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Embedding an oceanic mixed layer model into an ocean general circulation model of the East Sea (Japan Sea)

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Abstract: The oceanic mixed layer model (OMLM) is coupled with the ocean general circulation model (OGCM) of the East Sea, where the Mellor-Yamada Model is used for the OMLM. The coupled model is used to investigate the impact and the possible improvement achieved by the OMLM with the particular interest in the realization of the SST. The OMLM is found to prevent continuous warming of deep water and to improve convective mixing during the cooling season. On the other hand, the insufficient mixing near the surface, prescribed in the Mellor-Yamada Model, causes the overestimation of the SST during the warming season. It is shown that the problem can be resolved by correcting the surface boundary condition of turbulence. It is also shown that the circulation is not significantly affected by the embedding of the OMLM in the East Sea.

1. Introduction

Recently, substantial efforts are being given to the prediction of the climate system of the earth, in which the ocean plays an important role. Among the many facts of the ocean's role in the climate system, the influence of the sea surface temperature (SST) is most essential. Hence is required the more accurate oceanic mixed layer model (OMLM), as it is indispensable to determine the sea surface temperature (SST) (see, for example; CANE, 1993). Furthermore, the reliable prediciton of the oceanic mixed layer is also important for the various applications including fisheries and underwater telecommunication as well.

A large number of one dimensional models have been developed to simulate the oceanic mixed layer, dealing with only the vertical transport of heat (see, for example; KRAUS, 1988). However, the presence of significant horizontal transport of heat often severely restricts the applicability of one-dimensional models; thus necessitates the three-dimensional mixed layer model including the circulation. The effects are especially important in the equatorial ocean, where intensive studies on such a model have been carried out for the proper prediction of the SST in association with El Niño and Southern Oscillation (ENSO) phenomenon (SCHOPF and CANE, 1983; CHEN *et al.*, 1994; CHANG, 1994).

Heat budget analysis suggests that the horizontal transport of heat owing to the advection cannot be neglected either in the East Sea (KATO and ASAI, 1983). This is also evident from the fact that the satellite images of the SST shows the strong correlation with the circulation patterns such as the propagation of the Tsushima Current flowing in through the Korea Strait (Tsushima Strait) and the location of a front (OSTROVSKII, 1995). It is thus apparent that the three dimensional model is required for the prediction of the mixed layer in the East Sea, too.

On the other hand, the necessity for the proper parameterization of the upper ocean process increases in order to improve the ocean general circulation model (OGCM). The conventional OGCM's, in which constant values of vertical eddy viscosity and eddy diffusivity are used, show many undesirable aspects such as the continuous warming of the deep sea and the inappropriate variations of the SST

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(WASHINGTON *et al*., 1980; SEUNG and YOON, 1995). Moreover, the circulation pattern also appears to be often significantly affected by the inclusion of the OMLM (CHASSIGNET and GENT, 1991; STERL and KATTENBERG, 1994).

There have been several studies in which the embedding of the OMLM into the OGCM is taken into consideration. They applied the OMLM either of bulk model type in which the energy budget of a whole mixed layer is dealt with (ADAMEC *et al*., 1981; ALDERSON, 1990; SCHOPF and CANE, 1983; HENDERSON-SELLORS, 1986; MCGREARY *et al*., 1993; STERL and KATTENBERG, 1994; OBERHUBER, 1993), or of turbulence model type in which the turbulent flux terms are parameterized (ROSATI and MIYAKODA, 1988; NAGAI *et al*., 1992). In general the embedding of the OMLM's of bulk model type has an advantage of smaller computational demand, but has difficulties in adjusting to fixed grids and in describing many phenomena including the formation of a seasonal thermocline. The subject of the simulation was either the global ocean (ADAMEC *et al*., 1981, ALDERSON, 1990; HENDERSON-SELLORS, 1986; OBERHUBER, 1993; ROSATI and MIYAKODA, 1988) or the regional ocean (SCHOPF and Cane, 1983; MCGREARY *et al*., 1993; STERL and KATTENBERG, 1994, NAGAI *et al*., 1992).

From the perspective of investigating the embedding of the OMLM into the OGCM the East Sea also offers an ideal opportunity, since it is endowed with many typical characteristics of the large oceans in spite of the small size. For example, it is a relatively deep ocean as deep as 3700 m, and there appear most of the phenomena characterizing the global ocean such as the western boundary current, the thermohaline circulation and the topographic effects. There have been several cases of investigating the OGCM of the East Sea (SEUNG and YOON, 1995; HOLLOWAY *et al*., 1995; SEUNG and KIM, 1989; KIM and YOON, 1994; YOON, 1982; SEKINE, 1991). However, they all used constant vertical eddy viscosity and eddy diffusivity, and the effects of embedding a mixed layer are still unknown in the East Sea.

Therefore, in this paper the circulation model of the East Sea, into which the OMLM is embedded, is attempted for the purpose of predicting the SST and the three dimensional structure of the mixed layer, while ascertaining the effects of the embedded OMLM on the simulation of the circulation in the East Sea.

The results are examined based on the comparison with the observation data, particularly with the SST data. Based on this analysis the problems in embedding the OMLM into the OGCM is elucidated, and the suggestions are made for the improvement.

2. Model

The OGCM used in this simulation was the GFDL MOM (PACANOWSKI *et al*., 1993) which is originated from the Bryan and Cox Model (COX, 1984), and it was modified for the East Sea in a similar way to KIM and YOON (1994). Figure 1 shows the domain of the model with topography as well as the areas of detailed study which will be discussed in section 3. The total volume transport through the southern inlets (see Fig. 1) was given by an average 2 Sv with the seasonal variation of ± 0.4 Sv; the maximum in August and the minimum in February. The influx was assumed to flow out through the Soya and Tsugaru Straits with the ratio of volume transport 6 : 4. The baroclinic components of the incoming velocity through the southern inlets were determined from the geostrophic flows based on the T, S data obtained from Korea Fisheries Research and Development Agency (1986). As for the boundary conditions of temperature and salinity the observed data were applied in the southern inlets and the open boundary conditions were applied in the Soya and Tsugaru Straits, respectively.

