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An Effect of the Eddy Intrusive Transport Variations Across the Shelfbreak on the Korea Strait and the Yellow Sea
Part 1: Barotropic Model Study

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대륙붕사면에서의 에디 유입에 의한 해수수송량 변화가 대한해협 및 황해에 미치는 영향
제 1 부 : 순압 모델 연구

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A time-dependent primitive two-dimensional calculation is conducted to investigate the variations of volume transport onto the Yellow Sea and the Korea Strait with real bathymetries and to tract the Lagrangian movement of water particles. A series of experiment of the barotropic Kuroshio intrusions shows that the eddy induced branching of Kuroshio has sufficient intensity as to modify the continental shelf circulation. This intrusion seems to be one of the important forcing terms such as winds, tides and buoyancy that can also affect the dynamics in the region of the continental shelf.

Transport variations across the shelfbreak due to the branching of Kuroshio which come particularly from the southwest of the Kyushu Island, have a strong relationship with the transport variations across the Korea Strait and in the southern area of the Yellow Sea. The particle trajectories of the model results are well agreed with the trajectories of satellite tracking drifters obtained by one of the WOCE/TOGA program except the longer travel time period in the present model.

대한해협 및 황해의 해수수송량 변화와 水粒子의 라그랑지안(Lagrangian) 이동경로의 추적을 위하여 실제의 해저지형을 고려한 시간의존적 간략화된 2차원적 수치모델의 계산을 수행하였다. 이 일련의 수치실험에서 에디에 의한 쿠로시오 해류의 지류들은 대륙붕의 해류순환을 조율할 수 있을 정도의 충분한 강도를 지니고 있음을 보여준다. 대륙붕 지역에서의 이러한 해수유입은 바람, 조류 및 부력 등과 같이 해수운동에 영향을 미치는 중요한 영향력들 중의 하나로 사료된다.

대륙붕사면의 해수수송량 변화는 쿠로시오 지류, 특히 큐슈섬의 남서지역에서의 수송량 변화가 대한해협 및 황해 남부지역의 수송량과 밀접한 관련이 있음을 보여준다. 모델에 의한 水粒子의 궤적은 WOCE/TOGA 계획의 일환으로 얻어진 인공위성추적 표류부이(drifter)의 궤적과 잘 일치하고 있으나 그 이동 시간이 현재의 모델에서는 다소 더 걸리고 있는 점이 다르다.

INTRODUCTION

Western boundary current by a topographic feature on continental slope produces meanders which are caused by baroclinic instability. The interaction processes between western boundary current and continental shelf depend on whether the shelf water is stratified or well mixed. The Kuroshio, the well known western boundary current, flows along the East China Sea continental slope/shelfbreak from Taiwan (25° N, 122° E) to about 300 km southwest of the Kyushu Island, Japan (29° N, 127° E). Observations suggest that not all of the Kuroshio is deflected seaward but part of the shelfward branching of Kuroshio to become the Tsushima Current and the Yellow Sea Warm Current (Nitani, 1972).

Satellite data prove that the propagating frontal meanders of the Kuroshio along the shelfbreak have branches intruding shelfward (Sugimoto et al., 1988). The branches are made up of cumulative intrusions of eddies from the Kuroshio across the shelfbreak and flow through the Korea Strait (Huh, 1982). These propagating frontal meanders remain essentially stationary and coincide with nodes of a topographic standing wave (Oey, 1988). The topographic standing wave has a wavelength of about 200 km which is almost equal to the meander wavelength of $2\pi R_0 \cong 150 \sim 200$ km, where R_0 is the baroclinic Rossby radius of deformation. We can expect intermittent shelfward intrusions near the blocking upstream of 200 km at the period of about 10-20 days if the crest of the meander coincides with the topographic standing wave (Oey and Chen, 1991).

These frontal meanders should affect the near sea but it is not well known yet. According to Nitani (1972), most parts of the Tsushima Current enter into the East Sea (Japan Sea) through the Korea Strait, and some parts of the current branches off west of the Goto Islands before reaching the Korea Strait turn northwest and enter into the Yellow Sea. But the main feature of the Yellow Sea Warm Current varies with the abundance and decay of the Yellow Sea Cold Water. Can these intrusive eddy activities be of sufficient intensity as to modify the circulation and water-mass balance of the Yellow Sea and the Korea Strait?

Worthington and Kawai (1972) suggest that the frontal meanders which seem to be relevant to the Kuroshio appear to be more barotropic. The baroclinic instabilities due to the stratification of shelf are ignored in the present study, which can affect the shelfward flow variations locally, but assume it will be not much in view of the total volume fluxes. In this paper, we perform time dependent, two-dimensional model experiments to discuss volume transports over the shelf and to show that transport variations across the Korea Strait are strongly related to transport variations across the shelfbreak, particularly, near the southwest of the Kyushu Island.

