Large Scale Ocean Response Driven by Winds and Circulation in the Yellow Sea**

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Summary

The theory of long-period, large-scale coastally trapped waves has been developed for a double-shelf topography shown in the Yellow Sea. For this topography, the Kelvin waves are important modes, which are mainly responsible for the sea level fluctuations. The other modes are continental shelf waves, which are mostly responsible for the current fluctuations.

A double-shelf wave model developed from the theory of double-shelf waves has been applied to calculate winter-time wind-driven current and sea level fluctuations in the Yellow Sea. Comparison to the measurements shows that most of the long-period current and sea level fluctuations in the Yellow Sea in winter time are basically due to the large-scale ocean responses driven by winds. With a more realistic coast line for the China coast, the model reproductions have been improved, specially near the southern boundary of the Yellow Sea.

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Introduction

Continental shelf wave has been observed in various parts of the world (Hamon, 1962, 1966; Mooers and Smith, 968) and the theory for a single shelf has been developed(Buchwald and Adams, 1968; Gill and Schumann, 1974; Huthnance, 1975, 1978; Kundu and Allen, 1976; Clarke, 1977; LeBlond and Mysak, 1978; Brink and Allen, 1978; Louis, 1978; Mysak et al., 1979, 1980, 1981; Spillane, 1980; Brine, 1983). Now, there is little doubt about that the continental shelf wave plays an important role in the coastal ocean responese to an applied wind stress in a single shelf case.

Recently, Hsueh and Romea(1983) also found evidence of coastally trapped waves in the Yellow Sea. They have shown that along the west coast of Korea, there is a free wave propagation to the north and there is a high coherency between sea level fluctuation and the alongshore wind. In comparison to other shelf areas, the Yellow Sea, however, features a different kind of geometry. The Yellow Sea (Fig. 1) is bounded by land to the east, to the west, and to the north. And it is connected with the East China Sea to the south. Two continental shelves meet together in the Yellow Sea. The Korea shelf and china shelf are adjoined along the Yellow sea trough so that the bottom slope is reversed across the Yellow Sea trough. The Yellow Sea is characterized by a north-south running channel with a double shelf cross section. Thus, north-south propagating long waves are naturally excited by alongshore wind stress.

The theory of the coastally trapped waves over a double shelf topography shown in the Yellow Sea has been recently studied and the wave model has been developed by using the theory(Pang, 1987 : Hsueh and Pang, 1989). The wave model for a double shelf has been made by solving the free problem and by integrating a set of familiar first order wave equations. With the wave model, we can calculate sea level and velocity fluctuations.

The wave model has been applied to the Yellow Sea to reproduce sea level and alongshore velocity fluctuations during January to March 1986. We have observations from the Yellow Sea at 4 points along the deep trough and 2 points in the middle of the Korea shelf for the winter of 1986. Previously, we have used the simplest model with straight coast lines and shown that sea level and alongshore velocity fluctuations are largely reproducible.

In spite of the success, there are still quite a few discrepancies between the observations and the model results. Some of them is possibly due to the geostrophically calculated wind stress used in the model. Others might be due to the assumptions. The model uses the homogeneous boundary condition for all the incoming waves along the southern boundary and the homogeneous boundary condition for the incoming continental shelf waves along the northern boundary. Another possible reason of the discrepancy that should be mentioned is the way that the northern boundary region is dealt with. The modelling of the northern boundary region is the simplest possible and needs to be modified in the future. However, the more interesting reason related to the dynamics is guessed the bottom slopes of the model topography. We have previously used straight

