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Comparison of RIAMOM and MOM in Modeling the East Sea/Japan Sea Circulation

Ho Jin Lee^{1*}, Jong Hwan Yoon², Hideyuki Kawamura², and Hyoun-Woo Kang³

¹*Division of Ocean Science, Korea Maritime University
Dongsam-Dong 1, Youngdo-Gu, Pusan 606-791, Korea*

²*DSRC, Research Institute for Applied Mechanics, Kyushu University
Fukuoka, 816-8580 Japan*

³*Coastal & Harbor Engineering Laboratory, KORDI
Ansan P.O. Box 29, Seoul 425-600, Korea*

Abstract : The seasonal variations in the circulation of the water mass in the East Sea/Japan Sea have been simulated using a free surface primitive ocean model, RIAMOM (RIAM Ocean Model), comparing the results from GFDL-MOM1 (Geophysical Fluid Dynamics Laboratory Modular Ocean Model, version 1.1, hereafter MOM) with the GDEM (Generalized Digital Environmental Model) data. Both models appear to successfully reproduce the distinct features of circulation in the East Sea/Japan Sea, such as the NB (Near-shore Branch) flowing along the Japanese coast, the EKWC (East Korean Warm Current) flowing northward along the Korean coast, and the NKCC/LCC (North Korean Cold Current/Liman Cold Current) flowing southwestward along Korean/Russian coast. RIAMOM has shown better performance, compared to MOM, in terms of the realistic simulation of the flow field in the East Sea/Japan Sea; RIAMOM has produced more rectified flows on the coastal region, for example, the narrower and stronger NKCC/LCC than MOM has. There is however obvious differences between the model results and the GDEM data in terms of the calculation of the water mass; both models have shown a tendency to overpredict temperature and underpredict salinity below 50m; more diffusive forms of thermocline and halocline have been simulated than noted in GDEM data.

Key words : East Sea/Japan Sea, circulation, RIAMOM, MOM

1. Introduction

The presence of abundant oceanic features characterizes the circulation of the East Sea/Japan Sea. Specifically, the East Sea/Japan Sea contains processes such as cyclonic (subpolar) and anticyclonic (subtropical) gyre systems, mesoscale eddies and deep convection. The East Sea/Japan Sea however has an area approximately two orders smaller than the open ocean and may then adjust more rapidly; the turnover time in the East Sea/Japan Sea is of the order of 100 years, which is at least one order of magnitude smaller than that of the oceanic conveyor-belt system (Tsunogai *et al.* 1993; Kim *et al.* 2001). The fact

that the East Sea/Japan Sea possesses most of the open ocean characteristics, though smaller in their size, and the fact that a considerable amount of climatological data is available allow us to choose it as an ideal basin not only for numerical experiments to study oceanic processes of the global ocean, but for verification of the model performance.

Since the modeling study of Kim and Yoon (1999) using MOM, efforts at the Research Institute for Applied Mechanics (RIAM), Kyushu University, has been directed to simulate the circulation by integrating a longer-term free-surface model equipped with improved numerical schemes on a finer grid. For that, the model called RIAMOM, which was originally developed at RIAM by Lee and Yoon (1994) and was used for reproducing the oceanic circulation and water mass formation in the Yellow Sea

*Corresponding author. E-mail : hjlee@hhu.ac.kr

and the East China Sea (Lee 1996; Hirose *et al.* 1999), has been implemented in the East Sea/Japan Sea with some modifications. In the course of this process, a model comparison study was initially carried out on the coarse grid used in the previous study.

This paper has been prepared to compare exclusively the responses of RIAMOM and MOM as a way of verifying RIAMOM equipped with some new features of numerical schemes such as an energy and enstrophy-conserving advection scheme (the generalized Arakawa scheme) and a slant advection scheme along with a free-surface. The well-known MOM is a rigid-lid model with a centered approximation of advective terms (Pacanowski *et al.* 1991, 1993). The model domain and grids are identical to Kim (1996) and Kim and Yoon (1999), but the volume transport at the inflow open boundary has been updated on the basis of more recent observations and the wind forcing at the sea surface has been imposed using the re-evaluated ECMWF (European Center for Medium-Range Weather Forecasts) data. The vertical eddy diffusivity has been reduced as one-fifth of the value used by Kim (1996). A focus is made in this study on the surface and intermediate circulation of the East Sea/Japan Sea.

