Journal of the Korean Society of Oceanography
Vol. 33, No. 4, pp. 212—218, December 1998

A Note on the Outflow Boundary Conditions in Modeling the East Sea Circulation

YOUNG HO SEUNG AND KYOUNG-HO CHO
Department of Oceanography, Inha University, Inchon 402-751, Korea

Three different outflow boundary conditions are considered in modeling the East Sea circulation. The first one is that of the conventional constant volume transport (CT). The second one is the Orlanski radiation boundary condition (OR). The third one is that of the constant sea level just outside the outflow boundary (SL). In the third condition, the outflow current is set to be driven by the sea level differences across the outflow open-boundary lines, based on the recent knowledge that the Tsushima Current is driven by the sea level differences across the inflow and outflow boundaries. In case of OR it takes too much time to reach the steady state, resulting in a large increase of Tsushima Current Water in the basin and low level of kinetic energy. Both CT and SL reach the steady state in a relatively short time. However, SL is more recommendable, because it is based on physical background and generates less numerical noises than CT.

INTRODUCTION

In most of East Sea models (*e.g.* Yoon, 1982a, 1982b, 1982c; Seung and Kim, 1993; Seung and Yoon, 1995; Kim, 1996; Seung and Kim, 1997), the inflow transport is either held constant or varying seasonally. In all these models, the outflow volume transport is taken the same as the inflow volume transport in order that the continuity is always satisfied. This outflow boundary condition is certainly based on the numerical reason rather than the real physics because it is not believed that the total volume of the Tsushima Current (TC) Water inside the East Sea always remains exactly the same. It seems that the outflow transport is controlled by the conditions at the outflow boundary, particularly by the pressure gradients developed across the open-boundary lines. This presumption is based on the recent knowledge that the TC is driven by the sea level differences across the inflow and outflow boundaries connecting the basin to the open oceans (Toba *et al.*, 1982; Ohshima, 1994). In this regard, an inter-comparison of some outflow boundary conditions is made. Three boundary conditions are considered here: that of constant volume transport (CT), the Orlanski radiation boundary condition (OR; Orlanski, 1976) and that of constant sea level just outside the outflow boundary (SL). In the last one, the outflow is set to be gravitationally accelerated toward the open ocean. This study thus aims at providing East Sea circulation modelers with a reference about the open-boundary condition.

MODEL

The model used in this study is the early version of Miami Isopycnic Coordinate Ocean Model (MICOM) developed by Bleck and Boudra (1986). This model adapts primitive equations in the framework of isopycnic coordinate and allows the free surface. Since the purpose of this study is only to compare three outflow boundary conditions with each other, the simplest model ocean is considered, *i.e.*, the reduced gravity model. Although MICOM allows outcropping of isopycnals, this property is not explored in this study. The model ocean is initially filled with the 300-m-thick upper water representing the TC Water over the motionless deep water. The upper layer is then driven by the inflow and by either the outflow or the outward pressure gradient developed near the outflow open boundary. The relative density difference between the upper and lower layers is taken as 10^{-3}. Horizontally, the model is gridded with resolution 0.2° by 0.2° in latitude and longitude. For lateral dissipation of momentum, the biharmonic formulation of eddy viscosity is employed which preserves eddy-like disturbances better than the Laplacian formulation.

