Numerical Simulation of the Regional Ocean Circulation in the Coastal Areas of China①

Zhang Yaocun (张耀存) and Qian Yongfu (钱永甫)
Department of Atmospheric Sciences, Nanjing University, Nanjing 210093

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ABSTRACT

The regional ocean circulation in the coastal areas of China (including a part of the western Pacific Ocean, the South China Sea and the Bay of Bengal et al.) is simulated by using the improved Princeton University ocean circulation model (POM). Compared with the modeling results obtained by the large-scale ocean general circulation model (OGCM), the basic ocean circulation features simulated by the regional ocean circulation model are in good agreement with that simulated by OGCM and some detailed characteristics such as the regional ocean circulation, sea temperature, salinity and free sea surface height have also been obtained which are in good accord with the observations. These results indicate that the regional ocean circulation model has good capability to produce the regional ocean circulation characteristics and it can be used to develop coupled regional ocean-atmospheric model systems.

Key words: *Numerical simulation, Regional ocean circulation, Coastal areas of China*

1. Introduction

In recent years, many studies on the mechanism of the regional climate formation and variation have been done by using nested high-resolution regional climate models. The regional climate models have presented better performances in simulating regional climate features than large-scale general circulation models (GCM) because of the accurate representations of high-resolution topography, detailed underlying surface characteristics, land surface processes and planetary boundary layer parameterization. However, the ocean part within the model domain has been treated simply, by only taking into account the thermal effect of the ocean, with no effect of the ocean circulation. In fact the ocean circulation in the coastal areas such as the East China Sea and the South China Sea can also influence the regional climate formation, change and prediction. Therefore it is of significance to develop coupled regional climate model systems for improving the capability to simulate and predict regional climate changes over the eastern Asia and for studying the effects of the ocean circulation in the coastal areas on the regional climate.

The improved regional ocean circulation model developed in the Princeton University (POM) has been used to simulate the ocean circulation in the coastal areas including a part of the western Pacific Ocean, the South China Sea (SCS) and the Bay of Bengal et al. and to evaluate the model performance to simulate the coastal ocean circulation in preparation for developing coupled regional ocean-atmosphere model systems.

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2. Brief description of the regional ocean circulation model

The regional ocean circulation numerical model (POM) was designed by Blumberg and Mellor in the Princeton University (Blumberg and Mellor, 1983, 1987), then improved by Chu et al. and Qian et al. (Chu, et al., 1996; Chu, et al., 1997; Qian, et al., 1998). This model is characterized by treating the topography of the ocean bottom and can successfully simulate the coastal ocean circulation such as the Gulf stream and becomes one of the most widely applied ocean circulation models in the world. The POM has the following features: (1) horizontal curvilinear coordinates and an "Arakawa C type" staggered grid point system, (2) sigma coordinates in the vertical direction with the hydrostatic and Boussinesq approximations, (3) a free sea surface, (4) a real bathymetry, (5) a second–order turbulence closure scheme for the vertical diffusion, and (6) horizontal diffusivity coefficients calculated by the Smagorinsky parameterization scheme. In order to economize the integration time and increase the model stability, barotropic and baroclinic modes are separated in POM and different time steps are adopted for numerical integration of the ocean circulation model, in which the time step is 60s for the barotropic mode and 2400s for the baroclinic mode. The model domain is 70–140°E, 5°S–45°N with $1^\circ \times 1^\circ$ horizontal resolution and 10 sigma coordinate levels, which includes a part of the western Pacific Ocean, the South China Sea and the Bay of Bengal.

It is very important for a regional ocean circulation model to deal with the lateral boundary conditions but an appropriate treatment on the lateral boundary conditions is quite difficult at present due to the lack of the ocean circulation observation. For the convenience of the treatment on the lateral boundary conditions, the daily temperature and salinity on the lateral boundary are provided by interpolating the monthly mean temperature and salinity data obtained by Levitus to each day and the non–gradient extrapolation method is used to give the lateral boundary condition of the ocean current. The atmospheric forcing includes wind forcing and thermodynamic forcing. The monthly mean climatological wind stress data set obtained by Hellerman and Rosenstein is interpolated linearly in time to provide the daily wind stress data for individual days. The thermodynamic forcing consists of the solar short–wave radiation, infrared long–wave radiation, sensible heat flux and latent heat flux which are calculated by simple empirical methods. The seasonal variation of the solar radiation is taken into account. The effects of the model precipitation i. e. the fresh water flux on the salinity are not included in the present regional ocean circulation model.

