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A well-mixed warm water column in the central Bohai Sea in summer: Effects of tidal and surface wave mixing

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[1] A well-mixed water column is observed over a 20 m ridge in the central Bohai Sea, surrounded by stratified water of much colder temperatures. We use a three-dimensional model to investigate its formation mechanisms. The results show that both tidal and surface wave mixing are important for homogenizing the water column, the former reaching 10 m above the bottom and the latter penetrating 10 m beneath the sea surface. The ridge enhances the intensity and vertical extent of tidal mixing, allowing it to connect with the downward penetration of wave mixing. Removing either the bathymetric ridge or wave mixing fails to reproduce this well-mixed water column. The inclusion of the surface wave mixing warms the bottom water by 5–6°C in both the warm water column and surrounding cold water. Wave mixing displays a maximum in the central Bohai Sea basin, which is confirmed by satellite altimeter data and a wave model simulation.

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1. Introduction

[2] The Bohai Sea located in 37°07′ ~ 41°N, 117°35′ ~ 121°10′E, is a shallow semi-enclosed sea that exchanges with the Yellow Sea through the Bohai Strait between Shan Dong and Liao Dong Peninsulas (Figure 1). As the only inner sea of China, the Bohai Sea has been intensively studied. The mean depth of the sea is about 18 m and its maximum depth is about 30 m in the central basin. Because of its shallow depth, many previous studies have treated the Bohai Sea as barotropic one. This is a good approximation for winter when intense cooling by the cold and dry northwesterly monsoon destroys density stratification, allowing bathymetry to imprint on the sea surface temperature (SST) and wind [*Xie et al.*, 2002; *Huang et al.*, 2005; *Ma et al.*, 2006].

[3] In summer the sea is stratified in most areas except near the coast. Recent investigations reveal complex structures in the temperature, salinity and circulation distribution in summer, in which tides, especially the M2 tide, play an important role [*Wan et al.*, 2004; *Wu et al.*, 2004a, 2004b]. A marked feature in summer is existence of a warm water column in the central Bohai Sea, which is surrounded by cold water below the mixed layer. Figure 2a shows this thermal structure in the transect (Figure 1) that has been visited every summer since 1976. The center of the warm water column is located at 39°N, 120°E, with a nearly uniformed temperature of about 24°C. It is anchored by a sea-bottom ridge with a depth slightly less than 20 m. The cold bottom water surrounding this water column has core temperatures of about 20°C on the southwest side and 18°C on the northeast side, respectively. A seasonal thermocline with a thickness of 10 m caps this cold bottom water. The warm water column above the ridge is well mixed from the surface to bottom, indicating strong mixing there. Strong mixing is also found near the southwest and northeast coasts with vertically uniform temperatures.

[4] In summer 2000, a large-scale survey was conducted in the Bohai Sea (section 2). Figure 2b and Figure 3a show water temperature measured during this survey, which captures the warm water column (~24.5°C) in the central Bohai Sea surrounded by cold water. The cold bottom water originates from the Yellow Sea, flowing into the Bohai Sea along the north side of the Bohai Strait [*Bao et al.*, 2004a]. This well-mixed warm water column has relatively high chlorophyll concentration (Figure 3b), possibly mixed down from the euphotic zone. At 18 m, soluble oxygen is also at a local minimum in the warm water column (Figure 3c). This warm water column and its temperature structure have been reported in recent observational studies [*Jia and Sun*, 2002; *Liu et al.*, 2003; *Bao et al.*, 2004a], but to our knowledge its formation mechanism has not been discussed in the literature. Numerical simulations [*Huang et al.*, 1999; *Wei et al.*, 2001; *Lin et al.*, 2002; *Bao et al.*, 2004b] have so far failed to reproduce this vertically uniform column of warm water.

[5] The present study examines the formation mechanism for this well-mixed warm water column by numerical experiments. The results show that the use of a new detailed bathymetry dataset substantially improves the simulation of tidal mixing and thermal stratification. Surface wave mixing is necessary to produce the vertically uniform water column over the ridge in the central Bohai Sea. Recent studies show

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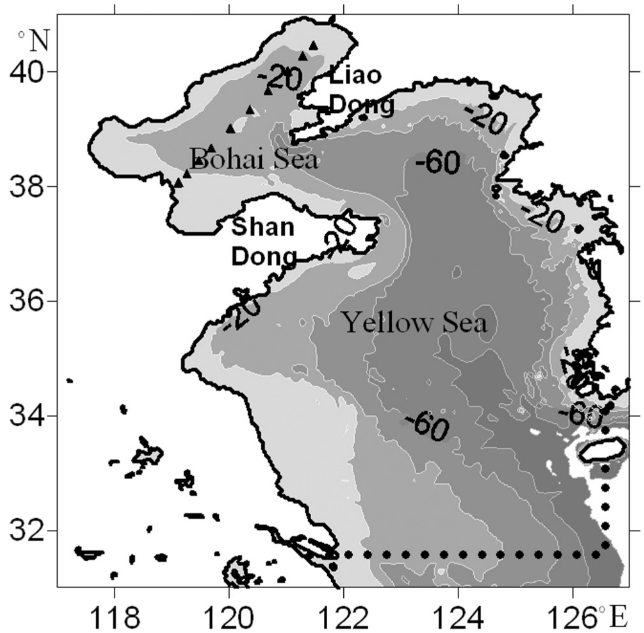