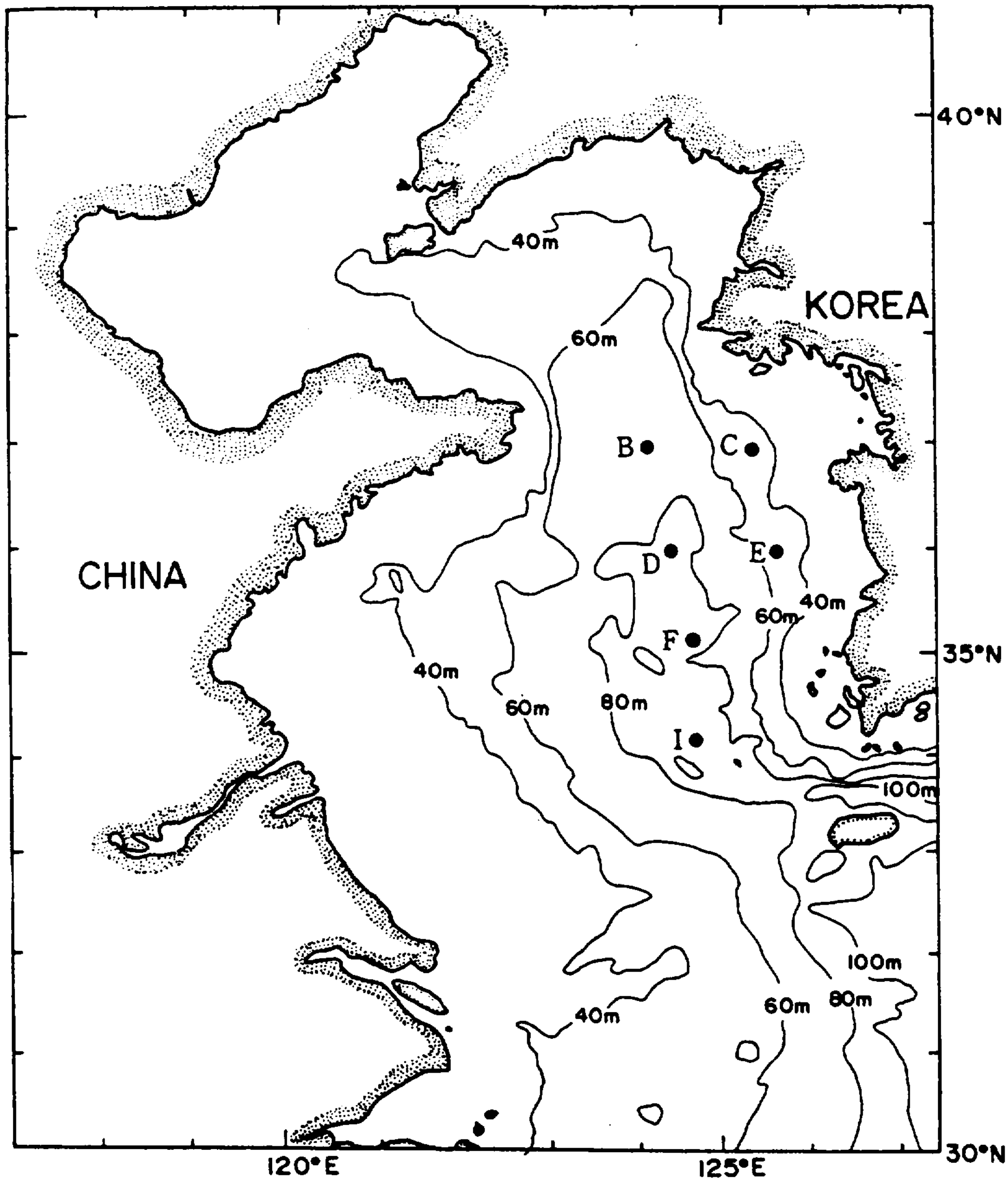

Fig. 1. Map of the Yellow Sea region. Depths are in meters. Dots mark the locations of current meter moorings for the period of January 10 to April 12, 1986.

coat lines with which the bottom slope is constant along the coast lines. However, the real ocean shows a lot of variations of bottom slopes. In this study, a little more realistic coast line has been used to improve the reproductions.

Theory

The processes by which the wave model has been made is shown in Fig. 2. First, we solved the free problem for a double shelf bottom topography. We get the dispersion relation, and from the dispersion relation get the proper eigenvalues, which are phase speeds here, and the eigenfunctions. The next step is to solve the forced problem. We derived the first order wave equation in which the geometry, friction, and wind stress are incorporated. By integration of the wave equation, we solved the wave functions. With the eigenfunctions and the wave functions, we combine them to get the sea level and alongshore velocity. We finally compare these model results with observations.

In this paper, a barotropic, large-scale, and low-frequency water movement has been studied. For the free problem, we have used infinite channel with various bottom topography. First, a exponential bottom topography has been used to get insights easily from the simple solutions. As expected, we have found tow infinite sets of waves propagating in opposite directions. For a convenience, we call a set of waves propagating northward the Korea waves and