3. Experiment design and preliminary results

In order to simulate the coastal ocean circulation and the temperature and salinity conditions, the model was initialized by the monthly mean temperature and salinity of Levitus and was driven by the monthly mean wind stress data of Herllerman and thermodynamic fluxes described above. The total integration time is 3 years, during which the annual climatological forcing is repeated for three cycles. The model reached a quasi–equilibrium state in the third year. The third year's output of the seasonal mean ocean current, temperature, salinity and free sea surface height in winter, spring, summer and autumn respectively will be analyzed compared with the other modeling results.

3.1 *Free sea surface height*

In the tropical Pacific Ocean area, the height of the sea surface is higher in the west than in the east due to the action of the western land boundary and the easterly trade wind, leading

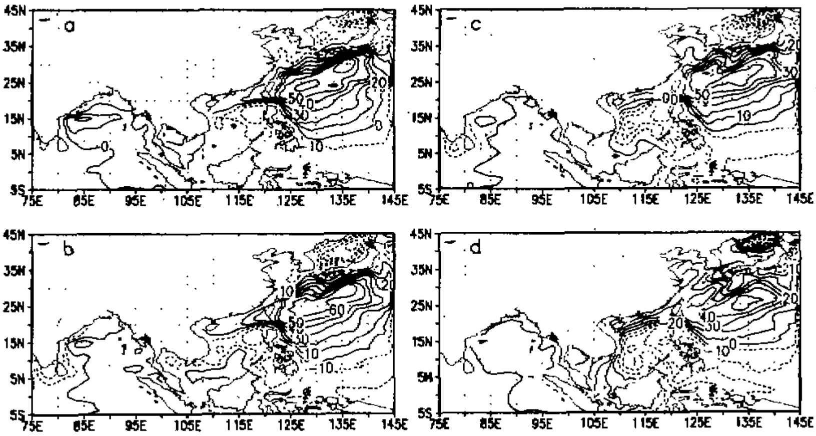

Fig. 1. The simulated free sea surface heights in spring (a), summer (b), autumn (c) and winter (d).

to the balance between the east–west pressure gradient and the sea surface wind stress. Because of the seasonal variations of the wind stress, the fluctuation of the sea surface height induced by wind field also has seasonal changes correspondingly. Fig. 1 shows the simulated free sea surface heights in spring, summer, autumn and winter respectively. It is found from Fig. 1 that a positive fluctuation of the sea surface heights appears in the subtropical region from the east of Taiwan to the south of Japan in all seasons, with a maximum of about 60 cm in summer and autumn located in the east of Taiwan Island, and the difference of the sea surface height between summer and winter in this region is about 10 cm. A positive fluctuation of the sea surface height occurs in the north part of the South China Sea and a negative fluctuation in the south part of the South China Sea in every season, and a little seasonal change appears in these regions. In the Japan Sea, a negative fluctuation exists in four seasons, with a low sea surface height in summer and autumn. In the Bay of Bengal, a positive fluctuation occurs in spring and winter and a negative fluctuation appears in the coastal region of the Bay of Bengal in summer and autumn with a maximum fluctuation in summer, in which the seasonal difference and value is small, Compared with results modeled by large–scale ocean circulation model, the fluctuation obtained in this paper in the western Pacific region is in good agreement and the sea surface height in the coastal region is also well simulated, which cannot be resolved in large–scale models (Zhang et al, 1991; Zhang, 1995).

3.2 *Ocean currents*

The surface ocean currents in spring, summer, autumn and winter in the model domain are given in Fig. 2. Compared with results modeled by large–scale ocean circulation models, the basic features of the ocean circulation obtained by the regional ocean circulation model are in good agreement and the detailed characteristics of the regional ocean circulation can also be obtained. It is found from Fig. 2 that there exists the same pattern of the ocean current in the region of the eastern Philippines in every season, which consists of the north–westward Kuroshio current that is formed by the westward ocean current encountering the Philippines and changing direction, and the seasonal variation in the current direction is less but the