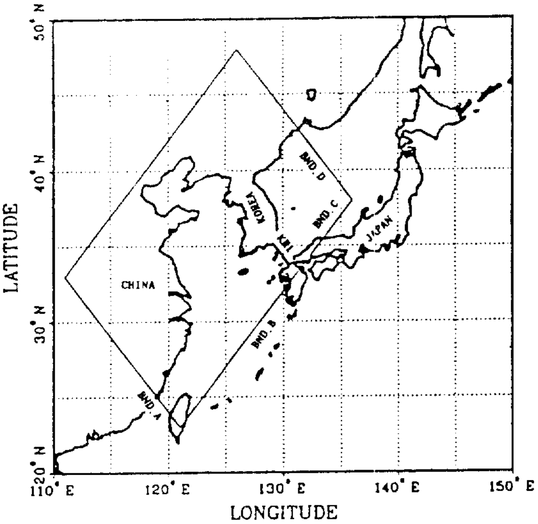

Fig. 1. Location of the study area squared by the solid line. The BND. A, B, C, and D are the open boundaries where transports are specified. Marked 'KRI' is the section between Pusan and Simonoseki.

METHODOLOGY

A time-dependent primitive two-dimensional finite difference model is used for the investigation of water-mass responses due to intrusive meanders across the shelf by the Kuroshio. The study area as shown in Fig. 1 is about 2200 km in x-direction (southwest-northeast) and 1480 km in y-direction (southwest-northwest). The grid spacing is linearly variable but almost constant in both x and y directions with values changing from 11.15 km to 12.6 km. The model consists of the East China Sea, the Yellow Sea, the Korea Strait, and part of the East Sea as shown in Fig. 2. The bottom topography of the model domain varies wide. The total number of grids are 180 in the x-direction and 120 in the y-direction.

The model solves for the depth-averaged two-di-

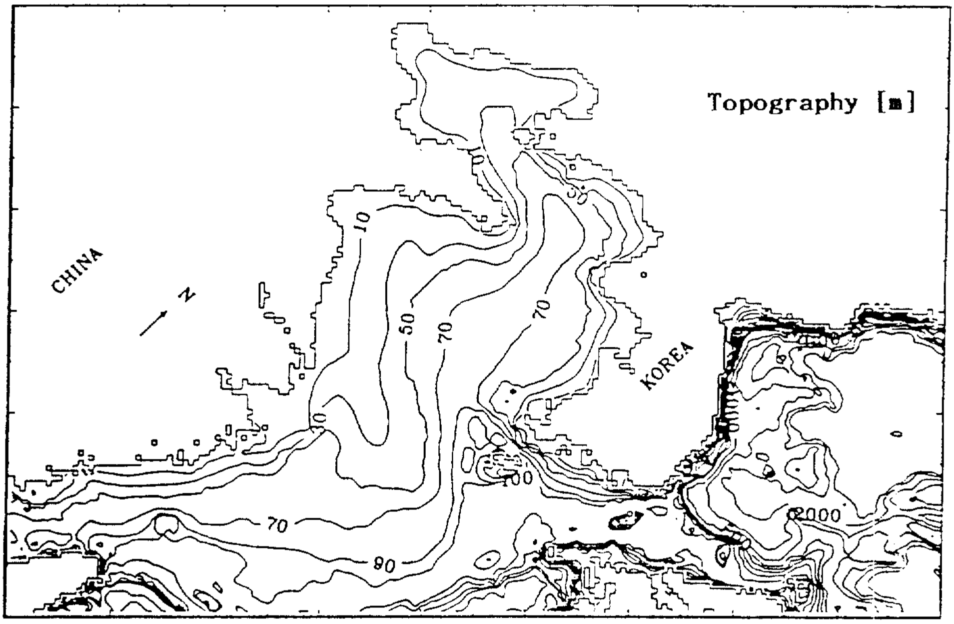

Fig. 2. Bottom topography of the model domain with unit of meter.

mensional velocities. The barotropic two-dimensional mode is calculated using the free surface gravity wave speed based on the Courant Friedrichs Levy (CFL) condition which is one of the numerical computational stability condition. The detailed description of the equations can be found in Blumberg and Mellor (1983).

The normal and tangential velocities are zero at all side lands, and a radiation condition is used for the two-dimensional velocities along the open boundaries so that the flows are free across the boundaries:

$$(N\cdot U)_t + C(N\cdot U)_n = 0$$

where N is a unit outward vector normal to the boundary, U the velocity vector, subscript t denotes time, subscript n is an axis normal to boundary and C is a phase speed equal to $(gH)^{1/2}$ for this simulation.

Instead of specifying elevation at open boundary, we specify the transports which are already observed in part (Nitani 1972; Shaw 1989) or calculated by numerical simulations (Oey and Chen, 1991), and obtain the ageostrophically balanced boundary elevation using iterative methods (You et al, 1992). We specify the influx across the Taiwan Striat as 0.8 Sv (Boundary "A" in Fig. 1) and another influx, from about 400 km southwest off the Kyushu Island to the Kyushu Island, as 3.2 Sv (Boundary "B" in Fig. 1). We assume that there is no influx or outflux from Taiwan to about 400 km southwest off the Kyushu Island. One of outflux is specified across the open boundary of the northeast East Sea as 2.5 Sv (Boundary "D" in Fig. 1). The other outflux is specified from the Honshu Island, Japan to the southeast East Sea as 1.5 Sv (Boundary "C" in Fig. 1). These outflux may not be true values, but we use this approximation because the flow pattern of the East Sea is not the main concern at the present simulations.

