La mer 30: 139–147, 1992
Société franco-japonaise d'océanographie, Tokyo

A numerical study on the barotropic transport of the Tsushima Warm Current*

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Abstract: A barotropic numerical model is run over the N.W. Pacific Ocean to examine the formation of the Tsushima Warm current. Analysis of the results with various different parameter values indicate that the Tsushima Current is a downstream extension of Taiwan Warm Current. The parameters determining the transport of Tsushima Current are friction (mostly bottom friction), the depth difference across the East China Sea continental slope and the total transport of Kuroshio. Local wind does not change the transport much but changes the flow pattern such that for southerly wind, the transport is through the Taiwan Strait and for northerly wind, it is through the eastern side of Taiwan.

1. Introduction

The Tsushima Warm Current (TSWC) is defined as the current entering the East (Japan) Sea through the Korea Strait, between Korea and Japan, and joins the Kuroshio through the northern straits, north of Japan (Fig. 1). Based on dynamic computation, the amount of volume transport of TSWC is known to be less than 2 Sv. (c.f. MORIYASU, 1972; YI, 1966), equivalent to a few percent of the Kuroshio transport. The TSWC water is generally considered as a mixture of Kuroshio and East China Sea (ECS) shelf waters (e.g., LIM, 1971).

The Kuroshio water flows along the ECS continental slope (Fig. 1) and part of it crosses the slope to form the TSWC. Up to present, there are a few different views on the formation of TSWC. These consist of one or a combination of the following components: First, it may be a broad northward transport of the Kuroshio and the ECS shelf waters along the shelf edge (LIM, 1971; NAGATA, 1981). Secondly, it may be a contribution from periodic intrusions of Kuroshio water, especially in summer near the northern end of slope, southwest of Japan (HUH, 1982). And finally, it may be a direct branch of the Kuroshio. The branch may occur either at the southwestern end of the slope, near Taiwan, or at the northeastern end of it, southwest of Japan. The latter one is alluded by the schematic chart of NITANI (1972, see Fig. 2) and the former one, by GUAN (1986). Actually, this former one is verified and termed Taiwan Warm Current which may feed the TSWC according to GUO *et al.* (1987). According to these observations (GUO *et al.*, 1987), the Taiwan Warm Current consists of two components: one is the current through the Taiwan Strait, between Taiwan and mainland China, and the other is the current through the northeastern tip of Taiwan.

Many numerical models perfomed in this region are not suitable for the study of TSWC because they eigher exclude the Korea Strait (e.g. CHAO, 1990) or treat it as an open boundary (HSUEH *et al.*, 1986; WANG and SU, 1987). TAKANO and MISUMI's (1990) 3-dimensional model comprises the whole North Pacific Ocean and may be appropriate to examine the TSWC if their grids are further refined. A simple analytic model is also proposed by MINATO and KIMURA (1980) to explain the dependence of TSWC transport on external parameters. According to their model, the bottom friction and the shelf depth relative to the Kuroshio depth are major factors controlling the transport; the transport increases with decrease of friction and increase of shelf depth. However, they assumed narrow openings where the current is uniformly geostrophic. In reality, the continental slope of

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* This is partially supported by Inha University.

