Annual Cycle of Stratification and Tidal Fronts in the Bohai Sea: A Model Study

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In general, competition between buoyancy mechanisms and mixing dynamics largely determines the water column structure in a shelf sea. A three dimensional baroclinic ocean model forced by surface heat fluxes and the 2.5 order Mellor-Yamada turbulence scheme is used to simulate the annual cycle of the temperature in the Bohai Sea. The difference between the sea surface temperature (SST) and sea bottom temperature (SBT) is used to examine the evolution of its vertical stratification. It is found that the water column is well-mixed from October to March and that the seasonal thermocline appears in April, peaks in July and then weakens afterwards, closely following the heat budget. In addition, the Loder parameter based on the topography and tidal current amplitude is also computed in order to examine tidal fronts in the BS, which are evident in summer months when the wind stirring mechanism is weak.

1. Introduction

According to the conventional understanding, the water column structure in shelf seas is controlled by two opposite physical mechanisms: buoyancy and mixing (Simpson and Hunter, 1974; Bowers and Simpson, 1987; Chen, 2003). The former stratifies and stabilizes the water column by enhancing the potential energy (PE), whereas the latter weakens its stability through the de-stratifying process. Among the two factors contributing to buoyancy formation, the heat flux plays a more important role because it functions everywhere throughout the year, though the freshwater flux also plays a considerable role in regions of freshwater influence (ROFI), especially in the wet season. In genuine marine environments, mixing is produced through the dissipation of turbulent kinetic energy (TKE), which is not only generated from bottom friction, but also driven by wind input of turbulent kinetic energy and the internal processes that come from internal wave breaking, shear and gravitational instabilities, etc. TKE always competes against PE in the water column: when it is strong enough to overwhelm PE, mixing occurs; otherwise, the stratified configuration is maintained. In times when tidal mixing contributes most to the production of TKE, tidal fronts are often observed between sufficiently mixed regions and highly stratified regions (Simpson and Hunter, 1974; Bowers and Simpson, 1987; Zhao et al., 2001), which are generally characterized by sharp horizontal salinity or temperature gradients and are able to block the free exchange of materials effectively. Therefore, a better understanding of the evolution of stratification and the position of tidal fronts is needed for a thorough knowledge of ecosystem dynamics as well as pollutant transportation in shelf seas.

The Bohai Sea (BS) is a semi-enclosed shelf sea with a mean depth of about 18 m (Fig. 1). Hydrodynamics in the BS have been intensively studied in past decades (Fang and Yang, 1985; Zhao and Shi, 1993; Huang et al., 1996, 1999; Wei et al., 2004; Liu et al., 2005). However, little attention has been paid to the evolution of its stratification. Huang et al. (1996, 1999) have given a brief analysis based on the simulated seasonal variation of the temperature profiles along two cross sections. Using the stratification model formulated by Simpson and Hunter (1974), Zhao et al. (2001) have presented a detailed description of tidal fronts in the BS under weak wind conditions. These studies are substantive, but do not reveal the comprehensive temporal and spatial variation of stratification in the BS. This paper attempts to discuss this problem by means of the simulated SST and SBT. In addition, by computing the Loder parameter (1986), this paper further examines the tidal fronts in the BS during summer months, which are characterized by weak wind mixing (Zhao et al., 2001).
The north of China belongs to the typical temperate continental climate and is characterized by the long-term drought, which determines the seasonality of river discharges into the Bohai Sea. Moreover, the rapid economic development in regions around the BS necessitates a huge consumption of freshwater, so the river runoff has shrunk further in past decades. Taking the Yellow River—the largest freshwater source of the BS as an example, the annual number of days of discontinuity has increased from tens of days in the 1950s to more than 100 days in the early 1980s, and to more than 200 days currently. Just because of the drastic reduction of the total river discharge, salinity in the BS has increased at a rate of 0.074 psu a\(^{-1}\) from 1960 to 1997 (Lin et al., 2001). Therefore, the present study more concerns buoyancy formation induced by heat budget, and the freshwater influence is tentatively neglected.

2. Model Description

2.1 General features of POM

The model employed in this study is a three dimensional, primitive equation ocean model originally developed by Blumberg and Mellor (1987), conventionally called POM. Some basic characteristics of this model are summarized as follows: it is a free surface model using the sigma coordinate system to represent the irregular bottom topography; the simulation of vertical mixing and horizontal viscosity is achieved through the 2.5 order Mellor-Yamada (1982) turbulence closure scheme and the Smagorinski scheme, respectively. A more detailed description of this model has been given by Mellor (2002).

