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Eddy-Resolving Simulations for the Asian Marginal Seas and Kuroshio Using Nonlinear Terrain-Following Coordinate Model

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An eddy-resolving free-surface primitive-equation model with nonlinear terrain-following coordinates is established to study the exchange of water masses among the Asian marginal seas and their adjacent waters. A curvilinear coordinate system is used to generate the horizontal grid with a variable resolution for the regional oceans from 5°S to 45°N and 100°E to 155°E. The higher resolution region has about a 10 km by 10 km grid covering the complex geometry of the coastal marginal seas, while the lower resolution region has about a 30 km by 30 km grid covering the eastern Pacific. The model is initialized by the Levitus annual climitology and forced by the monthly mean air-sea fluxes of momentum, heat, and freshwater derived from the Comprehensive Ocean-Atmosphere Data Set. High-resolution and low-viscosity are identified as the key factors for a better representation of the exchange of waters through narrow straits and passages between the marginal seas and their adjacent waters. The dynamics of the loop currents and eddies in the South China Sea and Celebes Sea are examined in detail. It has found that the anticyclonic loop and detached eddies from the Kuroshio through the Luzon Strait play an important role in transporting warm and salty water into the South China Sea, while the cyclonic circulation of the Mindanao Current in the Celebes Sea plays a role in contributing cold water to the Indonesian throughflow. The deep undercurrent of the western Pacific is shown to provide fresher water to the South China Sea and Celebes Sea. These modeling results suggest that the exchange processes via the narrow straits and passages are of fundamental importance to the maintenance of water masses for the marginal sea region.

Key words: Ocean modeling, S-coordinates, Asian marginal seas, Exchange of water masses

INTRODUCTION

The Asian marginal seas have a highly complex geometry as they are interconnected by a number of narrow straits and passages. These marginal seas include the South and East China Seas (SCS and ECS), Japan Sea, Sulu Sea, Celebes Sea, and the Philippine Sea, interconnected by the Luzon Strait, Taiwan Channel, Makassar Strait, and the Sibutu Passage. The combination of geometry, connectivity with the Pacific and Indian Oceans, and the seasonally reversing monsoon winds contributes to one of the most complicated current systems in the world oceans. As the most energetic western boundary current of the Pacific, the Kuroshio is particularly difficult to simulate with a numerical ocean model due to the different processes and the wide range of time and length scales associated with its dynamics (Hsueh *et al.*, 1997; Su 1998). The circulation pattern and interbasin exchange of water masses in the region have been of great interest because of their effect on the El Nino-Southern Oscillation (ENSO) development and the global thermohaline circulation (Webster and Lukas 1992; Miyama *et al.*, 1995; Metzger and Hurlburt 1996; Morey *et al.*, 1999; Hu *et al.*, 2000). Nevertheless, this regional ocean provides an idealized and challenging area in which one can test ocean model capabilities of simulating an unstable oceanic jet, eddies, and exchange of waters coincident with steep bottom topography and complex geometry.

Most of the previous modeling studies focus on some individual basin of the marginal seas. For example, Pohlmann (1987) used a three-dimensional baroclinic model of the SCS and Java Sea, but the boundary condition at the Luzon Strait has no inter-

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*Corresponding author: song@pacific.jpl.nasa.gov actions with Pacific Ocean and the Sulu Sea was closed. Shaw and Chao (1994), Chao *et al.* (1996), Chu *et al.* (1999) employed the three-dimensional, primitive equation models to investigate the seasonal variations of the SCS circulation. At their open boundaries, bimonthly transport estimates from Wyrtki (1961) were applied. Hsueh *et al.* (1997) focused on the Kuroshio flow-through in the ECS, based on the Bryan-Cox model with a domain between 22°N and 35°N and between 119°E and 135°E. Recently several basin-scale models of the Sea of Japan have been developed. Among those are Hogan and Hurlburt (2000) who used a high-resolution layer model to simulate the general circulation of the Japan/East Sea. Hirose (1999) assimilated the TOPEX/POSEIDON altimeter data into a circulation model of the Japan Sea using an approximate Kalman filter method. Although these studies reveal important features of an individual sea circulation, less information is given on the connectivity among these marginal seas owing to the limitation of their model configurations. Some models overcome this limitation by using large-scale model, but with few vertical layers or with simplified physics. Those studies include Metzger and Hurlburt (1996) who used the 1/5°, 1.5-layer global reduced gravity thermodynamic Navy layered ocean model (NLOM) to study the coupled dynamics of the SCS, the Sulu Sea, and the Pacific Ocean. However, eddy-resolving, three-dimensional, free-surface, primitive-equation model with realistic bottom topography has not been used to study the general circulation of the whole region.