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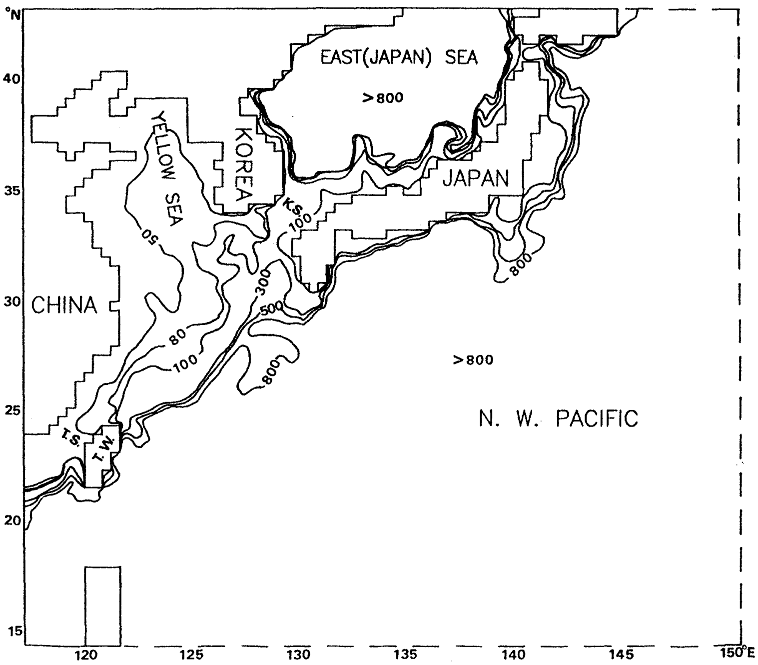

Fig. 1 Model domain with bottom topography (depth in meters). Solid lines are closed boundaries and dotted lines are open boundaries. T.W. means Taiwan. K.S. and T.S. mean Korea and Taiwan Straits, respectively.

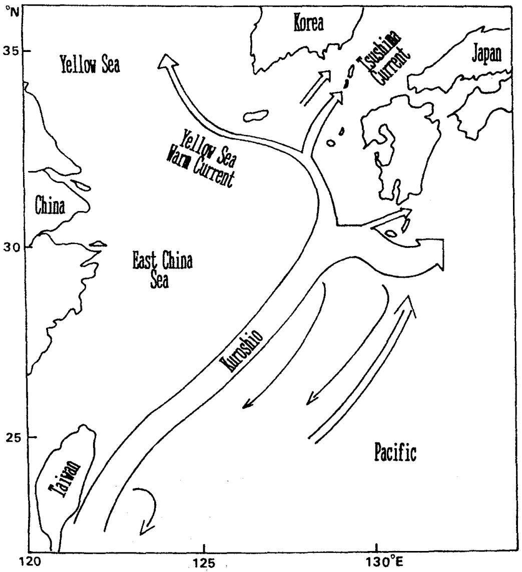

Fig. 2. Schematic diagram of the Kuroshio system in the East China Sea region.

the East China Sea, which is the inflow opening of the TSWC, is so wide that this assumption does not seem appropriate.

The aim of this study is to answer the question how the Kuroshio Water crosses the continental slope to form the TSWC. This question arises especially because the theory of potential vorticity predicts only the flows parallel to the depth discontinuity. The whole N.W. Pacific is taken as the model domain, thus making the TSWC free of open boundary condition, with acceptably small grid for examining the formation of TSWC. Only barotropic component is considered though it does not seem adequate especially in summer when the baroclinicity increases. Nevertheless, the barotropic dynamics seems to be helpful in understanding the process that goes on because most of the Kuroshio water brought up onto the shelf area more or less experiences the topographic changes (UDA and KISHI, 1974; FAN, 1980). To check the importance of factors determining the transport of TSWC, the model is run for various external parameters.

2. Model

The model domain roughly corresponds to the western half of the North Pacific Substropical Gyre, ranging 15° N–43° N and 117° E–150° E