2. Models

Description of model equations and numerics

RIAMOM assumes hydrostatic balance with Boussinesq approximation, and solves the three-dimensional, non-linear, primitive external and internal mode equations on the Arakawa B-grid system. The internal mode equations of the model in the spherical coordinates are:

$$\frac{1}{R \cos \phi} \frac{\partial u}{\partial \lambda} + \frac{1}{R \cos \phi} \frac{\partial}{\partial \phi} (v \cos \phi) + \frac{\partial w}{\partial z} = 0, \quad (1)$$

$$\begin{aligned} \frac{\partial u}{\partial t} + L(u) - \frac{uv \tan \phi}{R} - fv = & -\frac{1}{\rho_0 R \cos \phi} \frac{\partial P}{\partial \lambda} + \frac{\partial}{\partial z} A_v \frac{\partial u}{\partial z} \\ & + A_h \nabla^2 u - \frac{u}{R^2 \cos^2 \phi} - \frac{2 \sin \phi}{R^2 \cos^2 \phi} \frac{\partial v}{\partial \lambda}, \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\partial v}{\partial t} + L(v) - \frac{u^2 \tan \phi}{R} + fu = & -\frac{1}{\rho_0 R} \frac{\partial P}{\partial \phi} + \frac{\partial}{\partial z} A_v \frac{\partial v}{\partial z} \\ & + A_h \nabla^2 v - \frac{v}{R^2 \cos^2 \phi} + \frac{2 \sin \phi}{R^2 \cos^2 \phi} \frac{\partial u}{\partial \lambda}, \end{aligned} \quad (3)$$

$$\frac{\partial P}{\partial z} = -\rho g, \quad (4)$$

$$\frac{\partial T}{\partial t} + L(T) = \frac{\partial}{\partial z} K_v \frac{\partial T}{\partial z} + K_h \nabla^2 T, \quad (5)$$

$$\frac{\partial S}{\partial t} + L(S) = \frac{\partial}{\partial z} K_v \frac{\partial S}{\partial z} + K_h \nabla^2 S, \quad (6)$$

where t is the time, λ is the longitude, ϕ is the latitude, R is the radius of the earth, f is the Coriolis parameter ($=2\Omega \sin \phi$, Ω the earth's angular velocity), g is the gravitational acceleration, P is the pressure, ρ is the density of seawater, ρ_0 is the reference density, u and v are the zonal and meridional components of the currents, respectively, w is the vertical component of the currents, A_v and A_h denote the coefficients of vertical and horizontal eddy viscosity, respectively, T and S represent seawater temperature and salinity, respectively, and K_v and K_h are the coefficients of the vertical and horizontal eddy diffusivities, respectively. The advection and Laplacian operators denoted by L and nabla ∇^2 , respectively, are defined as:

$$L(\mu) = \frac{1}{R \cos \phi} \frac{\partial}{\partial \lambda} (u \mu) + \frac{1}{R \cos \phi} \frac{\partial}{\partial \phi} (v \mu \cos \phi) + \frac{\partial}{\partial z} (w \mu), \quad (7)$$

$$\nabla^2 \mu = \frac{1}{R^2 \cos^2 \phi} \frac{\partial^2 \mu}{\partial \lambda^2} + \frac{1}{R^2 \cos \phi} \frac{\partial}{\partial \phi} \left(\cos \phi \frac{\partial \mu}{\partial \phi} \right). \quad (8)$$

The UNESCO equation of state adapted by Mellor (1991) is used to calculate the density. The external mode equations are derived by integrating equations (1) to (3) in the vertical. For details, see Lee (1996).

MOM is a rigid-lid model and uses the simple centered formulation for the momentum advection. The time integration is executed using a leapfrog scheme with a periodic Euler backward step. Opposite to this, RIAMOM has a free surface that permits external gravity waves. A mode splitting method suggested by Blumberg and Mellor (1987) is used to reduce the calculation time. To prevent nonlinear instability, the generalized Arakawa scheme, which conserves both potential energy and enstrophy (Mesinger and Arakawa 1976), is used in the horizontal advection of momentum. In this study, we use the vectorized form of the generalized Arakawa scheme for the parallel machine in which the so-called slant advection effect (Ishizaki and Motoi 1989, 1999) at topographic steps is incorporated to correctly represent the vertical advection of the horizontal momentum along the steep bottom topography. The time integration is executed using a leapfrog scheme with an Asselin time filter (Asselin 1972).