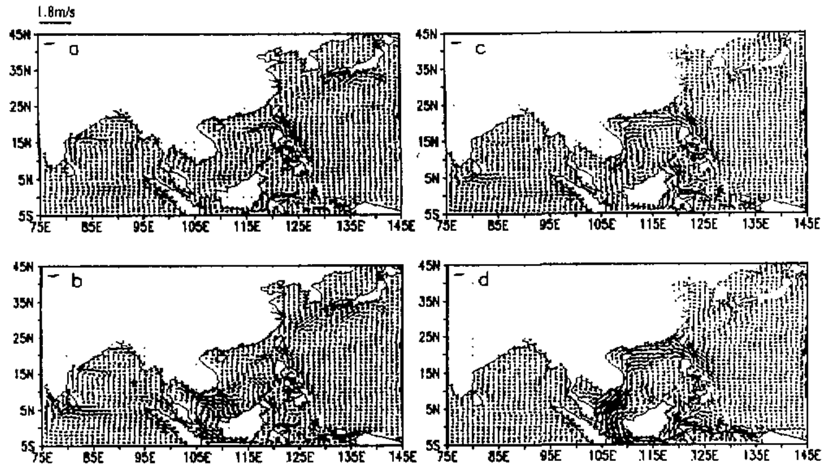

Fig. 2. The simulated surface ocean currents in spring (a), summer (b), autumn (c) and winter (d).

speed of the surface Kuroshio current is stronger in summer than in winter. These accord well with the ocean investigations (The editorial Committee of the China Natural Geography, CMS, 1979). In the region of the South China Sea, the seasonal changes in the ocean current occur clearly. In winter, the current euters the northern part of the South China Sea through Taiwan Strait, Bashi Channel and Balintang Channel, then crosses the South China Sea and exits through the java Sea, whereas in summer, the current goes into the South China Sea through the java Sea and Balintang Channel, then flows out through the Balabac Strait and the Taiwan Strait, accompanying less out–flow current in the north Bashi Channel. It is found from the comparison of the surface ocean currents that the ocean current in the regions of the southern and northern South China Sea, the Bay of Thailand and the Beibu Gulf in winter is fully opposite to that in summer, and seasonal change of the current is apparent. These are in good accord with the results obtained from the ocean investigations (The editorial Committee of the China Natural Geography, CMS, 1979). However, the ocean current in the eastern South China Sea in summer is different from the ocean investigations in which the simulated current is in–flow in the Balintang Channel, whereas the observational current is out flow, which is in agreement with modeled results (Li et al., 1994). In the northern East China Sea and the Huang Sea, the surface ocean current in winter is contrary to that in summer. In the Japan Sea, the current remains the same pattern in all seasons, but the current speed in spring and summer is larger than that in autumn and winter. In other ocean areas such as the Bay of Bengal, Andaman Sea and the Indian Ocean, the ocean current is in agreement with the real condition, and there exist significant seasonal changes in the ocean current and the current speed in summer is larger than that in winter.

It is found from the analyses of deep level current (250 m in depth) the in–flow current from the Pacific Ocean into the South China Sea is basically dominated in the Bashi and Balintang Channels in all seasons, only a weaker out–flow from the South China Sea into the Pacific occurs in the northern Bashi Channel (see Fig. 3). In the model domain there exists an equatorial counter current apparently in the Indian Ocean areas and the seasonal change is very little, and the rip current in the western part of the Bay of Bengal is also significant at the

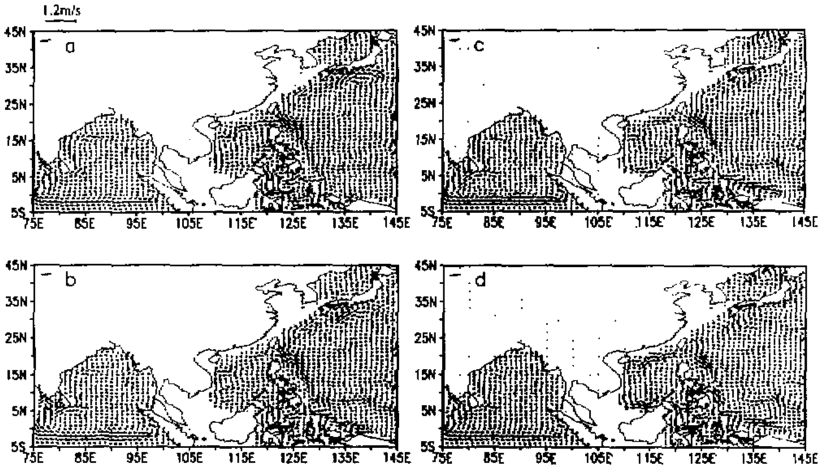

Fig. 3. The ocean currents at 250 m in spring (a), summer (b), autumn (c) and winter (d).

depth of 250 m and the Pacific Kuroshio current in all seasons is clearer at 250 m than in the surface layer.