The model was spun-up from the initial state for 180 days to get a sufficiently stable state. The model was excuted for another 20 days to see the flow responses due to the transport variatons across the open boundaries.

The computations and plots were performed at the super computer CRAY-2S in KIST (Korean Institute of Science & Technology), Korea.

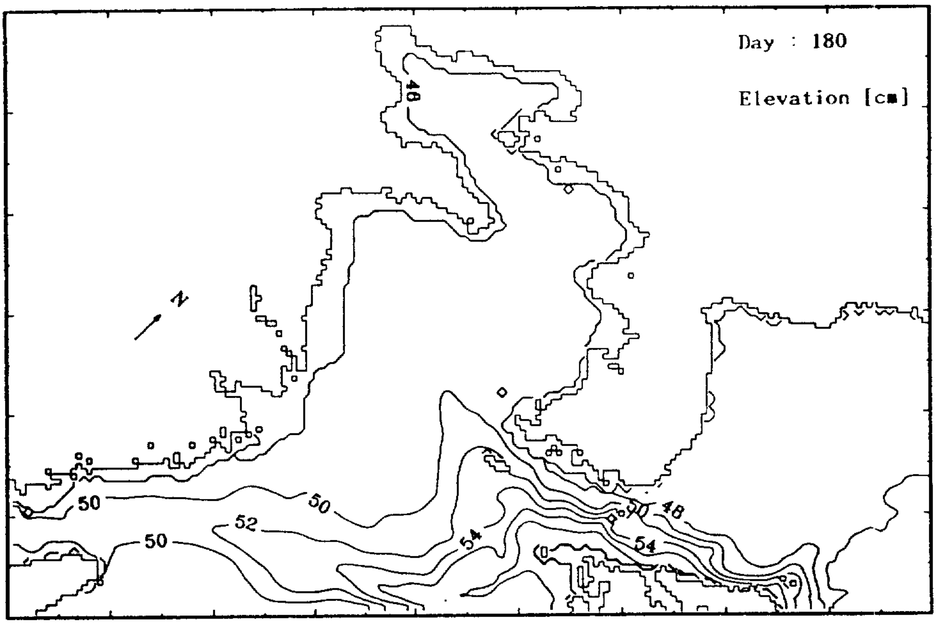

Fig. 3. Surface elevation at t = 180 days since the model started to spin up with no variations in transports across the open boundaries (see Fig. 1). The contour interval is 2.0 cm.

RESULTS AND DISCUSSION

Fig. 3 shows the elevation contours at the 180-day after the model spin-up. The northward sea level drop in the Korea Strait is matched with observations (Oh et al, 1993). Of course, the absolute values can not be obtained through the branching of Kuroshio alone. The northward dip in elevation of about -10^{-7}, or -10.0 cm in about 1000 km which is from near the southwest of the Kyushu Island to near the Santung Peninsula in the Yellow Sea. This value agrees with that reported by the Blanton et al. (1989), which is the typical sea surface slope when the water is implied to the continental shelf across the shelfbreak.

We conduct a series of experiment of transport variations across the open boundaries of "BND. A", "BND.B", "BND.C", and "BND.D" (Fig. 1) after 180 days model spin-up time. Fig. 4 shows that the transport fluctuation is 0.25 Sv across "BND.A" and "BND.C" and 1.0 Sv across "BND. B" and "BND.D". The maximum influx across the open boundaries occurs about t = 182 days and the minimum influx about t = 188 days. The period

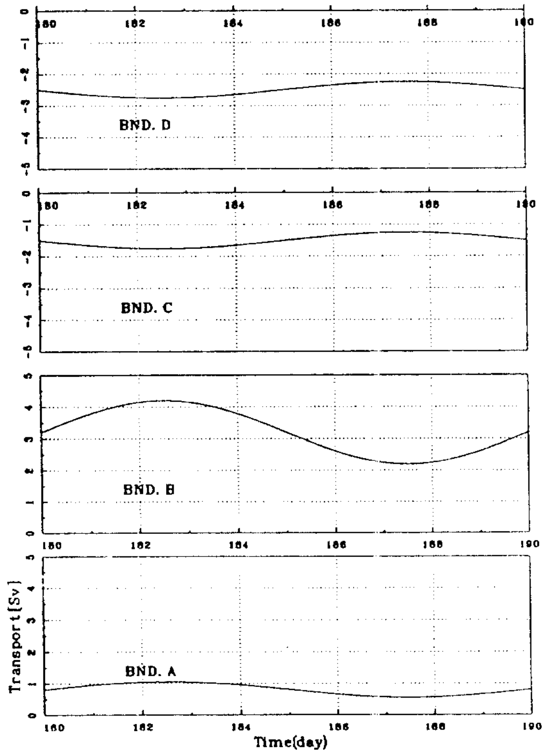

Fig. 4. Fluctuations of the transport in each open boundary (see Fig. 1), which are applied in the model after t = 180 days from the model spin-up.

