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Diagnostic analysis on the northern South China Sea winter counter-wind current

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Abstract The winter counter-wind current (also named the South China Sea Warm Current (SCSWC)) in the northern South China Sea (SCS) has been known well for decades, but its mass and momentum origination have not be quantitatively evaluated before. In this paper, the high resolution three-dimensional ocean circulation model is adopted to reproduce the circulation in the northern SCS. The diagnostic analyses are performed to investigate the momentum budget in the northern SCS continental shelf/slope and the momentum propulsion of the SCSWC. It is indicated that the across-shelf pressure gradient and the across-shelf transport are responsible for the formation of the SCSWC, while the along-shelf pressure gradient is balanced by the surface stress, bottom stress, and Coriolis force. The magnitude of the terms in the along-shelf momentum equation is smaller than that in the across-shelf one. The analysis on the momentum budget in the northern SCS will benefit the marine environmental prediction in the future.

Keywords: northern South China Sea, counter-wind current, ocean circulation model, momentum diagnoses, geostrophic adjustment.

It has been about 40 years since the counter-wind current (also named the South China Sea Warm Current (SCSWC)) in the northern South China Sea (SCS) was discovered[1]. The SCSWC appears in the inner-shelf off eastern Guandong and the open sea off western Guangdong. It flows counter the northeastly wind from the surface to the deep layer in winter, except for the period in which the current in its surface layer is replaced by the southwestward Ekman drift sometimes when the winter monsoon prevails[2]. The SCSWC has been drawn attention to for decades because it has a counter-wind feature in winter and it plays an important role in the water exchange between the SCS and the East China Sea[3]. The data analyses of the 10-year (1975—1984) hydrographic observations showed that the SCSWC, coastal current and the slope current (also named the SCS branch of the Kuroshio (SCSBK)) were the major current system in the northern SCS[4]. Based on the historical observations, Guo *et al.*[5] proposed that the southwestward slope current originated from the Kuroshio in winter, and the slope current may be a branch of the Kuroshio that intruded into the SCS through the Luzon Strait. The South China Sea Institute of Oceanology carried out the "dynamical experiments on the SCSWC" in February-March in 1982 through *in situ* observations and the results indicated that the circulation in the northern SCS deep-sea area is dominated by the baroclinic current, i.e., the geostrophic current can be used to represent the circulation in that area. The isotherm and the isopycnic (σ_t) lines in the across-shelf sections all show an upslope tendency, and the temperature show a weak declination from the axis of the slope current and the SCSWC to the south and the north respectively over there[6].

In winter, the averaged wind speed in the northern SCS is about 7—10 ms^{-1}, the westward surface Ekman drift is stronger than in other seasons[7]. Why the SCSWC can flow counter the wind? According to the data analyses or the numerical experiments, many oceanographers proposed various explanations on the problem. Zhong[4] proposed that the SCSWC was a continuation of the SCSBK over the continental slope, where the westward flowing SCSBK turned to the northeast owing to the blocking effect of the shelf break. Ma[8] indicated that the SCSWC came from the reflection of the extended Kuroshio and the veered slope current at the shelf break, the anticyclonic eddy in the northeast SCS was also contributive. Ye[9] suggested that the thermodynamic force drove the SCSWC flowing counter the wind. According to the numerical experiments, Chao *et al.*[10] pointed out that the periodical relaxation of the northeasterly winds would strengthen the SCSWC intermittently. Besides, the surface elevation gradient induced by the intruded Kuroshio would drive the northeastward current in the northeast SCS, while the along-shelf gradient counterbalances the bottom stress[11]. Hsueh and Zhong[12] proposed that the imposed pressure head along the continental shelf break generated a flow that resembled the SCSWC. The Kuroshio intrusion is responsible for the pressure head, and the SCSBK fed the SCSWC through a weak onshore flow. Yuan *et al.*[13] suggested that the convergence of the surface water was necessary for the formation of the SCSWC at the northeast SCS continental slope, and the baroclinic effect led to the co-existence of the high surface elevation and the warm water.