Recently, Li *et al.* (1998) observed a closed current ring near the slope off the Chinese coast in the SCS. The ring is a warm core; anticyclone centered at about 21°N and 117.5°E with a scale of 150 km. Its near surface current is estimated to be about 1 m/s from ADCP measurements and from geostrophic calculations. T-S diagrams show that the water characteristics inside the ring are different from those of the SCS and suggest an origin from the Kuroshio. These observations indicate the formation of eddies might be part of the intrusion process of the Kuroshio. Eddy formations are common features in coastal oceans and have been observed in a variety of locations within the Asian marginal seas (e.g. Fang 1995; Qiu *et al.*, 1990; Fang and Fang 1998). It is not clear what role the eddy plays in balancing water mass for both the marginal seas and the Pacific and Indian Oceans.

The main objectives of this study are to develop an eddy-resolving model based on the nonlinear terrain-following coordinate (**s**-coordinate) ocean model of Song and Haidvogel (1994) and to examine the role of eddies in exchange of water among the Asian marginal seas and the Pacific and Indian Oceans. Recently, the S-Coordinate Rutgers University Model (SCRUM, Song and Haidvogel 1994) has been developed into a parallel version, called the Regional Ocean Modeling System (ROMS, Shchepetkin and McWilliams 2001), which allows to model large area with eddy-resolving resolutions on parallel supercomputers. This is the first time that such a parallel ocean model is applied to the Asian coastal waters. The rest of this paper is organized as follows. In Section 2, we briefly describe the numerical model and its configuration for the Asian marginal seas and the northwest Pacific region. In Section 3, several model results will be reported. Concluding remarks will be provided in Section 4.

THE MODEL CONFIGURATION

The Regional Ocean Modeling System (ROMS) used here is the free surface, primitive equation, finite-volume numerical model based on the nonlinear terrain-following coordinate (**s**-coordinate) of Song and Haidvogel (1994). The **s**-coordinate is an extension to the traditional sigma-coordinate used in the Princeton Ocean Model (Blumberg and Mellor 1987) and is able to provide enhanced resolution at either the sea surface or sea floor, which is a valuable feature for handling steep topography in coastal oceans. Such a nonlinear vertical coordinate system was first used in the S-Coordinate Rutgers University Model (SCRUM) originally developed by Song and Haidvogel (1994). The ROMS is a parallel version of SCRUM with a variety of new features, including the Jacobian schemes of Song (1998) for reducing pressure gradient errors over steep topography, and alternatives for high-order upstream-biased advection, for subgridscale parameterization, and for high performance computing on parallel computers. Examples of applying this model to regional and basin-scale oceanographic problems are referred to Haidvogel *et al.* (2000), Malanotte-Rizzoli *et al.* (2000), and Song *et al.* (2001).

The horizontal grid for the Asian marginal seas and their adjacent waters employs a horizontal curvilinear coordinate system with a variable resolution covering from 5°S to 45°N and 100°E to 155°E. The higher resolution region has about a 10 km by 10 km grid covering the complex geometry of the Asian marginal seas, while the lower resolution region has about a 30 km by 30 km grid covering the western Pacific.

The use of a curvilinear grid allows us to better resolve the narrow straits and passages of the Asian marginal seas, and the eastern boundary of the Pacific Ocean. The underlying bottom topography is extracted from ETOPO5, with a minimum depth of 20 m near the coastal wall and a maximum depth of 5000 m in the deep ocean. The water depth is discretized into 20 levels following the s-coordinate with stretching parameter θ=4 to allow a good representation of the surface boundary layer everywhere in the domain.

Several horizontal mixing operators in curvilinear coordinates are implemented in ROMS, including Laplacian and biharmonic forms for viscosity and diffusivity. Both Laplacian and biharmonic tensors can be rotated to follow the s-coordinate, geopotential and isopycnal levels. The associated mixing coefficients for momentum and tracers can either be constants, grid-size-dependent, or time varying. In this study, the Laplacian rotated to geopotential levels with constant coefficients is used. Small values of horizontal viscosity and diffusivity are used and they are 10 and 2 m^2/s, respectively. The vertical mixing is treated implicitly by the generalized Crank-Nicholson method as described by Song and Haidvogel (1994).

