sv unit) for the input waters of (A) 20Sv and (B) 40Sv through a 300km-width section east of Taiwan. Waters freely flow out through the eastern boundaries.

condition show that waters can flow up to the Korea Strait without any external force or without any density field. It seems to be done by geostrophic adjustment. After quick adustments, they just follow isobaths.

Including Reynolds Stress

The reason Reynolds Stress is suggested as a driving force of the Tsushima Current by Ichiye (1984) is that while some observation data of current show southeast flows west of Kyushu as shown in Fig. 1 (B), the observation data of temperature and salinity show rather northwest intrusions of warm and saline waters(Kondo, 1985). It can be interpreted as a result of the residual flow suggested by Rossby(1936) during lateral diffustion process.

Ichiye(1984) applied Rossby's residual flow (6) to Munk's viscous boundary current (7) (Munk, 1950).

$$u=-\frac{1}{f}\frac{\partial \overline{u'v'}}{\partial x}=\frac{A_h}{f}\frac{\partial^2 v}{\partial x^2} \text{ at } x=0(\text{at coastal boundary}) \quad (6)$$

$$v=(2/\sqrt{3})V_o \cdot \sin(\sqrt{3}/2\ x) \cdot \exp[-2^{-1}(x-x_0)] \quad (7)$$

x is non-dimensional distance from coast(x=0) and characteristic distance L could be given by $(A_h/\beta)^{1/3}$, where A_h and β are horizontal eddy viscosity and latitudinal variation of Coriolis parameter (Pedlosky, 1979). $\overline{u'v'}$ is Reynolds' Stress. In Munk's model, u=0 at x=0 because $-\partial p/\partial y=0$. If this condition does not counteract the lateral stress in (6), there is lateral velocity from (6) as follows:

$$u=-\frac{1}{f}\left(\frac{A_h}{\beta^2}\right)^{1/3} \cdot V_o \cdot \exp(3^{-3/2}\pi) \quad (8)$$

Thus, if there is no alongshore pressure gradient, there is onshore lateral transport.

Calculating Reynolds Stress along two lines A and B, which are on the left edge of the Kuroshio as shown in Fig. 3. from GEK data obtained by JODC Atlas, Ichiye(1984) showed onshore residual currents, which are toward the East China Sea, by Reynolds Stress values of $82cm^2/sec^2$ along A line and $-275cm^2/sec^2$ along B line. When the mean depth and length are 200m and 355km, transport of the Tsushima Currnet is $1.27\times10^6m^3/sec$, which is comparable to the estimated mean transport of $2.2\times10^6m^3/sec$.

However, he seems to make a mistake in inter preting numerical model results to confirm his theory. To do it, he has chosen a numerical model result in his another paper(Ichiye and Li, 1984). However, in that model, he used a forced boundary condition, under which Reynolds Stress can not make any effect to the output flux in the Korea Strait. To see the effects of Reynolds Stress, a free boundary condition should be used.

Fig. 10 shows the model result including the Reynolds Stresses calculated by Ichiye(1984) along the lines A and B in Fig. 3 with a free boundary condition. The input circumstance is the same as in Fig. 6 (A) (30Sv input flux through a 300km-width section east of Taiwan). Comparing with the result of Fig. 6 (A), the output flux in the Korea Strait increases by about 1.3Sv, which is almost close to the value estimated by Ichiye. It confirms Ichiye's idea.

However, in spite of its some effect, Reynolds Stress does not seem to be a primary forcing of Tsushima Current. The model result does not show any particular branching by the Reynold Stress west of Kushu as suggested by Uda(dotted paths in Fig. 13). The branching flows west of Kushu are just local phenomena and also shown in other model results, where Reynolds Stress is not included, such as Fig. 6 (A). West of Kushu, some of isbaths branch in the adjacency of the lines A and B in Fig. 3. Since waters follow such isobaths, some waters naturally branch west of Kushu. However, the branching shown in the model result does not seem to be a fundamental pattern. The fundmental pattern is a wide spreading flow, which is following isobaths, over a Rossby Deformation Radius, as mentioned previously.

The output flux increment in the Korea Strait by Reynolds Stress is only a part, but significant. It shows a possibility that the Tsushima Current can be significantly affected by various forces.

