Tidally Induced Cross-frontal Mean Circulation:

A Numerical Study[1]

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Abstract

The linear decomposition of the circulation across a tidal front suggested by an analytical model (Dong et al. 2004) is examined using a two-dimensional numerical model. Three basic experiments are performed for a homogenous ocean, and winter and summer fronts, respectively, in which the cross-frontal circulation can be interpreted within the context of the analytical solution. Through a series of numerical experiments, the sensitivity of the circulation to tidal strength, topography horizontal scale, frontal strength, and vertical eddy viscosity are examined. The effects of assumptions in the analytical model are also examined through comparison between numerical and analytical solutions. The ratio between the tidal excursion distance to the topographical scale is crucial to the Ekman cell in the homogenous ocean. With a greater density gradient, both the Bernoulli and Ekman cells are enhanced. The uniform eddy viscosity and linearization in the analytical model maybe overestimates the bottom flow in the Ekman cell and weakens the Bernoulli cell on the shallower region, respectively. The influence of the internal tide on cross-frontal circulation is discussed.

1. Introduction

In a tidal frontal zone, the cross-frontal mean flow is of the order of 1 cm/s, one order of magnitude smaller than the along-frontal flow (Loder and Wright 1985; Loder et al. 1992; Chen et al. 1998). However, its importance in practical application cannot be ignored. In fact, the tidally induced upwelling and downwelling, which produce vertical transport of nutrient and other materials important for biological productivity, are caused by the cross-frontal mean circulation (Tee 1985). The mechanism for the formation of the circulation may help one better understand the water exchange and sediment transport across the front.

An analytical model characterizing the tide-induced cross-frontal mean circulation is developed by Dong et al. (2004, referred as Dong04 hereafter):

$$\psi(x,z) + E_V{}^2 \frac{\partial^4 \psi}{\partial z^4} = B_U \frac{\partial \rho}{\partial x} - \frac{\partial (TSU)}{\partial z} + \frac{1}{E_V} \int_0^z (TSV)\,dz + \psi(x,0) \tag{1}$$

where Ψ is the stream function, ρ the density, E_V the vertical Ekman number, B_U the burger number, and TSU and TSV related to cross-shore and along-shore tidal stresses respectively. The four terms on the right side of the equation represent four types of mechanisms driving the multiple-cell cross-frontal mean circulation similar to those found in previous studies (Tee 1985; Loder and Wright 1985; Chen and Beardsley 1998; Blaas and Swart, 2002; Chen et al. 2003). Within the confines of the linear system, the cross-frontal mean circulation is decomposed into four generic cells: the clockwise frontal cell (first term), the clockwise Bernoulli cell (second term), the counter-clockwise Ekman cell (third term), and the Stokes drift (fourth term) (facing in the direction with the shallow water to the left). The Bernoulli cell, with an onshore flow near the bottom and an offshore flow at the surface, is driven by the spatial variation of tidal kinetic energy. The Ekman cell, with the offshore flow near the bottom and onshore flow near the surface, is driven by an along-shore mean current which can be induced by the tidal rectification, flowing in the direction with the shallow water on the right in the northern hemisphere. The frontal cell is in the same sense as the gravitational tendency, which acts to enhance the Bernoulli cell and weaken the Ekman cell. The Stokes drift is directed in the same direction as the incoming surface gravity waves. The decomposition provides a dynamical framework to interpret and understand the complex structure in the cross-frontal circulation.

To obtain the analytical solution, certain assumptions are made, which may not be applicable to the real ocean, where the nonlinearity may not be neglected, the vertical viscosity is not uniform and the frontal structure interacts with the circulation. Here we use a numerical model to study the cross-frontal mean circulation and examine the applicability of the analytical model. In the numerical study, since primitive equations are used, the interaction between tidal and mean currents is fully incorporated and many assumptions of the analytical model are no longer necessary.

This paper is organized as follows. In Section 2, the numerical model configuration, three basic numerical experiments and their comparisons with the analytical model are described. Section 3 is the sensitivity study. Section 4 and 5 are the discussion and the summary, respectively.