The model starts with the initial condition of annual mean temperature and salinity (Levitus and Boyer 1994, Levitus *et al.*, 1994). The surface forcing is the monthly mean air-sea fluxes of momentum, heat, and freshwater derived from the Comprehensive Ocean-Atmosphere Data Set (COADS) climatology. For the heat flux, a thermal feedback term is applied. The choice of lateral boundary conditions is critical for regional ocean modeling. Two different boundary conditions are used in the model, namely, a close wall condition with no flux across the solid north and west boundaries, and an open boundary condition with a 6-grid wide buffer zone in the south and east. Within the buffer zone, model temperature and salinity are relaxed towards the monthly climatology with relaxation time scale ranging from 2 days to 30 days near the outer edges. More detail description of the open boundary can be found in Macheillo *et al.* (2001).

MODEL RESULTS

The model has been run for 3 years from a state

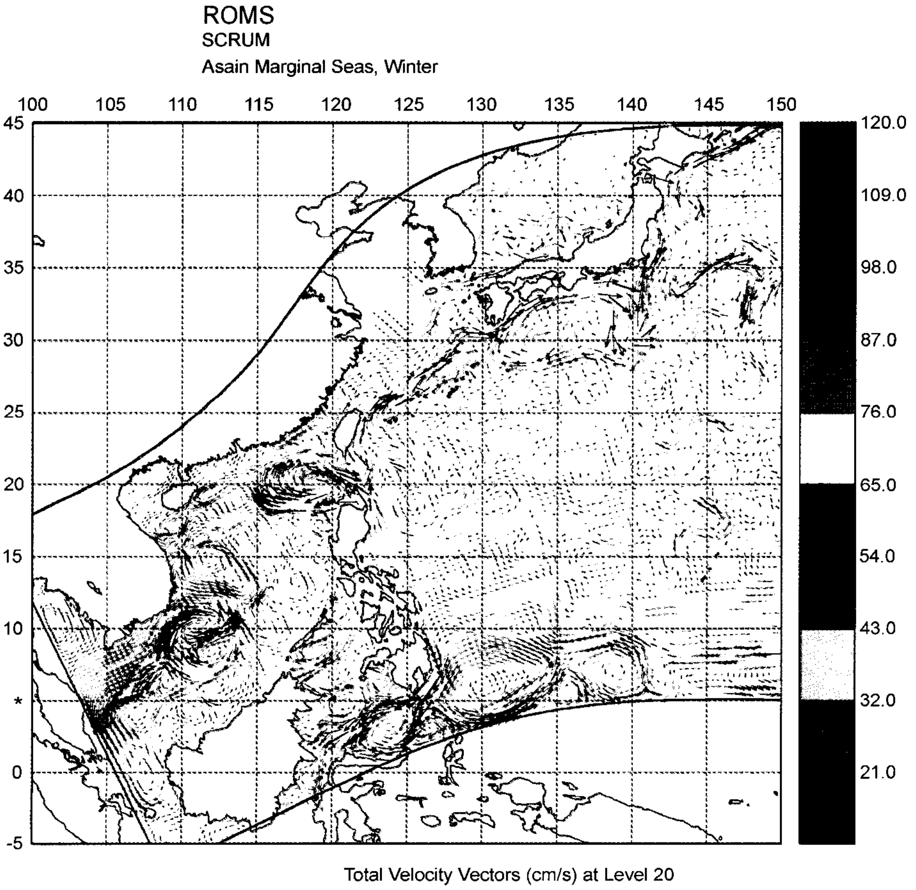

Fig. 1. Surface velocity field in summer. Color bars are speed units in cm/s.

of rest to reach a dynamical quasi-equilibrium. Some of the modeling results from the last year run are analyzed and presented below.

Surface layer circulations

The circulation pattern in the surface layer of the marginal seas is better studied (e.g. Wytki 1961; Shaw 1991; Hsueh *et al.*, 1997; Su and Lobanov 1998) than those in the deep layers. The general agreement of these previous studies is that the overall upper-layer circulation pattern is mostly driven by the seasonally reversing monsoon winds that are northeastly in winter and southwestly in summer. To examine the seasonal variations, we present the surface circulation from the model run in both winter and summer season in Fig. 1 and 2, respectively. Both results show that the North Equatorial Current bifurcates at the eastern Philippines coast to form two major boundary currents: the northward flowing Kuroshio and the southward Mindanao Current (MC). The bifurcation point is located at about 13°N, consistent with the observational estimations of Wyrtki (1961) and Toole *et al.* (1990). However, the Kuroshio seems stronger in summer than in winter, while the MC seems stronger in winter than in summer. These results are in agree with the monsoon winds as the southwestly summer winds intend to strengthen the northward Kuroshio and the reversal winter winds intend to strengthen the southward MC.