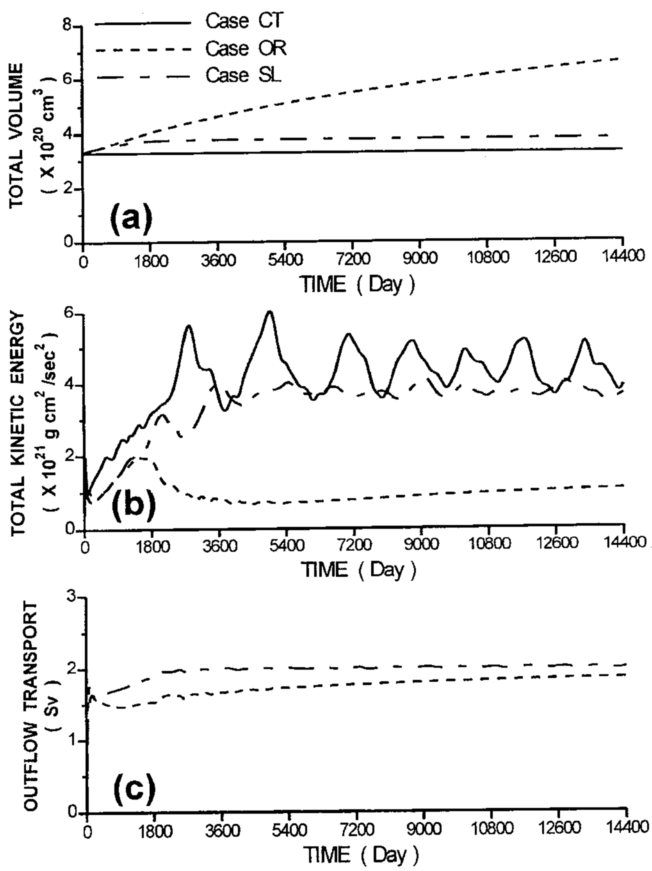

Fig. 1. Time serieses of (**a**) total volume, (**b**) total kinetic energy and (**c**) outflow transport of the model Tsushima Current Water for the cases CT, OR and SL. The outflow transport of the case CT is fixed at 2 Sv.

The eddy viscosity coefficient is proportional to both the square of grid size and the absolute value of the total deformation of the horizontal motion field, following the scheme developed by Smagorinsky (1963). The proportional factor in this formulation is taken as 0.4. Slight change of this factor dose not alter the results. There is no local forcings such as wind stress and heat/salt flux. In reality, the TC Water does not have uniform thickness, although mostly less than 300 m thick, and is subject to local forcings mentioned above. However, we focus on only examining the behaviors of outflow boundary conditions and neglect the factors mentioned above.

Through the inflow open boundary, 2 Sv of TC Water enters the model ocean. The inflow current is perpendicular to the meridional and zonal grid lines extending, respectively, from 33.8°N to 34.8°N and from 128.4°E to 130.2°E in the southwestern corner of the model ocean (*c.f.* Figs. 2-4). The TC Water also leaks out of the basin through the two outflow open boundaries located on the eastern wall near the latitude 41°N and 46°N (*c.f.* Figs. 2-4). Three cases are considered for the outflow boundary condition. In the first case, the transport is held fixed at the same value of the inflow transport (CT) as is conventionally done in most previous models. In the second, the Orlanski radiation boundary condition (OR) is applied. This condition is widely used as open-boundary condition and seems to be less artificial than CT. Lastly, the sea levels just outside the outflow boundaries are held fixed at the value of initially motionless state (SL) so that the outflow may be driven by the pressure head developed just inside the outflow boundaries. SL is based on the physical background that the Tsushima Current is driven by the sea level differences between the East China Sea near the inflow boundary and the Northwest Pacific near the outflow boundaries (*c.f.* Toba *et al.*, 1982; Ohshima, 1994). Since the outflow boundaries are narrow, the outflow currents are assumed to be perpendicular to the open boundary lines and to be accelerated only by the outward pressure gradient associated with the pressure heads developed near the outflow boundaries.

RESULTS

For each case, the model is run for about 40 years which is much longer than the theoretical spin-up time $L/\beta R^2$ ($\sim$11 years) where L ($\sim 10^3$ km) is the basin scale, β ($\sim 10^{-11}$/sec · m) is the planetary beta and $R=(g'H)^{1/2}/f$ ($\sim$17 km) is the Rossby radius with g' ($\sim 10^{-2}$ m/sec^2) the reduced gravity, H ($\sim$300 m) the approximate upper layer thickness and f ($\sim 10^{-4}$/sec) the Coriolis parameter. Time series of total upper layer volume and total kinetic energy are shown in Fig. 1 for each case. For OR and SL, time series of outflow volume transport are also shown. For CT, the total volume is well conserved as is so schemed. The total kinetic energy shows fluctuations with periods of several years which seem to be due to the disturbances generated during the spin-up process. These disturbances seem to be associated with the pressure drop created near the outflow boundary by the artificially imposed outflow transport. On long time scale, the kinetic energy does not seem to vary significantly in 40 years. For OR, the outflow transport does not reach the expected value 2.0 Sv in 40 years. Correspondingly, the total volume increases, even in 40th year although the rate of increase slowly diminishes