The sizes of horizontal grids were 1/6 degree in both longitude and latitude. The coefficients of horizontal eddy viscosity and eddy diffusivity were taken as 3×10^6 cm^2/s and 1.5×10^6 cm^2/s, respectively. To asses the impact of the OMLM on the OGCM the case without the OMLM were also carried out. In that case the coefficients of vertical eddy viscosity and eddy diffusivity were set to be 1.0 cm^2/s. Vertically 24 layers were used with particular emphasis on the upper ocean process, ranging from 7.5 m

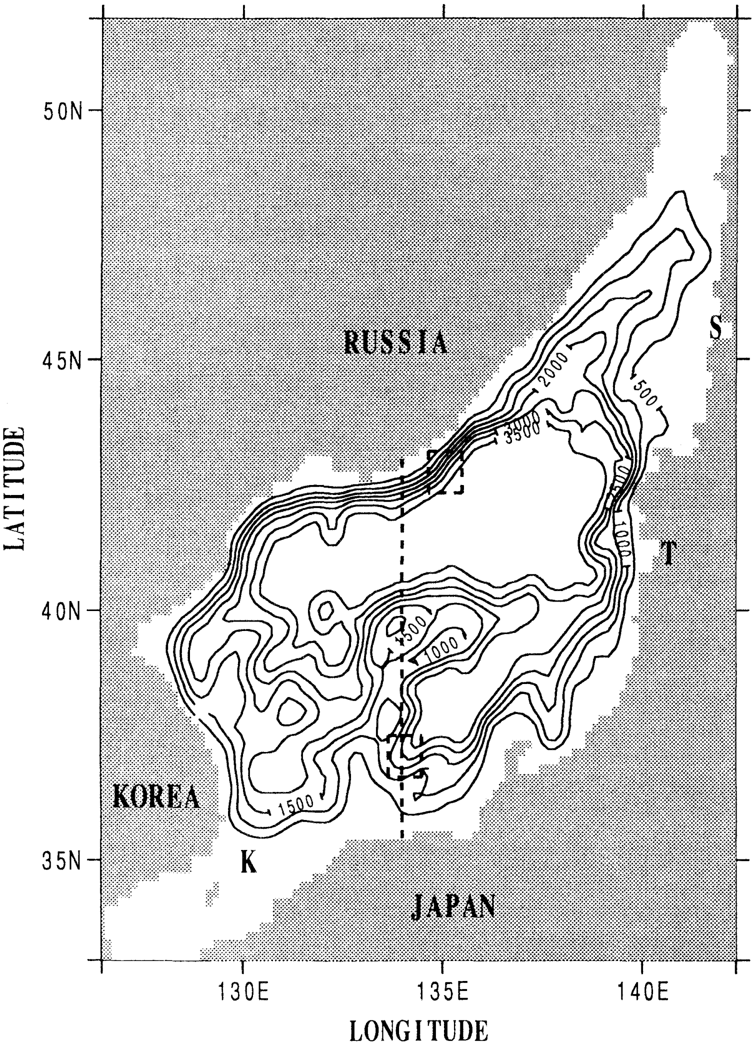

Fig. 1. Model domain with topography. Contour intervals are of every 500 m. The dotted line is the cross section in which the vertical temperature profils are made in Fig. 10, 11 and 12. Two squares represent the regions where the seasonal variations of the SST were calculated to be shown in Fig. 8. Here K represents the location of the Korean Strait, T the Tsugaru Strait and S the Soya Strait, respectively.

at the surface to 900 m at the bottom.

For the boundary conditions at the sea surface, monthly mean values of wind stress by NA *et al.* (1992) and heat flux by HIROSE *et al.* (1996) were used. The data of heat flux Q were not wholly prescribed values, but are given partially in terms of the temperatures of the sea surface T_s and the air above T_a, i.e.,

$$Q=Q_1+Q_2(T_a-T_s) \quad (1)$$

with the prescribed values of Q_1 and Q_2 which vary with position and months. The restoring boundary condition was used for salinity using the observed sea surface salinity data.

The Mellor-Yamada Model of the level 2 and 1/2 was applied as the embedded OMLM (MELLOR and YAMADA, 1982). The Mellor-Yamada Model has been known to have the tendency to insufficient mixing near the sea surface which causes too shallow mixed layers and thus the overestimation of SST (MARTIN, 1985, ROSATI and MIYAKODA, 1988; NOH, 1996).

The Mellor-Yamada Model of level 2 and 1/2 includes the equation for the turbulent kinetic energy (TKE) E as well as the equation for velocity, temperature and salinity. That is

$$\frac{dE}{dt}=F+P_s+P_b-\varepsilon \tag{2}$$

where F is the flux of TKE, P_s and P_b are shear and buoyancy production and ε is dissipation. The surface boundary condition for E was determined by MELLOR and YAMADA (1982) from the assumption that all other terms are negligible except shear production and dissipation near the surface so that

$$P_s-\varepsilon=0 \tag{3}$$

which applies to the case of the turbulent boundary layer near the solid wall such as the atmospheric boundary layer. This gives

$$E=Au*^2 \tag{4}$$

with $A=3.25$, where $u*$ is the friction velocity due to the wind stress. However, in the case of the ocean, in which the surface boundary is not rigid, both the observations(SHAY and GREGG, 1984; GARGETT, 1989) and the results from the recent large eddy simulation (SKYLLINGSTAD and DENBO, 1995) show that the TKE near the surface boundary is much larger in the ocean than in the atmosphere by one order of magnitude. This strongly suggests that (3) cannot be satisfied near the ocean surface. It was also shown by NOH (1995) that a seasonal thermocline cannot be formed during the warming season if the flux of TKE (F) is neglected in (2); thus the SST is overestimated. Based on these facts the surface boundary condition of TKE is assigned using the value ten times larger than that calculated from (3) in the present simulation, i.e., $A=32.5$.