2.2 Vertical boundary conditions

Wind stress and bottom friction function at the sea surface (\(\sigma \rightarrow 0\)) and sea floor (\(\sigma \rightarrow -1\)), respectively, so the vertical boundary conditions for momentum equations are expressed as follows

\[
\frac{K_M}{D} \left[ \frac{\partial U}{\partial \sigma} \right] - \frac{1}{\rho_a} \left( U_{10}^2 + V_{10}^2 \right)^{1/2} \left( U_{10}, V_{10} \right) \quad \sigma \rightarrow 0
\]

(1)

\[
\frac{K_M}{D} \left[ \frac{\partial U}{\partial \sigma} \right] = C_D \left( U^2 + V^2 \right)^{1/2} (U, V) \quad \sigma \rightarrow -1
\]

(2)

where \(K_M\) is the vertical eddy viscosity; \(D = H + \eta\), in which \(H, \eta\) indicate the water depth and the sea surface elevation, respectively; \(U, V\) are the \(x, y\) components of current speed; \(\rho_a\) is the density of air; \(U_{10}, V_{10}\) are the \(x, y\) components of wind speed 10 m above sea surface; \(C_D\) is the drag coefficient at the sea surface, which is calculated from the bulk formula presented by Large and Pond (1982). In Eq. (2) \(C_z\) is expressed as follows

\[
C_z = \max \left[ \frac{0.2k^2}{\ln \left( \frac{1 + \sigma_{kb-1}}{z_o} \right)^2}, 0.001 \right]
\]

(3)

where \(k = 0.4\) is the Von Kármán constant; \(z_o\) is the seafloor roughness assumed to be 0.01 m; \(\sigma_{kb-1}\) is the thickness of the sigma layer near the seafloor; 0.001 on the right-hand side of Eq. (3) is the minimum drag coefficient for bottom stress in the Bohai Sea, which was estimated by Zhou and Fang (1987).

Vertical boundary conditions for the temperature equation are expressed in the form of heat flux, as

\[
\frac{K_H}{D} \frac{\partial T}{\partial \sigma} = -\left( Q_s - Q_b - Q_e - Q_h \right) / \left( C_p \rho \right) \quad \sigma \rightarrow 0
\]

(4)

\[
\frac{K_H}{D} \frac{\partial T}{\partial \sigma} = 0 \quad \sigma \rightarrow -1
\]

(5)

where \(K_H\) is the vertical diffusivity; \(T\) is seawater temperature; \(C_p, \rho\) indicate the specific heat and density of seawater, respectively.

In Eq. (4), solar radiation \(Q_s\) is computed using a real-time irradiation model (Liu and Yin, 2006), which is a function of solar height and cloud parameter, and is able to simulate the variation of short wave radiation at the BS surface. \(Q_b, Q_e\) and \(Q_h\) represent the outgoing long wave radiation flux, evaporative heat flux and sensible
heat flux, respectively, which are calculated using a modified version of the bulk formula originally developed by Ahsan and Blumberg (1999), as follows

\[
Q_a = \varepsilon \cdot \beta \left[ 9.52 \times 10^{-6} \cdot T_a^6 \cdot \left( 1 + 0.17 C^2 \right) - T_i^6 \right] \tag{6}
\]

\[
Q_e = \left( 9.2 + 0.53 \cdot U_w^2 \right) \left( e_a - e_s \right) \tag{7}
\]

\[
Q_h = 0.47 \cdot \left( 9.2 + 0.53 \cdot U_w^2 \right) \left( T_a - T_i \right) \tag{8}
\]

where \( \varepsilon = 0.97 \) is the emmissivity of seawater; \( \beta = 5.67 \times 10^{-8} \) is the Stefan-Boltzman constant (unit: W m\(^{-2}\)K\(^{-4}\)); \( T_a, T_i \) indicate air and sea surface temperature in K, respectively; \( e_a, e_s \) indicate saturated vapor pressure in mbar at air and sea surface temperature, respectively; \( U_w \) indicates wind speed in ms\(^{-1}\); \( C \) is cloud parameter.

In addition, Eq. (5) implies that the heat flux at the sea bottom is assumed to be zero.