Although the mechanism for the formation of the SCSWC has draw much attention and much progress has been achieved in the past decades, the three-dimensional momentum term balance of the circulation in the area where SCSWC flows have not be investigated, and the evidence for the dynamical origination of the SCSWC has not be achieved. The purpose of this paper is to use the high resolution three-dimensional circulation model to diagnose the circulation in the northern SCS continental shelf/slope in winter. Combining with the *in situ* observations, the formation of the SCSWC is discussed through the momentum budget.

1 Model configuration

The three-dimensional primitive equation model POM (Princeton Ocean Model) (Blumberg and Mellor[14]) is applied to investigating the circulation in the northern SCS in winter. The horizontal orthogonal curvilinear coordinates are used with the spatial resolution about 18 km. The vertical sigma coordinate has 33 levels. The model domain includes the whole SCS and part of the southern East China Sea and the western Pacific Ocean (Fig. 1(a)). With the real topography, the WOA01 (World Ocean Atlas 2001) data set[15] is used to prescribe the initial temperature and salinity field. The surface wind forcing is obtained from the NCEP (National Centers for Environmental Prediction) reanalysis[16] climatological January wind velocity (Fig.1(b)). The surface buoyancy forcing is neglected. The lateral open boundary is preserved according to the real bathymetry. The Simple Ocean Data Assimilation (SODA) reanalysis products1) are used to provide the boundary information. The simulations involve two stages. Firstly, the model runs diagnostically for 60 days (temperature and salinity are fixed to the initial fields), and then continues with prognostic run for another 60 days. After the adjustment, the circulation will come to the quasi-equilibrium state. The volume-averaged mechanical energy indicates (figure not shown) that the mechanical energy increases very fast in the first 10 days diagnostic run. After the subsequent low-frequency adjustment, the diagnostic circulation reaches the quasi-equilibrium state. At the beginning of the prognostic run, the noise comes from the inconsistency between the initial hydrographic data and the bottom topography is removed by advection and diffusion and the dynamical adjustment of the flow to the bottom topography and wind[17], so the mechanical en-

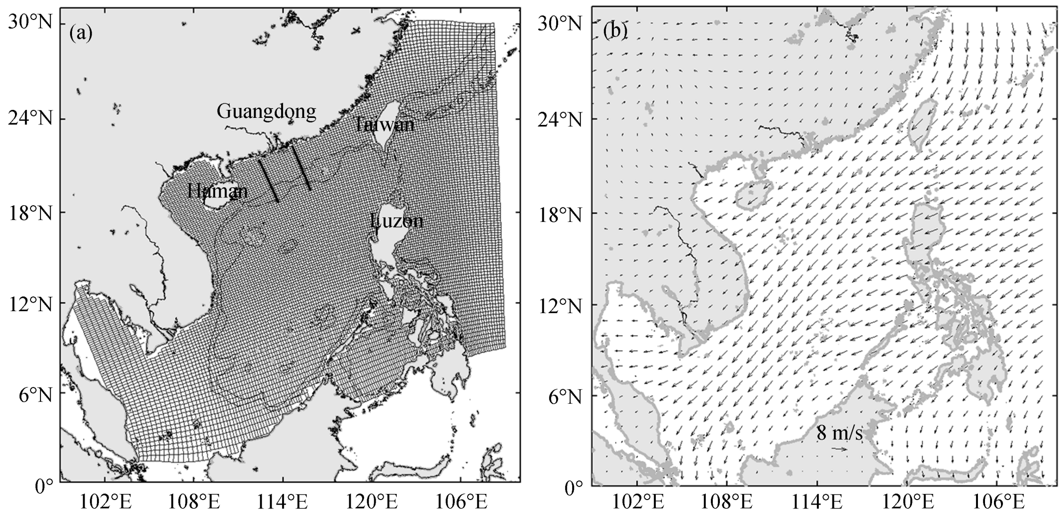

Fig. 1. (a) Model domain and grid configuration, superimposed with the 200 m and 1000 m isobath. The across-shelf transects are labeled I and II from west to east. (b) NCEP climatological January wind field.

1) Carton J A, Giese B S. SODA: A reanalysis of ocean climate. submitted to J Geophys Res, 2006

ergy decreases very fast and then comes to the low-frequency adjustment. According to the assessment, 60 days prognostic run is enough for the circulation to reach the quasi-equilibrium state.