Table 1. Description of experiments

Parameter	Coeff. of Horizontal Viscosity	Kuroshio Depth	Bottom Drag Coef.	Wind Stress Magnitude	Wind Direction *	Total WBC Transport
EXP. NO.	Am (cm^2/sec)	He (cm)	Cd	τ (dyne/cm^2)	α (°)	$\Psi_{\max}$ (Sv.)
EXP. 1	1.E7	3.E4	0.002	0	0	60
EXP. 2	1.E7	3.E4	0.002	1	0	60
EXP. 3	1.E7	3.E4	0.002	1	45	60
EXP. 4	1.E7	3.E4	0.002	1	90	60
EXP. 5	1.E7	3.E4	0.002	1	135	60
EXP. 6	1.E7	3.E4	0.002	1	180	60
EXP. 7	1.E7	3.E4	0.002	1	225	60
EXP. 8	1.E7	3.E4	0.002	1	315	60
EXP. 9	1.E7	3.E4	0.002	0.5	45	60
EXP.10	1.E7	3.E4	0.002	2	45	60
EXP.11	1.E7	1.5E4	0.002	0	0	60
EXP.12	1.E7	5.E4	0.002	0	0	60
EXP.13	1.E7	8.E4	0.002	0	0	60
EXP.14	1.E6	3.E4	0.002	0	0	60
EXP.15	1.E8	3.E4	0.002	0	0	60
EXP.16	1.E7	3.E4	0.0005	0	0	60
EXP.17	1.E7	3.E4	0.008	0	0	60
EXP.18	1.E7	3.E4	0.002	0	0	30
EXP.19	1.E7	3.E4	0.002	0	0	90
EXP.20	1.E7	3.E4	0.002	0	0	120

* Wind direction is measured clockwise from north.

(Fig. 1). It has a continental slope separating the deep Kuroshio region from the shallow ECS shelf area. Since the model is barotropic, the deep Kuroshio region is assumed to have uniform depth. The depth is normally taken as 300m but different values are also used to examine its effect. The model ocean is homogeneous and assumed to have a rigid-lid surface.

The usual GCM model described by SEMTNER (1974) is used and the barotropic circulation expressed by stream function is obtained. The ocean is spun up not by direct wind forcing but by imposing an open boundary condition along the eastern boundary. In terms of stream function, this reads

$$\Psi = \Psi_{\max} \sin\ (\pi y/\mathrm{L})$$

where Ψ is the transport stream function with total Western Boundary Current (WBC) transport $\Psi_{\max}$; L, fixed in this study, is the meridional dimension of the model basin; and y is the meridional position measured from the southern boundary. Twenty experiments with different conditions are performed (Table 1). For each experiment, steady state is reached after 150 days of integration (see Fig. 3 for example). In the above expression, $\Psi_{\max}$ is normally taken as 60sv. (NITANI, 1972), but different values are also used in experiments 18–20. Along the coastal boundary, no-slip condition is applied but along the southern and northern open boundary, slip boundary condition is assumed. At the ocean surface, no wind stress is usually assumed but uniform wind stresses are sometimes applied, in experiments 2–10, to examine the effect of local monsoon. At the ocean bottom, a quadratic bottom stress is imposed with various drag coefficient, such as those given in experiments 16 and 17. Stream functions over islands are obtained using the Hole Relaxation Method (TAKANO, 1974).

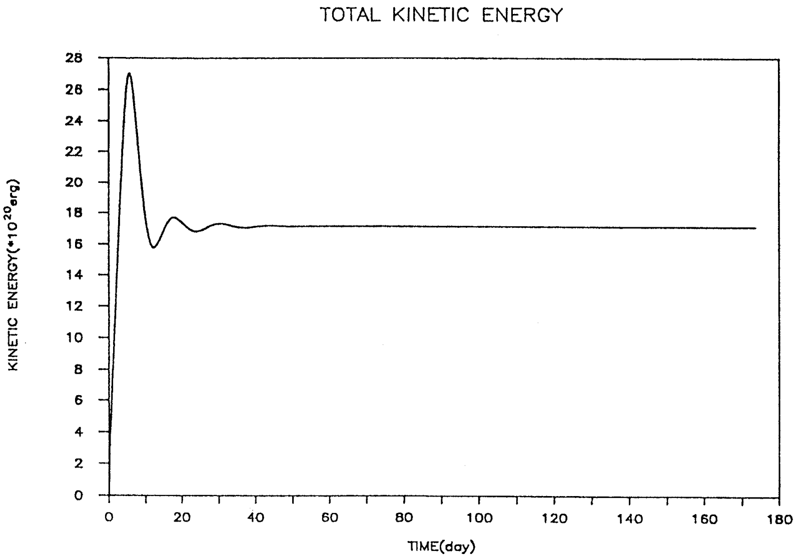

Fig. 3. Time variation of total kinetic energy for experiment 1 (see Table 1).