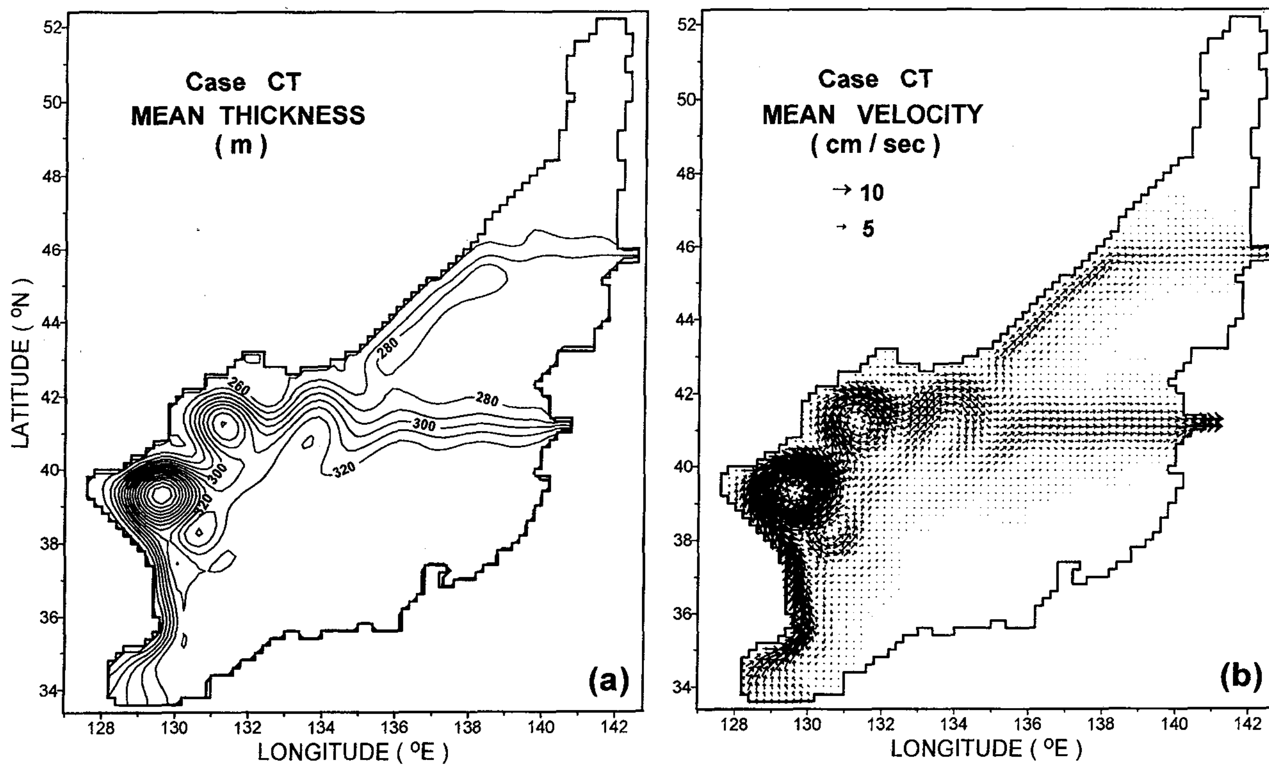

Fig. 2. Distributions of (**a**) mean layer thickness and (**b**) mean velocity for the case CT.