Fig. 1. Model domain and bottom topography of the East Sea/Japan Sea.

Model domain and grids

The model domain and basic grid configuration taken in this study are identical to those of Kim (1996). The model area covers the sea region from 126.5°E to 142.5°E in longitude and from 33°N to 52°N in latitude; the model has two inflow regions, Cheju Strait and the cross-section parallel to the latitude connecting the southern part of Cheju Island to the west coast of Kyushu, and has two outflow regions, Tsugaru Strait and Soya Strait (Fig. 1).

Both of the latitudinal and longitudinal grid intervals are chosen as 1/6° to approximate the model region on the horizontal plane. The size of the grid boxes defined over the vertical domain varies. A total of 19 variable levels have been adopted in the deepest part (in detail, with intervals of 15, 15, 20, 25, 30, 35, 35, 35, 50, 75, 100, 150, 200, 300, 450, 600, 600, 600 in meters). The depth field shown in Fig. 1 has been extracted from the ETOPO5 global depth data (NCAR 1989).

Eddy viscosity and diffusivity

In this study, the vertical eddy viscosity (A_v) and diffusivity (K_v) coefficients are set to 1.0 cm²/sec and 0.1

cm²/sec, respectively, while the horizontal eddy viscosity (A_h) and diffusivity (K_h) coefficients are set to values about six orders higher than the vertical counterparts (3×10^6 cm²/sec and 3×10^5 cm²/sec, respectively). The eddy viscosity values are exactly the same as those used by Kim (1996), while the eddy diffusivity values are one-fifth of those used in Experiment I by Kim (1996). In case the convective adjustment process is needed a larger value of the vertical eddy diffusivity coefficient has been used (in detail, 10⁴ cm²/sec).

Volume transports at the inflows and outflows

At the inflow regions, we have specified seasonally-varying volume transports. The volume transport of the Tsushima Warm Current (TWC) has been prepared on the basis of regular (six times a week) monitoring of the flow variation across the Korea/Tsushima Strait from February, 1997 to January, 2001 using an ADCP mounted on a ferry (Takikawa *et al.* 2003). The variation of the observed volume transport shows two maxima in May (2.94 Sv, 1Sv=10⁶ m³/sec) and October (3.04 Sv) with an annual average of 2.61 Sv. The minimum of the volume transport occurs around the middle of February, reaching about 1.88 Sv. The volume transport in August is just above the annual average (2.71 Sv). The outgoing volume transport through the Tsugaru Strait is fixed as 1.4 Sv throughout the calculation, taking into account the ADCP observation of Shikama (1994). The volume flowing out through the Soya Strait is then adjusted to maintain the mass balance within the domain. The volume transports are equally distributed to each grid along the open boundaries. The external component of velocity consistent with the inflow and outflow boundaries can be calculated from the volume transports and the section of the grids.

Along with the volume transports, temperature and salinity are imposed at the inflow boundary based on the monthly mean observations by the Fisheries Research and Development Agency of Korea (FRDAK 1986). The near-surface temperature reaches a maximum in August and a minimum in March showing a variation of about 12.6°C, while the near-bottom temperature reaches a maximum near November and a minimum in March showing a variation of about 4 to 4.5°C. The near-surface salinity reaches a maximum in March and a minimum in August showing a variation of about 2.8 to 3.0 psu, while the near-bottom salinity reaches a maximum in March and a minimum in October or November showing a variation of about 0.1 to 0.25 psu. Based on the observations, monthly mean values over a year are prepared in advance and are

repeatedly used for the multi-year integration.

The internal component of velocity consistent with the inflow boundaries is calculated from the prescribed temperature and salinity distribution along the boundaries based on the assumption of the thermal wind relation. No gradient condition ($\partial u / \partial n = 0$, where n is the normal direction to the open boundary) has been applied at the outflow boundary. The velocity component tangential to the open boundaries is set at zero. The non-slip, insulating, and impermeable boundary conditions are applied along the lateral land boundaries.

