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Air-sea interaction at an oceanic front: Implications for frontogenesis and primary production

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[1] Based on recent satellite observations, we hypothesize that there exists a significant air-sea interaction at the shelf-break front in the East China Sea. An idealized ocean-atmosphere coupled model was designed to test this hypothesis and to study the physical processes involved in such an interaction, with emphasis on the oceanic part. A positive feedback between ocean and atmosphere was identified in the model and its consequences were evaluated. We found that air-sea interaction, when combined with sloping topography, could provide a mechanism for the genesis of the shelf-break front. The resulting frontal circulation and vertical mixing could bring nutrient-rich subsurface water into the surface euphotic zone, thus making the frontal region a conspicuous place for primary production. *INDEX TERMS:* 4504 Oceanography: Physical: Air/sea interactions (0312); 4528 Oceanography: Physical: Fronts and jets; 4815 Oceanography: Biological and Chemical: Ecosystems, structure and dynamics; 4219 Oceanography: General: Continental shelf processes; 4255 Oceanography: General: Numerical modeling. **Citation:** Chen, D., W. T. Liu, W. Tang, and Z. Wang, Air-sea interaction at an oceanic front: Implications for frontogenesis and primary production, *Geophys. Res. Lett.*, *30*(14), 1745, doi:10.1029/2003GL017536, 2003.

1. Introduction

[2] The advent of satellite remote-sensing has greatly enhanced our ability to explore the ocean and the atmosphere, revealing numerous new phenomena that are difficult or even impossible to observe with conventional methods. One such revelation from recent satellite missions is the presence of jet-like surface winds at sharp oceanic fronts, suggesting a potentially important role played by local air-sea interaction in the genesis or modification of these fronts. The focus of this study is on the shelf-break front of the East China Sea, which separates the cold shelf water from the warm offshore Kuroshio water in winter and spring. We propose that such a front can be generated or at least sharpened by air-sea interaction, and that associated upwelling and vertical mixing can fertilize the surface euphotic zone, leading to increased primary production in the frontal region.

[3] Figure 1 shows the satellite observed sea surface temperature (SST) and wind fields in the East China Sea for the last three springs. 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. This thermal front has long been observed in satellite images [e.g., *Hickox et al.*, 2000], but the coexistence of the along-front wind jet was not discovered until recently. 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 feedback between SST and surface wind in the frontal region. Our purpose here is to explore the mechanism of this feedback and its physical and biological consequences.

[4] 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 vertical wind shear and thus strengthens surface winds [*Wallace et al.*, 1989]. This mechanism was invoked by *Xie et al.* [2002] to explain the distribution of surface winds in the East China Sea. 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 Figure 1, and it is thus explicitly applied to the idealized ocean-atmosphere coupled model used in this study.

2. Model Configuration

[5] The ocean model used here is the primitive-equation coastal ocean model of *Wang* [1982] and *Chen and Wang* [1990]. This model has been applied previously to many coastal ocean studies, including a recent study on internal tides in coastal frontal zone [*Chen et al.*, 2003]. Although the model by design is fully 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).

[6] 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

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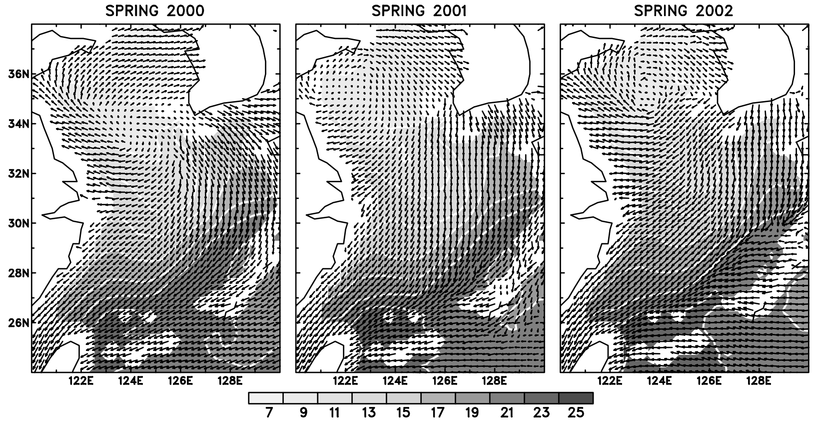

Figure 1. Spring time sea surface temperature (shading and white contours) and winds (vectors) in the East China Sea, showing a close association of jet-like surface winds with the shelf-slope thermal front. The data displayed here are March-April-May averages of the QuikSCAT wind and the TRMM sea surface temperature in the past three years. The unit of temperature is °C and the maximum wind vector is about 10 m/s.