Moreover, the length scale of turbulence l is prescribed as

$$l=\kappa(z+z_0)/(1+\kappa z/l_0) \tag{5}$$

for a given depth z, where z_0 is the surface roughness length scale, κ is von Karman constant and l_0 is the Blackadar length scale (MELLOR and YAMADA 1982). It was assumed that $z_0=0$ by MELLOR and MAMADA (1982) also in the same way as in the atmospheric boundary layer, neglecting the fact that the free surface of the ocean allows large eddies near the surface. This causes strong temperature and velocity gradients in the mixed layer contradicting the observation of the oceanic mixed layer having uniform temperature and velocity profiles, as mentioned by CANE (1994). To rectify this problem a larger value of the length scale was suggested as $z_0=3.5$ m by NOH (1996), and the same value was used in this model.

Since the upper ocean processes are of main concern in this paper, much shorter time scale is required compared to that required for the circulation in the deeper ocean. We carried out the model run for 15 years, which was found to be sufficient to reach the equilibrium in the upper ocean (STERL and KATTENBERG, 1994). Actually major patterns and values with regards to the temperature and the circulation from the simulation did not vary noticeably after 5–6 years as far as the upper ocean is concerned. We present the results based on the comparison among three different simulations; the OGCM without the embedded OMLM (MO), the OGCM with the embedded OMLM whose surface boundary condition for turbulence is modified (MA) and the OGCM with the embeddded OMLM which is the original Mellor-Yamada Model (MB).

3. Results

Figures 2 and 3 show the surface currents from the simulation without the embedded mixed layer (MO) and with the embedded mixed layer (MA) during the warming season of May-June (MJ) and during the cooling season of November-December (ND). Figs. 4 and 5 are the corresponding transport stream functions. Here MJ and ND represent the calculation results at the ends of May and November, respectively. The result from both cases of MO and MA reproduce well the general pattern of the circulation such as the split of the Tsushima Current (TC) to the East Korean Warm Current (EKWC) along the Korean Peninsula and the Nearshore Branch along the Japanese Island (NB), the separation of the EKWC and the eddies along the front following the separation. The seasonal variations in the EKWC, the NB and the North Korean Cold

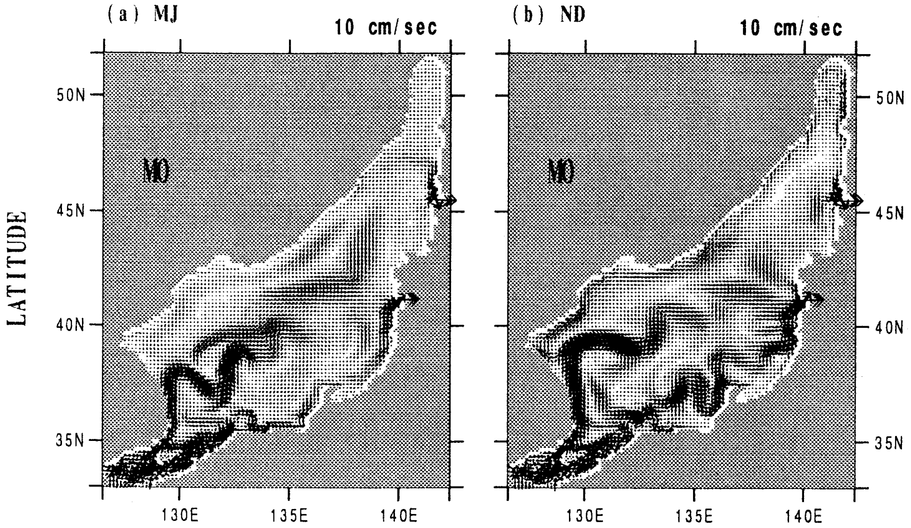

Fig. 2. Surface current velocity fields calculated from MO ; (a) MJ, (b) ND.

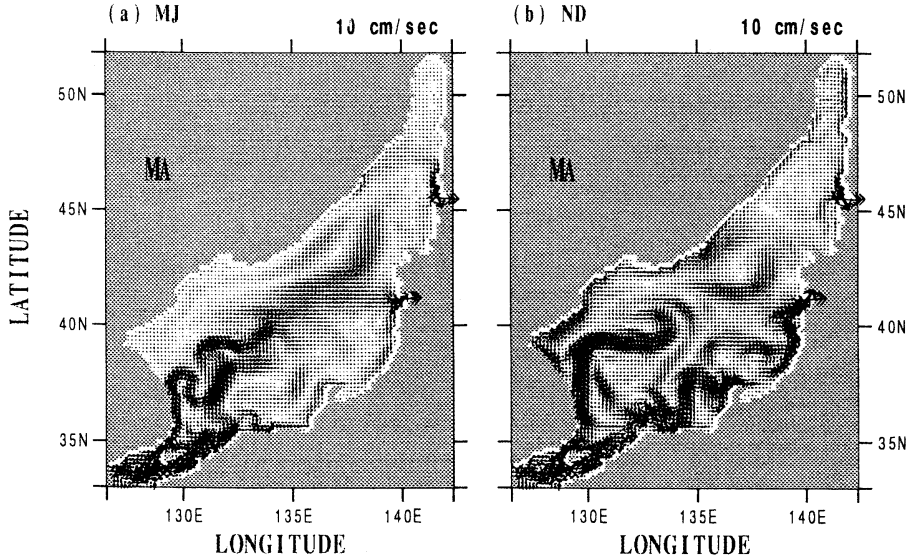

Fig. 3. Surface current velocity fields calculated from MA ; (a) MJ, (b) ND

Current (NKCC) are also in good agreements with the previous results (KIM and YOON, 1994; SEUNG and YOON, 1995). Moreover, the overshooting of the EKWC, which has caused a trouble in many previous models (SEUNG and KIM, 1993; KIM and YOON, 1994; HOLLOWAY *et al.*, 1995), does not occur in both MO and MA. Major difference of the present simulation is that heat flux is used as the surface boundary condition instead of SST. It possibly implies that heat flux boundary condition may produce more realistic temperature profiles below the sea surface, if referred from the fact that the overshooting disappears in the robust diagnostic model in which the observation temperature profiles below the sea surface are maintained (SEUNG and YOON, 1995). More investigation is required, however, for better understanding of the situation.