Figure 1. Bathymetry of the Bohai and Yellow Seas. Dots denote the open boundaries of the numerical model. Triangles represent the locations of stations along a routine hydrographic transect.

that both tidal and wave mixing are important in the East China Sea, which feature a thin mixed layer in summer [*Qiao et al.*, 2004a; *Ma et al.*, 2004; *Yang et al.*, 2004]. The well-mixed warm water column in the central Bohai Sea serves as a good illustration of mixing effects by tides from the bottom and by surface waves from the top.

[6] The rest of the paper is organized as follows. Section 2 briefly introduces the data sets. Section 3 describes the numerical model. Section 4 analyzes the simulation results and examines the formation mechanism for the warm water column. Section 5 gives a summary.

2. Data

[7] Figure 2a is derived from the 24-year climatology of summer observations for 1976–1999. This transect consists of 10 fixed stations from the southwest to the northeast across the Bohai Sea, surveyed at least four times a year including once in summer.

[8] In August 2000 a large-scale survey involving 9 ships took place in the Bohai Sea. There were more than 60 stations in the Bohai Sea, with the distance between stations usually less than 20 km. The measurements included temperature, salinity, current velocity, oxygen, fluorometer chlorophyll, PH, turbidity, and nutrient. This survey revealed the warm-column temperature structure characterized by the high chlorophyll and low oxygen (Figure 3). We use this data set along with other observed data to initialize the numerical model.

[9] The Topex/POSEIDON (T/P) altimeter data are used to provide significant wave height in the Bohai Sea. Fortunately a T/P orbit track ran just across the central Bohai Sea near the routine hydrographical transect. We bin the data into 10 boxes along the satellite track, each 0.3° wide, and average the significant wave height in each box for thirteen summers from 1993 to 2005.

[10] The QuickSCAT sea surface vector winds from 1999 to 2005 are used to generate the monthly climatology wind field used in the numerical model.

3. Model

[11] The Princeton Ocean Model (POM), a three-dimensional primitive equation ocean model is used for this study. The model includes the level-2.5 Mellor-Yamada turbulence closure scheme and uses a sigma coordinate to resolve variations of bottom topography [*Blumberg and Mellor*, 1987]. The climatology temperature and salinity derived from historical observations are used as our model initial conditions [*Lin et al.*, 2002]. At the sea surface, the model is forced by monthly climatologically SST and SSS, respectively. The SST climatology is derived from the advanced very high resolution radiometer (AVHRR) infrared data for a 10-year period of 1990–1999 [*Bao et*

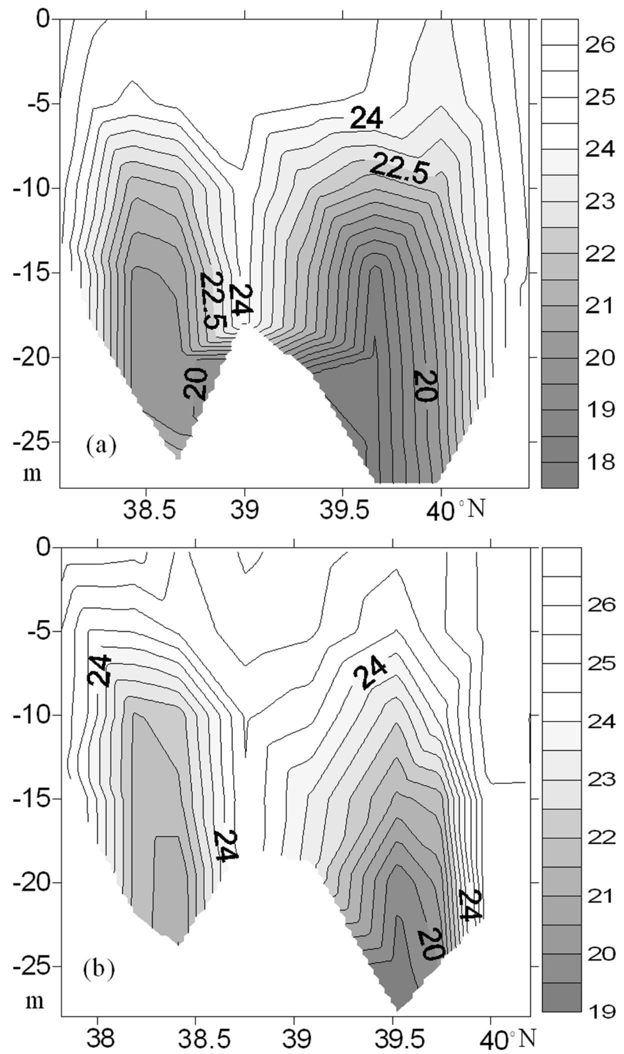

Figure 2. Averaged water temperature (°C) in summer derived from routine hydrographical surveys from 1976–1999 (a) and 2000 (b) along the transect marked in Figure 1.

