Mechanisms of shelf-break frontogenesis

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Abstract
The shelf-break front is an omnipresent phenomenon in coastal oceans all over the world, but there is still no definitive explanation for the genesis of such a front. It is possible that different mechanisms are operative at different times and locations, but all of them should have something to do with the sharp change of bottom topography near the shelf-break. A couple of recently proposed mechanisms of shelf-break frontogenesis are discussed. One of them invokes a flow convergence produced by local air-sea interaction over sloping topography, whereas the other relies on the depth dependence of wind-induced shear dispersion. These novel ideas are based on new observational evidences and previous theoretical studies, and they are demonstrated here using an idealized ocean-atmosphere coupled model and a stand-alone ocean model. The air-sea interaction mechanism seems plausible for the shelf-break front in the East China Sea, and the shear dispersion mechanism is likely to be applicable to the shelf-break front off the northeastern United States.

Key words: shelf-break front, air-sea interaction, shear dispersion

1 Introduction

Numerous observations, including in-situ hydrographic surveys and satellite remote-sensing, have long revealed the existence of an oceanic front over the continental shelf-break in many parts of the world (Hickox et al., 2000; Ullman and Cornillon, 1999; Fedorov, 1983). The front marks the boundary between the relatively fresh and cold shelf water and the saltier and warmer offshore water, and it is often a location of high primary production due to the enhanced nutrient supply associated with the frontal circulation. The shelf-break front takes a simple form through winter and early spring, with isotherms and isohalines intersecting both seafloor and sea surface. During summer months, the surface thermal signature of the front is masked by the formation of a seasonal thermocline, but the bottom portion retains its winter structure. Thus the real challenge is to explain the formation and maintenance of the front in winter and spring time, which is the focus of many previous studies as well as our work here.

At present, there are basically two types of views on the genesis of the shelf-break front, from either a two-dimensional or three-dimensional per-
spective. Most of the earlier studies have considered the shelf-break front as fundamentally a two-dimensional phenomenon arising from cross-shore processes (Csanady, 1984, 1978; Flagg and Beardsley, 1978; Hsueh and Cushman-Roisin, 1982; Ou, 1983). In a particularly illuminating exposition of this view, Csanady (1984) studied the frontal properties forced by the surface wind and river runoff. With the coastal buoyancy flux providing the source of the density stratification, the anchoring depth of the front—where vertical mixing just overcomes the stratification—varies in an inverse manner. On the other hand, Ou (1983) invoked geostrophic adjustment as a mechanism for the sharpening and maintenance of the shelf-break front. All of these ideas involve some kinds of flow convergence and depend on the density contrast across the front, while in reality the front may have a rather weak density signature due to the canceling effects of temperature and salinity.

The three-dimensional view of the shelf-break frontogenesis was first provided by Chapman (1986). He prescribed an alongshore flow spanning the whole shelf, so the offshore Ekman flow expels the property gradient to the shelf-break where it is trapped. In Chapman and Lentz (1994) and Chapman (2000), the alongshore flow was no longer prescribed, but induced by a coastal buoyancy discharge. The same Ekman flow propels the buoyant water offshore, but only to a depth where the upstream discharge may be fully accommodated within the frontal zone (Wright, 1989) and where the Ekman flow would feed into the interfacial layer (Chapman, 2000). There are at least two problems with this explanation. First, the frontal depth does not strongly depend on the topographic slope, which led Chapman (2000) himself to question the relevance of his model to shelf-break frontogenesis. Second, the shelf-break front is often observed in regions with no upstream flow and it does not exhibit systematic alongshore variations as that depicted in the above three-dimensional model.

The frontogenesis mechanisms considered here are both two-dimensional, in the sense that they do not rely on any alongshore variations. One of these ideas was inspired by recent satellite observations, which revealed the presence of jet-like surface winds at sharp oceanic fronts, particularly at the shelf-break front in the East China Sea, suggesting a potentially important role played by the local air-sea interaction in the genesis or modification of these fronts. The other idea came from the need for a frontogenesis mechanism that does not involve buoyancy forcing, and thus can be applied to the regions where the shelf-break front has a weak density contrast, such as off the northeastern United States. The diffusivity mechanism we previously proposed for the winter tidal front (Ou et al., 2003), if modified by replacing the tidal dispersion with wind-induced shear dispersion, seems to be a possible candidate. In this paper, these two mechanisms are described and demonstrated with numerical experiments in Sections 3 and 4, respectively, followed by summary and discussion in Section 5. The models used for these studies are described in the next section.