2.3 Open lateral boundary conditions

The so-called Flather radiation condition (Marchesiello et al., 2001) is adopted at the open lateral boundary for the normal component of the external velocity field, as

\[
u_n = u_T + \sqrt{g/\Delta} (\eta - \eta_T) \tag{9}
\]

where \( u_n \) and \( u_T \) are the depth-mean current speed and prescribed tidal current speed, respectively; \( n \) denotes the normal vector at the open boundary; \( \eta \) indicates the sea surface elevation at the nearest interior non-open-boundary, which is calculated from the continuity equation; \( \eta_T \) indicates the prescribed tidal height at the open lateral boundary, and is expressed as the superposition of 8 major tides—K\(_1\), O\(_1\), P\(_1\), Q\(_1\), M\(_2\), S\(_2\), N\(_2\) and K\(_2\)

\[
\eta_T = \sum f_i H_i \cos(\omega_i \cdot t + (\nu + u_i) \cdot g_i) \tag{10}
\]

where \( f_i \) is the nodal factor; \( \nu_i, u_i \) are the Greenwich initial phase and nodal correction, respectively; \( \omega_i \) is angular frequency; \( g_i, H_i \) are phase lag and amplitude, respectively; subscript \( i \) indicates tidal constituent.

The Orlanski radiation condition (1976) is applied to the normal component of the internal velocity field at the open lateral boundary, which allows the internal wave to pass through the boundary with little reflection. An upstream advection scheme is used for the calculation of temperatures at the open lateral boundary (Mellor, 2002).

2.4 Model design

The 5 min resolution is adopted in both latitudinal and longitudinal directions, and 10 sigma layers are divided in the vertical direction. The time step assigned to the external and internal mode is 15 seconds and 450 seconds, respectively. The atmospheric surface fields such as air temperature, relative humidity, cloud cover fraction, saturated vapor pressure, and barometric pressure are interpolated from the climatology volume of Marine Atlas of Bohai Sea, Huanghai Sea and East China Sea.

Table 1. Comparisons of harmonic constants at 14 tidal gauge stations.

<table>
<thead>
<tr>
<th>Station No.</th>
<th>Name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>K(_1)</th>
<th>M(_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( \Delta H(\text{cm}) )</td>
<td>( \Delta g(\text{°}) )</td>
<td>( \Delta H(\text{cm}) )</td>
<td>( \Delta g(\text{°}) )</td>
</tr>
<tr>
<td>1</td>
<td>Hulutao</td>
<td>39°13’N</td>
<td>121°36’E</td>
<td>2.5</td>
<td>-3.2</td>
</tr>
<tr>
<td>2</td>
<td>Taipingjiao</td>
<td>40°03’N</td>
<td>121°54’E</td>
<td>1.4</td>
<td>-4.6</td>
</tr>
<tr>
<td>3</td>
<td>Yingkou</td>
<td>40°38’N</td>
<td>122°09’E</td>
<td>0.1</td>
<td>4.7</td>
</tr>
<tr>
<td>4</td>
<td>Huludao</td>
<td>40°43’N</td>
<td>121°00’E</td>
<td>0.8</td>
<td>3.9</td>
</tr>
<tr>
<td>5</td>
<td>Qinhuangdao</td>
<td>39°54’N</td>
<td>119°36’E</td>
<td>2.9</td>
<td>4.3</td>
</tr>
<tr>
<td>6</td>
<td>Luanhekou</td>
<td>39°25’N</td>
<td>119°18’E</td>
<td>2.2</td>
<td>-1.1</td>
</tr>
<tr>
<td>7</td>
<td>Caofeidian</td>
<td>38°58’N</td>
<td>118°29’E</td>
<td>1.6</td>
<td>0.0</td>
</tr>
<tr>
<td>8</td>
<td>Tanggu</td>
<td>39°06’N</td>
<td>117°43’E</td>
<td>2.4</td>
<td>-2.6</td>
</tr>
<tr>
<td>9</td>
<td>Qihekou</td>
<td>38°36’N</td>
<td>117°35’E</td>
<td>-2.8</td>
<td>-5.0</td>
</tr>
<tr>
<td>10</td>
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<td>118°16’E</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>11</td>
<td>Wanwangou</td>
<td>38°25’N</td>
<td>118°47’E</td>
<td>-2.8</td>
<td>2.9</td>
</tr>
<tr>
<td>12</td>
<td>Xiaopinghe</td>
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<td>118°58’E</td>
<td>3.5</td>
<td>4.9</td>
</tr>
<tr>
<td>13</td>
<td>Taipingwan</td>
<td>37°10’N</td>
<td>119°48’E</td>
<td>3.1</td>
<td>0.3</td>
</tr>
<tr>
<td>14</td>
<td>Penglai</td>
<td>37°49’N</td>
<td>120°45’E</td>
<td>0.8</td>
<td>-3.6</td>
</tr>
</tbody>
</table>
which are monthly mean climatologies in the 1980s. The wind field over the Bohai Sea is interpolated and extrapolated from observations at coastal ocean stations (Yang et al., 2005). The initial temperature and salinity field are set to 5.5°C and 31 psu homogeneously throughout the BS. In the course of simulation, temperature variation is forced by heat flux at the sea surface and the heat transfer process in the water column, whereas salinity is kept constant. Because it is the temperature difference instead of the density difference between sea surface and sea bottom that is used to examine the evolution of stratification, the comparably coarse treatment of salinity does not affect the modeled results significantly for the present study.