2. Numerical Experiments

a. Configuration of Numerical Model

The Princeton Ocean Model (POM), a sigma-coordinate, free surface and primitive-equation model is applied to the present study (Blumberg and Mellor, 1987). In the model the vertical mixing is parameterized using the level 2.5 turbulence closure scheme (Mellor and Yamada, 1982) as modified by Galperin et al (1988). To focus on the cross-frontal process, the model used here is configured on a two-dimensional cross-shore plane (x-z). The topography has an exponential form, as used in Dong04,

$$h = \begin{cases} h_0 \exp(\frac{x - x_0}{L}), x > x_0 \\ h_0, x < x_0 \end{cases} \tag{2}$$

if $h > h_m$, $h = h_m$.

where h_0 and h_m are the water depths at the inshore and offshore sides, respectively, L the e-folding distance, x_0 the inshore width. In the following basic experiments, we set $h_0 = 30$ m, $h_m = 300$ m, L=10 km and $x_0 = 20$ km. The horizontal grid size is 1 km and the vertical grid consists of 40 equally spaced sigma-levels. The time steps for the barotropic and baroclinic modes are 6s and 120s respectively. Semi-diurnal tides (M_2) are imposed through a periodic surface displacement at the offshore edge of the model domain, and a sponge layer appended to the edges attenuates the reflected waves. The amplitude of the surface elevation at the offshore edge is set at 0.5 m so the tidal current at the inshore edge is about 1 m/s. Since we are concerned with tide-driven circulation, surface wind forcing and heat flux are set to zero. The same model with similar configuration has recently been used to study tidal frontogenesis (Ou et al, 2003) and diapycnal flow within the tidal front zone with passive tracers (Dong et al, 2004).

b. Basic Experiments

Three basic numerical experiments are performed for a homogenous ocean and for a stratified ocean pertaining to winter and summer fronts, respectively. In winter, due to strong surface cooling and wind stirring, the tidal front extends from the bottom to the surface. In summer, the tidal front is formed between well-mixed inshore water and stratified offshore water, and it intersects both the surface and the bottom. The cross-frontal circulation of the three experiments is interpreted with the dynamical framework of the analytical model.

(1) Homogenous Ocean

It takes about 3 tidal cycles for the model tidal current and elevation to become quasi-stable and the mean flow to be established. The peak tidal amplitudes are 0.96 m/s for cross-shore current and 0.66 m/s for along-shore current at the inshore edge (Fig. 1a and 1b). The phase lags of cross- and along-shore tidal currents in Fig. 1c and 1d show the tide current in the bottom leads that at the surface and the cross- and along-shore tidal currents are near 90 degrees out of phase.

The model is run for 20 tidal cycles. The last ten cycles are used to calculate the mean fields, which are shown in Fig. 2. The sea surface elevation (Fig. 2a) with a peak over the shelf is consistent with that in Dong04. The along-shore mean current (Fig.2b), flowing in the direction with the shallow water on the right, has a peak value of 15 cm/s.

This can be explained by tidal rectification (Loder 1980; Ou 1999 and 2000). Fig. 2c shows that the vertical eddy viscosity decreases offshore and its maximum occurs a few meters away from the bottom where the strongest local current shear occurs.

Fig. 2d shows that the cross-shore mean circulation is composed of three cells with velocities ranging from -0.6 cm/s to 1 cm/s. Two clockwise cells are located on the inshore and offshore sides, corresponding to the Bernoulli cells. Another cell is located between the two with opposite sense of rotation, corresponding to the Ekman cell. The offshore flow in the upper layer on the inshore side is due to the Stokes drift.