2 Analyses and discussions

2.1 Model-data comparisons

Fig. 2(a) shows the velocity field at 15 m depth in the northern SCS after 60 days prognostic run (the solid line denotes the position of the SCSWC). The SCSWC originates from the eastern side of the Hainan Island and flows northeastward in the outer-shelf of Guangdong. It is strengthened as it flows across the inner-shelf of eastern Guangdong and Fujian, and finally flows into the East China Sea through the Taiwan Strait. The southwestward Guangdong coastal current flows along the onshore side of the SCSWC. The simulated results compare favorably with the observed current vectors in winter off the southeastern China coast[2] (Fig. 2(b)). The southwestward slope current flows along the offshore side of the SCSWC, and the intruded Kuroshio forms a loop current and then flows out of the SCS from the southern side of the Taiwan Island. It is discernable that the slope current entrains the Kuroshio water as it flows southwestward.

Two across-shelf transects are selected in the northern SCS continental shelf/slope, which are labeled transects I and II respectively (shown in Fig. 1(a)). The prognostic along-shelf velocity are shown in Fig. 3((a), (b)), where the positive (negative) represents the

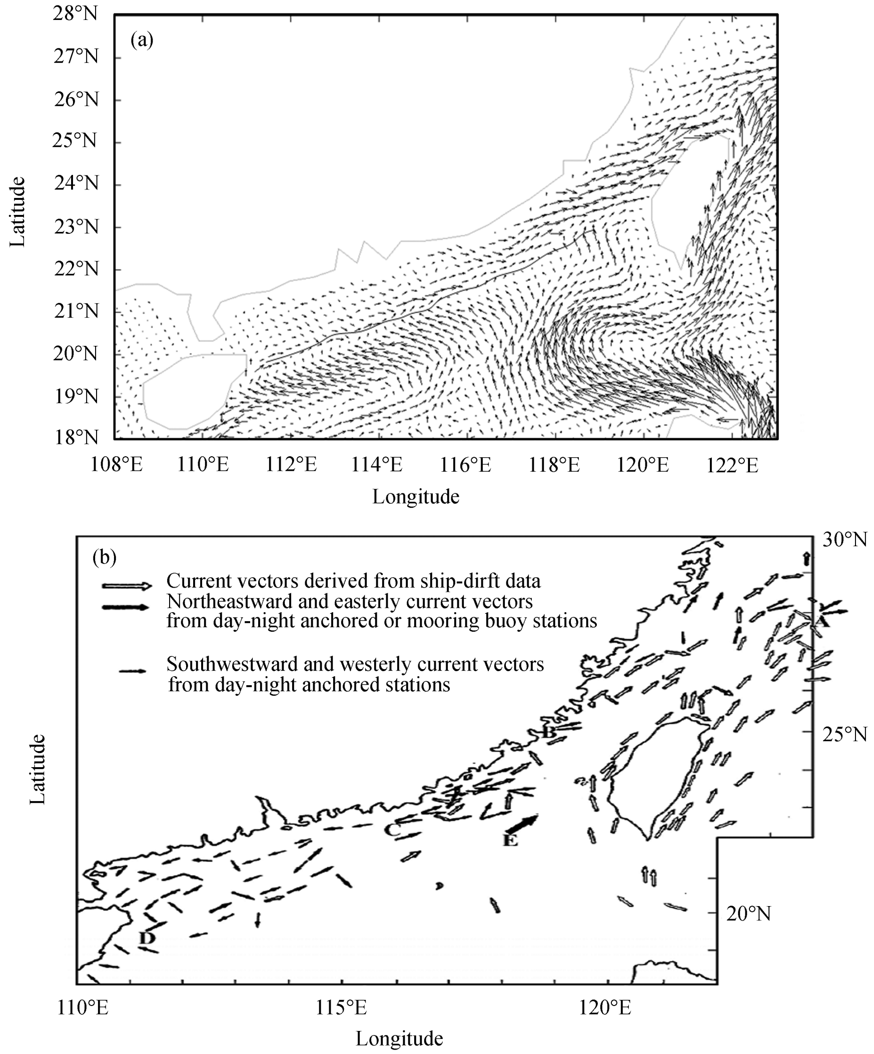

Fig. 2. (a) Velocity field at 15 m depth in the northern SCS after 60 days prognostic run. The solid line denotes the position of the SCSWC. (b) Observed current vectors in winter off the southeastern China coast (after Guan[2]).