Including Wind Stress

Monsoon winds can not drive primarily, but can affect incidentally the Tsushima Current because the Yellow Sea is quite shallow and monsoon winds

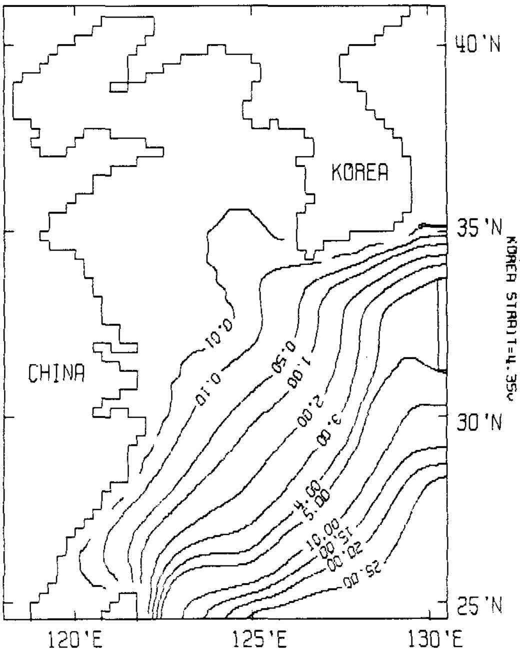

Fig. 10. Stream lines(in Sv unit) for the input waters of 30Sv through a 300km-width section east of Taiwn, in the case of including the Reynolds Stress calculated by Ichiye(1984) along the lines A and B in fig. 3. Waters freely flow out through the eastern boundaries.

are prominent in this area. It seems to be a primary driving force of seasonal circulation on the Yellow Sea(Pang *et al.*, 1992; Pang, 1992). Therefore, we will finally check their effects. In Fig. 11, steady southerly and northerly winds of 10m/sec are included in (A) and (B), respectively. The input circumstance is also the same as in Fig. 6 (A) (30Sv input flux through a 300km-width section east of Taiwan).

The model results show that the winds shift the flows on the East China Sea and drive some flows on the Yellow Sea. The circulations on the Yellow Sea are not clearly shown in the figures, but along both coasts, waters generally flow in by southerly wind and out by northerly wind, and in the middle, vice versa. The flows in the middle are therefore reversed to wind direction and called upwind-flows (Par, 1986; Pang, 1987; Hsueh and Pang, 1989; Pang *et al.*, 1992; Pang, 1992). On the East China

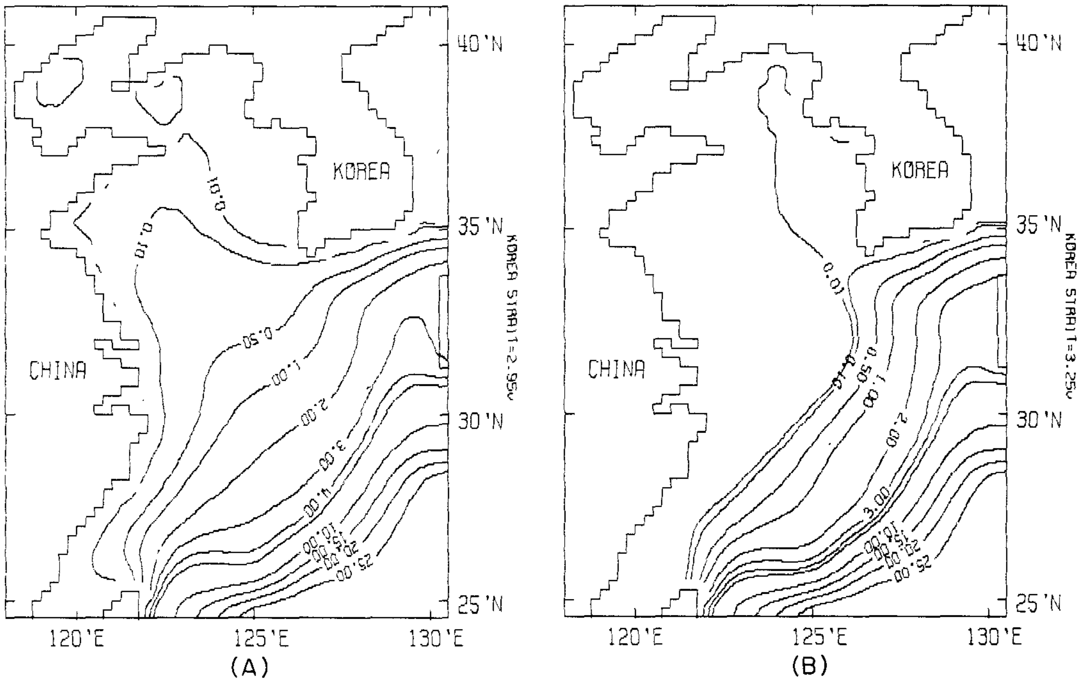

Fig. 11. Stream lines(in Sv unit) for the input waters of 30Sv through a 300km-width section east of Taiwan, in the case of including (A) southerly and (B) northerly steady winds of 10m/sec. Waters freely flow out through the eastern boundaries.