The phase difference between the cross- and along-shore tidal currents is greater than 90 degrees at the bottom and less than 90 degrees at the surface (Fig 1c and 1d), which is consistent with the analytical result (Dong 2002). The tidal stress is defined as

$$\overline{u'v'} = 0.5 u_m v_m \cos(\Delta\theta)\,, \tag{3}$$

where u and v are cross- and along-shore currents, the prime denotes the tidal components, the subscript m the tidal amplitude and $\Delta\theta$ the phase difference between u' and v'. The tidal stress is negative at the bottom and positive at the surface, and its amplitude decreases offshore. Its horizontal variation drives the cross-shore mean circulation: onshore near the bottom and offshore near surface, forming the Bernoulli cell. The along-shore current, flowing in the direction with the shallow water on the right, drives a circulation that is offshore near the bottom and onshore at the surface. This circulation is called Ekman cell because its mechanism is similar to the Ekman dynamics.

Comparing Fig. 2 with analytical solutions in Dong04, we see similarities and differences between the numerical and analytical solutions. Both show a three-cell structure, suggesting that the analytical model has captured the essential physics of the cross-shore circulation. In the numerical model, however, the inshore Bernoulli cell is stronger than the offshore one, and the Ekman cell is weaker with its center located farther away from the bottom. The differences are explained in Section 3.

(2) Winter Front

The front that produces the frontal circulation cell is specified in Dong04. In the numerical model, however, the front is generated by a frontogenesis mechanism, whose location and structure depend on the initial and boundary conditions.

For winter front, the density variation is dominated by salinity. In this basic experiment, the initial salinity varies linearly from 32.5 PSU to 33.0 PSU between the inshore and offshore sides and temperature is set constant (10^oC). The radiation condition is applied to both sides. The tidal forcing is the same as that used for the above homogenous case. Ou et. al. (2003) has demonstrated that a winter front can be generated from an initial condition of uniform lateral gradient. After 10 tidal cycles, a quasi-equilibrium state is reached, and the density front is shown in Fig. 3a. Compared with the homogenous case, the along-shore mean current (Fig. 3b) is enhanced, and the vertical eddy viscosity (Fig. 3c) is reduced within the frontal zone.

The cross-shore circulation is plotted in Fig. 3d. Comparing with the circulation in the homogenous ocean shown in Fig. 2d, one may see that both have a three-cell structure, but the offshore Bernoulli cell and the Ekman cell in the middle have been enhanced in the frontal case. The offshore Bernoulli cell strengthening is due to the flow associated with winter front, as suggested by the analytical model. It is also possible that the enhancement is partially due to the weaker eddy viscosity, see Section 3d for more discussion. In the presence of the front, the along-shore current is strengthened, which may lead to the enhancement of the Ekman cell.

(3) Summer Front

To generate a summer front, we set initial condition to be a stratified temperature field (the salinity is set constant: 33 PSU), which is 13^o C above 30 m, decreasing linearly to 10^o C from 30 m to 42 m and 10^o C below 42 m, and the corresponding density (σ_θ) ranges from 24.8 to 25.3. The radiation condition is applied to both sides. A quasi-equilibrium state is reached after 10 tidal cycles. As shown in Fig. 4a, the initial stratification in the shallow region is destroyed by the strong tidal mixing, but it remains in the deep water. Thus a two-branch summer front is formed. Fig. 4b shows the mean along-shore current with a maximum velocity about 30 cm/s, much greater than that in the homogeneous ocean. The vertical viscosity, plotted in Fig. 4c, shows a decrease within the frontal zone as compared with that in the homogenous ocean.

Two branches of the summer front have the opposite density gradient: the density increases offshore in the lower branch but decreases offshore in the upper branch. Therefore the gravitational circulations associated with the two branches are opposite as well: clockwise in the lower branch and counter-clockwise in the upper branch. The cross-frontal circulation shown in Fig.4d is consistent with this deduction. Because of the density gradient, there are more cells than in the homogenous ocean (Fig. 2d). Specifically, the offshore clockwise cell is split into two clockwise cells by a counter-clockwise cell associated with the upper branch of the front. Compared with the homogenous case, both the Bernoulli and Ekman cells have been strengthened, with the latter being reflected in the stronger along-shore flow.