northeastward (southwestward) flow. The spatial distribution of the velocity at transect I resembles that at transect II. The currents flow in the opposite direction and in the band-like structure, which include the southwestward coastal current, the SCSWC and the southwestward slope current. The volume transport of the slope current is about 5—11Sv, which is consistent with the observations[6]. The geostrophic velocity at the meridional sections along 111°E and 113°E in December 1984 are shown in Fig.3(c) and (d))[4] respectively. Comparing the simulated results with the observations indicates that both the spatial distribution and the magnitude of the currents are well consistent.

2.2 Momentum diagnoses

After analyzing the long-period observational data at stations along the coast of the southeastern China coast, Fang and Zhao[18] proposed that the sea surface slope was the main forcing that drove the counter-wind current in the northeast SCS, while the contribution of the wind stress, barometric pressure and water density were much smaller. However, the sea surface slope is slow near the western Guangdong coast and shows a southwestward inclination. Their results did not explain the formation of the counter-wind current east of the Hainan Island. The modeled surface elevation in the northern SCS after 60 days prognostic run is shown in Fig. 4. There is a high surface elevation belt imposed on the continental shelf break, i.e. the across-shelf surface elevation gradients exist in the northern SCS, and the directions of them are opposite in the shelf and the slope. Combining with the velocity field, we find that the SCSWC and the slope flow side-by-side with the high surface elevation belt in the middle of them. In the coastal area, there is obvious surface elevation declination in the along-shelf direction from eastern Guangdong to Zhejiang. The surface elevation slope is very slow near the coast of western Guangdong, which is consistent with the observations. The spatial distribution of the surface elevation indicates that the formation of the SCSWC is correlated with the across-shelf pressure gradient, and there is a dynamical linkage between the SCSWC and the southwestward slope current. In order to illustrate the momentum term balance in this area further, the modeled three-dimensional circulation will be diagnosed in the following.

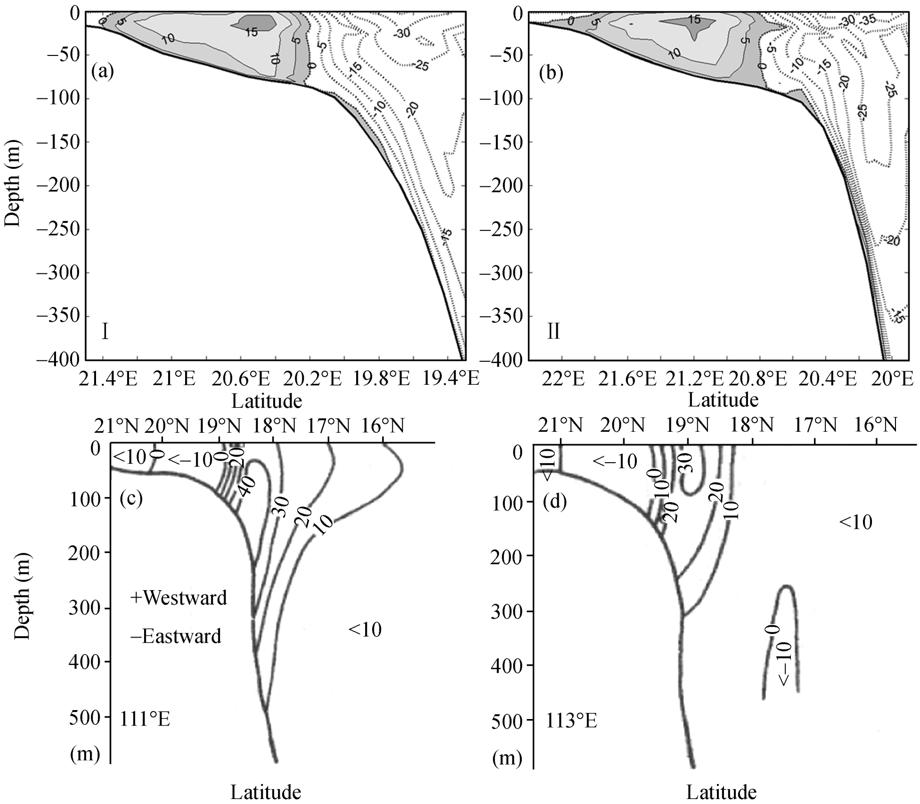

Fig. 3. (a) Across-shelf transects of the along-shelf velocity (cm/s) at transect I and II after 60 days prognostic run. The contour interval is 5 cm/s. (b) Geostrophic velocity in Dec. 1984 along the 111°E and 113°E meridional sections (after Zhong[4]).