2 Model configuration

The same ocean model is used for all the experiments shown in the following sections, though an atmospheric component is added for the study of air-sea interaction mechanism. The model is an updated version of the primitive-equation coastal ocean model of Wang (1982) and Chen and Wang (1990). It has been applied to various coastal ocean studies, including some recent work on fronts (Chen et al., 2003; Chen et al., 2003). The model uses Mellor’s (1982) level-2.5 turbulence closure scheme for vertical mixing and Smolarkiewicz’s (1984) anti-diffusive scheme for tracer advection—both essential for
minimizing non-physical mixing and maintaining frontal sharpness. Although the original model is three-dimensional, it is configured here on a two-dimensional cross-shelf section and uniformity is assumed in the along-shelf direction. Such a configuration has often been used to study frontal dynamics because of the large aspect ratio of front (i.e., the along-front scale is much larger than the cross-front scale).

For the experiment on air-sea interaction mechanism, the effective model domain is 600 km wide, with a sponge zone on either side to damp out unwanted signals. Topography is chosen to mimic that in the East China Sea. The model has a horizontal resolution of 6 km and a vertical resolution of 5 m. The time step is set to 10 min and the coupling between the ocean and the atmosphere takes place at each time step. The simple atmosphere component follows the concept of Lindzen and Nigam (1987). The main premise is that the atmospheric boundary layer is mixed well enough to assume a coherent vertical temperature profile, and the influence from free atmosphere above is negligible. Thus, in a linear, steady-state model, the boundary layer pressure and wind fields can be diagnostically determined from the sea surface temperature (SST) distribution. Some parameters of the original model, which was configured for the tropics, had to be adjusted here. It was done in such a way that model winds, when forced with the observed SST, were comparable to observed winds in magnitude.

For the experiment on shear-dispersion mechanism, the model is configured over an exponential topography, with a width of 100 km and a depth varying from 20 m at the coast to 500 m offshore. The horizontal resolution is 500 m, and the vertical grid spacing is 5 m in the top 100 m and 10 m in the rest of the water column. Unlike the experiment with the coupled model, where no external forcing is needed, the stand-alone ocean model in this case is forced by a periodic alongshore wind stress. On the basis of observations, we assume that the inshore water is fresher and colder—but only slightly lighter—than the offshore water. Initially, both salinity and temperature have a uniform cross-shore gradient, and we want to see if the gradient would sharpen near the shelf-break after the wind forcing is switched on. Two sets of experiments are carried out, with the equation of state switched off and on, referred to as unstratified and stratified cases, respectively. The unstratified run allows a closer comparison with analytical solutions, and the stratified run provides a more realistic simulation of the observed situation.

3 Mechanism I: air-sea interaction

Figure 1 shows the satellite observed SST and wind fields in the East China Sea for the three springs of 2000 ~ 2002. It is evident that there were strong winds blowing along the shelf-break front in every spring, despite the fact that spring is the transition season of the Asian monsoon system. The close association of the wind jet with the front, and its persistence at a time when the large-scale monsoon winds are generally weak, indicate that the wind jet is probably driven by local processes, and that there might be some sort of feedbacks between the SST and the surface wind in the frontal region. There are at least two possible explanations for the observed wind maxima at oceanic fronts. First, an enhanced atmospheric boundary layer mixing may take place when cold air moves across the front to the warm side, which reduces the vertical wind shear and thus strengthens surface winds (Wallace et al., 1989). Second, a surface thermal front may produce a cross-front pressure gradient which drives along-front low-level winds (Lindzen and Nigam, 1987). This latter mechanism seems more consistent with the observation shown in Fig. 1, and it is thus explicitly built into the idealized ocean-atmosphere coupled model.
mentioned above.

Fig. 1. Springtime SST (shading) and winds (vectors) in the East China Sea, showing a close association of jet-like surface winds with the shelf-slope thermal front. The data displayed here are March – April – May averages of the QuikSCAT wind and the TRMM SST in the past 3 a. The maximum wind velocity is about 10 m/s.