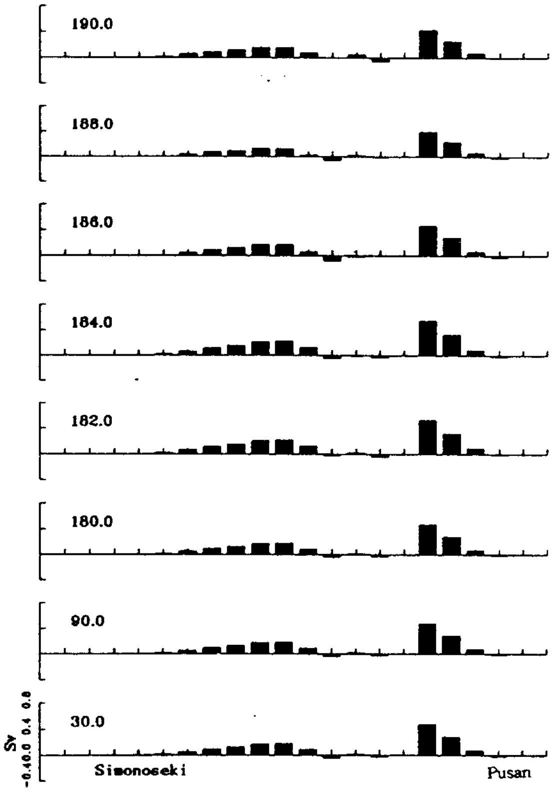

Fig. 5. Transport variations in the section between Pusan and Simonoseki marked 'KRI' in Fig. 1. Numbers in the upper left corner denote the time in day from computation start.

of the transport fluctuation is set to be 10 days so that it is the minimum period of the 'meander resonance' (Oey and Chen, 1991). When we consider the topographic blocking effects of the Kuroshio fronts near about 200 km southwest off the Kyushu Island, the flows due to the branching of Kuroshio pass through not from the Kyushu Island but from a little southwest off the Kyushu Island.

Fig. 5 shows the time series of the volume transport across the section of Pusan-Simonoseki denoted as "KR1" in Fig. 1. The y-axis represents a volume transport with the unit of Sv ($10^6\,m^3/sec$), the x-axis the distance between Pusan and Simonoseki. A positive volume transport means the volume transport into the East Sea and a negative is the opposite case. At t=60, 120, and 180 days, i.e., without variations in transport along boundaries, the total volume transport is about 3.4 Sv toward the East Sea. The backward transports viewed from the East Sea near the Tsushima Island are also detected. The volume transport in Pusan side is a little (about 0.2 Sv) bigger than that in Simonoseki side. These all phenomena are well matched with the observations which measured by the Japanese Navy (Lee, 1992).

From t=184 days to t=190 days in Fig. 5, We can see the transport fluctuations due to the imposed open boundary conditions which are shown in Fig. 4. At t=182 days, i.e. near the maximum influx from the open boundaries during this experiments, part of the negative volume transport (backward transport) disappears with the increment of total transport about 0.5 Sv. The impact of the transport variations due to the branching of Kuroshio seems to be more effective in the Pusan side than that in the Simonoseki side. This means that the Korean coast can be more affected than that of Japanese coast. The reason will be discussed later together with Fig. 6 and Fig. 7.

The northeastward (x-direction in the model) volume transport contours for each model grid (about 12.0 km) is shown in Fig. 6. A plot "A" is for the case of the constant transport through the open boundaries, which shows a clear influx into the Korea Strait from the southwest of the Kyushu Island, but it is weak in the Yellow Sea. The cases of the influx fluctuations in the open boundaries are from the plot "B" to plot "F" with the time interval of 2 days. These time series indicate that the northeastward transport fluctuations due to the shelfward branching intrusion of Kuroshio, particularly, near the Korea Strait is clear. However, the variations in the Yellow Sea is not so clear except near the Cheju Island and Mokpo, Korea. The range of the amount of volume transport is about O(0.3 Sv) when we compare plot "B" to plot "E".

Fig. 7. shows the northwestward (y-direction in the model) volume transport contours with the same contour interval and time step as in Fig. 6. The range of magnitudes is similar to the Fig. 6 case as O(0.3 Sv). The range of impact onto the