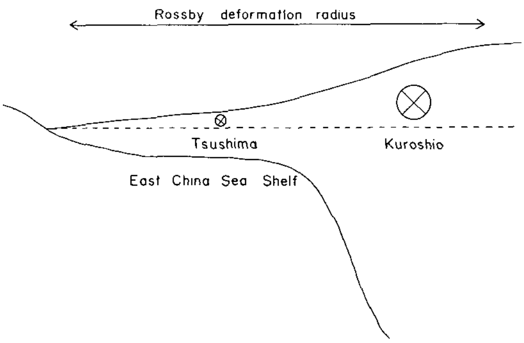

Fig. 12. A schmatic representation of sea level profile along the cross section of the flows in the East China Sea. The barotropic Rossby Deformation Radius in the East China Sea is about 500km. It drives flows over the almost whole range of the East China Sea.

Seas, the Tsushima Current is shifted northward by southerly wind and southward by northerly wind.

However, wind stresses does not play any significant role to the output flux in the Korea Strait. Comparing with the result of Fig. 6 (A), the output fluxes in the Korea Strait increase or decrease by about 0.1Sv, which is negligible.

Conclusion and Discussion

The dotted path in Fig. 13 shows a schmatic representation of Uda's idea on the Tsushima Current(1934). It branches out west of Kyushu from the Kuroshio and flows northward to the Korea Strait. Some of the Tsushima Water branch off again and flow to the Yellow Sea, which is called the Yellow Sea Warm Current. If the Tsushima Current flows as Uda's idea, it has to flow across isobaths in some places. Because crossing isobaths is not natural in oceans, it means that such a flow needs a driving force. Therefore, several driving forces have been suggested. They are a pulling force by sea level differences between the Korea and Tsugaru Straits, the Reynolds Stress west of Kushu, and the density fields on the East China Sea

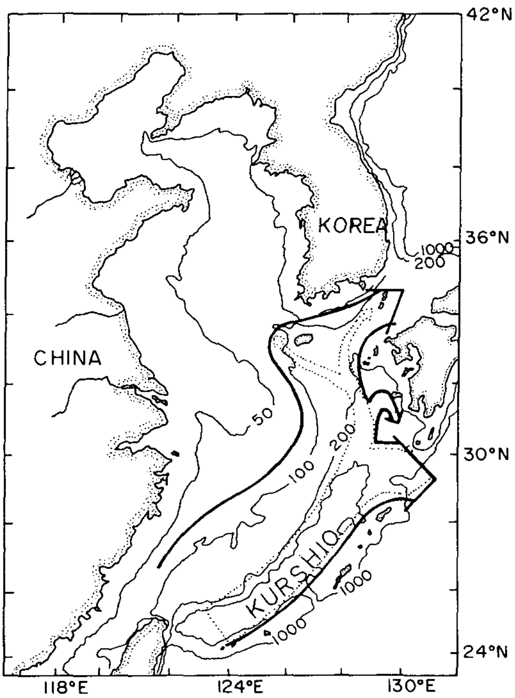

Fig. 13. A schmatic representation of barotropic flows in the East China Sea. Waters mostly flow out through the Tokara Strait south of Kyushu and a part(about 1/10) of them spreads out over the East China Sea and flows out through the Korea Strait following isobaths. Along isobaths, they branch off west of Kyushu(a part returns southward nearshore).

and so on. In this paper, we have studied numerically on which force really drives the Tsushima Current.