After leaving the northern part of the Philippine coast, the northward Kuroshio flows along a deep ridge that connects Luzon and Taiwan. The ridge serves as a sill between the Philippine Sea and the SCS. The sill is about 2000 m depth and is the only connection between the SCS water to the north Pacific water through the Luzon Strait. Model results in winter (Fig. 1) show that the Kuroshio crosses the sill entering the SCS on a northwest trajectory and makes a loop before exiting the SCS just south of Taiwan. Part of the loop current flows far west into the SCS and some of the water enters the Taiwan Strait and becomes a part of the South China Sea Warm Current (SCSWC). The formation of the loop current indicates that water from the Pacific Ocean intrudes into the SCS as observed by Nitani (1972) and Li and Wu (1989). However, in summer season (Fig. 2), there is no persistent intrusion loop current

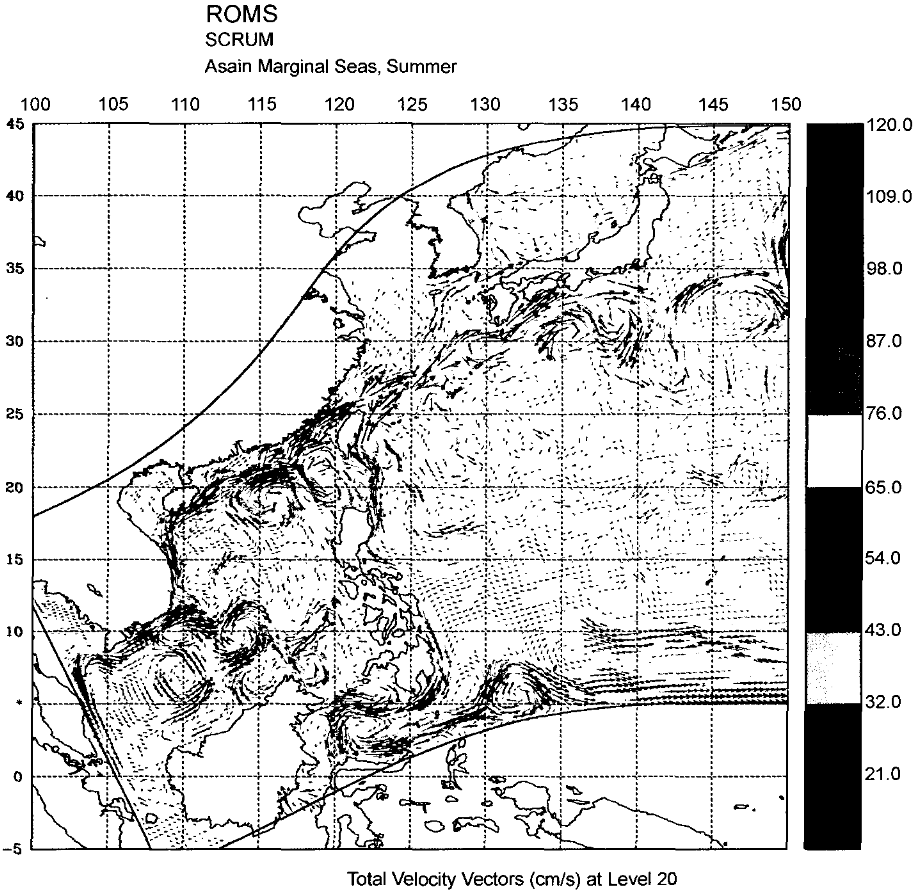

Fig. 2. Surface velocity field in winter. Color bars are speed units in cm/s.

to the SCS. The meandering Kuroshio forms an anticyclonic eddy in the SCS, which is at the same location of the observed warm-core ring of Li *et al.* (1998). The separated eddy drifts to the west for few weeks before mixing with the SCS water or joining the SCSWC. Clearly, the formation of detached eddies is an important process of transporting Pacific water mass to the SCS. The T-S characteristics analyzed by Li *et al.* (1998) support the hypothesis.