Now the question is how this SST-wind coupling can be frontogenetic. The along-shelf surface wind produced by a preexisting cross-shelf SST gradient with warmer water offshore can feed back to the ocean in several ways. It can drive a cross-shelf circulation with an onshore flow in the surface layer compensated by a returning flow at depths; it can cause turbulent mixing through mechanic stirring and shear instability; and it can enhance latent heat loss at sea surface which in turn cools SST and results in convective mixing. The combined effect of these processes depends on the water depth. In the deep offshore region, the warm water in the surface mixed layer is advected shoreward, with a weak seaward flow in the ocean interior. On the shallow shelf, however, the advection is dominated by the vertical mixing. Thus the cross-shelf circulation diminishes and the whole water column becomes well mixed. The basic physical processes involved in each case can be easily shown by running the coupled model with a flat-bottom ocean for different depths (Chen, Liu et al., 2003). It is then conceivable that, on a sloping coastal topography, a sharp front would be formed at a critical location that marks the transition from the stratified offshore water to the well-mixed shelf water.

To demonstrate frontogenesis through this air-sea interaction mechanism, we examine a coupled model experiment over realistic topography. Initialized with a broad front of uniform temperature gradient, the model was run for two months without external forcing. The time evolution of four selected surface variables is depicted in Fig. 2. Initially, a uniform along-shelf wind field is generated over the prescribed temperature gradient, which results in surface latent heat loss and onshore surface currents. Because of the depth dependence of the oceanic response to the atmospheric forcing, a front starts to form between the shallow inshore water and the deep offshore water. Accordingly, a wind jet is produced and it further strengthens the front and the associated circulation.
The wind jet and the front keep reinforcing each other as time goes by, clearly indicating a positive feedback between the atmosphere and the ocean. Fig. 3 shows a sequence of snapshots of the model temperature and flow fields for the upper 200 m. In response to the initial temperature gradient, the model generates an along-shelf wind which drives a large cross-shelf circulation cell. The shallow water inshore is then rapidly mixed, a front is formed between the well-mixed water and the stratified water, and the cross-shelf circulation is intensified at the front. The front and the associated circulation gradually advance seaward, both becoming increasingly stronger. By the fiftieth day, the front has become about three times sharper than the initial temperature gradient and has moved to the shelf-break.

4 Mechanism II : shear-dispersion

The importance of shear dispersion in horizontal mixing is well recognized in the tidal regime (Geyer and Signell, 1992; Zimmerman, 1986; Fischer et al., 1979), but it is the strong depth dependence of the resulting diffusivity (Okubo, 1967) that makes the dispersion a possible mechanism for frontogenesis. When combined with a small background diffu-
Ou et al. (2003) found that the vertically integrated diffusivity exhibits a minimum in the mid-shelf, which may account for the tidal front observed in the unstratified winter season (Ullman and Cornillon, 1999; Hill and Simpson, 1989). Farther offshore, the tidal dispersion becomes insignificant due to rapidly diminishing tidal currents, but the shear dispersion generated by oscillatory winds could take over. Surprisingly, despite its potential importance to horizontal mixing and hence property distribution, this latter process has not been examined to any significant degree in the literature. Some obvious questions include: What is the mechanics of wind-induced shear dispersion? What is the magnitude of the effective diffusivity and how does it vary across the shelf? And, particularly, can it lead to the generation of the shelf-break front?

Fig. 3. Model produced temperature fields and cross-front stream functions at different time from start. The contour interval for the stream function is 0.4 m$^2$/s and the circulation cells rotate counterclockwise when facing the paper. The maximum model depth is 800 m, but only the top 200 m is plotted here.

Ou and Chen (2006) addressed these questions using a combination of analytical and numerical models. The analytical solutions are obtained for an unstratified coastal ocean, and the mathematical details of model construction and derivation are somewhat similar to those of the tidal dispersion model (Ou et al., 2003), with tides replaced by oscillatory winds. As noted previously in the tidal regime, the vertically integrated (total) horizontal diffusivity has a maximum where the water depth equals the diffusive depth—defined as the reach of the vertical diffusion during one forcing cycle. Owing principally to the long synoptic time-scale that is characterized by the wind forcing, this depth lies over the outer shelf. When combined with effective mixing of the slope water by mesoscale eddies, the total diffusivity exhibits a minimum around the shelf-break, thus facilitating frontogenesis. Owing again to the long forcing period, the bottom Ekman flow is well developed at the diffusive depth, which would accentuate the gradient enhancement of the front. In essence, the wind-induced shear dispersion largely homogenizes the shelf water and, in the presence of other mixing processes that are limited to the offshore deep water, it would generate a front at the shelf-break. The most likely candidate for the offshore mixing is the me-
soscale eddies, which are prevalent in the slope waters (Gawarkiewicz et al., 2001; Churchill et al., 1993), but—because of their large vertical extent—are impeded from penetrating onto the shelf by the vorticity constraint.