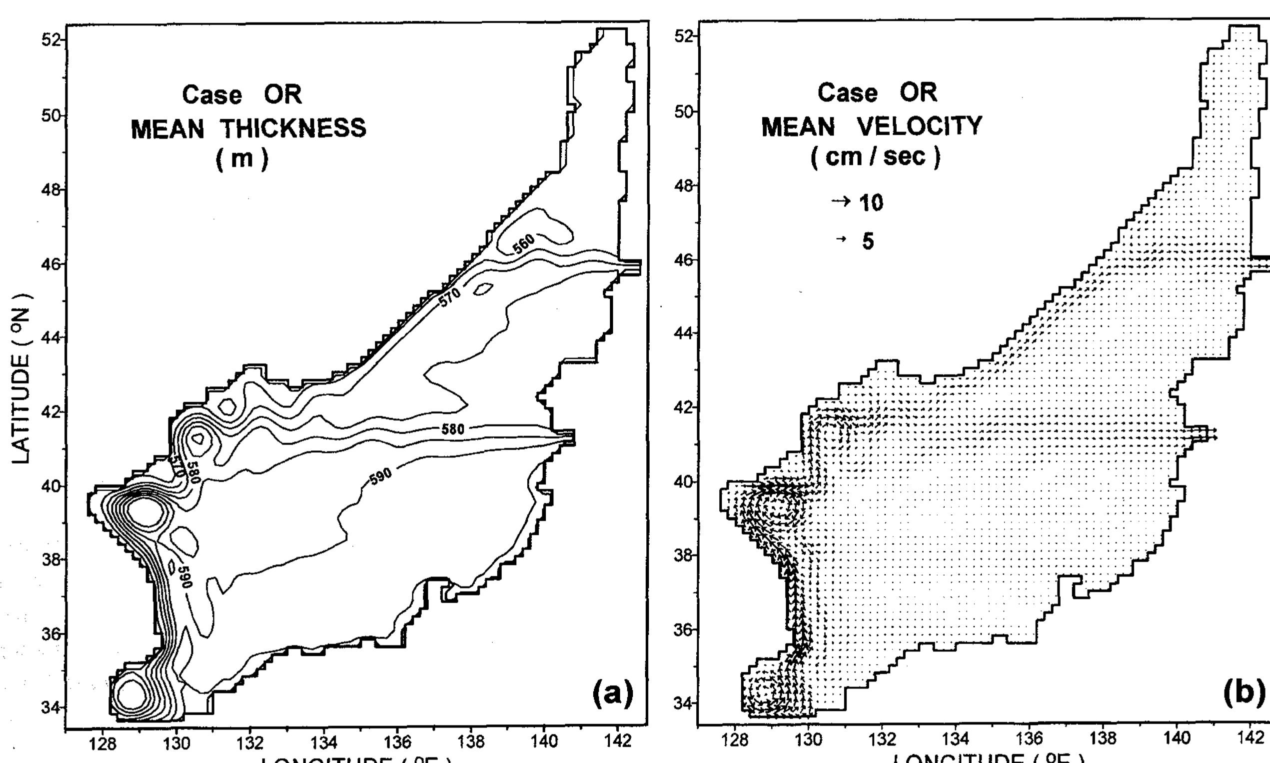

Fig. 3. Same as Fig. 2 but for the case OR.

with time. The total kinetic energy also increases indefinitely. The total kinetic energy of OR is much lower than those of the others and no significant energy fluctuation is observed. This fact may reflect the nature of Orlanski radiation boundary condition that it radiates efficiently disturbances out of the model domain. However, this scheme fails to create sufficient outflow, thus leading to much weaker circulation within the basin. For the case SL, the outflow transport reaches 2 Sv relatively in a short time (in less than 10 years). Correspondingly, the total volume reaches the steady state in a short time. The long term-averaged kinetic energy and the steady-state total volume are quite comparable to those of CT. A large difference between CT and SL is that the latter has energy fluctuation much less than the former, indicating that the latter generates less disturbances than the former.

Approximate mean fields of current and layer thickness are obtained by averaging the variables over the last 10 years (Figs. 2-4). The general feature of the three cases is that there is a western boundary current up to the latitude of outflow and zonal currents toward the outflow. Two large anti-cyclonic gyres develop just before the separation from the coast. No nearshore branch flowing along the Japanese coast is observed because there is no topographic effect (*c.f.* Yoon, 1982c). Distribution of the layer thickness is such that it almost complies with the geostrophic balance, as is evident by comparing it with distribution of current. There is a great similarity between CT and SL in both the layer thickness and velocity. However, OR has weaker current and thicker layer than the other two, as already indicated in Figs. 1a and 1b. For OR, a small cyclonic gyre is seen near the inflow boundary differently from other cases. In case of OR, the outflow transport is not so sufficiently developed that there might be pressure head developed near the inflow boundary, resulting in the recirculation gyre mentioned above.

Variances of current and layer thickness relative to the mean values are estimated at each grid point from the time series for the last 10 years (Figs. 5-7). These variances are considered as the disturbances consisting of the transient eddies generated during the process of spin-up and numerical noises. In general, disturbances are strongest where the two anti-cyclonic gyres occur in the mean field (*c.f.* Figs. 2-4). This seems to be due to the numerical noises generated near the outflow boundaries and westward propagating Rossby waves. As indicated in Fig. 1b, they are strongest in CT and weakest in OR.