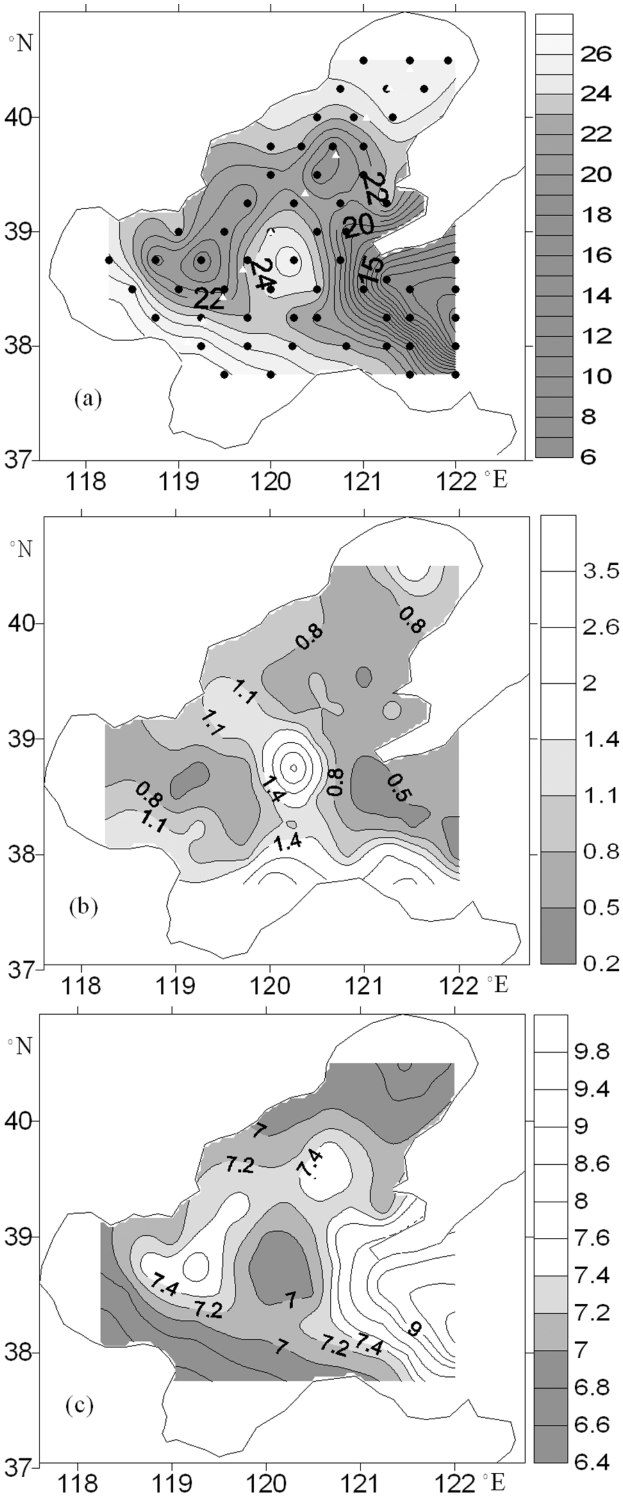

Figure 3. (a) Water temperature (°C), (b) chlorophyll (mg m^{-3}), (c) and soluble oxygen (mg l^{-1}) at 18 m observed in summer 2000 (see Section 2). Dots represent the locations of stations of the 2000 summer survey and triangles are the stations of the routine hydrographic transect.

al., 2002]. The SSS climatology is derived from historical observations. The monthly climatology wind field derived from the QuickSCAT sea surface vector winds is used to drive the model (section 2).

[12] The model domain is 117°25′–126°45′, 31°30′–41°15′ (Figure 1) with a horizontal resolution of 1/12° by 1/12° and 21 vertical sigma layers. On the southern open boundary, the temperature and salinity are restored toward a monthly climatology derived from routine hydrographical surveys along 31°N and 32°N as well as other nearby observations. The routine hydrographical surveys along 31°N and 32°N were conducted nearly every month. The data available to us cover a 39-year period from 1958 to 1996, with some months missing. The data used for the open boundary condition contain 90712 stations (Table 1). Since M2 is the most important tidal component in the Bohai and north Yellow Seas, we use the M2 tide as the surface elevation forcing on the open boundaries.