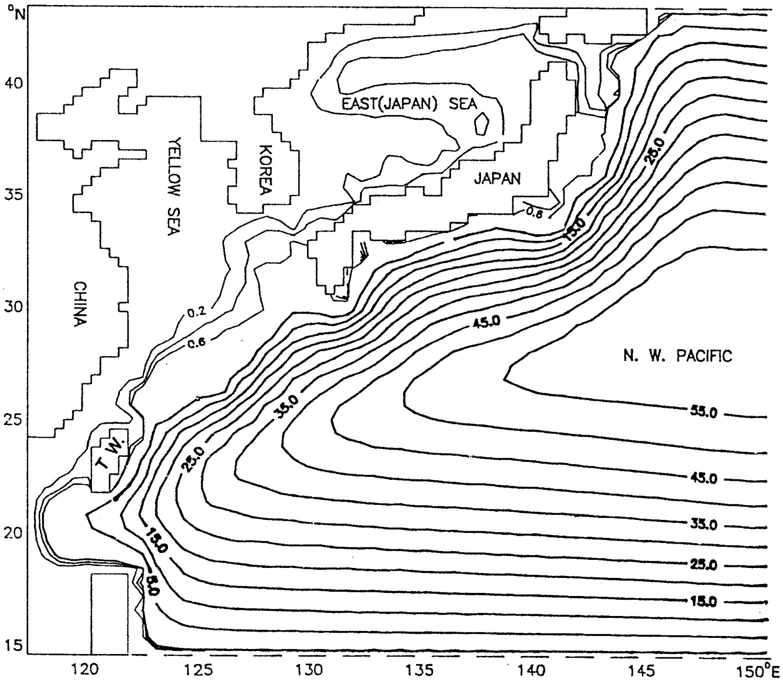

Fig. 4. Distribution of transport stream function (in Sv.) for experiment 1.

3. General flow pattern

Experiment 1 is taken as a standard case (Table 1) and its result is shown in Fig. 4. The Kuroshio water crosses the continental slope through the western and eastern sides of Taiwan and flows approximately along the isobath toward the East (Japan) Sea through the Korea Strait. The flow pattern around Taiwan is exactly the same as what is known as the Taiwan Warm Current (GUO *et al.*, 1987). This flow pattern indicates that the TSWC is the downstream extension of the Taiwan Warm Current.

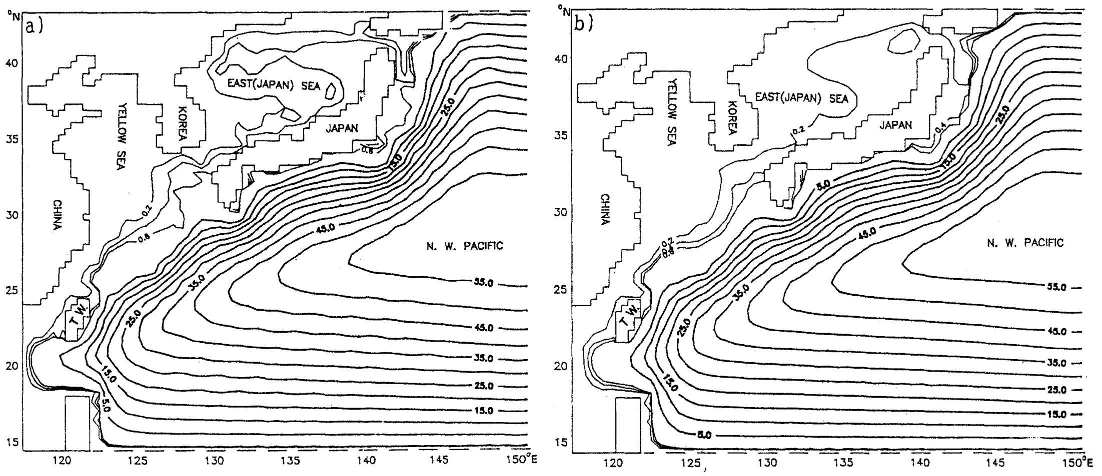

Fig. 5. Distributions of the transport stream function for experiments a) 14 and b) 15 of different eddy viscosity coefficients.