DISCUSSION AND CONCLUSION

From the results obtained in this study, it is found that OR takes longer time to reach the steady state

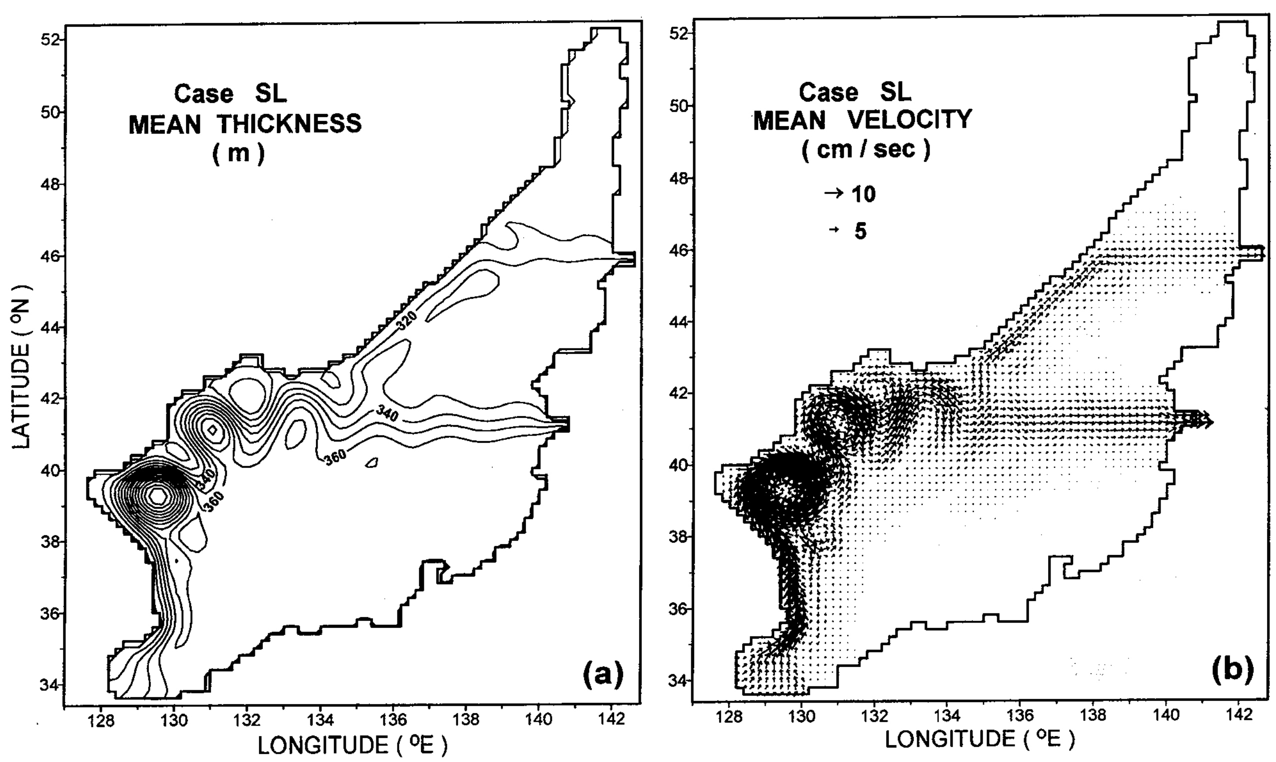

Fig. 4. Same as Fig. 2 but for the case SL.