In our numerical experiments, the shear dispersion is generated by an along-shelf wind-stress with an amplitude of $1.5 \times 10^{-5}$ N/cm² and a period of 10 d [based on the winter wind spectrum of Beardsley et al. (1985)], and the offshore eddy mixing is simply parameterized by a background diffusivity that varies as a linear function of depth so that it is negligible inshore but large offshore. Since the model has no heat or salt fluxes at the surface, the salinity and temperature distribution—when normalized by their cross-shore range—are identical, it suffices therefore to describe only the salinity field. Figure 4 compares the initial salinity distribution with that averaged over the fiftieth cycle for either unstratified or stratified model runs. In both cases, there is a distinct sharpening of the gradient at the shelf-break at the expense of the surrounding water. Given the absence of density stratification and hence buoyancy-driven circulation in the unstratified run, the most likely source for the gradient change in that case is the shear dispersion; the numerical solution thus provides a visual demonstration of the frontogenesis identified in our analytical model. The stratified solution is more complicated but closer to the observation, with the main difference being a more strongly sloped front. This is largely due to the asymmetry in vertical mixing between the positive and negative phases of the wind forcing. The density-driven frontal circulation also enhances the asymmetry.

With the model front anchored at the shelf-break, the main remaining question about its relevance is whether it can account for the observed frontal sharpness. To address this question, we have plotted in Fig. 5 the mean salinity gradient over the fiftieth cycle of the unstratified model run, along with the observed salinity gradient of a climatological front (Linder and Gawarkiewicz, 1998, based on the lower right panel of their Fig. 10). They have used depth-bin averaging to combine historical data to produce a climatological front on a nominal cross-shore transect, and the X’s are the estimated slope of the tangent to their curve, with the peak aligned with that of the model front. It is seen that the observed values fall practically on the curve of our standard case. Such close agreement is unexpected and must be somewhat fortuitous since there is no particular reason that the standard case should be more representative than the other cases and there is large uncertainty in estimating the observed gradient. In any event, the comparison suggests that although the

Fig. 4. a. The initial salinity field of uniform horizontal gradient; b. the salinity field averaged over an equilibrium cycle for the unstratified case, which shows the frontogenesis at the shelf break; c. same as b but for the stratified case. Note that the vertical column shallower than 100 m has been stretched two-fold for display purpose.
model front is not particularly sharp, such a gradient contrast in fact is commensurate with that observed.

With the above comparison, the numerical calculations have essentially validated the analytical model.

The stratified and unstratified solutions are further compared in Fig. 6, which shows the time evolution of surface and bottom salinity over two equilibrium cycles. At the surface, the frontal excursion is somewhat less in the stratified case because the surface velocity is weaker on the average due to the stronger surface layer mixing. Associated with the seaward frontal displacement in the stratified case, the salinity gradient on the shelf becomes much weaker as compared with that in the unstratified case. This is clearly due to the enhanced mixing, similar to the unstratified case of longer forcing period, as discussed earlier. As expected, the movement of the bottom front is 180° out of phase with that of the surface front in both unstratified and stratified cases, but the frontal excursions are greater in the latter case because the front is anchoring at a shallower depth where the bottom flow is stronger. The sharper bottom front and its more inshore location in the stratified case is a result of the cross-frontal circulation. The along-shelf geostrophic current associated with the front drives a convergent bottom flow at the foot of the front.

Despite the notable differences between the stratified and unstratified model runs, our model results seem to suggest that the shear dispersion discussed in the analytical model remains the dominant frontogenesis mechanism even in the stratified case. In fact, without the wind forcing and the resulting shear flow, the model is unable to generate a shelf-break front from an initial density field of uniform gradient. The stratified model is one step closer to reality, but it is still highly idealized. For example, there should be surface evaporative cooling associated with the wind forcing. We neglected this in order to isolate the effects of wind and to facilitate a direct comparison with the analytical model. In a test run where evaporation is included, the enhanced vertical
mixing pushes the bottom front farther offshore and anchors it more firmly at the shelf-break, in closer agreement with observations.