The model was initiated from Jan 1st and run for two climatological years, and the results of the second year are presented and analyzed.

3. Validation of the Simulations

The baroclinic tides were calculated and compared with observations at 14 tidal gauges (Fig. 1). The modeled and observed M$_2$ and K$_1$ harmonic constants are listed in Table 1, from which it can be seen that the simulations agree with the observations reasonably well. The root mean squares of amplitude and phase lag difference for K$_1$ tide are about 2.26 cm and 3.47°, respectively, while for M$_2$ tide they are 3.59 cm and 3.65°, respectively. The further error analysis shows that the relative error with respect to tidal amplitude is about 7.57% for K$_1$ constituent and 2.32% for M$_2$ tide. In addition, Table 1 also shows that some computed results are larger than observations whereas others are smaller, so it can be suggested that
systematic error is absent from the present simulations. Both this study and previous studies (Fang and Yang, 1985; Wei et al., 2004; Liu et al., 2005) have revealed that $M_2$ tide is dominant in the Bohai Sea, so the simulated co-amplitude and co-phase are presented in Fig. 2 for a better elucidation of the major tidal regime in the BS. Figure 2 shows two evident amphidromic points: one in the offshore of Qinhuangdao and the other near the old Yellow River mouth, where tidal range approximates zero. The largest tidal range occurs at the end of Liaodong Bay (northeast of the BS) and Bohai Bay (west of the BS), reaching as high as 4 m and suggesting the strong mixing dynamics there; comparably, the tidal range in Laizhou Bay (south of the BS) is rather small and no more than 1 m in general, so it is not surprising to see that the tidal mixing mechanism is weak in this bay.

The simulated annual cycle of seawater temperature was also examined by comparison with observations. The sea surface temperature (SST) used for checking simulations was recorded during 1982–1989 at four hydrological stations around the Bohai Sea, namely Longkou, Changxingdao, Qinhuangdao and Tanggu (Fig. 1). At those stations sea surface temperature was observed four times a day, so daily mean SST over eight years was obtained and is shown in Fig. 3, which also shows the simulated monthly mean SST at four stations, based on the climatologies in the 1980s. It can be seen that the modeled annual cycle of SST reasonably reflects the seasonal variation of measured SST at four hydrological stations. The root mean square of monthly mean SST is 0.83, 1.22, 1.49 and 1.47°C for Tanggu Station, Longkou Station, Changxingdao Station and Qinhuangdao Station, respectively. In addition, the simulated temperature profiles along the cross section i–ii (Fig. 1) are further examined. Figure 4 shows that the simulated monthly mean temperature profiles for February, May, August and November are reasonably consistent with observations, which reveals that the water column in the Bohai Sea is characterized by sufficient mixing in winter and spring, whereas there is evident stratification in summer and autumn. This phenomenon and its governing mechanism will be discussed in detail in the subsequent section.

The reasonable agreements between simulations and observations provide a warrant to investigate the evolution of stratification in the Bohai Sea by means of the simulated temperature difference between sea surface and sea bottom, and to understand the mechanisms contributing to the water column structure.