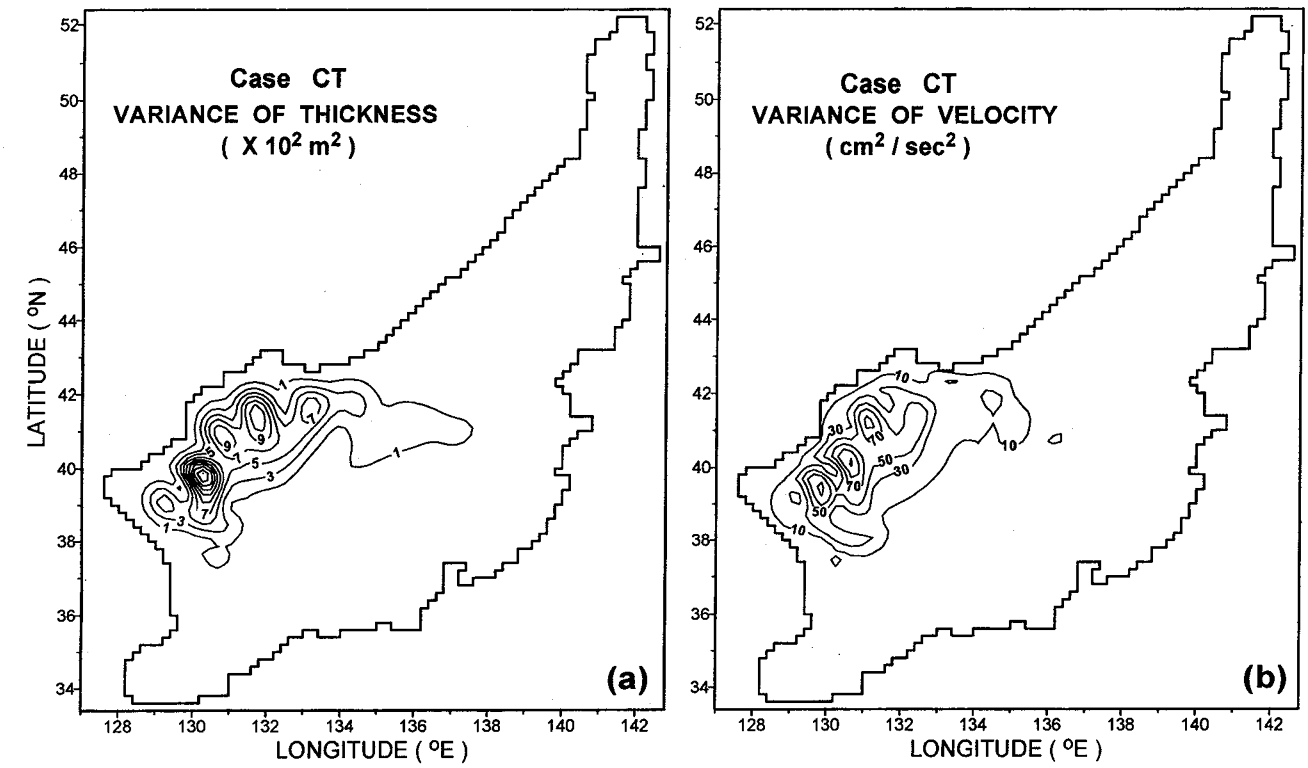

Fig. 5. Variance distributions of (**a**) layer thickness and (**b**) velocity for the case CT.