Traditionally, the Kuroshio is considered to enter the ECS through the so-called East Taiwan Channel between Taiwan and Yonakunijima Island, at the western tip of the Ryukyu archipelago (Nitani 1972; Johns *et al.*, 1997; Su 1998), while the SCSWC enters the ECS through the Taiwan Strait. The model results in Fig. 1 and 2 confirm the traditional view and show that the SCSWC is strong in summer and weak in winter due to the seasonally reversing monsoon winds. This seasonal variability is consistent with observations (Hu *et al.*, 2000). Together, the SCSWC and the Kuroshio form a broad current meandering along the continental shelf break of the ECS with complicated nonlinear recirculation gyres. These patterns suggest that strong flow-topography interactions are to be expected as the Kuroshio passes over the topographic ridges of the Ryukyu archipelago. The Kuroshio further bifurcates at around 30°N (Hsueh *et al.*, 1997), a small part of the flow on the left-hand side of the Kuroshio becomes the Tsushima Current entering into the Sea of Japan (Fang 1995), while the rest flows eastward out of the ECS through the Tokara Strait. The Kuroshio continuously flows northeastward along the Japanese coast. Meanders, eddies, and recirculation gyres are the dominant features. Finally it turns eastward and separates from the coast at about 35°N to the Pacific Ocean.

Flowing opposite the direction of the Kuroshio, the southward MC off the east coast of Philippine forms the Mindanao Eddy northeast of the Celebes Sea. Part of the MC water enters the Celebes Sea to form cyclonic circulations in the basin and retroflects eastward to join the meandering North Equatorial Count Current. The deep Celebes Sea has three opens, east to the Pacific, north to the Sulu Sea, and south to the Makassar Strait. The Makassar Strait is the main connection between the Pacific and Indian Oceans. It is known that the main source of the Indonesian throughflow within the Celebes Sea and the Makassar Strait comes from the North Pacifics MC, as shown by the water mass characteristics of Gordon (1995). Unlike the Kuroshio intrusion through the Luzon Strait, the MC forms a basin-wide cyclonic circulation within the Celebes Sea. Similar circulation patterns are also observed in an ocean general circulation model of Masumoto *et al.* (2001). As cyclonic circulation causes upwelling, the water within the Celebes Sea is colder than its surrounding waters and flows southward via the Makassar Strait to form the Indonesian throughflow. This circulation pattern suggests that the upwelling may play an important role in exchange water masses between the Pacific and Indian Oceans.

Deep layer circulations

As topography is one of the most important factors in controlling oceanic circulation, especially for coastal oceans and marginal seas, its representation in numerical models must be as accurate as possible. In this model, we have used the nonlinear terrain-following coordinate system of Song and Haidvogel (1994) to resolve the bottom topographic variations. Bottom layer circulation at 1000 m depth is shown in Fig. 3. As the model results in winter and summer are similar, only the summer result is given. The results clearly show the deep western boundary current (DWBC) along the slope of the western Pacific carrying ventilated waters equatorward. The flow is an undercurrent and is strongly constrained by the bottom topography. The path of the DWBC in the region is complex and includes recirculation gyres with spatial scales ranging from a few hundred kilometers to nearly basin scale. Its existence in North Atlantic and its role in maintaining a balanced meridional circulation have been studied extensively (e.g., Dickson and Brown 1994, Johns *et al.*, 1997), but the undercurrent is rarely studied for the Pacific. The DWBC associated with the Asian marginal seas can be divided into three parts. The first part flows southwest along the deep slope of the Ryukyu archipelago in the Pacific. It enters the SCS via the Luzon Strait to form a loop circulation. Clearly, deep North Pacific waters are transported to the SCS by the current. The second part of the undercurrent flows south along the east slope of Philippine and forms a loop in the eastern Celebes Sea. The third part meanders eastward to join the Equatorial undercurrent. Observational data for the DWBC is very limited; therefore, it is difficult to compare the model results with observations. On the other hand, the model run is still too short to confirm the deep layer circulations. We plan