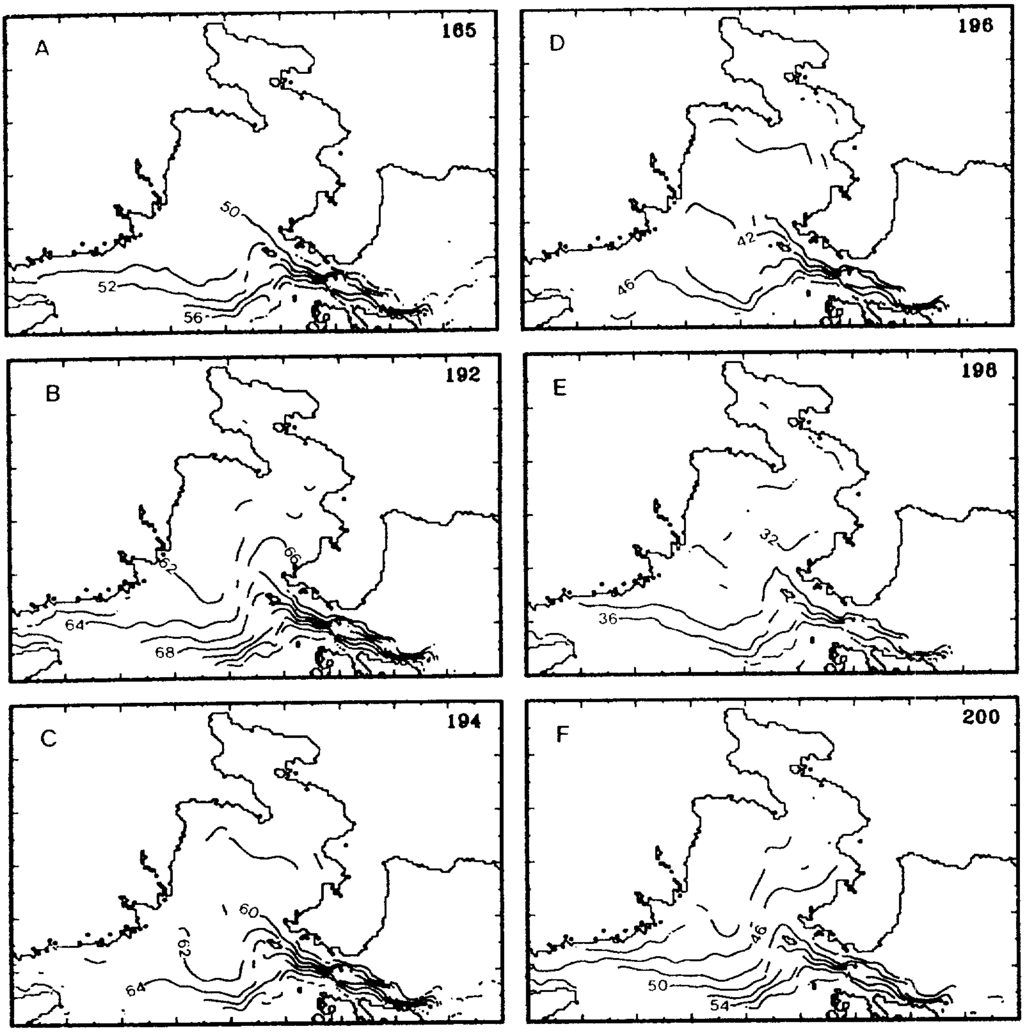

Fig. 6. Transport contours toward the northeast direction (x-direction in the model) with the interval of 2×10^3 m^3/sec. Numbers in the upper right corner denote the time in day from computation start.

Yellow Sea is widely spreaded due partly to the shallow water depth and due partly to outflux near the southeast of the Taiwan, and it seems more effective to the Korean coast than the Chinese coast.

In order to investigate the transport mechanism due to the branching of Kuroshio, we numerically track the Lagrangian movement of the water particles in several interesting stations as shown in Table 1. Fig. 8 shows trajectories of satellite tracking drifters released in 1991 and 1992 obtained by one of the WOCE/TOGA program, which is explained in detail by Lie et al. (1992). The particle trajectories of the model results are shown in Fig. 9. The initial drifter point of 32° N and 127° E (the most left point in Fig. 8-A) is the same position that "d" in Fig. 9. The particle passway of the one of model results ("d" in Fig. 9) is similar to the one of satellite tracking drifters which moves toward northeast and passes through close to the Tsushima island, then goes into the East Sea. The travel period is about three months in the present model case, which is about one month longer than the satellite tracking drifters one. This discrepancy