A part of it seems to return back to the Kuroshio along the coast, southwest of Japan. These are the general features throughout all experiments though some changes occur by local wind. The transport of TSWC amounts to 0.43 Sv. which is smaller than the known values, 1~2 Sv. (YI, 1966; MORIYASU, 1972). The discrepancy might come mostly from the neglect of baroclinicity. As seen later, large part of the total transport (TT) comes from the transport through Taiwan Strait (TST).

The result shown here indicates that all transports of Kuroshio water onto the shallow ECS take place through the southwestern end of the slope, i.e. by Taiwan Warm Current. A Rossby wave interpretation of this fact may be possible. Barotropic disturbances generated in mid-ocean propagate westward as the form of Rossby waves. The energy of these waves are normally trapped along the western boundary forming the Western Boundary Current. If the western boundary of the ocean borders a shallow marginal sea with large depth discontinuity, these waves become topographic waves and propagate southward along the discontinuity with the shallower part on their right of propagation direction in the northern hemisphere. When they reach to the coast, their energy is trapped at the coast by reflection in exactly the same way as the planetary waves are trapped along the western boundary. So, the penetration of western boundary current into the shallow marginal sea should take place within narrow region near the southern end of the slope.

4. Effect of viscosity coefficient

Experiments 1, 14 and 15 have different coefficients of eddy viscosity while other parameters are held the same. There is no remarkable difference in flow pattern among the three cases. However, a slight intensification of WBC (or thining of boundary layer) occurs at small coefficient (Fig. 5), as a linear theory predicts (MUNK, 1950). The TT and TST do not change much within the range of values considered (Fig. 6a); they seem to slightly decrease with the magnitude of coefficient. As noted previously, TST contributes to a large part of TT. The remaining contribution comes from the transport through the northeastern tip of Taiwan.

5. Effect of bottom drag coefficient

Experiments 1,16 and 17 have different drag coefficients with other parameters held the same. Comparision of these three experiments shows that small friction intensifies the WBC (thining of boundary layer) in agreement with STOMMEL's (1948) theory (Fig. 7). Both TT and TST decrease with increase of drag coefficient (Fig. 6b). This tendency is in agreement with MINATO and KIMURA's (1980) results. For small friction, TT is entirely from TST but for large friction, TST becomes small. The