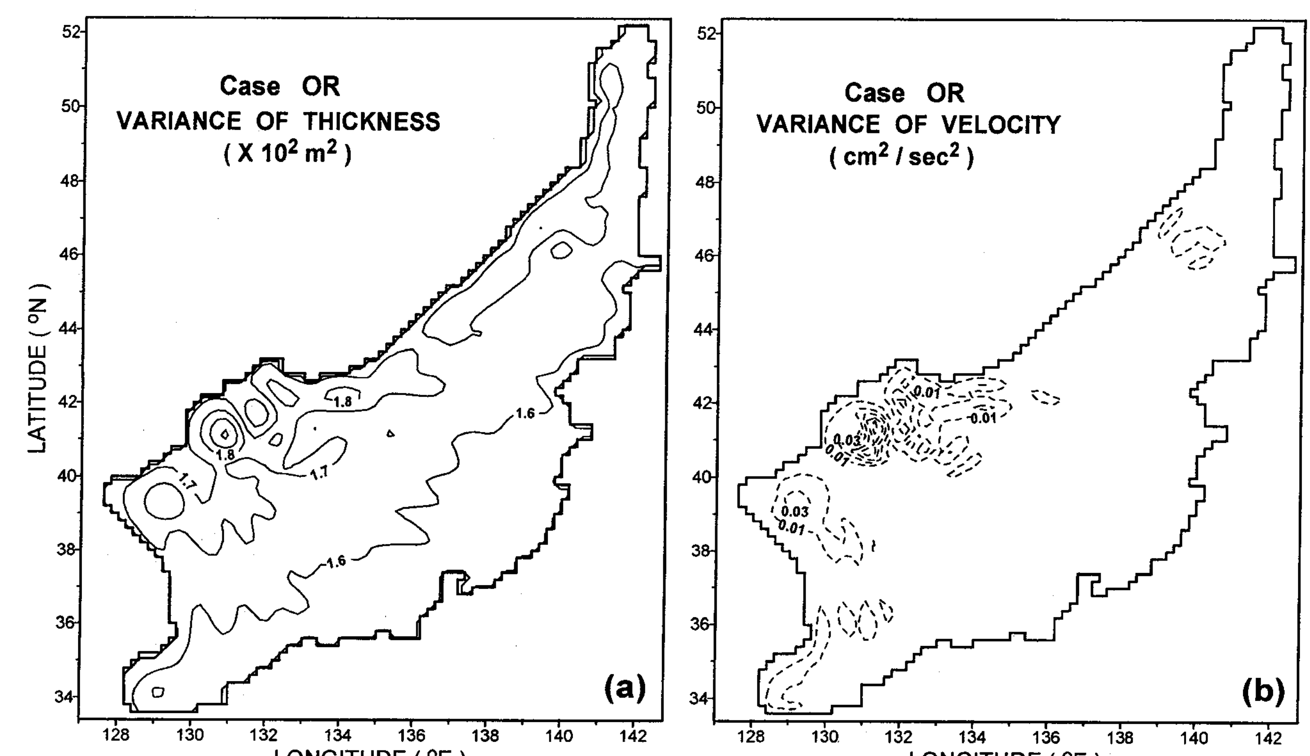

Fig. 6. Same as Fig. 5 but for the case OR. Contour line is dotted for the values smaller than the unity.

compared to the other two cases although it seems to generate least numerical noise compared with others. The Orlanski radiation boundary condition is therefore very inefficient in modeling the inflow-