Barotropic numerical model results show that the Tsushima Current is possible without any above force. Its fundamental flow pattern is not like Uda's idea,but just wide spreading flows over a Rossby Deformation Radius. The barotropic Rossby Deformation Radius on the East China Sea is about 500 km(The radius may be smaller, if the baroclinicity is significant). It covers most ranges of the East China Sea. Fig. 12 is a schematic sea level profile. When the Kuroshio Waters bump into the East China Sea, they are geostrophically adjusted and sea level slope is reformed. After the adjustment, the flows follow isobaths. A schematic representation of such a barotropic flows is depicted in Fig. 13. Therefore, the flow pattern in independent on the input circumstance, and so the output ratio through the Korea Strait is maintained. Because the ratio is maintained, the amount of output flux in the Korea Strait is determined by the amount of input flux.

West of Kyushu, a branching phenmenon is shown. Since isobaths branch there(the isobaths shallower than about 200m head towards the Korea Strait and the isobaths deeper than about 500m head towards the Tokara Strait south of Kushu) and waters follow isobaths, some of waters naturally branch off west of Kushu. Uda's idea might be based on the branching(Nof's explanation on the branching by gap flow in 1993 is based on Uda's idea). However, model results shows that the branching is not the fundmental dynamics to drive the Tsushima Current. Since the width of the barotropic current is wide, it can follow isobaths and the branching may be the result of such flows.(However, if a baroclinic part is significant, the flow width will be smaller and the flow pattern might be in different shape. The branching may become more important then. This will be the next subject.)

The Reynolds Stresses calculated by Ichiye (1984) partly contibutes to push waters to the Korea Strait. Its contribution is numerically confirmed with the free boundary condition. Although the effect of Reynolds Stress is only a part and so Reynolds Stress does not seem to be a major force to drive the Tsushima Current, its contribution is significant. It shows that the Tsushima Current could be significantly affected by external forces. In the real ocean, the Tsushima Current could be complicated by various forces.

There are a couple of comments to be mentioned in the barotropic flow as shown in Fig. 13. Since the flows just follow isobaths, the left edge part of the current flows around the Cheju Island, for example, along the isobath of 100m depth(the northern solid line in Fig. 13). This flow is more natural than the Yellow Sea Warm Current to cross the isobaths(dotted lines in Fig. 13). West of Kyushu, some of isobaths are bent to form a half circle so that the nearshore waters flow southward, which is a well-known phenmenon(Tsujita, 1957). The southward flows seem to form a anti-cyclonic circulation with the northward flows offshore.

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References

Beardsley, R. C., R. Limebyrnes, H. Yu and G. A. Cannon, 1985. Discharge of the Changjiang (Yangtze River) into the East China Sea. Cont. Shelf Res., 4:57~76.

Chao, S. Y., 1991. Circulation of the East China Sea, A numerical study. J. Oceanogr. Soc. Japan. 46:273~625.

Hsueh, Y. and I. C. Pang, 1989. Coastally Trapped Long Waves in the Yellow Sea. J. Phys. Oceanogr., 19(5):612~625.

Ichiye, T., 1984. Some problems of circulation and hydrography of the Japan Sea and the Tsushima current. Ocean Hydrodynamics of the Japan and East China Seas. Ichiye, T. editor, 2nd JECSS Workshop. 15~54.

Ichiye, T and L. Li, 1984. A numerical study of circulation in a notheastern part of the East China Sea. Ocean Hydrodynamics of the Japan and East China Seas. Ichiye. T. editor, 2nd JECSS Workshop. 187~207.

Kondo, M., 1985. Oceanographic investigations of fishery grounds in the East China Sea I, Characteristics of the mean temperature and salinity distributions measured at 50m and near the bottom. Bull, Seikai Reg. Fish. Res. Lab., 62:19~66.

Lim, D. B., 1971. On the origin of the Tsushima Current water, J, Oceanol. Soc. Korea, 6(2), 85~91.

Minato, S. and R. Kimura, 1980. Volume transport of the western boundary current penetrating into a marginal sea. J. Oceangr. Soc. of Japan, 36, 185~195.

Miyazaki, M. and S. Abe, 1960. On the water masses in the Tsushima Current Area. J. Oceanogr. Soc. Japan, 16(2), 19~28.

Munk, W. H., 1950. On the wind drive ocean circulation. J. Meteorol., 7:79~93.

Nitani, H., 1972. Beginning of the Kuroshio:Kuroshio. Stommel, H. and K. Yoshida, editor, Univ. of Tokyo Press, Japan. 129~163.

Nof, D., 1983, On the flow through broad gaps with application to the windward passage. JPO, 13 (10):1940~1956.

Nof, D., 1987. Penetrating outflows and the dambreaking problem. J. Mar. Res. 45:557~577.