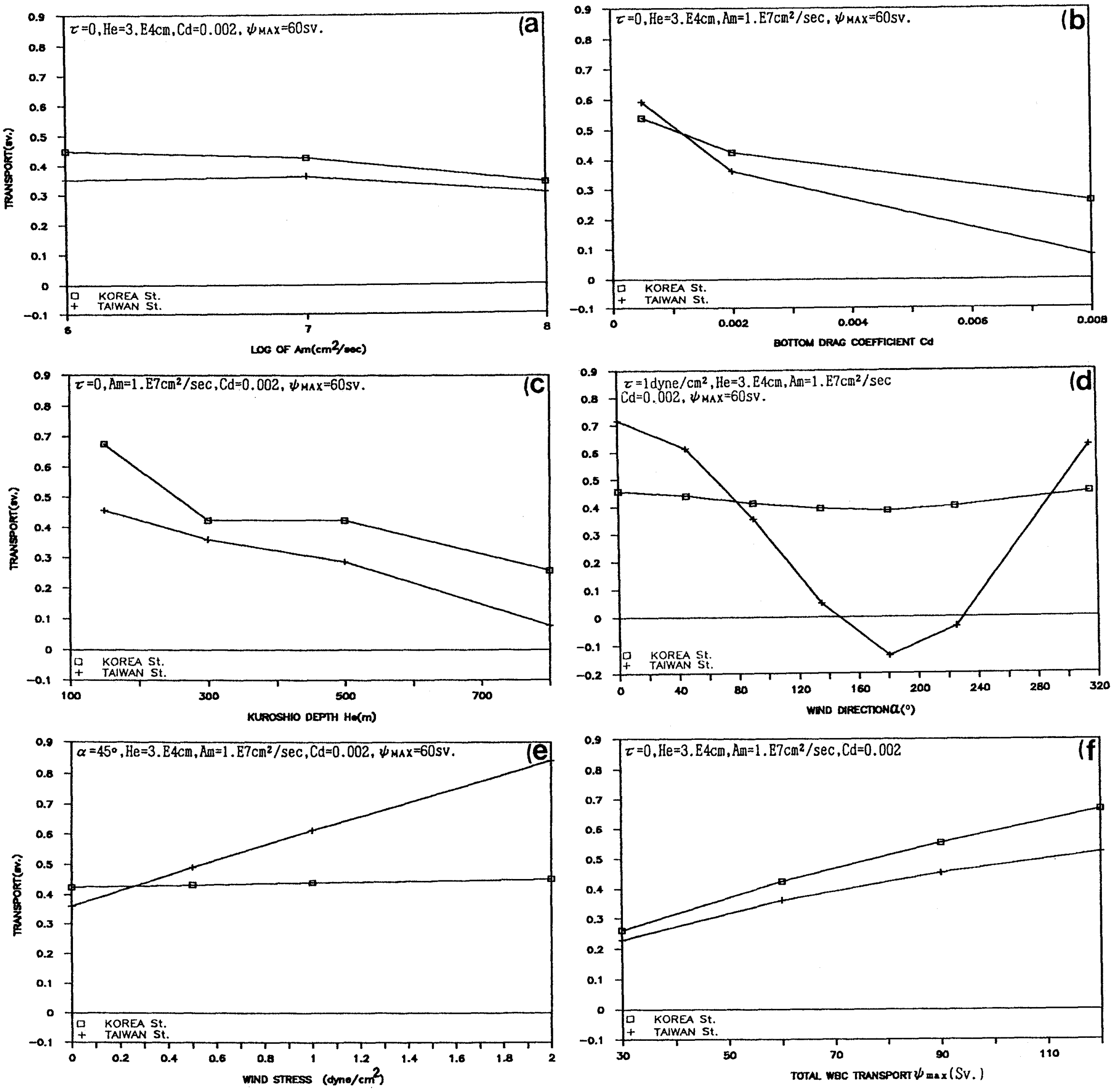

Fig. 6. Dependence of transports through the Korea and Taiwan Straits on the a) eddy viscosity coefficient, b) bottom drag coefficient, c) Kuroshio depth, d) wind direction, e) wind stress magnitude and f) the total WBC transport.

dependence of TST on the drag coefficient is thus larger than that of TT.

6. Effect of Kuroshio depth

Experiments 1, 11 and 13 have three different Kuroshio depths with other parameters held the same. Results of three experiments show that large Kuroshio depth intensifies the WBC (Fig. 8). It is conceivable that large depth diminishes the bottom friction, which then intensifies the WBC as explained previously. Both TT and TST decrease with increase of Kuroshio depth (Fig. 6c) in agreement with MINATO and KIMURA's (1980) results. In fact, large topographic change may hinder the transport of Kuroshio water across the steep slope. This tendancy seems more pronounced in TST than in TT because the proportion of the former to the latter becomes much reduced as the depth increases.