It is seen from the above analyses that the regional ocean circulation model only can simulate the basic features of the large–scale ocean circulation, but also can obtain the details of the ocean circulation such as the Gulf stream, the coastal current which cannot be resolved in large–scale ocean circulation models. Therefore, it has great potentialities to develop a regional ocean circulation model.

3.3 *The sea surface temperature*

The simulated sea surface temperature distributions in spring, summer, autumn and

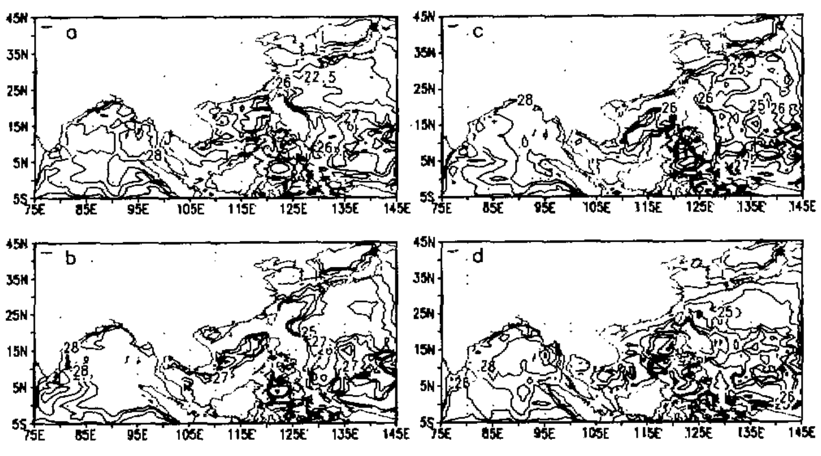

Fig. 4. The simulated sea surface temperature in spring (a), summer (b), autumn (c) and winter (d).

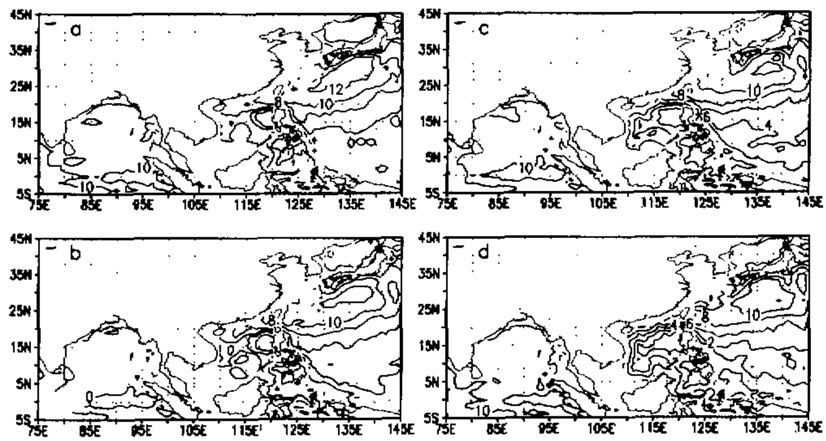

Fig. 5. The simulated sea temperature at 250 m in spring (a), summer (b), autumn (c) and winter (d).

winter in the model domain are shown in Fig. 4. We can see from Fig. 4 that the temperature in the area of the eastern Philippine and south of 15°N is high throughout the year and the change of the temperature is little, and the higher temperature region is broadest in autumn, which extends to the area of 30°N, and is limited in spring and the sea surface temperature is lowest. In the area of 25°N, the latitudinal distribution of the temperature is basically presented and the temperature decreases from south to north with maximum in autumn and minimum in spring, and the range of the temperature change in high latitudes is larger than that in low latitudes. In the South China Sea area, the temperature in the eastern and southern regions is higher in summer and autumn, and the temperature is higher in the southern part of the SCS than that in the northern part in spring and winter. In the Bay of Bengal, the temperature is higher throughout the year and the change is less, and a higher temperature region of 28°C appears first in the eastern Bay of Bengal in spring, then extends westward and northward, whereas the lower temperature occurs in the western Bay of Bengal in summer and autumn, which is probably related to the rip current, These are in agreement with real conditions.