Nof, D., 1988. Outflows dynamics. Geophy. Astrophys. Fluid Dynamics, 40:165~193.

Nof, D. and S.H. Im, 1985. Suction throught broad oceanic gaps. JPO, 15(12):1721~1732.

Nof, D., 1993. The penetration of Kuroshio water into the Sea of Japan. JPO, 23:797~807.

Pang, I. C., 1987. Theory of Coastally Trapped Waves and its application to the Yellow Sea. Ph. D thesis, Florida State Univ., 128.

Pang, I. C.,1992. Coastally trapped waves over a double shelf topography(III):Forced waves and circulations driven by winds in the Yellow Sea. Bull. Korean Fish. Soc., 25(6):457~473.

__________ and H.K. Rho and T.H. Kim, 1992. Seasonal variations of water mass distributions and their causes in the Yellow Sea, the East China Sea and the adjacent seas of Cheju Island. Bull. Korean Fish. Soc., 25(2):pp151~163.

Park, Y.H., 1986. Asimple theoretical model for the upwind-flow in the southern Yellow Sea. J. Oceanogr. Soc. Korea, 21:203~210.

Pedlosky, J., 1979. Geophysical Fluid Dynamics. Sprigner-Verlag, Berlin and New York, 624.

Rikishi, K and T. Ichiye, 1986. Tidal fluctuation of the surface currents of the Kuroshio in the East China Sea. Ocean Hydrodynamics of the Japan and East China Seas. Ichiye, T. editor, 2nd JECSS Workshop. 193~213.

Rossby, C. G., 1936. Dynamics of steady ocean currents in the light of experimental fluid mechanics. Papers in Phys. Oceanogr and Meteorol., 5:1~43.

Qiu B. and N. Imasato, 1990. A numercal study on the formation of the Kuroshio Counter Current and the Kuroshio Branch Current in the East China Sea. Continental Shelf Research, 10(2): 165~184.

Semtner, A. J., 1974. An oceanic general circulation model with bottom topography. Numerical simulation of weather and climate:Technical Report No. 9, Univ. of California, 99.

Takano, K., 1974. Ageneral circulation model for the world ocean. Numerical Simulation of Weather and climate, Technical Report No. 8, Department of Meterology, University of California, Los Angeles, 47.

Tsujita, T., 1957. The fisheries oceanography of the East China Sea and the Tsushima Strait. Reports of Fisheries Institute of Japan, 84:2~47.

Uda M., 1934. The results of simultaneous oceanographical investigations in the Japan Sea and its adjacent waters in May and June, 1932. J. Imp. Fisher. Exp. St., 5:57~190.

Yuan Y. and J. Su, 1984. Numerical modelling of the circulation in the East China Sea. Ocean Hydrodynamics of the Japan and East China Seas. Ichiye, T. editor, 2nd JECSS Workshop. 167~186.

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On the Origin of the Tsushima Current(I): Barotropic Case

대마해류의 기원에 대하여(Ⅰ): 순압인 경우

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대마해류는 큐슈 서쪽해역에서 갈라져 대한해협으로 북상하여 흐르는 것으로 알려져 왔다. 이럴 경우 해류는 등수심선을 가로질러야 하며 이를 위해 어떤 힘이 필요하다. 그러한 힘으로는, 대한해협과 쯔가루해협 사이의 해수면의 차이, Reynolds Stress, 밀도차이 등에 제시되어져 왔다. 이 논문에서는 순압인 경우에 이들의 역할을 수치모델을 사용하여 연구해 보았다.

모델 결과는 대마해류가 위의 어떠한 힘이 없이도 발생한다는 것을 보였다. 해류는 동중국해에서 등수심선을 따라 흐르며, 해류흐름은 외부의 힘에 의해서가 아니라 자신의 역학에 의해 발생하는 것으로 보인다. 그 역학은 육지에 의한 틈새(gap) 사이로 유출되는 흐름에서와 같다.

모델결과는 또한 이 해역의 해류가 Reynolds Stress와 같은 외부의 힘에 의해 영향을 받을 수 있다는 것을 보여 주며, 그럴 경우 실제 해양에서는 해류의 역학과 형태가 복잡하게 나타날 가능성이 있다. 그러나 순압모델 결과는 대마해류가 기본적으로는 지형균형(geostrophic adjustment)에 의한 것임을 보여준다.