Meanwhile, the effects of embedding the OMLM into the OGCM are not significant in the circulation. This supports the argument by

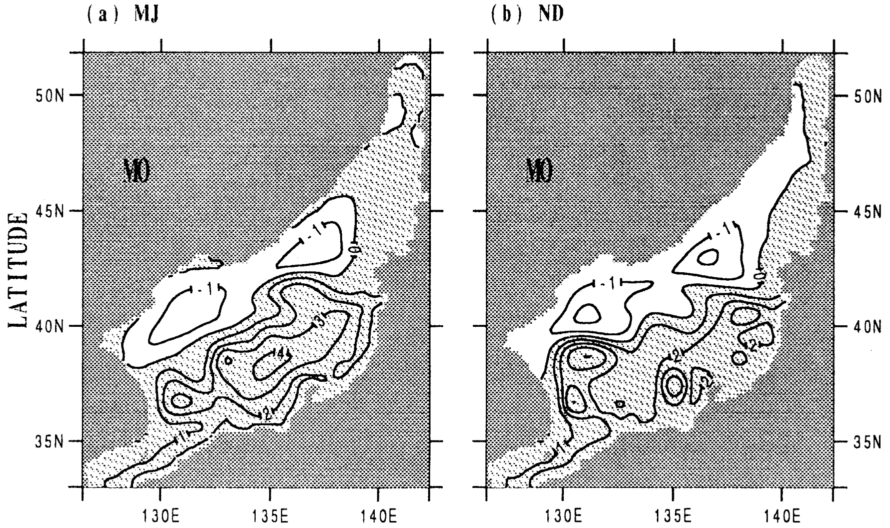

Fig. 4. Transport stream function calculated from MO ; (a) MJ, (b) ND.

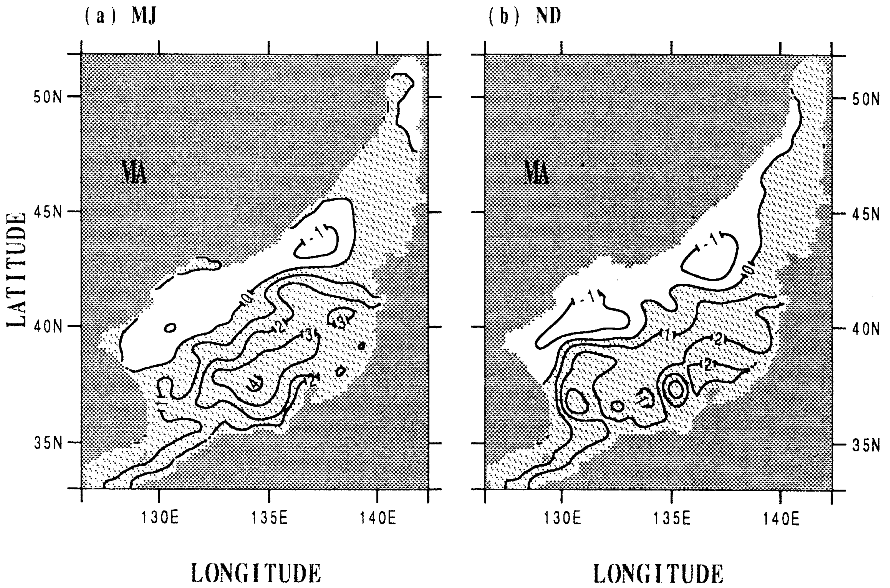

Fig. 5. Transport stream function calculated from MA ; (a) MJ, (b) ND.

HOLLOWAY *et al.* (1995) that the circulation in the East Sea is basically determined by the influx through the Korea Strait, the topography and the wind stress. One minor difference between two simulations is observed near the separation point off the Korean Peninsula where more intensive meandering of the current is observed in MJ in the case of MA, resembling the eddy pattern observed by LIE *et al.* (1995). The result from the OGCM from MB, which is not shown here, also shows very similar circulation pattern as that from MA.

On the other hand, the SST distribution shows significant differences among the simulations MO, MA and MB. Fig. 6 shows the SST distribution in MJ and ND obtained from the observation, and Fig. 7, 8 and 9 show the corresponding results from the simulations of MO, MA and MB. The observation data are from Japan Oceanographic Data Center (JODC). The