The simulated sea temperature distributions in spring, summer, autumn and winter at the depth of 250 m are shown in Fig. 5. It is seen from Fig. 5 that the temperature at 250 m is higher in the eastern area of Taiwan and the southern area of Japan throughout the year but is relatively lower in winter. In the area of the South China Sea, the temperature at 250 m is lower than other ocean areas and the region of lower temperature expands in winter and shrinks in spring. In the Bay of Bengal, the sea temperautre remains about 10°C and the seasonal change is little. The vertical cross–sections from surface to 800 m along 30°N are given in Fig. 6. It can be seen that the seasonal change in temperature also exists clearly at the depth of 800 m, but the range in deep layers is smaller than that in surface layers. In the coastal areas of China, the thermocline is seen apparently in spring and winter, and the surface temperature distribution is uniform in summer and autumn and the high temperature region is deeper. In addition, the temperature above 500 m at 128°E is higher than that in other longitudes due to the effect of the Kuroshio current. Compared with the real conditions, the detailed features

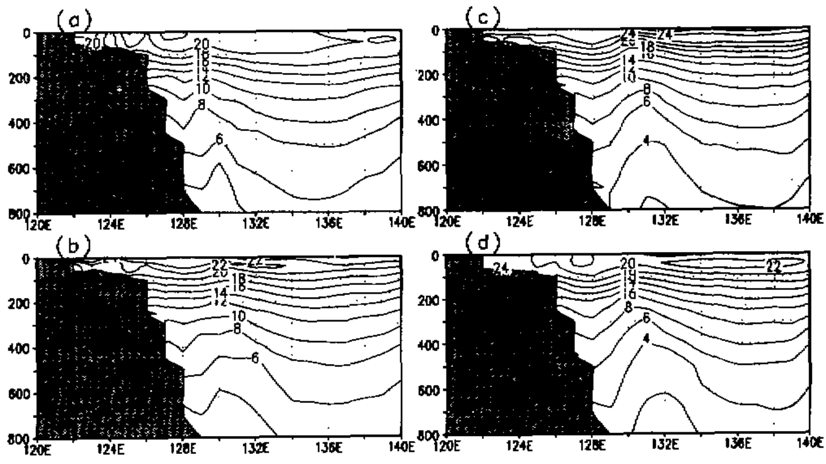

Fig. 6. The vertical cross-sections from surface to 800 m along 30°N (a) spring (b) summer (c) autumn (d) winter.

of the vertical distribution of the temperature obtained from the regional ocean circulation model are more in good agreement with the observations than that simulated with large-scale ocean circulation models.

3.4 *Salinity*

It is found from the analyses on the sea surface salinity distributions (omitted) that the salinity in the Pacific region of the model domain is higher with a maximum in the extent of 15–35°N in summer and a minimum in spring. In the coastal areas of China, the salinity in the Huang Sea, the Bo Sea and the East China Sea decreases from south to north, the highest salinity appears in the South China Sea and the seasonal change is little. The salinity in the Bay of Bengal is also higher and reduces from south to north, and the gradient of the salinity in the northern area is larger in winter and smaller in summer.

4. Concluding remarks

It is seen from the above analyses of the simulated results that the improved regional ocean circulation model (POM) can quite well simulate the regional ocean circulation in the coastal areas of China including a part of the western Pacific, the South China Sea and the Bay of Bengal. This model can obtain not only the basic features of the ocean circulation similar to the results simulated by large-scale ocean circulation models, but also the detailed features of the regional ocean circulation such as the coastal current. The simulated regional ocean circulation, temperature, salinity and free surface height are in good agreement with the observational results. Therefore this model has good performance in simulating the regional ocean circulation and can be further used to develop a coupled regional air-sea interactive model system.

However, due to lack of enough ocean observational data, it is difficult to develop a perfect regional ocean circulation model. The results obtained in this paper are preliminary.

There are many aspects to improve, especially the treatment on the lateral boundary conditions, which might be solved by nesting the regional ocean circulation model with the large-scale ones.

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