3.1. Bathymetry

[13] Bathymetry is important for tidal mixing. We use two topography datasets to test its effect on the thermal structure of the summer Bohai Sea. The ETOPO5 topography, (Figure 4a) on a 1/12° grid, is widely used in numerical studies but is rather smooth and does not have the bathymetric ridge that appears to anchor the summer warm water column in the central Bohai Sea. The second topography dataset is derived from observations and admiralty chart in 2002 when a large-scale survey was conducted [*Wang and Lin*, 2006]. Hereafter we will refer to it as the 2002 bathymetry. Compared with an old admiralty chart in the 1980s, *Wang and Lin* [2006] found that the bathymetry changes in many areas and these changes affect the Bohai Sea circulation. The 2002 topography shows many fine structures, in particular an obvious ridge in the central Bohai Sea with a depth less than 20 m (Figure 4b).

3.2. Vertical Mixing

[14] Ocean circulation models often overestimate SST and underestimate the mixed layer depth in summer [*Martin*, 1985; *Kantha and Clayson*, 1994]. It is believed that this problem is caused by insufficient surface mixing. *Craig and Banner* [1994] and *Mellor* [2003] suggested that surface waves enhance the mixing in the upper ocean. Considering vertically dependent radiation stresses and the Doppler velocity for a vertically varying current field, *Mellor* [2003] derived the equations with terms that represent the production of turbulence energy by currents and waves, allowing three-dimensional ocean models to handle surface waves together with currents. Recently, *Hu et al.* [2004] included additional wave mixing calculated from the formula of *Yuan* [1979] in their East China Sea simulation, and confirmed the importance of wave mixing in the upper ocean stratification. The present study adopts a parameterization of *Qiao et al.* [2004b, 2006] (hereafter Qiao-Yuan scheme), in which the wave-induced vertical viscosity/

Table 1. Number of Data Used for the Southern Open Boundary Condition

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Data number	4390	8473	4467	9495	8558	9366	7165	10076	5079	9862	7264	6517

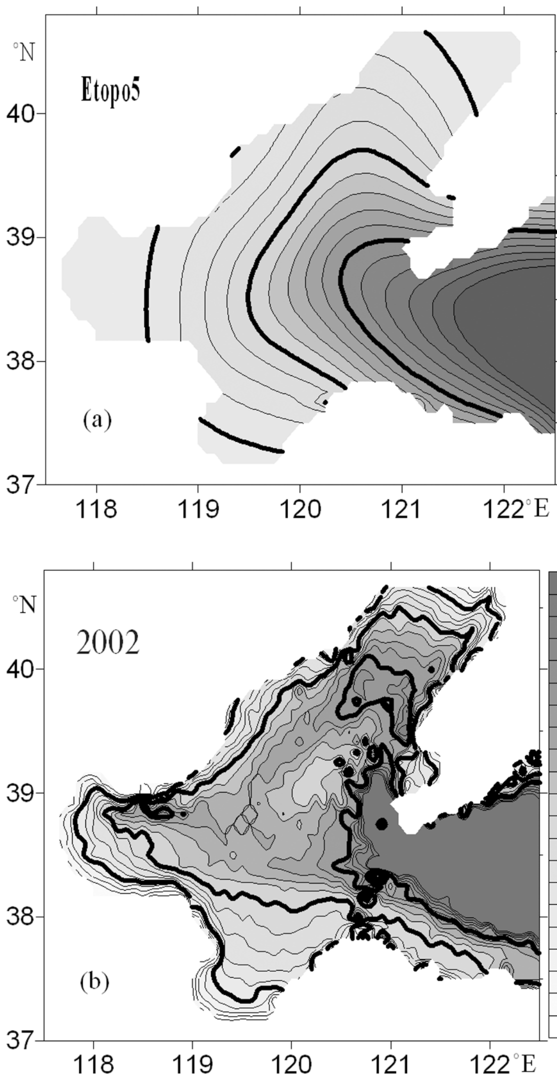

Figure 4. (a) ETOPO5 and (b) 2002 bathymetries (m) in the Bohai Sea. Contour intervals are 2 m while the 10, 20 and 30 m contours are thickened.

diffusivity B_v was expressed as a function of wave number spectrum:

$$B_v = \iint_{\vec{k}} E\left(\vec{k}\right) \exp(2kz) d\vec{k} \frac{\partial}{\partial z} \cdot \left[\iint_{\vec{k}} \omega^2 E\left(\vec{k}\right) \exp(2kz) d\vec{k} \right]^{1/2}$$

where $E(\vec{k})$ represents the wave number spectrum, ω is the wave angular frequency, k is the wave number, and z is the vertical coordinate axis downward positive with $z = 0$ at the surface. To calculate the wave spectrum, we use the Laboratory of Marine Science and Numerical Modeling (MASNUM) wave model [*Yang et al.*, 2005] developed at the First Institute of Oceanography, the State Ocean Administration, China, based on the WAM wave model. We include the Qiao-Yuan scheme for the wave-induced mixing in our numerical study. Following *Qiao et al.* [2004b, 2006], we add the wave-induced mixing coefficient B_v calculated from the MASNUM wave model to the coefficient derived from the Mellor-Yamada scheme (denoted with the subscript c),

$$Km = Kmc + B_v, \quad Kh = Khc + B_v,$$

where Km and Kh are the vertical viscosity and diffusivity used in the model, respectively.