Sea surface and sea bottom boundary conditions

The boundary conditions for momentum at the sea surface and bottom are:

$$\begin{aligned} A_v \frac{\partial(u, v)}{\partial z} \Big|_{z=0} &= \frac{(\tau_{w\lambda}, \tau_{w\phi})}{\rho_0}, \\ A_v \frac{\partial(u, v)}{\partial z} \Big|_{z=H} &= \frac{(\tau_{b\lambda}, \tau_{b\phi})}{\rho_0}, \end{aligned} \quad (9)$$

where $\tau_{w\lambda}$, $\tau_{b\lambda}$ and $\tau_{w\phi}$, $\tau_{b\phi}$ are zonal and meridional components of shearing stresses, respectively. Subscripts in the equation (9) denote the depth levels whose derivatives are taken. At the sea surface, the monthly mean wind stresses of the re-analyzed ECMWF data are imposed and, at the sea floor, the usual quadratic bottom friction ($\rho_0 C_d (u_b, v_b) \sqrt{u_b^2 + v_b^2}$, where u_b and v_b are near-bottom velocities, respectively) is used along with the drag coefficient (C_d) of 0.0026. The monthly mean wind stresses are calculated from the daily wind stress data with a horizontal resolution of 0.5625° in both longitude and latitude from January 1992 to December 1997.

While the bottom boundary conditions for temperature and salinity are given as a zero flux in line with that of the seabed, a thermohaline forcing is used at the sea surface as:

$$K_v \frac{\partial T}{\partial z} \Big|_{z=0} = \frac{Q_T}{\rho_0 C_p}, \quad K_v \frac{\partial S}{\partial z} \Big|_{z=0} = Q_S, \quad (10)$$

where Q_T and Q_S are the heat and salt fluxes, and C_p is the specific heat of seawater at constant pressure. The surface flux of heat (Q_T) is given as an improved Haney type suggested by Hirose *et al.* (1999), which is expressed as:

$$Q_T = Q_1^* + Q_2^* (T_a - T_1) \quad (11)$$

where Q_1^* and Q_2^* are the heat flux coefficients which were updated by Hirose *et al.* (1999), T_a the air

temperature, and T_1 , the simulated water temperature at the first level below the sea surface. The long-term monthly mean coefficients, Q_1^* and Q_2^* , recalculated from the climatological data (Hirose *et al.* 1996) are used to specify the heat flux at the sea surface.

A Newtonian type restoring boundary condition is applied to the salt flux at the sea surface with the constant damping time of 10 days. That is,

$$Q_S = \gamma^{-1} (S_s - S_1) \quad (12)$$

where γ is the restoring time scale (10 days), S_1 the simulated water salinity at the first level below the sea surface, S_s the observed sea surface salinity. For S_s , we have used the long-term monthly mean sea surface salinity data constructed by Kim (1996) on the basis of the observed sea surface salinity data obtained from the Japan Oceanographic Data Center (JODC), the Fisheries Research and Development Agency of Korea (FRDAK) and the Far Eastern Hydrometeorological Institute of Russia (FEHMI).

3. Results

Both models (RIAMOM and MOM) have been integrated for a period of 100 years from the initial state of no motion. The horizontally uniform temperature and salinity fields with the vertical distributions identical to those of Kim (1996), are given as initial conditions for the temperature and salinity. From the CFL condition, the external time interval is set at 20 seconds and the internal time interval is 60 times longer than the external one. Results to be shown below are model outputs from an additional 1 year run.

In addition to the comparison of the two model results, we have used the U.S. Navy's unclassified GDEM monthly mean temperature and salinity data on a $1/6^\circ \times 1/6^\circ$ grid for the comparison with model results. The primary data source of the GDEM is the U.S. Navy's Master Oceanographic Observation Data Set (MOODS), which is a composite dataset based on observations from various sources from 1930-97 (Chu *et al.* 2001).

Comparison between model results and GDEM data

Fig. 2 shows horizontally averaged, annual-mean vertical profiles of temperature and salinity from MOM (dotted line), RIAMOM (dashed line) and the GDEM data (solid line). We can see that the two model results agree well with each other. Considerable differences between the model results and the GDEM data are however seemingly apparent. It is noted that the difference between the model

Fig. 2. Vertical profiles of temperature (left) and salinity (right), calculated from the time-averaged and area-averaged values over model domain and 1 year. Solid, dotted, and dashed lines are for the GDEM Data, MOM, and RIAMOM, respectively.

results and the GDEM data gradually increases below 50 m; more diffusive forms of thermocline and halocline have been simulated than noted in the GDEM data. The difference is about 2°C in temperature and 0.07-0.1 psu in salinity below 300 m. There might be many possible sources for these errors. The inherent numerical diffusion, which is approximately proportional to the grid size, can be one of them. The schematic computational diffusion originating from the upstream scheme used in the vertical advection of the tracer might be another possible reason for the occurrence of higher temperatures. Furthermore, the inaccuracy of the heat and salt flux imposed on the sea surface also may give rise to overestimating or underestimating the heat and salt content of the East Sea/Japan Sea. For example, the incorporation of high frequency atmospheric components which we excluded in this study might reduce the deviation of the subsurface temperature and salinity.