4. Seasonal Variation of Stratification

In this section the difference between sea surface temperature (SST) and sea bottom temperature (SBT)—
ΔT is used to examine the evolution of stratification in the Bohai Sea. Following Bowers and Simpson (1987), it is assumed that the water column is sufficiently mixed if ΔT < 0.5°C whereas the vertical stratification arises if ΔT > 2°C. The regions with 0.5°C ≤ ΔT ≤ 2°C are tentatively regarded as the tidal fronts in times that tidal mixing plays the most important role in producing turbulent kinetic energy (TKE), which is most evident in summer months when the weak climatological wind field dominates in the BS. In Fig. 5, the difference between SST and SBT is shown for four seasons represented by January, April, July and October. In order to elucidate the stratification evolution more clearly, Fig. 6 also displays the monthly mean net heat flux at the BS surface. It is found that the evolution of stratification depends closely on the total heat budget. Based on the modeled results, ΔT is less than 0.5°C throughout BS before March, meaning that no stratification forms and the water column is fully mixed, which just corresponds to the negative heat budget during those months. As time continues into April, the positive heat flux increases markedly, so the vertical stratification begins to form in the Laizhou Bay, central basin and the Bohai Strait, which is ascribed to the combined effect of strengthened buoyancy due to heat and a weakened mixing mechanism due to weak wind stirring. Figure 6 shows the positive heat budget increases continuously from April and peaks in July, so the stratification area also expands accordingly until July when it reaches its widest extent (Fig. 5). Although the heat budget starts to decrease in August, the positive heat gain for seawater is still enough to maintain stratification in the water column. As time continues into September, the heat budget decreases drastically compared to the previous month, and nears zero; on the other hand, the combined mixing mechanism due to tide and wind forcing strengthens correspondingly, so there is a pronounced breakup of the seasonal thermocline. In October, when the heat budget has become negative, the water column resumes the fully mixed state in most parts of BS, except the outside of Bohai Strait where the stratification can last longer. The synthetic interaction of heat budget and tidal as well as wind stirring mechanisms in the BS results in the evident stratifications in the summer months and sufficient mixing in the winter months, which has been verified by observations (Huang et al., 1996, 1999; Zhao et al., 2001).

As stated previously, the water column configuration is determined by the competition between the potential energy (PE) induced by buoyancy mechanisms and the turbulent kinetic energy (TKE) induced by mixing mechanisms. As we know, tidal forcing does not change significantly all the year round; on the other hand, the Bohai Sea is characterized by the simultaneous effect of minimum climatological wind field and maximum heat budget in the summer months, so the strongest PE is produced and this enables the water column to become stratified and stabilized. As for the winter months, the heat flux is negative, suggesting that the air temperature is
lower than the sea surface temperature (SST), so the sea surface temperature may be even less than the sea bottom temperature due to heat flowing out from the sea surface into the atmosphere. As a consequence, the colder surface waters will enhance the vertical mixing in the water column, if it is not frozen. In addition, the climatological wind field over the BS also reaches a maximum in the winter months, which further strengthens the mixing mechanism in the water column.

5. Tidal Front Phenomenon in the Bohai Sea

Tidal fronts are often observed between highly stratified regions and sufficiently mixed regions in the summer months when wind stirring is weak in the Bohai Sea (Zhao et al., 2001). In this section a parameter method is used to examine the tidal front phenomenon in the BS by tentatively neglecting the wind mixing mechanism.

Assume that the buoyancy and mixing mechanism are merely produced by heat flux and tidal currents, respectively; then the potential energy (PE) and turbulent kinetic energy (TKE) in the water column can be approximately expressed as

\[ PE = \frac{1}{2} g \alpha \frac{QH}{C_p} \]  
\[ TKE = \frac{4 \delta}{3 \pi} \rho \gamma U^3 \]

where \( Q \) is heat flux at the sea surface; \( \alpha \) is the thermal expansion coefficient; \( g \) is gravitational acceleration; \( \gamma \) is the drag coefficient for bottom stress; \( \delta \) is the efficiency of tidal mixing; \( U \) is tidal current amplitude.

If heat budget \( Q < 0 \), just as October to February indicate (Fig. 6), then PE becomes negative based on Eq. (11a), which means that PE due to heat flux will not contribute to stratification formation in this case and the water column is well mixed, so tidal fronts do not exist in the BS.