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 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 observed SST, were comparable to observed winds in magnitude.

[7] Two sets of model experiments are presented here, one starting with a broad thermal front in a flat-bottom ocean and the other with more realistic bottom topography and temperature stratification. For simplicity, salinity is set to a constant so that density is solely determined by temperature. The effective model domain is 600 km wide, with a sponge zone on either side to damp out unwanted signals. Radiation boundary condition is applied to all ocean model variables at both boundaries. The model has a horizontal resolution of 6 km and a vertical resolution of 5 m. The time step is set to 10 minutes and the coupling between the ocean and atmosphere takes place at each time step.

3. Results

[8] The basic physical processes involved in the model air-sea interaction are first illustrated in a pair of flat-bottom cases, each run for two months without external forcing. Figure 2a shows the evolution of the temperature and flow fields for the case with a water depth of 200 m. Initialized with a broad front of uniform temperature gradient, the model is able to generate an along-front surface wind (not shown), which in turn produces a large cross-front circulation cell in the ocean. As time proceeds, the circulation cell continues to push surface water onshore and bottom water offshore, sharpening the temperature gradient toward the cold side at the surface and toward the warm side near the bottom. The surface mixed layer is much deeper than the bottom one because wind stirring and latent heat loss, in addition to shear instability, contribute to the turbulent mixing there. The model behavior in Figure 2a would remain the same in a deeper ocean except for a thicker middle layer.

[9] However, the same is not true when the model ocean is much shallower. As shown in Figure 2b, the evolution of the model fields is totally different for a water depth of 100 m. Since the thickness of the water column is now thinner than the combined depth of the surface and bottom mixed layers, the two layers merge and the whole water column is mixed. The horizontal advection of temperature is no longer strong enough to create two separate boundary layers in the presence of vertical mixing. The circulation is much weaker due to mixing of momentum, as compared to that of stratified deeper ocean. It is interesting to note that the whole front is now moving offshore as a result of the cooling caused by wind-induced evaporation. In light of the

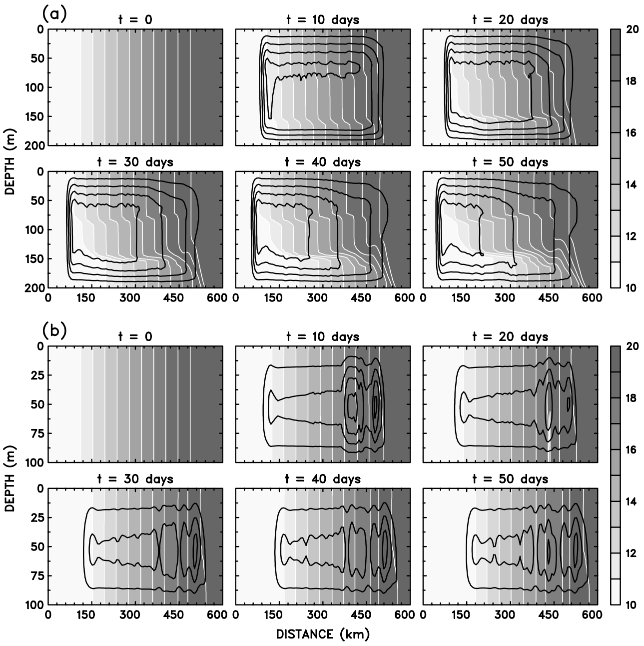

Figure 2. Model produced temperature fields (shading) and cross-shelf stream functions (solid curves) at different times from start for (a) 200 m and (b) 100 m flat-bottom ocean. The contour interval for stream function is 0.4 m^2/s and the circulation cells rotate counterclockwise when facing the paper.