The prominent feature in the circulation is the strongest clockwise cell located at the center of the front, that is maybe caused by other factors not included in the analytical model, such as internal tide and nonlinearity, which is discussed in Section 4 in detail.

3. Sensitivity Study

Consistent with Dong04, the above experiments show the cross-frontal circulation can be interpreted within the context of four generic cells: the Ekman cell, the Bernoulli cell, the Frontal cell and the Stokes drift. The sensitivity of the cross-frontal circulation to the model configuration and parameters is examined here, with specific attention to tidal amplitude, topography horizontal scale, frontal strength, and vertical eddy viscosity. With these additional runs, we can also assess how the assumptions of Dong04 may affect the cross-frontal circulation.

a. Tidal Amplitude

We perform a group of experiments (Group A) of different tidal amplitudes. With the same topography as that in the homogenous case, the cross-shore peak tidal currents at the inshore side vary from 0.2m/s to 1.8m/s.

Fig. 5 shows the cross-shore and along-shore mean currents when the peak tidal current at the inshore side are 0.2m/s, 0.6m/s and 1.0m/s, respectively. In Fig. 5a and 5b, the tide is weak, resulting in the weak along-shore current, which leads to an Ekman cell too weak to be discerned. With the increase in the tidal strength, the along-shore flow is enhanced (Fig, 5d and 5f) and the Ekman cell becomes stronger and splits the Bernoulli cell into two (Fig. 5c and 5e). Fig. 6 shows that the volume transport associated with the Ekman cell increases with the tidal current much more than that with Bernoulli cells. The difference stems from the different generation mechanism of the Bernoulli cell and Ekman cell. The former due to the spatial variation in tidal kinetic energy does not change much when the topography is fixed, and the latter driven by the along-shore flow varies as the square of the tidal amplitude.

b. Horizontal Topography Scale

We perform a series of experiments (Group B) with horizontal topography scales L (defined in (1)) varying from 2km to 25km, while keeping the same tidal amplitude (1.0m/s) of the homogenous case.

Fig. 7 shows the cross-shore and along-shore mean currents when the horizontal scale of the bottom topography is 5km, 10km and 15 km, respectively. When the scale is small (5km), the strong tidal rectification results in a strong along-shore flow, which in turn drives a strong Ekman cell. With the topography scale increasing, both Ekman and Bernoulli cells weaken. Fig. 8 shows that the volume transports of the three cells decrease with the increase of the horizontal topography scale, and that the decrease in the inshore Bernoulli cell is much more than the Ekman cell. The reason for the difference is the following: when the topography horizontal scale is smaller, the spatial variation in the tidal kinetic energy is larger, thus the Bernoulli cell is stronger. The Ekman cell, which is driven by the along-shore flow, becomes weaker when the along-shore flow is weaker.

The comparison between Group A and B shows that the increase in tidal amplitude has similar influence as the decrease in topographic scale on the Ekman cell. In fact, Huthnance (1973) and Loder (1980) pointed out that the along-shore flow induced by the tidal rectification strongly depends on the ratio of tidal excursion distance to the horizontal topography scale**.** When the tidal amplitude increases, the tidal excursion distance becomes greater, which is equivalent to a decreasing topographic scale.

c. Frontal Strength

In Dong04, the tidal front is specified externally, and so there is no interaction between the front and the tidal currents, which may affect the cross-frontal mean circulation. We perform two groups of experiments, Group C and D, to examine such influence. Group C is a series of experiments using different salinity gradients in the setting of the winter front case (the total salinity difference varying from 0.1 PSU to 1.0 PSU). For Group D, we consider the summer front with different stratification (the temperature difference between 30m and 42 m depths varying from 1˚C to 4˚C).

The results from Group C are shown in Fig. 9, where three cells, two Bernoulli cells and one Ekman cell, are clearly identified, which agree with Dong04. With the increase in the density gradient, both Bernoulli cells are enhanced, as indicated by their volume transports (Fig. 10). This is because the gravitational circulation induced by the front is in the same flow direction as the Bernoulli cell. The Ekman cell is also enhanced (Fig.9) and its volume transport increases (Fig. 10). This is because the increase in the along-shore flow due to the presence of the winter front drives a stronger counter-clockwise Ekman cell.