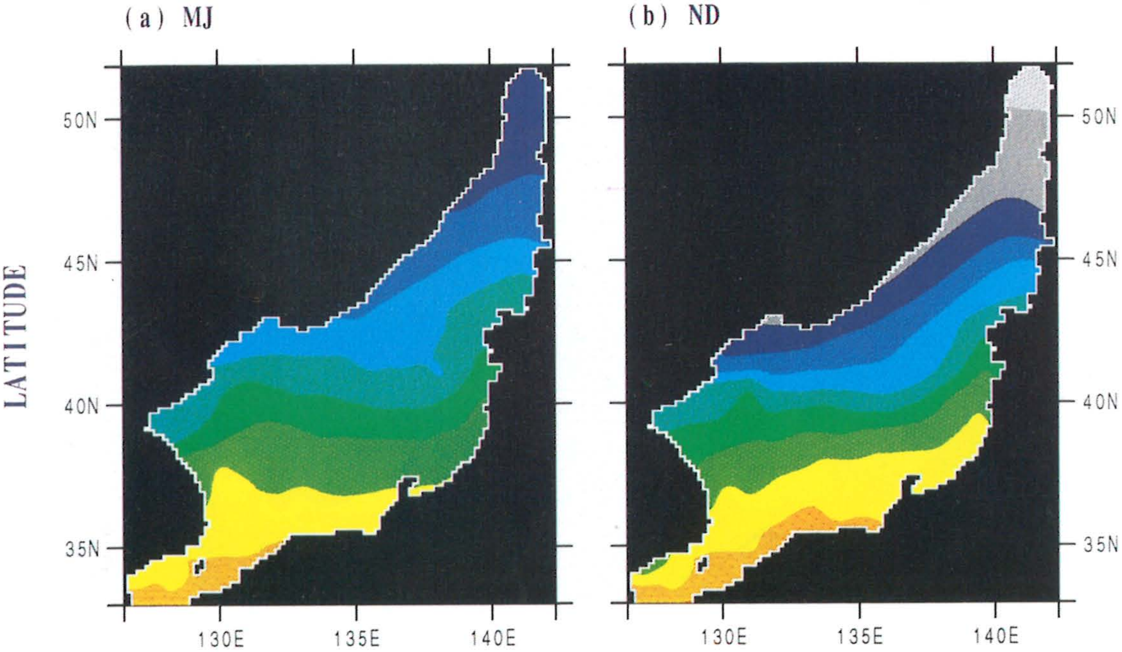

Fig. 6. The distribution of SST from the observation data : (a) MJ, (b) ND.

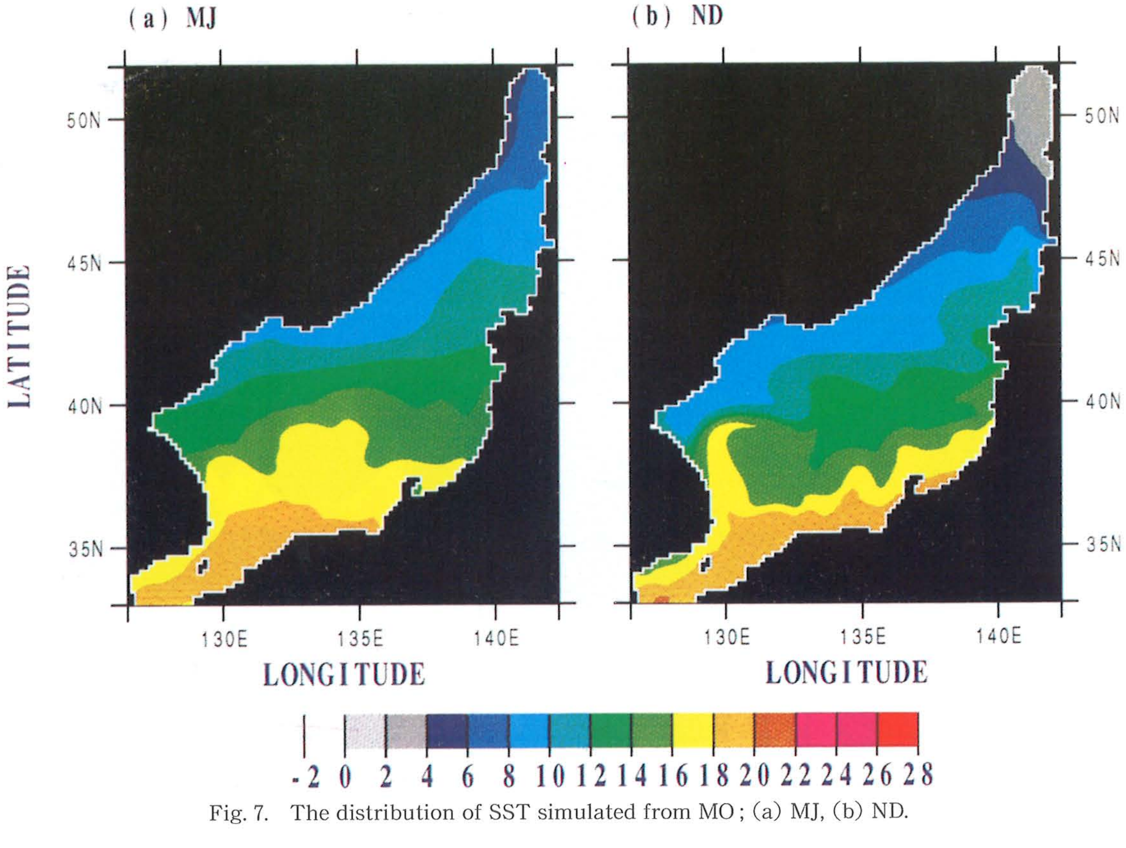

Fig. 7. The distribution of SST simulated from MO ; (a) MJ, (b) ND.