[15] *Qiao et al.* [2004b] implemented this new vertical mixing in the POM model and showed that including the

Table 2. Model Experiment Designs

Experiment	Topography	Mixing Scheme
EXP1	ETOPO5	Mellor-Yamada
EXP2	2002	Mellor-Yamada
EXP3	2002	Mellor-Yamada + wave mixing

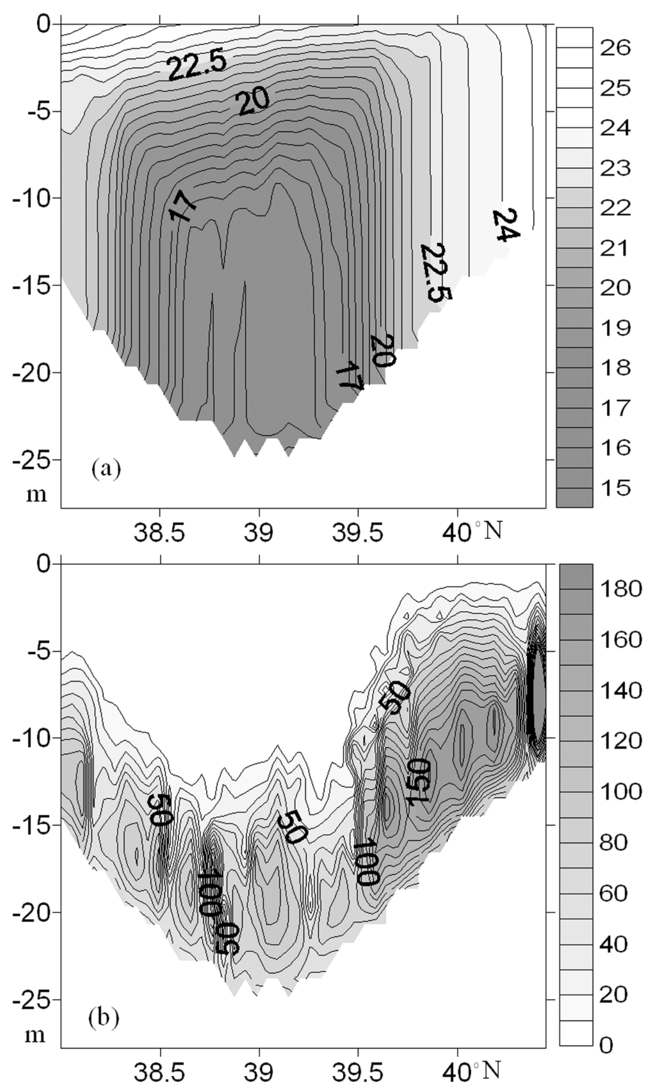

Figure 5. (a) Water temperature (°C) in summer (June–August) and (b) vertical diffusivity (cm^2 s^{-1}) along the routine hydrographic transect in the Bohai Sea (Figure 1) derived from EXP1. Contour intervals are 0.5°C in (a) and 10 cm^2 s^{-1} in (b).