The results from Group D are shown in Fig. 11. With the weak stratification (Fig. 11a), the density gradients in the two branches are weak, thus the cross-frontal circulation is similar to the homogenous case with three cells identifiable. With the stronger stratification (Fig. 11b-d), the density gradients in the two branches increase, thus the counter-clockwise cell induced by the upper branch splits one Bernoulli cell into two, and the clockwise circulation by the lower branch enhances the Bernoulli cell. The location and structure of the front depends on the relative intensities of the stratification and tidal mixing (Simpson and Hunter, 1974). With the tidal amplitude fixed, the increasing stratification pushes the front onshore, and the inshore Bernoulli cell, being dominated by the Ekman cell, might become hard to discern.

d. Vertical Eddy Viscosity

Through a series of experiments (Group E), we examine the sensitivity of the cross-shore circulation to the vertical eddy viscosity. With the topography and tidal strength fixed in the homogenous ocean, a uniform vertical eddy viscosity is set varying in a certain range ($0.001m^2/s$ to $0.08m^2/s$). When the viscosity is small ($0.001m^2/s$), only one Bernoulli cell exists, shown in Fig. 12a. When the viscosity is $0.005m^2/s$, an Ekman cell cuts in from the bottom. When the viscosity is larger than $0.01m^2/s$, the three-cell structure is present. The volume transports of the three cells varying with vertical eddy viscosity are shown in Fig. 13. The transports of the inshore Bernoulli cell and the Ekman cell decrease with the viscosity increasing, respectively, but the Bernoulli cell seems more sensitive to the change in viscosity than the Ekman cell.

To examine the effect of the homogeneity of the vertical viscosity on the cross-shore circulation, we compare the case of the model-calculated viscosity with one using homogenous viscosity. For the basic case with homogenous ocean in Section 2a, the viscosity by the turbulence model is plotted in Fig 2c. Based on an estimate of the vertical diffusivity (Zimmerman 1986), with the vertically averaged tidal current $U_0 = 0.76 m/s$ at the inshore boundary where the depth is 30 m, the averaged vertical viscosity is $0.02 m^2/s$. The cross-shore circulation with this uniform value of vertical eddy viscosity is plotted in Fig 12c. Compared with Fig.2d, the Ekman cell is enhanced with the homogenous vertical eddy viscosity, which is because the viscosity from the turbulence model is smaller near the bottom. The larger vertical eddy viscosity may pull down the cell to the bottom.

The inshore Bernoulli cell is stronger than the offshore Bernoulli cell in Fig. 12, which is different from Dong04 where the inshore Bernoulli cell is weaker than the offshore Bernoulli cell. The strengthening of the inshore Bernoulli cell may be arisen from the nonlinearity which is neglected in Dong04 linear model. The nonlinear terms in mean momentum equations tend to enhance the Bernoulli cell because the spatial variations in the tidal and mean kinetic energies are in the same trend.

4. Discussion

a. *Influence of internal tide*

Chen et al (2003) discusses the interaction between tidal front and internal tide with the emphasis on the physical processes at the tidal frequency. It is interesting to examine how the internal tide affects on the cross-frontal mean circulation at subtidal frequency. As pointed by Chen et al (2003), at the mid-latitude, the semi-diurnal internal tide is generated at frontal zone and propagates away from it. The scenarios are similar for summer and winter tidal front. To illustrate the influence of the internal tide, we study the summer front. The common practice to obtain the internal tide is to subtract the barotropic tide from the total tide (Holloway 1996; Chen et al, 2003). Fig.14 shows the semi-diurnal internal tide structure at four time steps: peak ebb, slack before flood, peak flood and slack before ebb. The dominant feature is the internal circulation cells. The topographical rectification of the internal tide maybe complicates the cross-frontal circulation. Fig. 15 shows the comparison of the cross-shore mean circulations among three cases with total tide, barotropic tide and “baroclinic” tide (subtracting the circulation with the barotropic tide from that with the total tide). It shows that the dominant feature in the circulation with the total tide is mainly contributed by that with “baroclinic” tide. The centered clockwise cell and offshore counterclockwise cell can be interpreted using the gravitational flow associated with density gradient. However, the inshore counterclockwise cell is not part of the Ekman cell, and the offshore clockwise cell apparently is not driven by density gradient, both of which maybe are due to internal tide. The strongest clockwise cell at the center of the front is also partially due to the rectification of the internal tide. It is a challenge to isolate the rectification of the internal tide from the gravitational flow because the two are tightly connected with each other. To quantitatively estimate the contribution from the internal tide on the mean cross-frontal circulation warrants a future study.