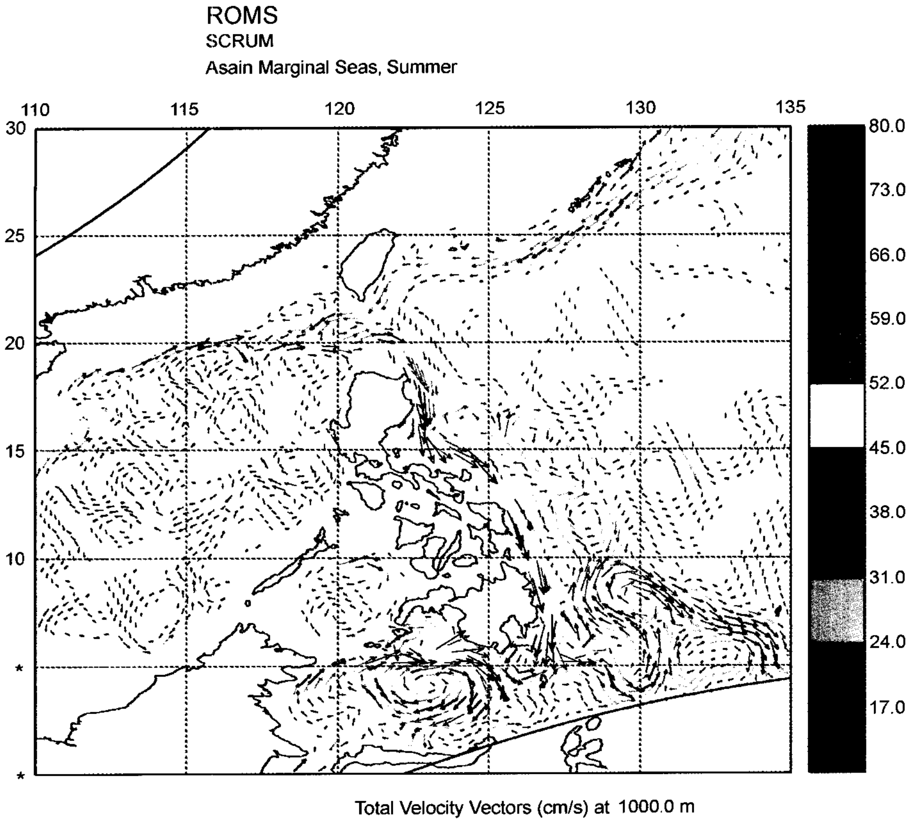

Fig. 3. Bottom velocity field at 1000 m in summer. Color bars are speed units in cm/s.

to use accelerating method for the deep layers in future runs.

Water exchanges between asian marginal seas and pacific

There are at least four major pathways for water exchanges between the Asian marginal seas and the Pacific: the eastern opening of the Celebes Seas, the Luzon Strait to the SCS, the Ryukyu archipelago to the ECS, and the Tsushima and Tsugaro Straits to the Sea of Japan. Here, we concentrate our study on the SCS and the Celebes Sea and present the model results of temperature and salinity for the local region at depth 200 m and 1000 m in Fig. 4.

The Celebes Sea is the major pathway for the Indonesian throughflow, which provides the only inter-basin exchange of water at low latitudes from the Pacific to the Indian Ocean. It is known that the throughflow plays an important role in ENSO development as it alters the Indonesian warm pool water (Webster and Lukas 1992). The magnitude, composition and variations of the throughflow are key elements in the thermohaline balance of the Pacific and Indian Oceans, and perhaps even in global thermohaline circulation (Masumoto and Yamagata 1996). Several studies have been carried out to determine the relative contributions to the throughflow from the saline South Pacific and the fresher North Pacific (e.g., Godfrey *et al.*, 1993; Wajsowicz 1993; Gordon 1995; Morey *et al.*, 1999). The temperature and salinity at depth 200 m and 1000 m in Fig. 4 show a tongue of low-salinity and cold water stretching west from the Pacific through the Celebes Sea suggests that this water mostly originates in the North Pacific. The water mass at 200 m in the Celebes Sea and Makassar Strait has a T-S property of 13°C and 34.60 ppt in the summer, about 4°C colder than the water at the same depth in the Sulu Sea. The cold-core at the center of the Celebes Sea indicates the cyclonic circulation pattern, which causes upwelling. The water mass at 1000 m near Halmahera Island has a T-S property of 4°C and 34.48 ppt, which is clearly from the DWBC along the eastern Philippine coast. Our hypothesis is that the MC branch retroflects into the Selebes Sea and forms cyclonic circulations. As a consequence, it causes upwelling of deeper cold water to the surface layer and transport relative cold water through the shallow Makassar Strait to Indian Ocean.