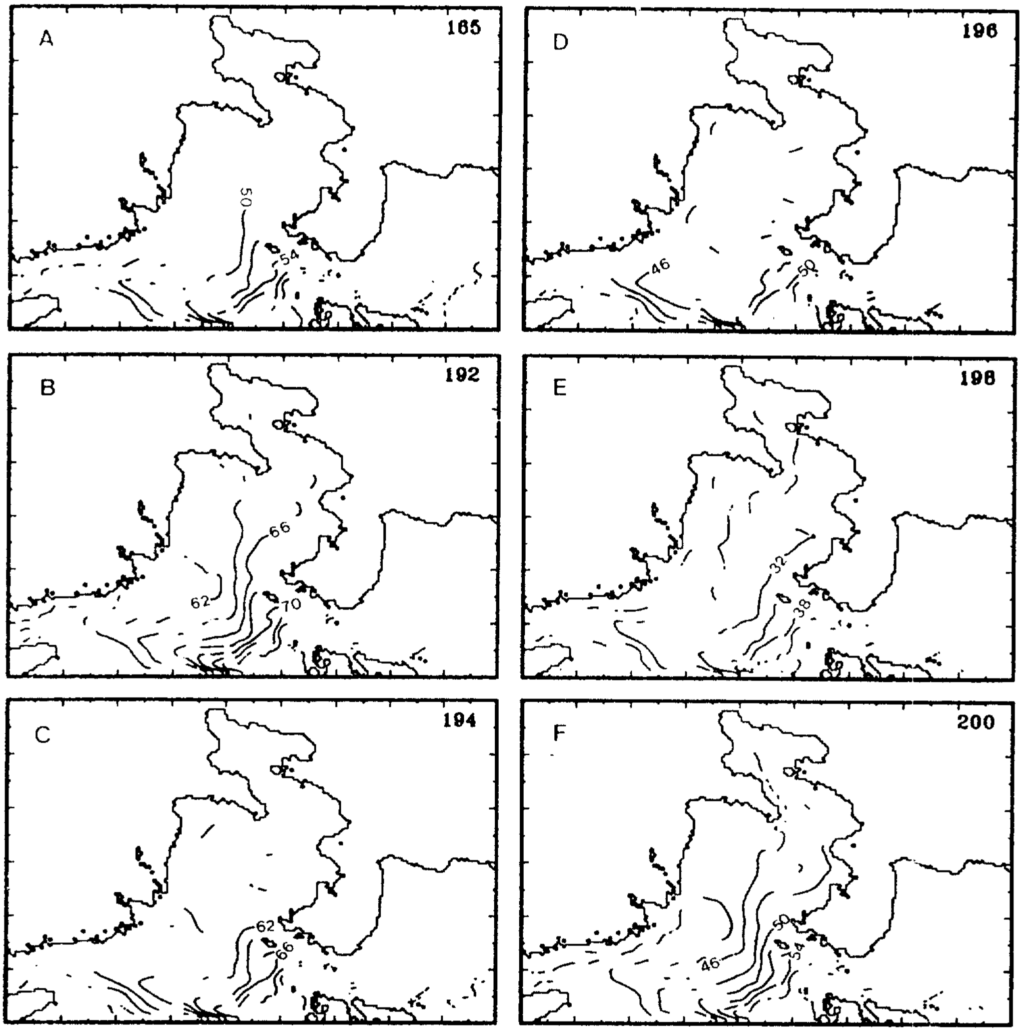

Fig. 7. As in Fig. 6 except the northwest direction (y-direction in the model)

may be due primarily to the model simplicity. We consider only the transport variations across the open boundaries, so that a lot of other ocean forcing terms such as winds, heatflux and tides should be included to get the similar results to the observations. However, the present model seems to well reproduce the passways even though we use this simple depth-averaged model.

The particles "a" and "b" in Fig. 9 are moving toward northwest slowly. The particle "c" goes up to the Cheju Island and pass through the Korea Strait fast. We track three particles near the Cheju Island as shown in "e", "f" and "g". They all move toward the Korea Strait close to the Korean coast rather than the Japanese coast. Fig 9-C case is similar to Fig. 8-B. The most left drifter in Fig 8-B goes northward and then is landing to Japan, which is similar pattern as "h" in Fig 9-C. Particles "i", "j" and "k" are almost trapped near the southwest of the Kyushu Island. These patterns also can be depicted in Fig. 8-B due to the topographic effect and prove the less effects of the branching of Kuroshio to the Korea Strait in these areas.

Fig 9-D shows the model particles movements near the west coast of Korea. They move very slo-