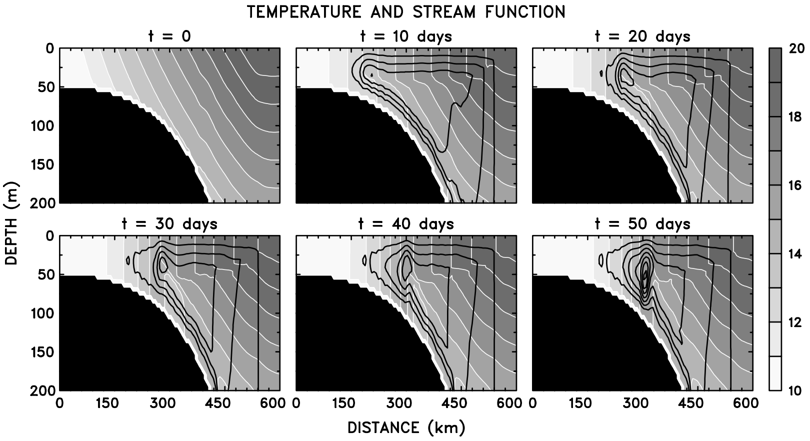

Figure 3. Similar to Figure 2 except for more realistic topography and stratification. The maximum model depth is 800 m, but only the top 200 m is plotted here.

results in both Figures 2a and 2b, it is 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 inshore water.

[10] We next examine the experiment that includes a continental shelf and a more realistic temperature distribution. Here the model has a minimum depth of 50 m at the inshore boundary and a maximum depth of 800 m in the offshore region. The initial temperature is the same as before at the surface, but it now has a vertical stratification that increases offshore. Though still idealized, this model setting is representative of the situation in the shelf-slope region of the East China Sea. Figure 3 shows the evolution of model temperature and flow fields for the upper 200 m. As expected, 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 day 50, the front has become about 3 times sharper than the initial temperature gradient and has moved to a location where the water is about 120 m deep.

[11] This sequence is consistent with what we have learned from the two flat-bottom cases. The same physical processes described there are at work here. In particular, there is a shoreward heat flux in the surface layer of the stratified deep water and a seaward negative heat flux from the mixed shallow water. Consequently, a sharp temperature front is created in between. In order to have a clearer picture of the local air-sea interaction involved, the time evolution of four selected surface variables are depicted in Figure 4. 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. It is evident in the figure that 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. Such a feedback could provide a mechanism for frontogenesis.

[12] A passive tracer is included in this experiment to evaluate the effect of the frontal air-sea interaction and the associated oceanic circulation on nutrient transport and primary production. Figure 5 shows the variation of a tracer (or some nutrient) that is originally depleted in the upper 100 m and is kept at 100% concentration in the water column below. As the time proceeds, the upper water column at the front is gradually replenished with the nutrient from below, due to vertical mixing and upwelling. There is also a significant upward nutrient transport in the stratified water seaward of the front, where a large portion of the upwelling associated with the frontal circulation takes place. Such