The SCS is the largest marginal sea in the Southeast Asia. It has a central deep basin with a maximum

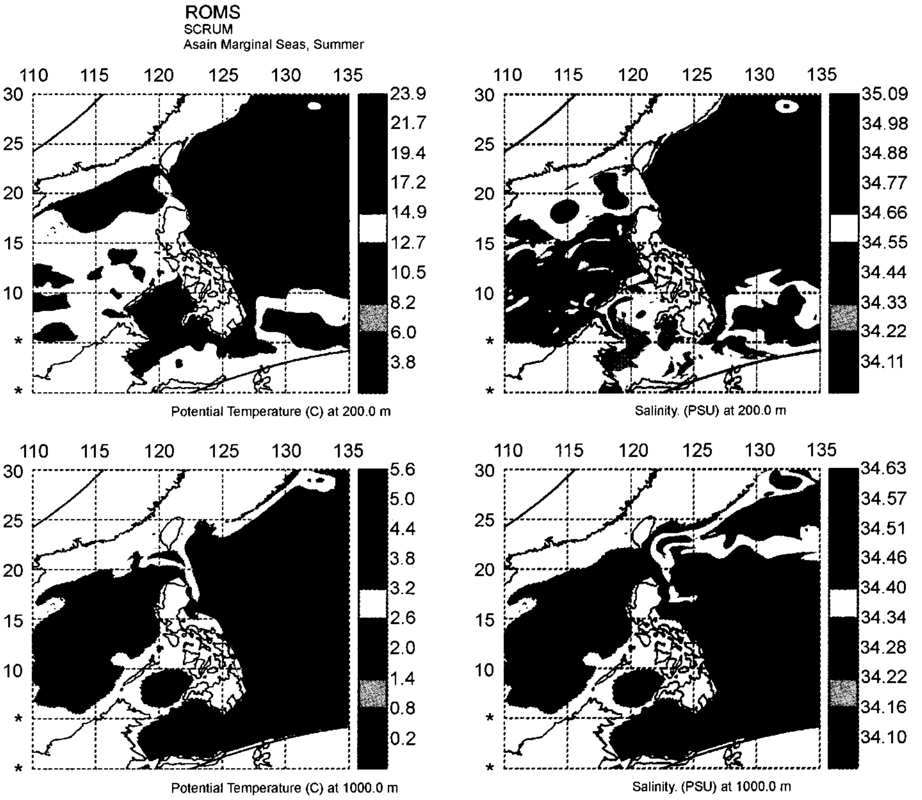

Fig. 4. Temperature (left panels) and salinity (right panels) at 200 m (upper panels) and 1000 m (lower panels).

depth 5000 m, bordered by two broad shelves shallower that 200 m in the northwestern and southwestern sides. Water masses in the basin can be traced to the waters in the western North Pacific: the deep water below 2000 m in the SCS is similar in T-S characteristics to the Pacific Deep Water (Nitani 1972), while the water above the thermocline is produced by mixing of the Pacific waters with coastal waters (Shaw 1989, 1991). Huang (1983) suggested that both eastward and westward currents are alternated spatially in the Luzon Strait and the maximum westward net transport (0–1200 db) occurs in winter, the medium in spring and the minimum in summer. Shaw and Chao (1994) pointed out that the water exchange between the SCS and the Pacific is mostly concentrated on the upper 300 m of the water column in the Luzon Strait. These studies clearly suggest that the Kuroshio strongly affects the water mass and circulation pattern in the SCS. However, it still remains unclear how the Kuroshio intrudes the northern SCS through the Luzon Strait. Our model results in Figs. 1–4 indicate that the water exchange between the SCS and the Pacific Ocean can be happen in the whole water column of the Luzon Strait. Particularly, Fig. 4 shows that warmer and salty water is transported to the SCS by the Kuroshio loop and ring in the 200 m depth, while cold and fresher water is transported to the SCS by the DWBC. The two anticyclonic rings at 200 m, one centered at about 115°E, 18°N and another at about 118°E, 20°N off the continental slope off Chinese Guangdong, have the same T-S characteristics of the Philippine water, suggesting an origin from Kuroshio as reported by Li and Wu (1989) and Li *et al.* (1998). In contrast to the 200 m level, the intrusion water at 1000 m, carried by the DWBC, comes far north on the continental slope of Japan as indicated by the temperature and salinity characteristics. This complicated intrusion water from Pacific should have profound impacts on the heat, salt, and energy budgets of the SCS (Shaw and Chao 1994).