For convenience, the horizontal momentum equations are represented by

$$\overbrace{v_t}^{a}+\overbrace{V\cdot\nabla v-A_m v_{xx}}^{b}+\overbrace{fu}^{c}+\overbrace{P_y}^{d}-\overbrace{(K_m v_\sigma)_\sigma}^{e}=0, \quad (1)$$

$$\overbrace{u_t}^{a}+\overbrace{V\cdot\nabla u-A_m u_{xx}}^{b}-\overbrace{fv}^{c}+\overbrace{P_x}^{d}-\overbrace{(K_m u_\sigma)_\sigma}^{e}=0, \quad (2)$$

where u represents the along-shelf velocity component, which direct to the northeastward, v represents the across-shelf velocity component, which direct to the onshore side, f is the Coriolis parameter, P is the pressure, K_m is the vertical viscosity coefficient, A_m is the horizontal viscosity coefficient, $\sigma=(z-\eta)/H$ is the vertical σ coordinate, H and η represent water depth and surface elevation respectively. The terms in the momentum equations (1) and (2) include the tendency term (a), nonlinear advection and diffusion term (b), Coriolis term (c), pressure gradient term(PG) (d) and vertical diffusion term (e). All terms are scaled by $H^{-1}\Delta t\times 10^{3}$ [19] and get the units in $(\mathrm{ms}^{-1})\times 10^{3}$.

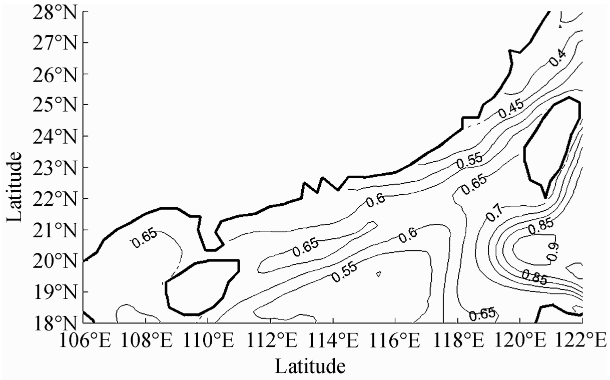

Fig. 4. Surface elevation (m) in the northern SCS after 60 days prognostic run. The contour interval is 0.05 m.

All terms in the momentum equations are evaluated in the sigma levels, and the near-surface depth, mid depth and the near-bottom depth are selected to investigate the momentum terms balance. It is of benefit to analyzing the momentum field in the sigma levels because it has advantage to illustrating the influence of the continental slope on the bottom circulation. The along-shelf momentum term balance at transects I and II are shown in Fig. 5. In the near-surface depth (Fig. 5(a)), the vertical diffusion term is one of the dominant terms owing to the wind stress stirring. The vertical diffusion term, together with the Coriolis term and the pressure gradient term is the leading terms in the along-shelf momentum balance. In the mid-depth, the momentum terms balance are controlled by the pressure gradient and the Coriolis term in the continental slope and the outer-shelf. The effect of the wind forcing is largely reduced and mainly confined in the inner-shelf, where the vertical diffusion term still is contributive to the momentum terms balance. In the near-bottom depth, the circulation is greatly influenced by the bottom stress and the vertical diffusion term is dominant along the continental shelf. The pressure gradient term, Coriolis term and the vertical diffusion term are the dominant ones. It is indicated that the flow was largely ageostrophic in the along-shelf direction. The pressure gradient, Coriolis, surface stress and bottom stress are all contributive to the momentum terms balance, while the contribution of other terms is small. In the mid-depth, the geostrophic feature only appears in the continental slope area.