Comparing the results from RIAMOM and MOM, it is apparent that the RIAMOM shows a tendency toward a slightly lower temperature of about 0.2°C and lower salinity of about 0.03 psu. A discussion on these differences will be undertaken later.

A four-dimensional comparison of model temperatures and the GDEM data at the same positions and months (February, May, August and November) is shown in Fig. 3.

It is noted that the simulated temperature distributions are in good agreement with the observed ones even though both models show a tendency to be about 1-2°C higher than the GDEM data. The correlation is up to 0.9 in the case of RIAMOM and 0.86 in the case of MOM at a depth of 100 m. We can see that the correlation is still fairly good in the case of the 200 m temperature. Although the result is not shown here, salinity at a depth of 100 m is somewhat poorly correlated with the observed one (the correlation coefficient is 0.67 in the case of RIAMOM and 0.61 in the case of MOM). The correlations becomes worse at a depth of 200 m: 0.550 in the case of RIAMOM and 0.552 in the case of MOM. The relatively poor correlation in salinity fields may come from the scarcity of observations. As noted by Chu *et al.* (2001), the number of salinity stations which contributed to the composition of the GDEM data is set at two or three times less than the number of temperature stations. In addition, observations north of 40°N are very sparse so that salinity fields are less reliable there. Therefore, the inaccuracy of data itself as well as the inaccuracy of the restoring sea surface salinity data might be a possible reason for the occurrence of the relatively large error in salinity fields.

Temperature and salinity distributions

Fig. 4 displays the simulated horizontal distributions of

Fig. 3. Four-dimensional comparison of calculated temperature and the GDEM data at same positions and at selected 4 months, February, May, August and November: RIAMOM at 100 m (top left), RIAMOM at 200 m (bottom left), MOM at 100 m (top right) and MOM at 200 m (bottom right).

temperature and salinity at a depth of 62.5 m in February. Shading is added for temperature values and salinity less than 3°C and 34.0 psu for the purpose of comparing the two results. Both models effectively reproduce the overall features of water masses of the East Sea/Japan Sea in winter, showing the formation of strong temperature fronts along 40°N and coastal regions on the side of the Korean coast between 38°N and 40°N, which seem to reflect the Subpolar Front and the northward advection of the EKWC, respectively. It is worthwhile noting that in both models the temperature in the sea region north of the Subpolar Front (shaded area in Fig. 4) is lower by about 1–1.5°C than that of Kim and Yoon (1999), although the temperature is still 1.5–2.0°C higher than the observed values.

Differences between the two results are also noticeable in the cold water region north of the Subpolar Front where the low temperature and low salinity water is located; the

temperature and salinity from RIAMOM are lower by about 0.5°C and about 0.02 psu than those of MOM, respectively. We have observed that there is a tendency for the Subpolar Front from MOM to shift northward by about 1° in latitude, compared with that of RIAMOM in the region west of 132°E. Taking into account the fact that the cold and low salinity water is mainly supplied by the current system along the Russian and the North Korean coasts, called the LCC and the NKCC, we can expect that the LCC/NKCC calculated by RIAMOM might be stronger than that calculated by MOM.

Without presenting detailed figures, we briefly describe the results in summer. Again, RIAMOM produces a comparatively colder and fresher water mass north of the Subpolar Front than MOM, but the positional difference in the computed water masses is lessened by about 0.5° as the force of the wind is weakened.