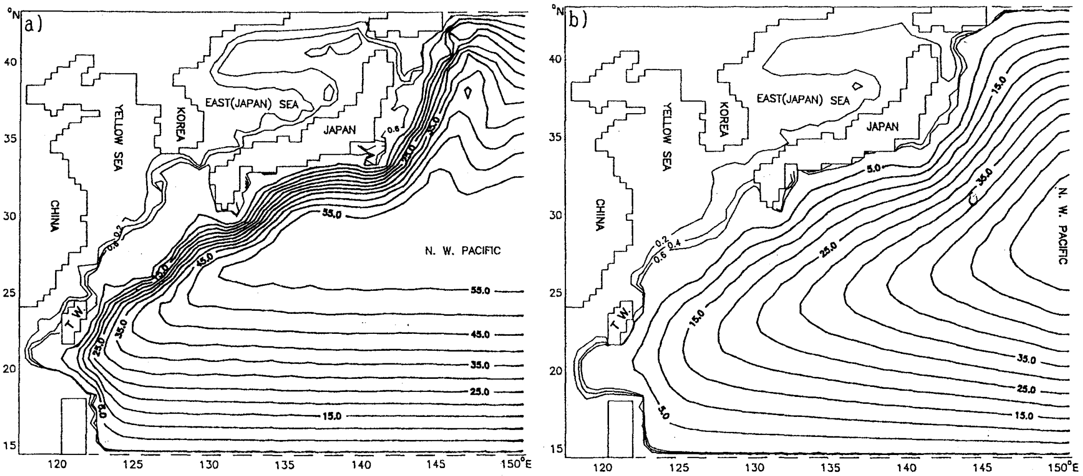

Fig. 7. Distributions of the transport stream function for experiments a) 16 and b) 17 of different bottom drag coefficients.

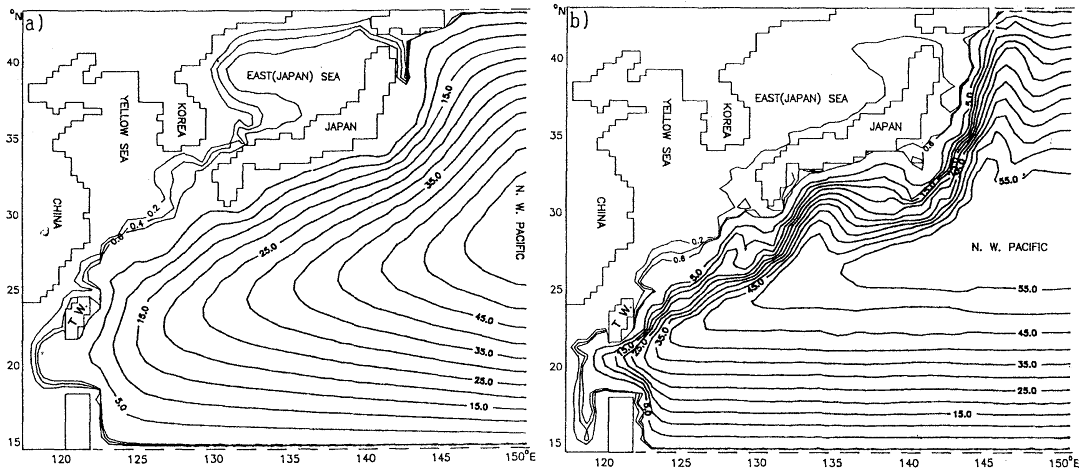

Fig. 8. Distributions of transport stream function for experiments a) 11 and b) 13 of different Kuroshio depths.

7. Effect of local monsoon

Experiments 1 through 10 have different wind fields with other parameters held the same. Among these 10 experiments, the largest contrast in flow pattern occurs between the cases of northerly and southerly winds (Fig. 9). The WBC is nearly the same but the transport pattern crossing the continental slope is quite different. For southerly wind, the transport is by TST whereas for northerly wind, it is by the transport through the northeastern tip of Taiwan. This fact is further clear in Fig.6d where TT and TST are given as functions of wind direction. The amount of TT does not vary much whereas that of TST largely fluctuates depending on wind direction. Under the southerly wind prevailing in summer, TST is larger than TT and the excess of the former over the latter returns back to the Kuroshio along the coast, southwest of Japan. Under the northerly wind prevailing in winter, TT is through the northeastern tip of Taiwan and TST reverses. The TST increases with, while the TT remains independent of, the magnitude of wind stress as shown for the case of southwesterly wind (Fig. 6e). This tendency is in good qualitative agreement with obsevations (GUO *et al.*, 1987) and numerical model (CHAO, 1990) performed in local area