The across-shelf momentum term balance at transects I and II is shown in Fig. 6. The spatial distribution of the terms in the two transects is similar. The geostrophic feature is obvious in all levels, i.e. the Coriolis term and the pressure gradient term are dominant in the terms balance, and the magnitudes of other terms are small. Besides, the direction of the pressure gradient term and the Coriolis term changes twice from the coast to the slope. As to the pressure gradient term, it is positive in the continental slope, then it changes to negative in the outer shelf, and finally it comes back to positive in the inner shelf again. Such a spatial structure of the pressure gradient corresponds to the southwestward slope current, SCSWC and Guangdong coastal current respectively. The basin scale cyclonic circulation is fully developed in winter, in which the water mass that originates from the West Pacific Ocean can be traced along the northern SCS continental slope[20], which enhances the baroclinic feature of the water in the continental shelf/slope. The temperature of the water near the coast is relatively lower than that in the outer-shelf in winter, which leads to the obvious density gradient over there. It is noticeable that the terms in the across-shelf momentum equation are largely quadruple in magnitude than those in the along-shelf one, which indicates that the band-like structure in the northern continental shelf/slope is mainly influenced by the across-shelf momentum budget.

The momentum terms balance suggests that the northeastward SCSWC is in geostrophic balance with the onshore pressure gradient, and the high pressure head exist in the middle of the SCSWC and the slope

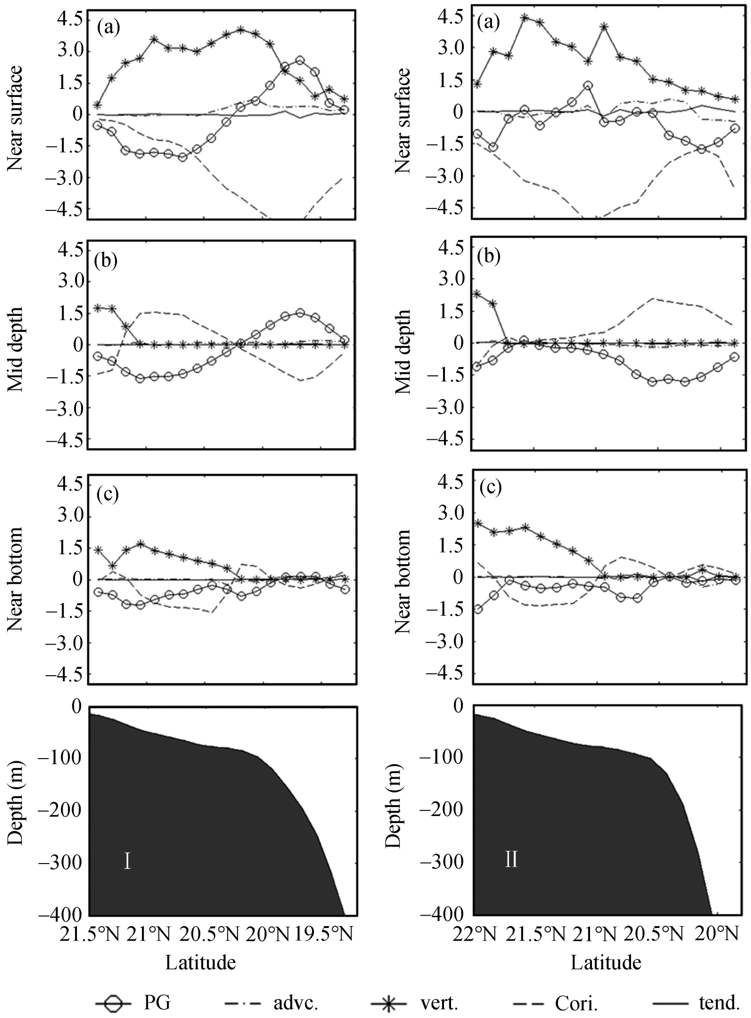

Fig. 5. The spatial distribution for the along-shelf momentum terms ($(ms^{-1})\times10^3$) at transects I (left) and II (right). The corresponding cross-shelf isobaths are indicated at the bottom for each transect, respectively.

current. The surface stress and the bottom stress are balanced by the pressure gradient force and the Coriolis force in the along-shelf direction. The high surface elevation belt is highly correlated with the water density structure in the northern SCS. Previous observations[4] indicate that the slope current has the tendency to climbing the continental slope as it flows southwestward and is blocked by the continental shelf. Such movement will induce the across-shelf transport. Owing to the potential vorticity conservation, the deflected current will veer in the anticyclonic tendency and counter-balance the across-shelf pressure gradient after the geostrophic adjustment. The existence of the anticyclonic eddies has been partly proved by *in situ* observations[5,6], and their formation is correlated with the density structure.