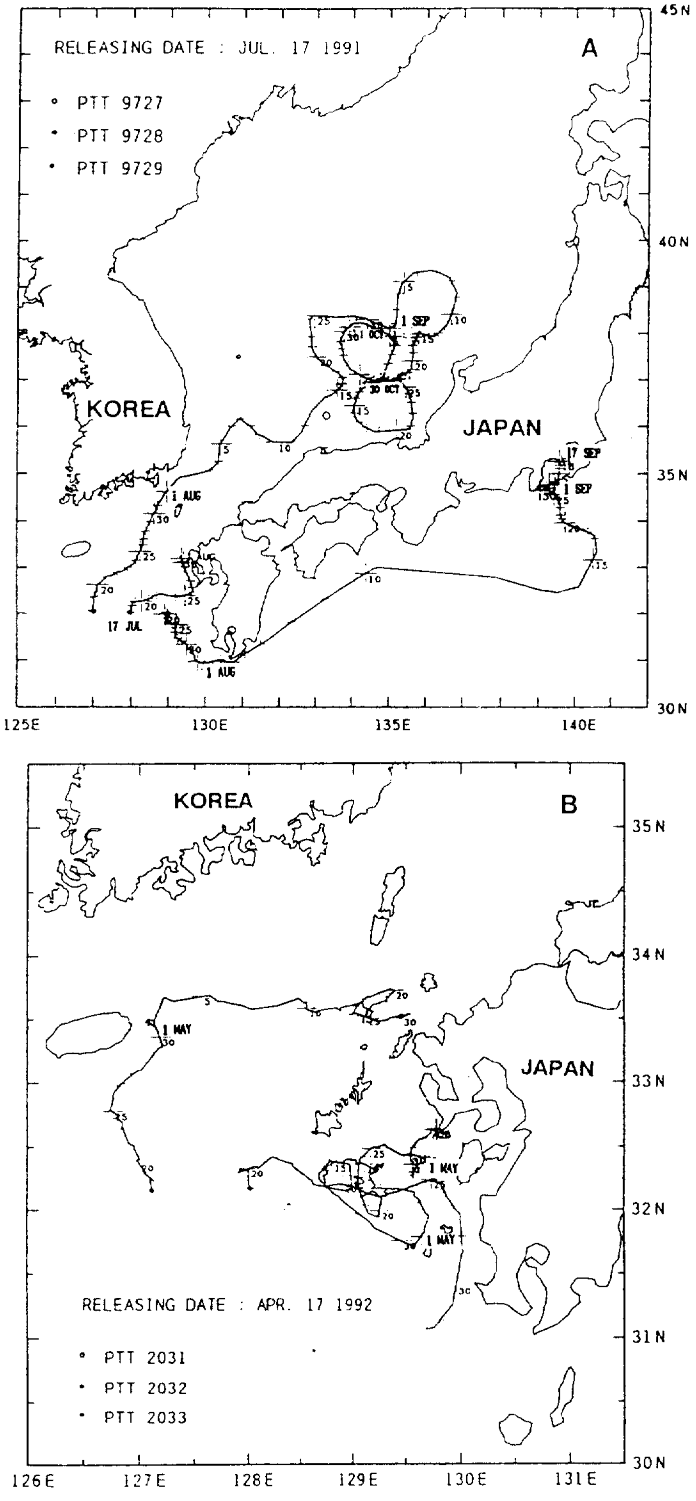

Fig. 8. Trajectories of satellite tracking drifters released (A) in July 17, 1991 and (B) in April 17, 1992. Cross marks denote the drifter location at 0 hour in GMT. (Reproduced from Lie et al., 1992)

Table 1. Release locations of the 15 particles.

Location	Longitude [°E]	Latitude [°N]
a	125.80	30.67
b	126.20	31.08
c	126.60	31.50
d	127.00	31.92
e	126.00	32.92
f	126.40	33.33
g	126.80	33.75
h	128.30	31.00
i	128.80	31.50
j	129.30	32.00
k	129.80	32.50
l	125.60	35.00
m	126.00	35.42
n	126.00	35.83
0	126.80	36.25

wly and toward southward. In the Yellow Sea, waters which are moving very slowly and toward southward near the coast are also observed in 1986 by satellite drifter buoys (Choi and Lie, 1992). The model results in the Yellow Sea (not shown all of the plots in here) are similar to the observations but the particle movements are much slower than the observations due to the absence of wind effects which will be a big portion in the shallow water depth, particularly upper layer waters. In general, the present two-dimensional model reproduces the particle trajectories quite well, and this encourages us to simulate the real prognostic three-dimensional model in the continental shelf zone with rea-

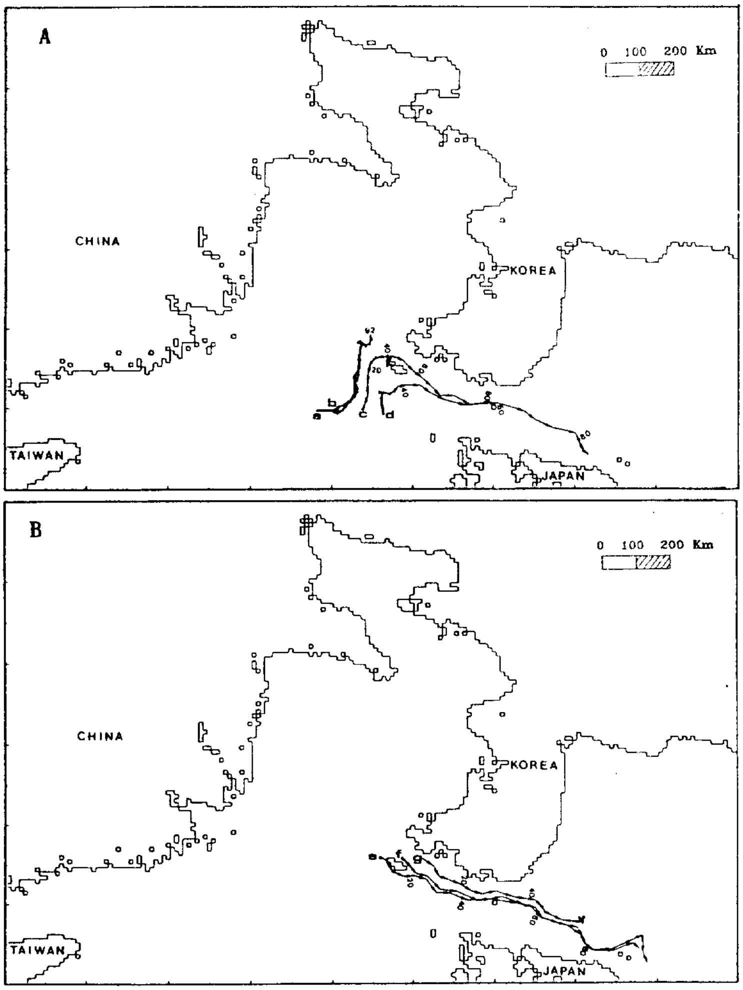

Fig. 9. Trajectories of the particles 'a' to 'n' calculated from the present model (see Table 1 for the released locations). Numbers along the trajectories denote the time in day from the release time which is counted zero.