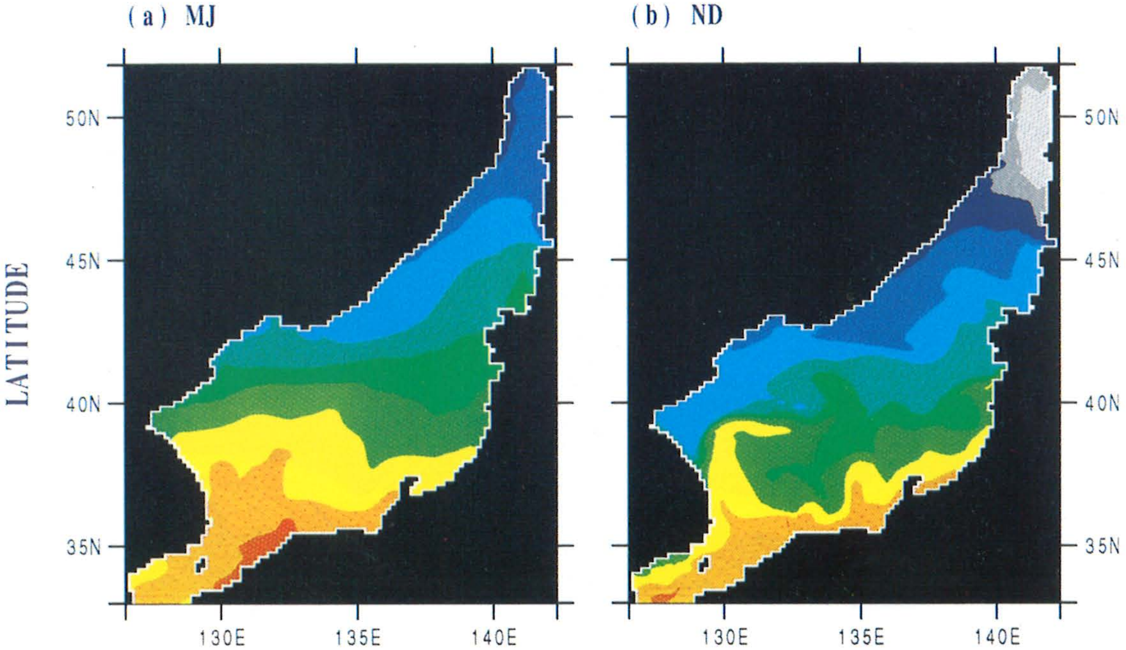

Fig. 8. The distribution of SST simulated MA ; (a) MJ, (b) ND.

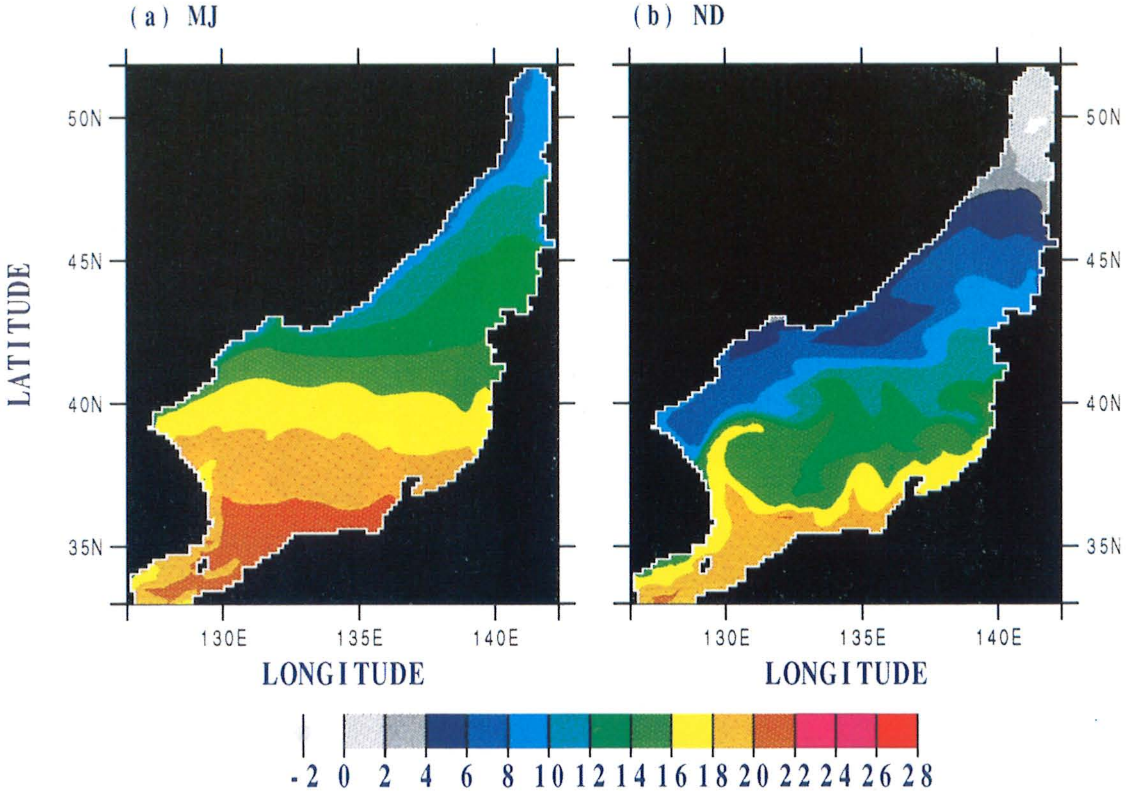

Fig. 9. The distribution of SST simulated from MB ; (a) MJ, (b) ND.

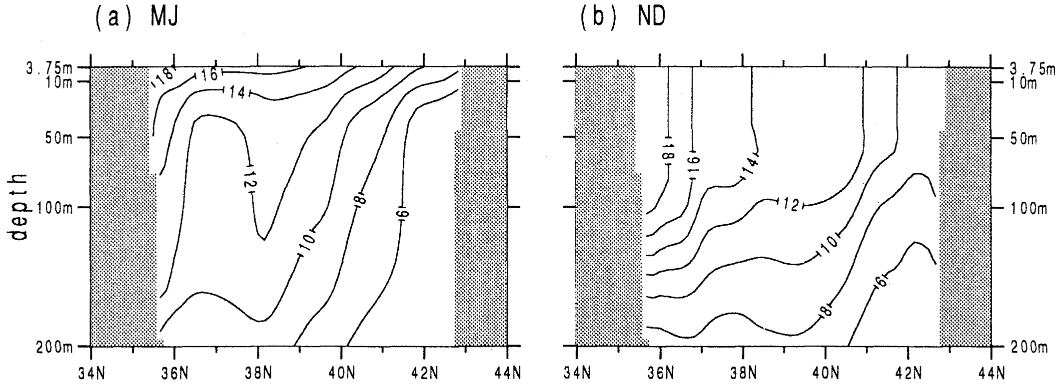

Fig. 10. Vertical temperature distribution along the north-south cross section along the longitude 134 E from MO ; (a) MJ, (b) ND.