b. Influence of others: vertical viscosity, wind and along-shore variation

From the above experiments, one may notice that in Dong04 the Ekman cell is overestimated due to the uniform vertical viscosity, and the inshore Bernoulli cell is weaker than it should be because of the linearity assumption. These shortcomings of Dong04 should be recognized.

The surface wind is not included in both numerical and analytical models. When the time scale of wind forcing is longer than the tidal period, the wind effect is significant, which may alter the structure of cross-frontal circulation. If the wind strengthens the along-frontal flow, one may expect the Ekman cell to be strengthened. In term of the sensitivity of the circulation to the vertical eddy viscosity, one may expect the influence arising from the surface cooling or heating, which is not considered here. In reality, the structure of the cross-frontal mean circulation may vary with the bottom topography and stratification. With the present study, one may better understand such dependence.

In a two-dimensional model, the effect of along-shore variation is excluded. Using the scale analysis, Dong et al (2004) demonstrates the circulation within the cross-frontal zone is quasi-two-dimensional. However, neglecting along-shore pressure gradient implies a tidal wave impinging to the sloping bottom at a right angle, obviously a special case. The effect of the along-shore pressure gradient on the along-shore residual current is discussed in Huthnance (1973) and Loder (1980). The along-shore current may in turn affects the cross-shore circulation through Ekman cell.

5. Summary

To verify the analytical model (Dong et al. 2004), a numerical model is applied to study the cross-frontal mean circulation. Three basic experiments are conducted for homogenous ocean and winter and summer fronts. It is found that the three-cell structure is a common feature except in the case of the summer front, when the offshore Bernoulli cell is split into two clockwise cells by a counter-clockwise cell associated with the upper branch of the front. Basically, the structure can be interpreted by the analytical model, which thus has captured the essential physics of the cross-frontal circulation.

A series of numerical experiments are performed to examine the sensitivity of the circulation to tidal amplitude, horizontal topography scale, stratification and the vertical eddy viscosity. The validity of the assumptions in the analytical model are also assessed thorough the model calculations. The ratio between the tidal excursion distance to the topographical scale is crucial to the Ekman cell in the homogenous ocean. With greater density gradient, both the Bernoulli and Ekman cells are enhanced. The uniform eddy viscosity used in the analytical model may overestimate the bottom flow in the Ekman cell. The linearity assumption in the analytical model may weaken the inshore Bernoulli cell compared with the numerical results from full equations. The influence of internal tide on the cross-frontal circulation exists, which may further complicate the multiple-cell structure of the cross-frontal mean circulation.

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Figure Captions

Fig. 1 For homogenous ocean: (a) cross-shore tidal current amplitude, the contour interval is 0.2 m/s, (b) the along-shore tidal current amplitude, the contour interval is 0.1 m/s, (c) and (d) are the lag phases for the cross- and along-shore tidal current, contour interval is 3.0 degree, respectively**.**

Fig.2 For homogenous ocean: (a) the cross-shore mean surface elevation, unit is cm, (b) the along-shore mean current, and the contour interval is 0.03 m/s, (c) the vertical eddy viscosity, and the contour interval is $0.01 m^2/s$, (d) the cross-shore mean circulation, the solid and dashed lines are denoted the positive and negative values, respectively, and the contour interval is 0.021 m^2/s.