Fig. 6. Salinity variations at surface (upper row) and bottom (lower row) over two equilibrium cycles for unstratified (left column) and stratified (right column) cases.

5 Summary and discussion

The omnipresent shelf-break front has intrigued oceanographers for many years, but there is still no consensus on the physical processes responsible for its genesis and maintenance. It is possible that different mechanisms are operative at different time and locations. However, because of the persistent frontal location, any reasonable mechanism should have something to do with the sharp change of bottom topography near the shelf-break. In this paper we have reviewed a couple of recently proposed mechanisms for the shelf-break frontogenesis. One of them invokes a flow convergence produced by the local air-sea interaction over sloping topography, whereas the
other relies on the depth dependence of wind-induced shear dispersion. These novel ideas are based on new observational evidences and previous theoretical studies, and they are demonstrated here using an idealized ocean-atmosphere coupled model and a stand-alone coastal ocean model. The air-sea interaction mechanism seems to be responsible for the spring sharpening of the shelf-break front in the East China Sea, and the shear dispersion mechanism is likely to be applicable to the shelf-break front off the northeastern United States.

The essence of the air-sea interaction mechanism lies in the cross-shelf circulation driven by the wind-SST interaction, and the depth dependence of this circulation. This is a local process that does not rely on any external forcing. As long as a cross-shelf thermal gradient exists, the frontogenesis will proceed through the positive feedback between wind and SST. Although the wind-induced evaporative cooling appears important, it is not essential for the mechanism to work. In a test case where the surface latent heat flux is turned off, a sharp front is still generated, though at a slightly inshore location. What matters the most for the frontogenesis here is the forced convergence of the shoreward surface flow when the stratified offshore water clashes with the well-mixed shelf water. It is worth noting that shear dispersion may also play a role in this case; the wind-induced cross-shelf shear flow, when combined with the strong vertical mixing, may be partly responsible for the homogenization of the shelf water. An implication of our findings is that the frontal circulation and vertical mixing could bring the nutrient-rich subsurface water into the surface euphotic zone, thus making the frontal region a conspicuous place for primary production (Chen et al., 2003).

It may seem odd to invoke dispersion as a mechanism for frontogenesis, but the depth dependence of the shear dispersion, and thus the spatial variation in the horizontal mixing, can be frontogenetic indeed. Together with Ou et al. (2003), we have identified three regimes of horizontal mixing in the coastal ocean as one proceeds offshore: they are associated with tides, wind-driven motion and mesoscale eddies, progressively. The first two are through the oscillatory shear dispersion explicitly modeled, the transition being due to their disparate forcing time-scales; the last is merely conjectured as limited to the slope water. It is the minimum mixing between these regimes that gives rise to the tidal and shelf-break fronts. The mechanistic unification of these two prominent but seemingly unrelated fronts lends support to this overlooked category of frontogenesis that stems from spatial inhomogeneity in the horizontal mixing. The two-dimensional cross-shore view of the shelf-break front differs from some recent studies that stress its along-shore evolution and gradual emergence. While these latter studies have delineated important dynamical features of the front, they fail to explain its anchoring at the shelf break—a defining characteristic of the front. According to our model, such topographic confinement merely reflects strong mixing from both sides; the wind-induced shear dispersion effective up to the outer shelf, and eddy mixing of the slope water.

Our numerical experiments are highly idealized and, consequently, the results presented here are more suggestive than conclusive. For the coupled model experiment, one possible limitation is the validity of the simple diagnostic atmosphere model adopted. Even if the basic assumptions of the model are valid, for which we have no solid proof yet, the model only provides average winds over the atmospheric boundary layer. To simulate the surface wind field accurately, a boundary layer model is probably needed. Another limitation is the two-dimensional model setting in both experiments, which excludes the effects of any alongshore processes. For example, aside from a prescribed offshore temperature gradient, the models do not take into account the
effects of the western boundary currents, which bring warm and salty water to the outer edges of the East China Sea and the Middle Atlantic Bight, and are likely to be responsible for creating a broad front in the first place. A more realistic and comprehensive simulation of the shelf-break frontogenesis awaits a three-dimensional ocean-atmosphere coupled model, which is our next goal.

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