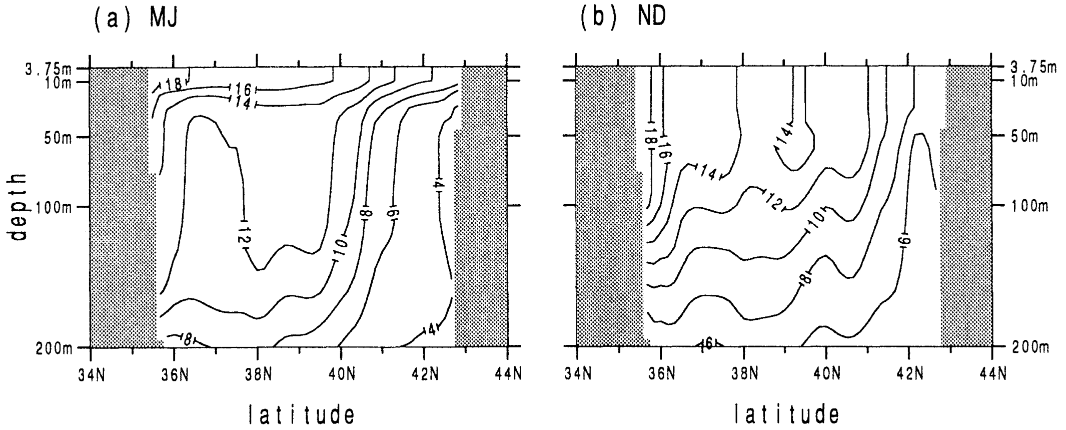

Fig. 11. Vertical temperature distribution along the north-south cross section along the longitude 134 E from MA ; (a) MJ, (b) ND.

most distinguished feature is that during the warming season (MJ) the simulated SST's are generally warmer than the observation data. Particularly, when the original Mellor-Yamada model is used (MB), it causes quite serious overestimation of SST. Meanwhile, the SST in the northern region is not sufficiently cooled during the cooling season (ND), particularly in the case of MO.

Also shown are the vertical distributions of temperature in the north-south cross section at 134E (see Fig. 1) for the cases of MO, MA and MB (Figs. 10, 11 and 12). During the warming season (MJ) the mixed layer is not observed in the cases of MO and MB, while reasonable mixed layers with uniform vertical temperature profiles are reproduced up to about 10–20 m in the case of MA in accordance with the observation (see, for example; KIM, 1994). What is also evident in the case of MO is the strong downward spread of the warm temperature of the upper ocean and the weak convection during the cooling season.

To asses the models in simulating the SST further, the seasonal variations of the SST in the region I and II from the observation and the simulations are made in Fig. 13, representing the most characteristic warm and cold regions, respectively.

The seasonal variation of SST from MO in Fig. 13 shows the cooler temperature during late summer in both regions and the warmer temperature during winter in the northern region (II) in comparison with the observation data and the other simulations MA and MB. The latter appears to be caused by insufficient

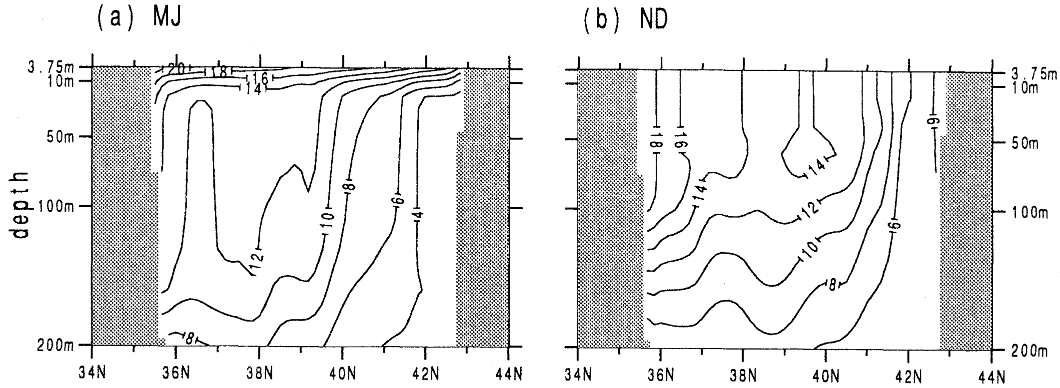

Fig. 12. Vertical temperature distribution along the north-south cross section along the longitude 134 E from MB; (a) MJ, (b) ND.

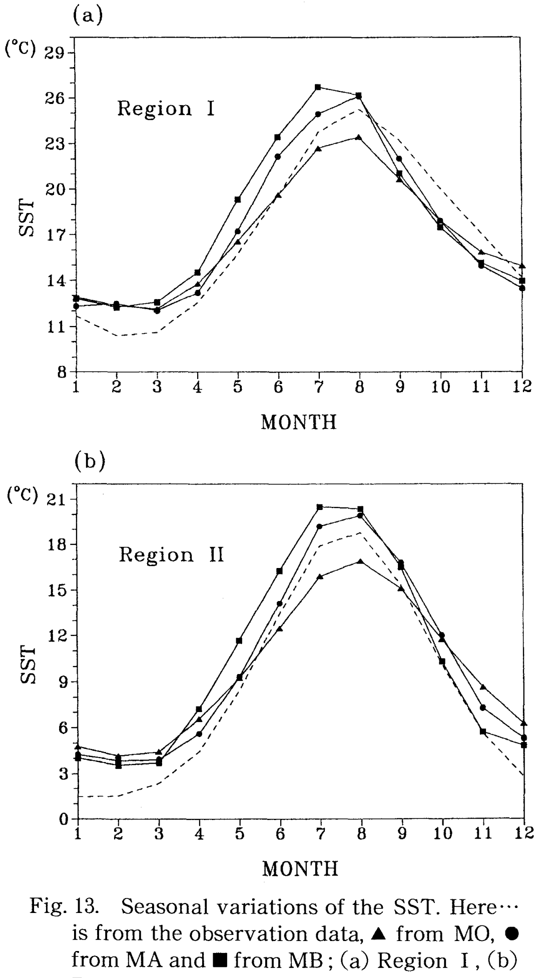

Fig. 13. Seasonal variations of the SST. Here··· is from the observation data, ▲ from MO, ● from MA and ■ from MB; (a) Region I, (b) Region II.

mixing, because only non penetrative convection occurs in this case, whereas the entrainment owing to convective turbulence contributes to the additional deepening of the mixed layer in the presence of OMLM. And the former is caused by the absence of a seasonal thermocline across which the downward vertical heat transfer is prohibited.