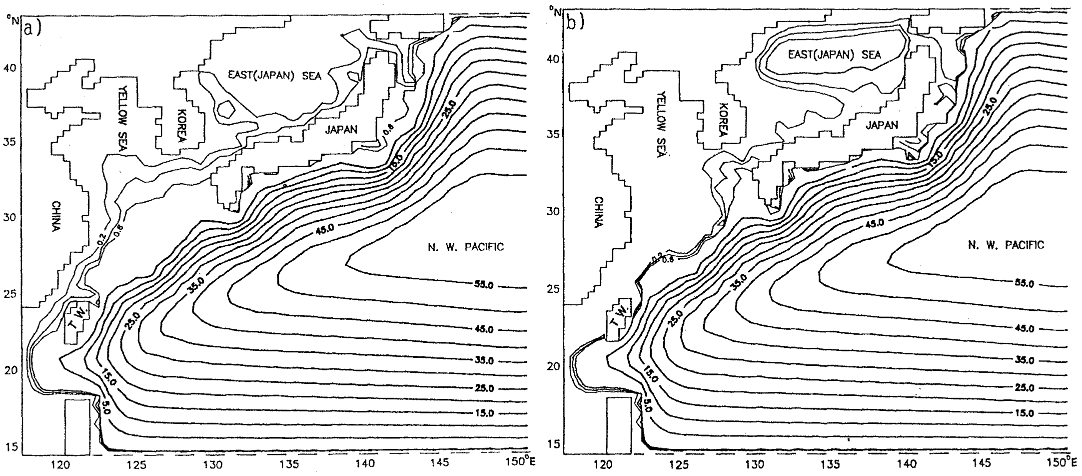

Fig. 9. Distributions of transport stream function for experiments a) 2 and b) 6 of southerly and northerly wind stresses, respectively.

though the transport through the northeastern tip of Taiwan appears more dependent on the seasonal monsoon.

8. Effect of total WBC transport

Experiments 1, 18, 19 and 20 have different total WBC transports with other paramenters held the same. Results of these experiments show the nearly same distribution pattern of stream functions (not shown) although they have different magnitudes. Both TT and TST increase monotonically with increase of the total WBC transport (Fig. 6 f) ; the former increases slightly more than the latter. The proportion of these transports to the total WBC transport, however, decreases slightly with increase of the WBC transport.

9. Concluding remarks

Results obtained in this study can be summarized as follows:

1) The so-called Taiwan Warm Current is confirmed to pass through both sides of Taiwan and the TSWC is just the downstream extension of it. A small part of Taiwan Warm Current Water returns back to the Kuroshio along the coast, southwest of Japan though it does not seem quite significant. It is shown that the western boundary current penetrates into the bordering shallow marginal sea through the narrow region near the southern end of the continental slope.

2) The transport of TSWC depends on the friction (both bottom and lateral, with the former to much larger extent), the depth difference across the continental slope and the total WBC transport. Smaller friction, smaller depth difference and larger WBC transport tend to increase the TSWC transport.

3) Transports through Taiwan Strait, through eastern side of Taiwan and back to the Kuroshio fluctuate depending on the local wind. However, the total transport of TSWC does not change significantly. It is fed by the transport through Taiwan Strait under the southerly wind in summer but by the transport through the eastern side of Taiwan under the northerly wind in winter.

This study is not complete in some respects. The results given above should be more fundamentally explained. Furthermore, the present model dose not include baroclinicity and neglects the buoyancy input from large fresh water sources along the Chinese coast. Also, a part of the transport through the Taiwan Strait may be originated from the South China Sea. These problems may be able to be resolved in near future.

Acknowledegements

This study is supported by the 1990 research fund from the Ministry of Education, Republic of Korea.

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