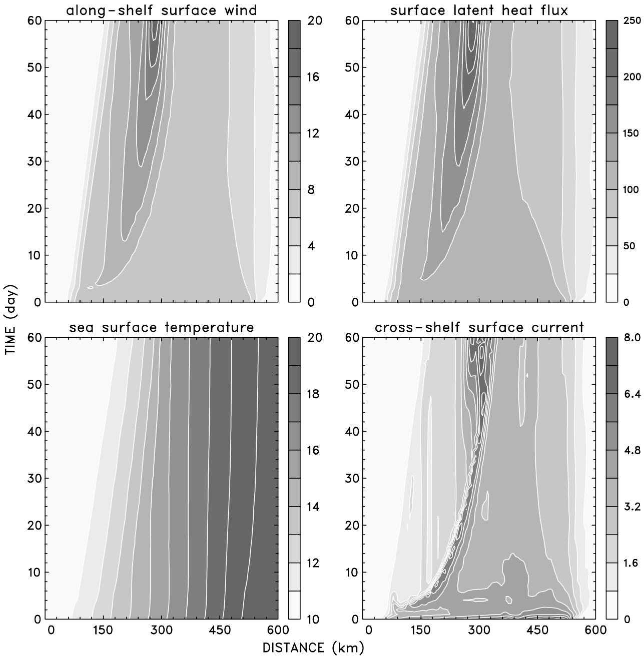

Figure 4. Variations of four surface variables as a function of time and offshore distance, showing the formation of shelf-break front and associated wind jet as a result of air-sea interaction. The units are m/s, w/m^2, °C and cm/s for wind, heat flux, SST and surface current, respectively.

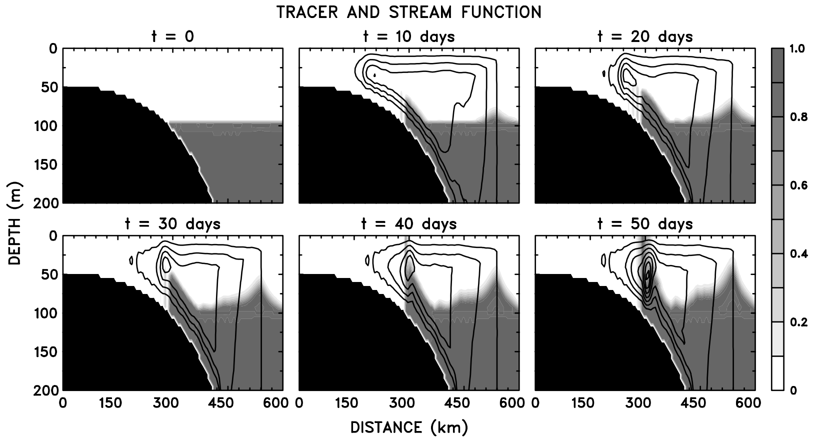

Figure 5. Same as Figure 3 except for tracer concentration and stream function. The tracer is originally absent in the top 100 m.

nutrient fluxes would favor localized growth of phytoplankton, which provides an explanation for the high primary production often found in frontal regions. Note that the high primary production does not have to be surface manifested. A subsurface maximum could occur, especially in the stratified region, when the nutrient is brought into the euphotic zone but not fast enough to the surface before it is consumed.

4. Summary and Discussion

[13] Based on recently acquired scatterometer wind data and radiometer sea surface temperature data, we hypothesized that there exists a significant air-sea interaction at the shelf-slope front in the East China Sea. An idealized ocean-atmosphere coupled model was then put forth to test this hypothesis and to study the physical processes involved in such an interaction, with emphasis on the oceanic part. A positive feedback between ocean and atmosphere was identified in the model and its consequences were evaluated. We suggest that air-sea interaction, when combined with sloping topography, could play an important role in the genesis of a shelf-break front, such as that in the East China Sea. The resulting 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.

[14] Shelf-break front is an omnipresent phenomenon in coastal oceans, but there is still no definitive explanation for the formation of such a front. It is likely that different mechanisms are operative at different times and locations, yet all of them should have something to do with topography. Here we propose a new mechanism for frontogenesis, which seems to be plausible for the shelf-break front in the East China Sea. The essence of this mechanism lies in the cross-shelf circulation driven by wind-SST interaction, and the depth dependence of this circulation. Although the wind-induced evaporative cooling appears important, it is not essential for the mechanism presented here. In a test case where 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.

[15] The model used in this study is highly idealized and, admittedly, the results presented here are more suggestive than conclusive. One possible problem is the validity of the simple diagnostic atmosphere model adopted. Even though 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 setting of the ocean model, which excludes the effects of any along-shelf processes. For example, aside from a prescribed offshore temperature profile, the model does not take into account the Kuroshio Current, which undoubtedly imparts an important regional influence. A more realistic simulation of the frontal air-sea interaction in the East China Sea awaits a three-dimensional model with an improved atmospheric component, which is our next task.

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