To examine the vertical structure of these water exchanges, we also present a cross-strait section from the model results in Fig. 5. The vertical section is along the line from the point (125°E, 0°N) to the point (120°E, 5°N), which crosses the eastern Celebes Sea and Luzon Strait. The upper panel is the temperature and the lower panel is the zonal velocity. The temperature structures show that the isotherms concave up across eastern Celebes Sea and concave down across the Luzon Strait. The thermocline concaves up or down about 150 m. These results clearly

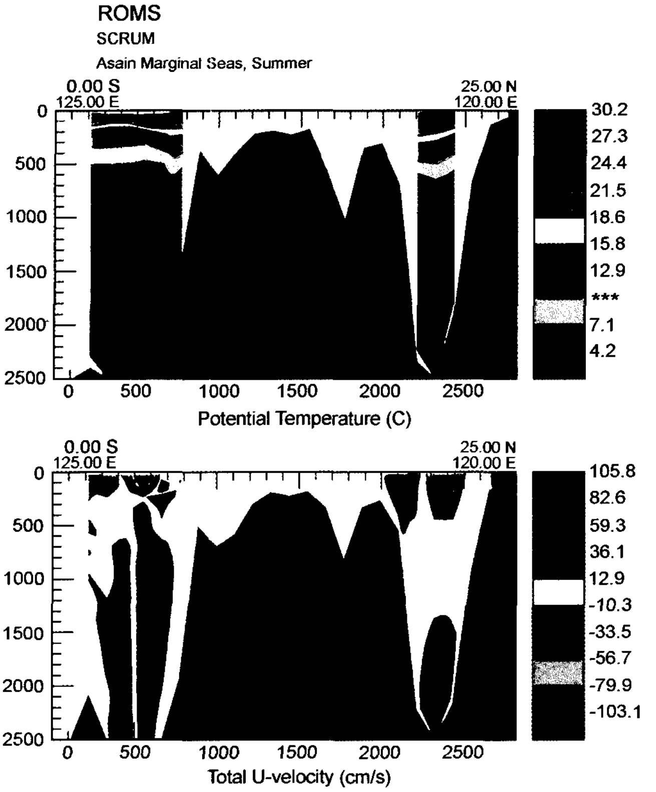

Fig. 5. Vertical section from (125°E, 0°N) to (120°E, 5°N) through the eastern Celebes Sea and Luzon Strait: upper panel is temperature and lower panel is zonal velocity.

suggest upwelling in the Celebes Sea and downwelling near the Luzon Strait. The surface layer zonal velocity shows an inflow in the northern side and an outflow in the southern side of the Celebes Sea. This feature indicates a cyclonic circulation in Celebes basin and is consistent with the upwelling temperature structure. On the contrary, the surface layer velocity in the Luzon Strait shows an inflow in the southern side and an outflow in the northern side of the cross-section. This feature indicates the cyclonic loop current or eddy is from Kuroshio, consistent with downwelling temperature structure. However, the bottom layer velocities in the two cross-sections are different. The bottom inflow and outflow in the eastern Celebes Sea are in the opposite directions of their surface layer, while the bottom flow in the Luzon Strain is mostly westward. These bottom layer circulations are consistent with the DWBC of the northwestern Pacific. In summary, the water exchanges between the marginal Seas and the Pacific are mostly influenced by the large-scale circulations of the Kuroshio, the MC, and the DWBC of the Pacific Ocean.

CONCLUSIONS AND DISCUSSION

It is demonstrated that the regional ocean model, ROMS, has the capability of handling one of the most complex regions of the world oceans. High-resolution and low-viscosity are identified as the key factors for a better representation of the exchange processes of waters through narrow straits and passages between the marginal seas and their adjacent waters. The dynamics of the loop currents and eddies in the SCS and Celebes Sea is examined in detail. Model results show that the anticyclonic loop and eddies, result of the Kuroshio intrusion through the Luzon Strait, play a role in transporting Pacific warm and salty water into the South China Sea, while the cyclonic circulation in the Celebes Sea plays a role in contributing cold water to the Indonesian throughflow. The deep western boundary current (DWBC) of the Pacific Ocean is found to provide fresher waters to the SCS and the Celebes Sea. However, it is not clear how much the eddy, Kuroshio, and DWBC contribute to the water mass of the SCS water and the Indonesian throughflow. The future study will focus on model-data comparisons to identify the critical dynamical processes responsible for the modeled circulation patterns.

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