The vertical sections of temperature, salinity and potential

Fig. 4. The horizontal distribution of the temperature (upper) and the salinity field (lower) at a depth of 62.5 m, computed from RIAMOM (left) and MOM (right), respectively.

density along 133°E in February and August are shown in Fig. 5 and 6, respectively. We can readily see that the two models respond similarly, yielding an uniform convective mixed layer of about 700 m in thickness and a subsurface salinity minimum beneath the TWC region which might correspond to the formation of the Upper Japan Sea Proper Water and the East Sea Intermediate Water (ESIW),

respectively (Kim and Chung 1984; Senjyu and Sudo 1994; Senjyu 1999). The values of the salinity minimum are slightly different from each other; RIAMOM gives the value of 33.97 psu, which is 0.03 psu fresher than that given by MOM (shaded region in Fig. 5 and Fig. 6). A dome-shaped pattern of the isopycnal surface still exists in summer, although the deep convection is terminated by

Fig. 5. Potential temperature, salinity and potential density along 133°E for RIAMOM (left) and MOM (right) in February. Shaded areas show the distribution of salinity less than 33.97psu (RIAMOM) and 34.0psu (MOM), respectively.

the surface heating. It is remarkable that the low salinity tongue penetrating into the subsurface region of the TWC is clearly reproduced by RIAMOM. Aside from the occurrence of higher temperatures and lower salinity, it is apparent that both results are qualitatively in accord with the characteristic features of the ESIW.

A noticeable difference between the two model results is seen around the northern end of the section where the low salinity coastal water exists. The cold and fresh water, which is surrounded by a 27.10 isopycnal line in Fig. 5, is much more concentrated in a narrow band in the results of RIAMOM. It is well known that a narrow cold and fresh water belt along the Russian coast extends from the Tatar Strait to the North Korean coast (Seung and Yoon 1995). According to the CREAMS (Circulation Research of the

East Asian Marginal Seas) expeditions in 1993, the low salinity water was found to have a narrow band along the Russian coast (see Fig. 2 in Yoon and Kawamura (2002)). Aubrey *et al.* (2000) also reported that a tongue of salty waters passes between 132°E and 133.5°E along 42°N and the low salinity coastal water (less than 33.90 psu) was limited in the narrow region north of 42°N, consequently forming a salinity front. We can see that MOM tends to reproduce a more diffusive form of the salinity front than RIAMOM.

Fig. 7 shows the calculated horizontal distribution of salinity at the depth of 385 m in February and August. The two models give similar results on the eastward extension of the subsurface low salinity water (shaded area in Fig. 7), the core of which is located in the sea

Fig. 6. Same as Fig. 5 except August.

region between 40°N and 41°N. The low salinity water seems to be separated from the Korean coast at around 40°N and extends up to 137°E. A notable difference between the salinity patterns of RIAMOM and MOM is found in the formation of an additional low salinity tongue at around 39°N. In case of RIAMOM, it appears that the lower salinity water continues to flow southward along the Korean coast and forms a low salinity core at around 38°N and successively separates from the coast, forming an additional low salinity tongue. On the other hand, MOM produces a relatively degenerated low salinity tongue there.

Flow fields at the upper and intermediate layers

Fig. 8 displays the mean flow fields from May to October (upper panel) and from November to April (lower panel) at a depth of 62.5 m. Both models appear to

effectively reproduce the distinct features of circulation in the East Sea/Japan Sea such as the NB flowing along the Japanese coast, the EKWC flowing northward along the Korean coast, and the NKCC/LCC flowing southwestward along the Korean/Russian coast. Overall patterns of circulation are in fairly good agreement with schematic patterns of the surface circulation in the East Sea/Japan Sea which were previously suggested in several papers (Yarichin 1980; Kim and Yoon 1996; Kim *et al.* 2001).

We can also see that the EKWC is significantly stronger in summertime (upper panel) than in wintertime, while the NKCC/LCC becomes pronounced in wintertime (lower panel) due to the strong winter monsoons. The EKWC breaks away from the Korean coast near 38°N in the results of both models. The separated flow meanders in both seasons but in considerably different forms; in summertime, the meandering is more intense, forming a closed anticyclonic

Fig. 7. The horizontal distribution of salinity at a depth of 385 m in February (upper) and August (lower), computed from RIAMOM (left) and MOM (right), respectively. Shaded areas show the distribution of salinity at less than 33.97psu (RIAMOM) and 34.0psu (MOM), respectively.

recirculation of about 100 km in radius and inducing a deep southward, narrow-banded counter current (up to 36.5°N) on the offshore side of the EKWC, while in wintertime forming the relatively shallow, broad-banded southward flow at the farther offshore side. This might attribute to the enhancement of the EKWC in summertime

(Seung and Kim 1993; Kim and Yoon 1999).