In the case of MB, the problem of the overestimation of the SST during the warming season by 2–3 ℃ is a quite serious defect, and it gets even worse with increasing vertical resolution contrary to the expectation. The insufficient mixing under the stabilizing heat flux cannot form a seasonal thermocline in this case as shown by NOH (1995), but leads to the sharp temperature gradients near the surface by prohibiting the downward heat transfer beyond the first layer (Fig. 12). Therefore the received heat is accumulated mostly in the first layer, and thus even higher SST appears with decreasing the thickness of the first layer.

The SST from MA is much improved compared to the case of MB, but it is still slightly warmer than the observation data in MJ. At this point it is not clear, however, whether the remaining overestimation of SST is due to the imperfect mixed layer model or due to the other effects neglected in the simulation such as the penetration of solar radiation and the high frequency wind stress fluctuation.

The discrepancy of the SST's with the observation data during September to November in the southern region (I), which appears in all

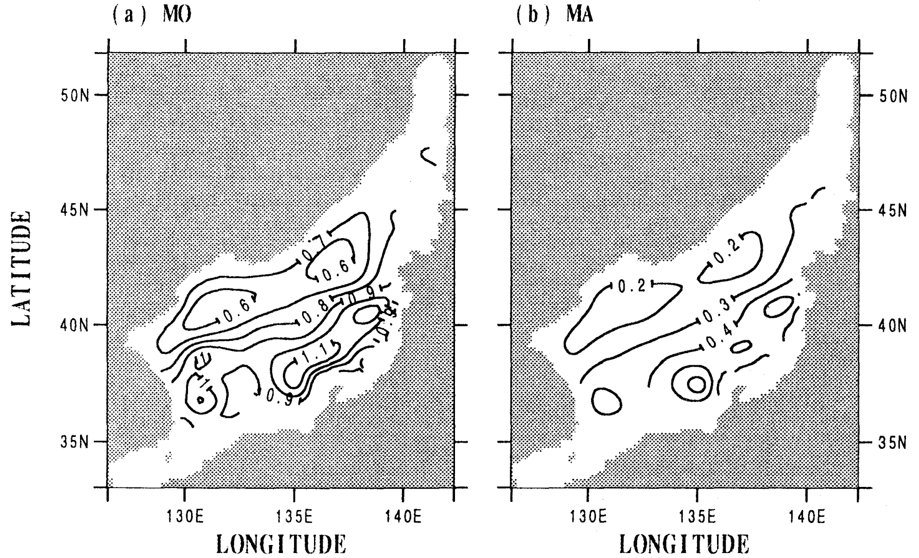

Fig. 14. Horizontal distibution of the annual mean temperature at the depth of 500 m; (a) MO, (b) MA.

three simulations, appears to occur because the southward current following the anti-cyclonic eddy off the Korean Peninsula carries the cold water from north rather than due to the mixed layer dynamics. It is also observed that the SST in the northern region (II) is still too warm during winter, although it is improved by the inclusion of the OMLM. This suggests that the parameterization of the convection process must be improved further.

Another important aspect to be noticed in association with the embedding of the OMLM is that it can prevent the excessive downward heat transfer below the mixed layer. In the OGCM without the embedded OMLM the temperature in the deep sea continues to warm up because of the large constant eddy diffusivity maintained below the mixed layer (SEUNG and KIM, 1993). The situation is much improved by the inclusion of the OMLM. For example, the typical temperature at the depth of 500 m is observed to be about 0.2−0.4℃ (KIM, 1994; MAIZURU Marine Observatory, 1985). The temperature at the same depth is overestimated as 0.6–1.1℃ in the case of MO, while those from MA is correctly 0.2–0.4℃ (Fig. 14).

Finally, it is also noticed that the simulation results of the SST are similar to the instantaneous satellite of the SST at the corresponding time (OSTROVSKII, 1995), rather than the JODC field observation data which was obtained by averaging the data throughout several years, thus filtering out the fluctuation. This suggests that the widely used method of utilizing the observed SST data as the surface boundary condition (SEUNG and YOON, 1995; SEUNG and KIM, 1993; KIM and YOON, 1994; HOLLOWAY *et al.*, 1995) may not be appropriate for high resolution models, in which the meso-scale eddies are resolved, as in this case.

4. Conclusion and Discussion

It has been shown that the embedding of the oceanic mixed layer model into the OGCM for the simulation of the East Sea can produce more realistic SST's and vertical temperature profiles and can prevent excessive downward propagation of heat, while its effect on the circulation is minimal.

It has been also found that the overestimation of the SST during the warming season, which is a common problem in the Mellor-Yamada Model, can be improved by increasing the turbulent kinetic energy and the length scale of turbulence near the sea surface. However, the more accurate surface boundary condition for the turbulence in the mixed layer has to be made in the future study, based on the microscale observations and the better understanding of the dynamics. Furthermore, it must be clarified how important are the impacts of the penetration of solar radiation and the high frequency wind stress fluctuation in the determination of the SST. Meanwhile, the too warm SST in the northern region in winter strongly suggests that the parameterization of convection process must be improved.

Finally, although the computational burden is already quite high in this simulation, the vertical resolution in the upper ocean is rather rough ($\Delta z = 7.5$m at the first layer) to describe various mixed layer phenomena in detail. When the major concern is the upper ocean process as in this case, it is desirable to devise the way of simplifying the deep ocean process without affecting the upper ocean process.

Acknowledgments

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