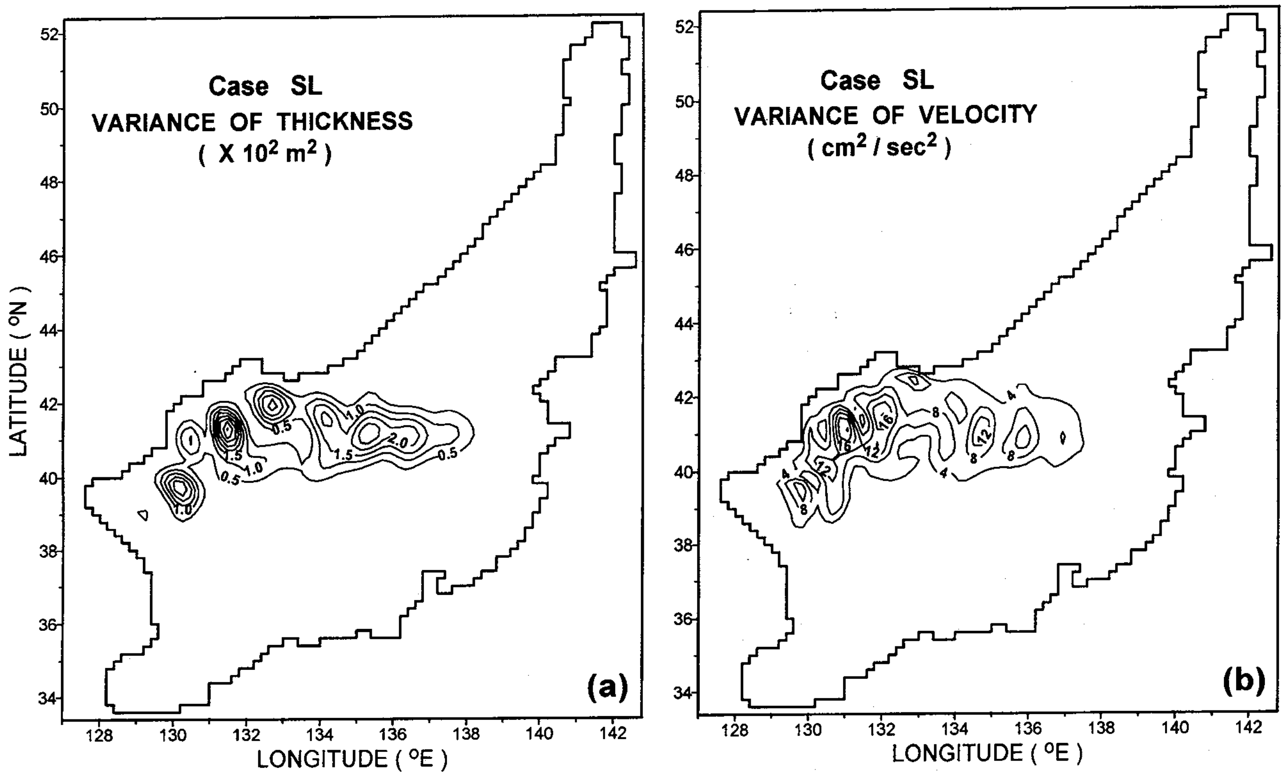

Fig. 7. Same as Fig. 5 but for the case SL.

outflow current system although it is not known whether the corresponding steady state results are realistic. Even if these results are realistic, they will certainly depend on the initial state. The cases CT and SL are very similar in reaching the steady state relatively in a short time. The only difference is that SL has less disturbance. Since the only difference between the two cases is the outflow boundary condition, it is certainly due to the difference in numerical noise which is generated by the mismatch between those computed inside the domain and the condition imposed at the open boundary. In fact, the mismatch between the inside dynamics and the imposed boundary condition is expected to be the largest for the condition CT because it is not based on any physical background. In conclusion, we recommend to East Sea circulation modelers the condition SL, *i.e.*, fixing the sea level (or pressure) just outside the outflow boundary at the value of initially motionless state. The results of this study may be applied to all semi-inclosed basins where the current is driven by the inflow and outflow associated with the sea level differences between the inside and outside of the basins. It may be interesting to perform the same experiment for the inflow boundary condition.

ACKNOWLEDGMENTS

This study is supported by Korea Science and Engineering Foundation (KOSEF) research grant 981-0405-018-2, by Basic Science Research Institute Program, Ministry of Education (1998) and by Inha University Research Support Program 1998. Comments from the referees were useful in making the text more comprehensive.

REFERENCES

Bleck, R. and D. Boudra, 1986. Wind-driven spin-up in eddy-resolving ocean models formulated in isopycnic and isobaric coordinates. *J. Geophys. Res.*, **91**: 7611–7621.

Kim, C.H., 1996. A Numerical Experiment Study on the Circulation of the Japan Sea (East Sea). Ph. D Thesis, Kyushu University, Fukuoka, 151 pp.

Ohshima, K.I., 1994. The flow system in the Japan Sea caused by a sea level difference through shallow straits. *J. Geophys. Res.*, **99**: 9925–9940.

Orlanski, I., 1976. A Simple boundary condition for unbounded hyperbolic flows. *J. Comp. Phys.*, **21**: 251–269.

Seung, Y.H. and K. Kim, 1993. A numerical modeling of the East Sea circulation. *J. Oceanol. Soc. Korea*, **28**: 292–304.

Seung, Y.H. and K.J. Kim, 1997. Estimation of the residence time for renewal of the East Sea Intermediate Water using MICOM. *J. Korean Soc. Oceanogr.*, **32**: 17–27.

Seung, Y.H. and J.H. Yoon, 1995. Robust diagnostic modeling of the Japan Sea circulation. *J. Oceanogr.*, **51**: 421−440.

Smagorinsky, J.S., 1963. General circulation experiments with the primitive equations: I. The basic experiment. *Mon. Wea. Rev.*, **91**: 99−164.

Toba, Y., K. Tomizawa, Y. Kurasawa and K. Hanawa, 1982. Seasonal and year-to-year variability of the Tsushima-Tsugaru Warm Current system with its possible cause. *La Mer*, **20**: 41−51.

Yoon, J.H., 1982a. Numerical experiment on the circulation in the Japan Sea. Part I. Formation of the East Korean Warm Current. *J. Oceanogr. Soc. Japan*, **38**: 43−51.

Yoon, J.H., 1982b. Numerical experiment on the circulation in the Japan Sea. Part II. Influence of seasonal variations in atmospheric conditions on the Tsushima Current. *J. Oceanogr. Soc. Japan*, **38**: 81−94.

Yoon, J.H., 1982c. Numerical experiment on the circulation in the Japan Sea. Part III. Mechanism of the Nearshore Branch of the Tsushima Current. *J. Oceanogr. Soc. Japan*, **38**: 125−130.

Manuscript received August 25, 1998
Revision accepted October 16, 1998