The Subpolar Fronts in both models are located a little further south than that in Kim and Yoon (1999). In general, the re-analyzed ECMWF wind used in this study has more spatial structures and stronger wind stress and wind stress curl than the Na wind (Na *et al.* 1992) used by

Fig. 8. Time-averaged velocity fields at a depth of 62.5 m for RIAMOM (left) and MOM (right); Averaged periods are from May to October, which represents the summer season (upper) and from November to April (lower), which represents the winter season, respectively.

Kim and Yoon (1999). Considering the fact that the formation of the cyclonic gyre, including the LCC/NKCC and the proper separation of the EKWC are strongly correlated with the positive wind stress curl (Seung 1992; Kim and Yoon 1996), the shift of the Subpolar Front in this study might arise from the intensified LCC/NKCC

due to stronger wind stress fields. It is notable that Kim and Yoon (1999) have used an isopycnal mixing scheme for the diffusion of tracers to suppress the overshooting of the EKWC, while this study has never used such higher order schemes for tracers.

A close examination reveals noticeable differences

between the two models. In the case of RIAMOM, the LCC is concentrated in a narrow band along the Russian coast, while, in the case of MOM, the LCC is formed in a relatively broad band and its main axis is shifted offshore. Particularly in winter (lower panel), it is evident that there are considerable differences in the strength of the NKCC flowing southward along the East Korean Bay. It seems that the NKCC from MOM is degenerated significantly

and the EKWC extends further northward, compared with the results of RIAMOM.

Similar features can be recognized in the NB. Both models well reproduce the NB which persists along the Japanese coast throughout the year. It is however noted that in the case of RIAMOM, the NB is much more severely trapped with a narrow belt along the coast. Moreover, it appears that RIAMOM produces current

Fig. 9. Same as Fig. 8 except 385 m.

patterns with more complex spatial variability including numerous eddies, especially in summer (upper panel) than MOM does.

Hase *et al.* (1999) have reported that two branches of the TWC are present along the Japanese coast based on intensive ADCP and CTD measurements. They suggested that the first branch of the TWC (the so-called NB) is confined to the narrow region along Japanese coast following the isobath at a depth shallower than 200 m and the second branch of the TWC flows roughly along the continental shelf break between 200-500 m depths with strong baroclinicity in nature. They also reported that the second branch of the TWC cannot always be found around the shelf break because its path is highly influenced by the development of eddies caused by the baroclinic instability. Though the second branch of the TWC is not clearly reproduced in this study, probably due to the poor resolution, we might sufficiently say that the results of RIAMOM are qualitatively consistent with observations

by Hase *et al.* (1999).

Fig. 9 shows the mean flow fields from May to October (upper panel) and from November to April (lower panel) at a depth of 385 m. Both RIAMOM and MOM produce southwestward flows west of the Noto Peninsula which might be a subsurface counter current flowing over the shelf break region (Yoon 1991; Kim and Yoon 1999; Hase *et al.* 1999). The subsurface counter current is stronger in summertime than in wintertime. The generation mechanism of the subsurface counter current is known to be related to the development of the second branch of the TWC (Yoon 1991).

In summertime (upper panel), both results show that the southward advection of the NKCC is hindered by the anticyclonic recirculation which is also shown in Fig. 8. Consequently, the southward extension of the NKCC at the subsurface layer shifts from the coastal region to the offshore side of the EKWC around the anticyclonic recirculation gyre. The differences between two models are more

Fig. 10. Time averaged velocity fields along 133E for RIAMOM (left) and MOM (right); Averaged periods are from May to October, which represents the summer season (upper) and from November to April (lower), which represents the winter season, respectively. Shaded areas denote westward currents.

remarkable in wintertime than in summertime. It is clearly seen that, in the case of RIAMOM, the NKCC extends up to the Korea Strait following along the continental slope, while, in the case of MOM, there is a relatively weak southward flow formed along the Korean coast.

Fig. 10 shows the distribution of current velocity for the vertical section along 133°E. Shading is added to denote the westward currents. We can readily see that the core of the LCC north of 42°N is stronger by about 4 cm/sec and is confined to a region with a narrower width in the result from RIAMOM than that of MOM. Since the low salinity waters of the coastal region and the ESIW are mainly supplied by the LCC, the RIAMOM might produce slightly lower temperatures and lower salinity than MOM does.

Flow fields at the bottom levels

The flow fields at the bottom levels of the models are of value for the comparison of model results. Fig. 11 displays the snapshots of the flow fields at bottom levels of the models in the middle of February. It is worthwhile noting that MOM produces a noisy pattern with grid-scale disturbances along the Russian coast where the steep bottom slope exists. This might attribute to neglecting the slant advection along the steep bottom topography in MOM as shown by Ishizaki and Motoi (1999) and Webb (1995).