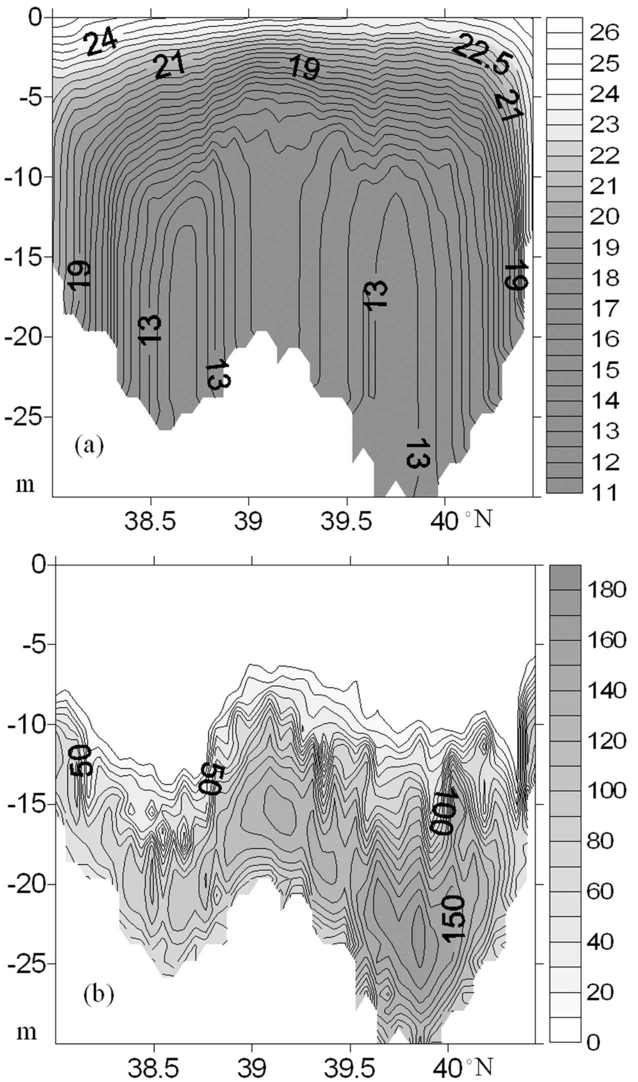

Figure 6. Same as Figure 5, but for EXP2.

wave mixing improved the global simulation of temperature structure in the upper 100 m. The Qiao-Yuan scheme has also been used to study coastal circulation and dynamics, including the circulation of the Yellow Sea Cold Water Mass [*Xia et al.*, 2006], upwelling off the Yangtze River estuary [*Lü et al.*, 2006], and thermocline structure of the Yellow Sea [*Qiao et al.*, 2004c; *Xia et al.*, 2004].

3.3. Experimental Design

[16] Three sensitivity numerical experiments (Table 2) are carried out: Exp1 uses the smooth ETOPO5 bathymetry and the standard Mellow-Yamada scheme for vertical mixing; EXP2 replaces ETOPO5 with the detailed 2002 bathymetry to test the effect of tidal mixing; and EXP3 uses the 2002 bathymetry and adds the wave mixing effect. All the experiments are run for four years to reach the steady state and we use the output of last year for the analysis.

4. Results

[17] Figure 5 shows the vertical distributions of summer temperature and diffusivity along the transect in Figures 1 and 2 with routine hydrographical observations derived from EXP1. One can see that upper-ocean temperature is well stratified in most of the transect except the northeast end, where shallow bottom depths allow tidal mixing to homogenize the water column. Tidal mixing is active as indicated by high diffusivity that extends for 10 m above the bottom, a layer in which temperature is vertically uniform. The bathymetrical ridge is missing in ETOPO5, and a single cold water mass occupies the bottom layer over most of the Bohai Sea, with core temperature slightly below 16°C. Surface mixing is weak in the original Mellor-Yamada parameterization, and there is virtually no surface mixed layer developing.

[18] In EXP2 the more realistic 2002 bathymetry is used. Surface mixing remains weak and a strong seasonal thermocline caps the cold bottom water except near the coast as shown in Figure 6. The bathymetric ridge in the central Bohai Sea has a clear signature in the temperature distribution in the bottom layer. Strong tidal mixing above the ridge erodes the thermocline up to 7 m beneath the sea surface, creating a relatively warm column separating two cold

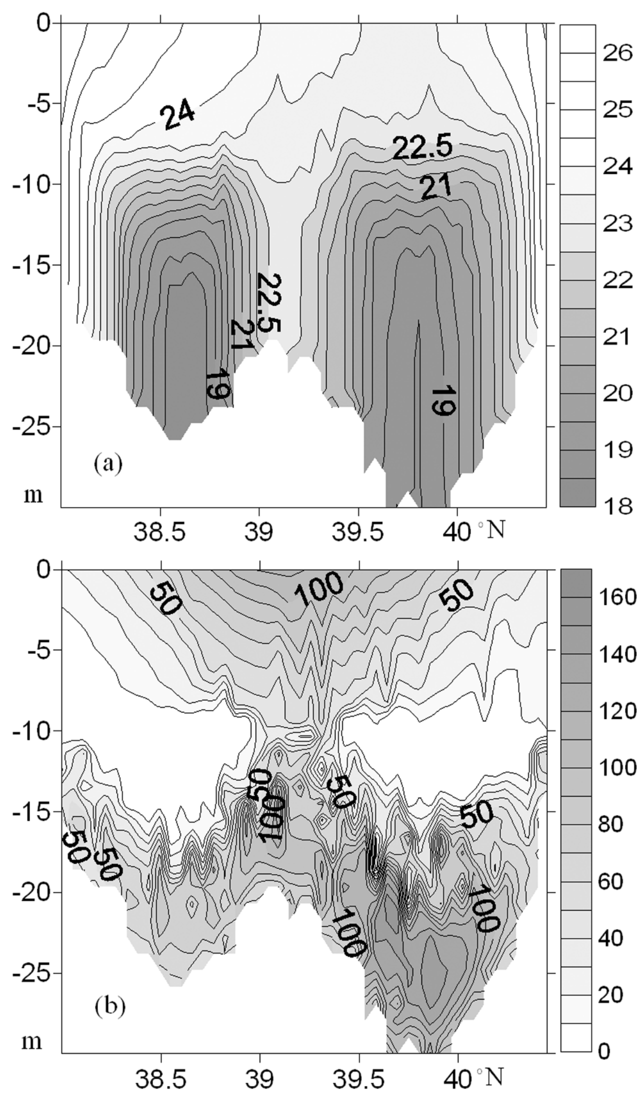

Figure 7. Same as Figure 5, but for EXP3.