Fig. 3 For winter front: (a) the density distribution (σ_t), the contour interval is 0.02, (b) the along-shore mean current, the contour interval is 0.03 m/s, (c) the vertical eddy viscosity, the contour interval is $0.01 m^2/s$, (d) the cross-shore mean circulation, the solid and dashed lines are denoted the positive and negative values, respectively, the contour interval is 0.021 m^2/s.

Fig. 4 For summer front: (a) the density distribution (σ_t), the contour interval is 0.01, (b) the along-shore mean current, the contour interval is 0.03 m/s, (c) the vertical eddy viscosity, the contour interval is $0.01 m^2/s$, (d) the cross-shore mean circulation, the solid and dashed lines are denoted the positive and negative values, respectively, the contour interval is 0.042 m^2/s.

Fig. 5 Group A: the tidal current amplitudes at the inshore edge are 0.2m/s, 0.6m/s and 1.0m/s for the upper, middle and lower panels, respectively. On the left side are the stream function of the cross-shore circulation, the solid and dashed lines are denoted the positive and negative values, respectively, and the intervals for (a), (c) and (e) are 0.0007 m^2/s, 0.0056 m^2/s and 0.0136 m^2/s, respectively. On the right side are the along-shore currents: the contour interval is 0.02 m/s.

Fig. 6 Group A: the volume transports of three cells vary with the tidal currents.

Fig. 7. Group B: the horizontal topography scales are 5 km, 10 km and 20 km for the upper, middle and lower panels, respectively. On the left side are the stream function of the cross-shore circulation, the solid and dashed lines are denoted the positive and negative values, respectively, and the intervals for (a), (c) and (e) are 0.0288 m^2/s, 0.0136 m^2/s and 0.0078 m^2/s, respectively. On the right side are the along-shore currents: the contour interval is 0.03 m/s.

Fig. 8 Group B: the volume transports of three cells vary with the horizontal topography scales.

Fig. 9. Group C: the initial salinity differences are 0.1 PSU, 0.2 PSU, 0.3 PSU and 0.4 PSU for (a), (b), (c), and (d), respectively. On the left side are the density distributions (σ_t), and the interval is 0.025. In the middle column are the stream function of the cross-shore circulation, the solid and dashed lines are denoted the positive and negative values, respectively, and the contour interval is 0.04 m^2/s. On the right side are the along-shore currents, and the contour interval is 0.03 m/s.

Fig. 10 Group C: The volume transports of three cells vary with the initial salinity differences.

Fig. 11. Group D: the initial temperature differences between the level 30 m and 42 m are 1˚C, 2˚C, 3˚C and 4˚C for (a), (b), (c), and (d), respectively. On the left side are the density distributions (σ_t), and the interval is 0.025. In the middle column are the stream

function of the cross-shore circulation, the solid and dashed lines are denoted the positive and negative values, respectively. The contour interval is 0.08 m^2/s. On the right side are the along-shore currents, and the contour interval is 0.03 m/s.

Fig. 12. Group E: the uniform vertical viscosities are 0.001 m^2/s, 0.005 m^2/s, 0.02 m^2/s, 0.03 m^2/s and 0.05 m^2/s for (a), (b), (c) (d) and (e), respectively. On the left side are the stream function of the cross-shore circulation, the solid and dashed lines are denoted the positive and negative values, respectively, and the contour interval is 0.04 m^2/s. On the right side are the along-shore currents: the contour interval is 0.03 m/s.

Fig. 13 Group E: the volume transports of three cells vary with the vertical eddy viscosity.

Fig. 14 Cross-frontal stream function (contour lines) and temperature (shades) at four different times, ¼ tidal period apart, during the 20th tidal cycle for the case of summer front. Contour interval is 0.2 m^2/s.

Fig. 15 Comparison of cross-frontal mean circulation: (a) with total tide, (b) with barotropic tide only, (3) with baroclinic tide. The contour lines are the stream function and the shades are the temperature. The contour interval is 0.042 m^2/s.