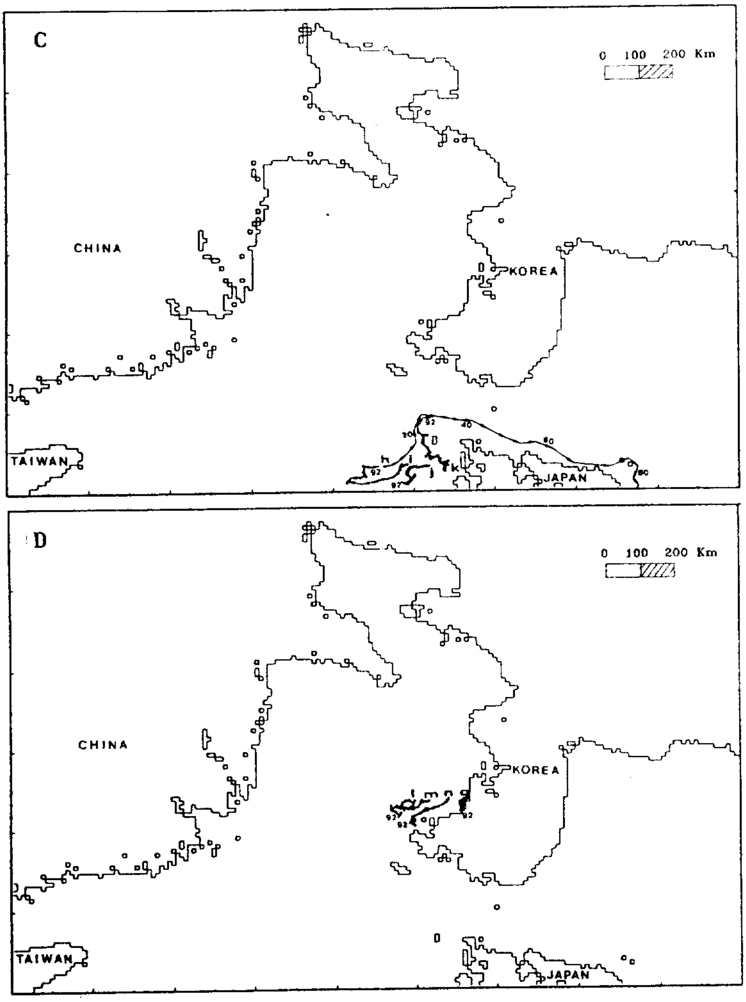

Fig. 9. Continued.

lity.

Most of flows (not shown in here) in this experiments seem to follow topography, particularly in the East China Sea and the Yellow Sea. This phenominon agrees with that the barotropic two-dimensional flow is almost geostrophic and will follow the topography (Csanady, 1978). Additionally, without variations in transports across open boundaries, there is a cyclonic flow in the Yellow Sea, which means the influx from the Taiwan Strait is dominant until encountering the stronger flows from the southwest of the Kyushu Island, then it turns to northward. In the present experiments, the externally imposed barotropic flow starting from near the shelfbreak zone, particularly from the southwest of the Kyushu Island has a tendency to turn northeastward like an injected plume into the sea water in the northern hemisphere (You et al., 1992). We can imagine 'pulsatile injected sea waters' across the shelfbreak onto the bay-like continental shelf such as the present model domain. Then, this flow encounters a block (Korea Peninsula) and should trun right in the northern hemishpere with more intensified waters than the other sides (Japan). Therefore, we can say that a more impact of the branching of Kuroshio can be expected in the Korean coast than either Japanese or Chinese coast.

CONCLUSION

A series of model experiments of the barotropic Kuroshio intrusions due to the 'meander resonance' indicates that the eddy induced branching of Kuroshio has sufficient intensity as to modify the continental shelf circulation where winds, tides and estuary-borne buoyancy can also affect the dynamics locally.

The variations of volume transport across the shelfbreak due to the branching of Kuroshio which come particularly from the southwest of the Kyushu Island have a strong relationship with the transport variations across the Korea Strait and in the southern area of the Yellow Sea. The model well reproduced the volume transport in the Korea Strait with barotropic mode, and the impact of the branching of Kuroshio is more affective to the Korean coast of the Yellow Sea than to the Chinese coast.

The particle trajectories of the model results are well matched with the trajectories of satellite tracking drifters obtained by one of the WOCE/TOGA program except the fact that the present model results show a little longer travel time period.

The present barotropic two-dimensional simulation gives us a good information for the understanding of the general patterns of volume transports and particle trajectories. Therefore, this model could be a good initial guideline for the future three-dimensional baroclinic mode calculations.

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