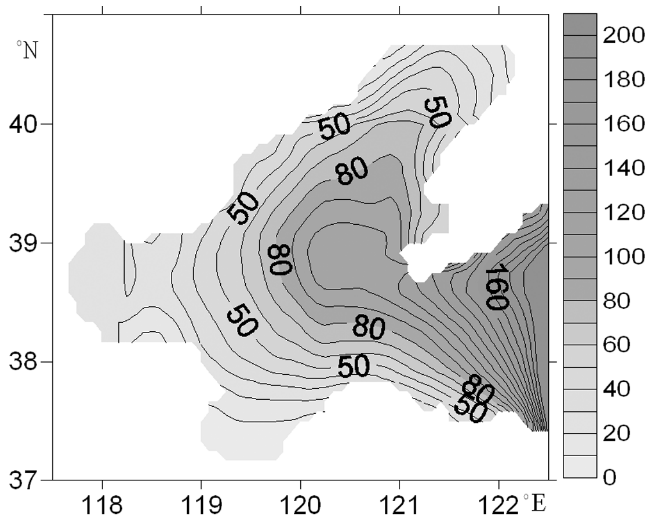

Figure 8. Wave-induced diffusivity B_v ($cm^2\ s^{-1}$) averaged in upper 5 m in EXP3.

cores, one on each side. The core temperature of the cold bottom water is 12–13°C, substantially colder than in EXP1. The 2002 bathymetry in EXP2 is much deeper than the ETOPO5 in EXP1, exceeding 25 m in the southern cold bottom water and 30 m in the northern cold bottom water. The increased depth makes it harder to mix with warm water in and above the thermocline, lowering the bottom temperature in EXP2 by 3°C. While the appearance of a warm water column over the bathymetric ridge is encouraging, temperature in the top 10 m is still stratified, and the bottom water is overall too cold by 6–8°C compared to observations.

[19] The inclusion of wave mixing in EXP3 has a dramatic effect on the simulated temperature. It enhances the vertical mixing in the upper 5–10 m and helps to develop a mixed layer about 7 m deep (Figure 7). The increased downward heat transport warms the bottom water temperature in two cold cores by about 6°C compared with EXP2. The temperature of the bottom portion of the cold cores now becomes about 19.5°C, close to observations. The warm-water column above the bathymetric ridge is now nearly vertical uniform in temperature as observed. Thus, the development of a nearly vertically uniform column of warm water in the central Bohai Sea results from the elevated tidal mixing from the bottom and enhanced wave mixing from the surface. Both the detailed bathymetry and wave mixing are essential.

[20] Wave-induced mixing is substantially stronger in the central Bohai Sea than near the coast (Figures 8 and 7b). This helps to destroy thermal stratification above the bathymetrical ridge. This enhanced wave mixing in the central Bohai Sea is qualitatively consistent with T/P observations of significant wave height. Available only on one track, the mean T/P wave height peaks in the central basin at 81.7 cm and decreases toward the coast at 63.2 cm in the north and 70.9 cm in the south in summer (Figure 9a). The decrease in wave height/mixing toward the coast is likely due to the smaller fetch and larger bottom dissipation of wave energy in the northeast and southwest basins than in the central Bohai Sea. In summer the southeast monsoon dominates the