In proposing a new advection scheme, Ishizaki and Motoi (1999) noted the importance of including the diagonally upward/downward momentum advection (so called the slant advection) along the bottom slope and an enstrophy conserving advection scheme (so called the

generalized Arakawa scheme) for the horizontal advection of momentum. According to their results, the most prominent difference in the velocity field appears along the steep coastal sea regions; the old Cox code run using the simple centered approximation of advective terms produces a noisy pattern with grid-scale disturbances, while the new scheme shows rectified flows. In addition, the noisy pattern does not appear in the two-dimensional barotropic flow. For these reasons, they concluded that the grid-scale disturbances appeared in the old Cox code run might be suppressed by means of slant advection, as also discussed by Webb (1995).

It appears that the noisy pattern enhances the horizontal diffusion, smoothing out more effectively the velocity field in MOM than in RIAMOM. Consequently, RIAMOM produces more rectified flows on the coastal region, for example, narrower and stronger NKCC/LCC, than MOM.

4. Concluding remarks

In this study, RIAMOM equipped with some new features of numerical schemes such as an energy and enstrophy-conserving advection scheme (the generalized Arakawa scheme) and a slant advection scheme along with a free-surface scheme has been adopted to simulate the circulation of the East Sea/Japan Sea, compared with results from a rigid-lid, centered advective scheme model, MOM, and the GDEM data.

The overall patterns of circulation computed from RIAMOM and MOM have been found to be in good agreement with each other and are, aside from higher

Fig. 11. Instantaneous velocity fields at bottom levels of RIAMOM (left) and MOM (right) in the middle of February. Colors denote bottom topography.

temperatures and lower salinity below 50 m, qualitatively comparable with the GDEM data. The results of RIAMOM are more encouraging in that, compared with the results of MOM, the simulated flows along the Korean/Russian coast are more rectified but less noisy, especially along the sea region where the steep bottom slope exists. This attributes to the inclusion of slant advection effects in RIAMOM, which has been devised by Ishizaki and Motoi (1999). Along with the difference in flow fields, the difference in the distributions of water mass is shown. Differences between the two results are noticeable in the cold water region north of the Subpolar Front where low temperature and lower salinity water is located; the temperature and salinity of RIAMOM are lower by about 0.5°C and about 0.02 psu than those of MOM, respectively. This consequence implies that RIAMOM produces a narrower and stronger NKCC/LCC than MOM does, supplying colder and fresher water to the north of the Subpolar Front region. The presence/absence of the external gravity waves might somehow affect the velocity fields and subsequently the water mass formation but their role appears to be small because the horizontal grid size is not sufficiently fine enough to resolve the narrow shelf. It might be necessary to incorporate tidal motion if the resolution is increased more than three times.

The comparison study has been found to be very encouraging and instructive, but there are many things that need to be improved and clarified in the future. We have not suffered in this study from the overshooting problem of the EKWC. It is believed that use of ECMWF wind data is the main reason for this as noted by Hogan and Hulburt (2000). However, Kim and Yoon (1999) could suppress the overshooting of the EKWC by introducing isopycnal mixing. Both may be causes of this. Thorough analysis will be needed on this matter. The most critical point of the model results (both RIAMOM and MOM) may be the inaccuracy of the water mass calculation. Both models have shown a tendency to overpredict temperature and to underpredict salinity below 50 m, generating more diffusive forms of thermocline and halocline than found in GDEM data. This may be due to uncertainty in heat and salt fluxes at the sea surface as well as the inherent limitations of the model structure. It is important to secure more reliable data sets especially in the northern part of the East/Japan Sea in the future. Regarding the model structure, numerical diffusion might be the source of the inaccuracy. In addition, the assumption of hydrostatic balance may be the prime reason in relation with validity in reproducing the proper intensity of deep convection.

Some brief comments are given on the research direction for the next stage. The most immediate concern is modeling on finer horizontal and vertical grids. Modeling on the 1/12° horizontal grid intervals are in progress and results are expected to be reported soon. Regarding the vertical grids, it is also our concern to allocate fine grids on the thermocline level. Use of a sophisticated turbulence closure for the vertical mixing and incorporation of tidal effects will be pursued in the future.

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