3 Conclusions

The three-dimensional ocean circulation model is used in this study to simulate the circulation in the northern SCS. The model results are well comparable with previous observations. The diagnostic analyses on the momentum equations indicate that the high pressure band exists in the middle of the continental slop and SCSWC. The onshore pressure gradient exists in the continental shelf while the offshore pressure gradient exists in the continental slope. It is the onshore pressure gradient that maintains the SCSWC in winter. Surface stress and bottom stress are balanced by the pressure gradient and Coriolis force. Observations suggest that water density and bottom topography are responsible for the climbing of the slope current and the formation of the anticyclonic eddies in the outer continental shelf.

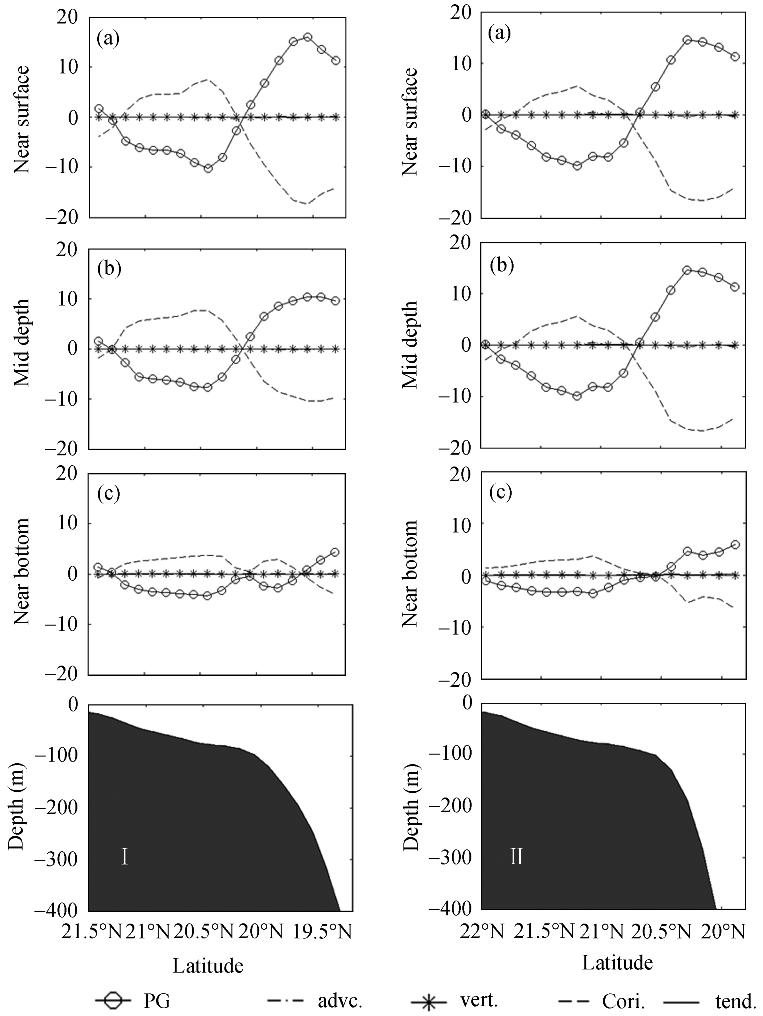

Fig. 6. The spatial distribution for the across-shelf momentum terms ((ms^{-1})×10^{3}) for transects I (left) and II (right). The corresponding cross-shelf isobaths are indicated at the bottom for each transect, respectively.

After the geostrophic adjustment, the veered slope current is balanced by the across-shelf pressure gradient and then joins the SCSWC flowing northeastward. The investigation on the momentum budget in the northern SCS continental shelf/slope is contributive to the progress of the marine environmental prediction in the northern SCS in future.

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