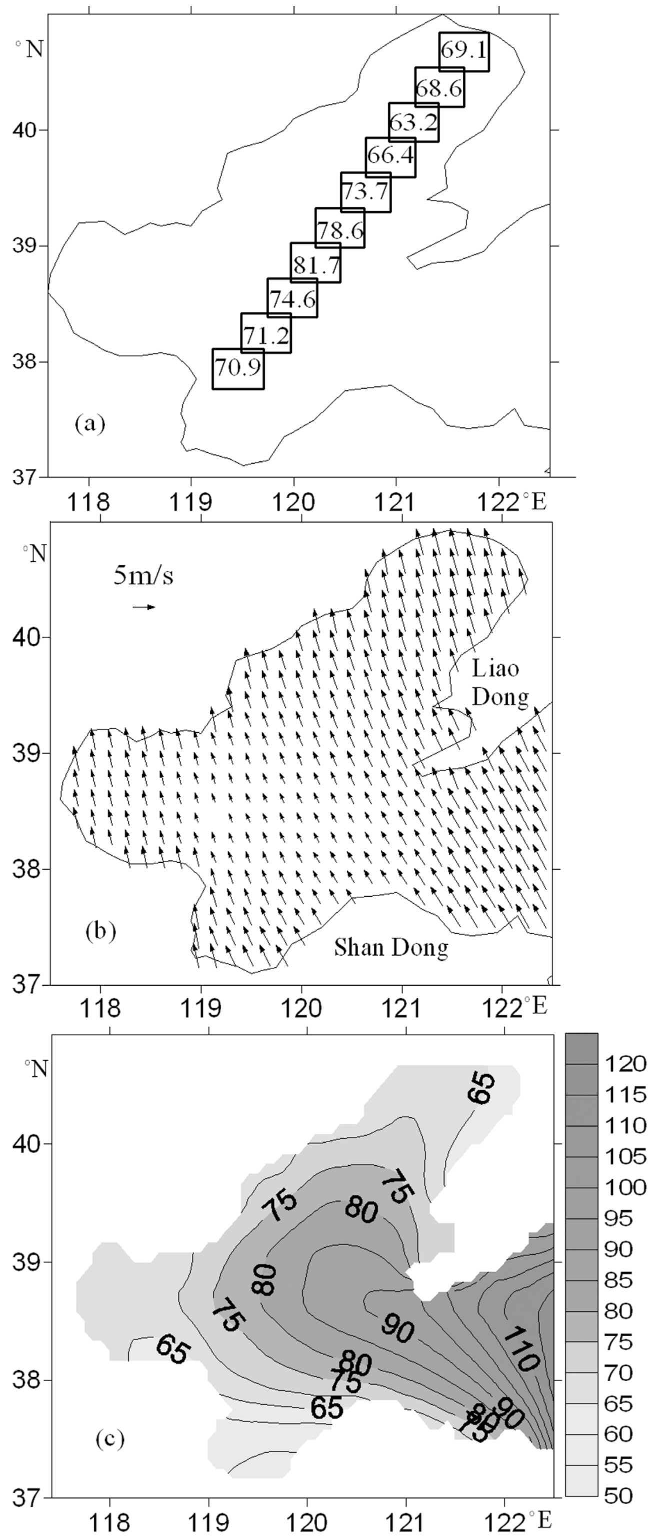

Figure 9. (a) Mean significant wave height (cm) in summer for 1993–2005 derived from T/P data. (b) Mean wind field in the Bohai Sea and Yellow Sea in summer for 1999–2005 derived from QuickSCAT data. (c) Mean significant wave height (cm) in summer derived from numerical model.

Bohai and Yellow Seas. Shan Dong and Liao Dong Peninsulas, respectively north and south of the Bohai Strait, limit the fetch and wave growth in the northeast and southwest Bohai basins. Furthermore, bottom friction may also dampen wave height in shallow water. Figure 9c shows the mean significant wave height in summer from the MASNUM wave model, which is used to calculate the wave mixing B_v. The model simulation reproduces the T/P observations quite well, with wave height above 80 cm in the central Bohai Sea and 60–70 cm in coastal regions to the northeast and southwest. Our result is consistent with the Marine atlas of the Bohai Sea derived from the historical observations [*Chen et al.*, 1992]. *Niu et al.*'s [1999] study also showed that wave height is small in the southern Bohai Sea due to a relatively shorter fetch and shallower water. According to *Qiao et al.* [2006], the wave-induced mixing coefficient B_v is proportional to the cube of wave height for a simplified monochromatic wave, that is

$$B_v = \alpha A^3 k \omega e^{-3kz}$$

where α is a constant and can be set to 1.0, A, k, and ω are the amplitude, wave number and frequency of monochromatic ocean surface wave, respectively. The wave amplitude is the most important term in determining the wave-induced mixing. Thus a 15–25% difference in wave height leads to a 50–100% difference in wave mixing.

5. Summary

[21] We have carried out a set of numerical experiments to investigate, step by step, the effects of bathymetry and surface wave-induced mixing on the summer stratification of the Bohai Sea. Our target phenomenon is a warm water column in the central Bohai Sea that is nearly vertically uniform in temperature and surrounded by cold bottom water capped by a strong seasonal thermocline. Both wave-mixing from the top and tidal mixing from the bottom are important for the formation of this well-mixed water column anchored by a 20 m deep ridge in bathymetry. Our simulation shows that the tidal mixing extends 10 m above the bottom while wave mixing penetrates 10 m below the surface. The bathymetric ridge elevates tidal mixing both in height and intensity, while wave mixing reaches a maximum in the central Bohai Sea. The enhanced mixing atop the ridge transports heat downward and keeps the temperature in this well-mixed water column as much as 5°C warmer than that in the surrounding bottom water. The enhanced downward heat transport by wave mixing also increase the temperature of the surrounding cold bottom water by about 6°C.

[22] Both the T/P altimeter observations and wave model display a maximum in significant wave height in the central Bohai Sea, corroborating our model simulation that wave mixing is strong in the mid-basin. This mid-basin maximum in wave height appears to be due to the longer fetch under the southeast monsoon.

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