If heat budget \( Q > 0 \) and assuming that positive PE and TKE are balanced, then the following equation can be derived

\[ \frac{H}{U^3} = \frac{8 \delta}{3 \pi} \frac{\rho \gamma C_p}{g \alpha Q} \]

Equation (12) was first formulated by Simpson and Hunter (1974), and its left-hand side is easy to calculate if the topography and tidal current amplitude are known, so this term is generally used to predict tidal fronts in shelf seas (Simpson and Hunter, 1974; Bowers and Simpson, 1987; Zhao et al., 2001). Based on a similar assumption of heating-stirring competition in the water column, a series of parameters have been developed aimed at different regions and different mixing mechanisms (Loder and Greenberg, 1986; Bowers and Simpson, 1987), which have a common form, as follows

\[ k = \log \left( \frac{H}{U^n} \right) \frac{3}{4} \leq n \leq 3. \]

When \( n \) equals 3 and 3/4, one derives the so-called Simpson parameter (1974) and Loder parameter (1986), respectively. By comparing the fitness of various parameters, Bowers and Simpson (1987) suggested that the Loder parameter seems the most applicable in shelf seas with a water depth of no more than 50 m. Given that the Bohai Sea is a typical shallow shelf sea with a mean depth of only 18 m, the Loder parameter is calculated and used to examine tidal front phenomenon in the BS which is
most evident in the summer months. The depth-mean $M_2$ current amplitude is used to substitute for $U$ in Eq. (13).

The distribution patterns of $k$ are given in Fig. 7, from which it can be seen that only at the end of three bays—Liaodong Bay, Bohai Bay and Laizhou bay—is $k$ less than 6, whereas in the central basin, Bohai Strait and the greater part of three bays, $k$ is larger than 6.5. The general distribution trend is that the higher value of $k$ appears further away from the coasts. Figure 7 also shows the evident narrow bands of seawater with the $k$ value between 6 and 6.5 in three bays. Therefore, if $6 \leq k \leq 6.5$ is presumably defined as the tidal fronts, just corresponding to $0.5 < \Delta T < 2$ in the previous section, $k < 6$ corresponds to the fully mixed regions and $k > 6.5$ to the highly stratified regions; then the predicted position of tidal fronts and distribution patterns of stratification area are reasonably consistent with that obtained using the temperature difference method in July (Fig. 5), when the wind stirring is least and buoyancy due to heat is the strongest.

It should be noted that though the $k$ value used to predict tidal fronts is calculated directly from the local topography and current amplitude, its genuine magnitude closely depends on the heat flux $Q$ according to Eq. (12). Figure 6 shows that the $Q$ value reaches its largest magnitude in July, so the $k$ value (between 6 and 6.5), assumed to correspond to tidal fronts, should be its smallest throughout the year. Following the above extrapolation, if the $k$ parameter is applied to other months, then its magnitude must be larger than 6–6.5, given the premise that $Q > 0$. Another point that should be stressed is that the $k$ parameter technique is most applicable to summer months when tidal mixing dominates in the BS. If such a method is extended to other months, wind stirring mechanisms must be included for a proper simulation of the production of turbulent kinetic energy.

Both the parameter technique and the temperature method discussed in the previous section are based on the assumption of heating-stirring competition in the water column, so it is not surprising to see that a similar tidal front position and stratification area distribution are achieved in the summer months when tidal mixing contributes most to the production of turbulent kinetic energy in the Bohai Sea. Despite some limitations of the parameter technique, its simplicity makes it a convenient method to predict the position of tidal fronts, which may significantly influence the ecosystem dynamics in the Bohai Sea (Su and Tang, 2002).

6. Conclusions

In this paper, a three-dimensional hydrothermal model is used to investigate the evolution of stratification in the Bohai Sea (BS). Modeled results agree well with observations. By analyzing the difference between sea surface temperature (SST) and sea bottom temperature (SBT), it is found that stratification comes into existence in April, peaks in July and then decays until October, when the water column resumes the fully mixed state in most parts of the BS, closely following the competition between the mixing dynamics and buoyancy mechanisms due to heat flux. Moreover, the Loder parameter is also calculated in this study to examine the tidal front phenomenon, which is most evident in the summer months, when the wind stirring mechanism can be tentatively neglected due to weak climatologies. Despite some limitations in application, its simplicity still makes it an attractive method to predict the position of tidal fronts in the BS. Understanding the evolution of stratification as well as tidal front position is significant for a thorough knowledge of the ecosystem dynamics in the Bohai Sea.

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Reference