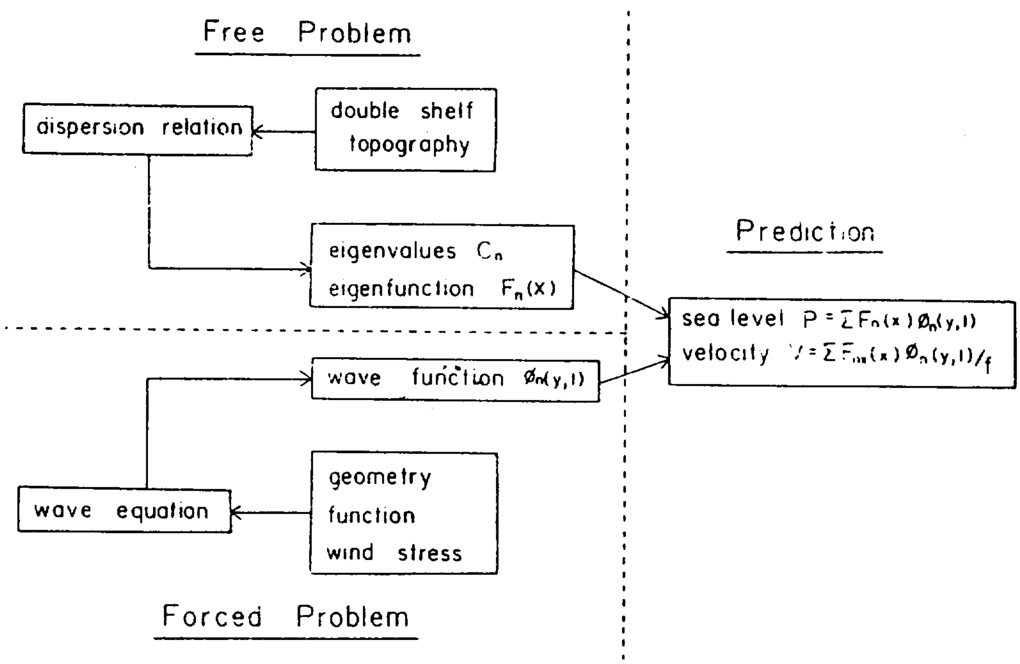

Fig. 2. Chart of the processes by which the wave model is made.

the other set of waves propagating southward the China waves. Both waves propagate with coast on their right hand sides and the phase speeds of each set of waves are determined dominantly by the steeper shelf. For a linear bottom topograohy with a horizaontal divergence, the first modes show the Kelvin wave characteristics. The modes are horizaontally divergent and their amplitudes decay exponentially across the channel. The phase speeds vary inversely propotional to shelf width.

For the forced problem, we derived the first order wave equations, using the orthogonality of eigenfunctions. The frictionless eigenfunctions used here are proved to be orthogonal and complete. To solve the forced problem, the first order wave equations have been integrated by the numerical method of characteristics. We used a simple sinusoidal wind forcing and a finite channel length which is much smaller than the decay distances of the Kelvin waves and larger than those of the continental shelf waves. From this theoretical work, we have found that over a double shelf topography, sea levels and velocities are, respectively, accounted mainly for the presence of the Kelvin waves and the continental shelf waves.

Application

We applied the wave model to reproduce the observed sea level and alongshore velocity fluctuations forced by the geostropically calculated winds from the pressure chart during the period of January 13 to March 29, 1986. In the wave model, we devide the

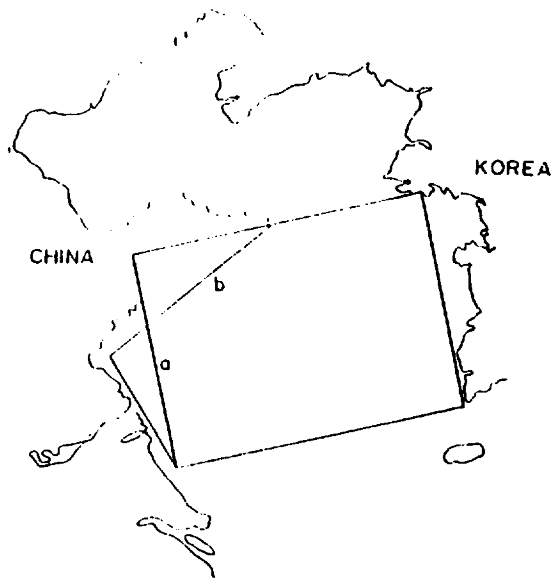

Fig. 3. Model domains of (a) straight coast lines and (b) more realistic coast lines.

Yellow Sea into two parts. One is the main region that is bounded to the south by the tip of Korean peninsula and to the north by the Shandon Peninsula. The other is the northern boundary region that occupies the area to the north of the Shandon Peninsula. The northern boundary region is modeled to transmit only Kelvin wave.

For the main region, straight coast lines and a more realistic coast lines have been used. Figure 3 show the model regions of straight and a more realistic coast lines. In either case, the cross section of the channel is a linear double shelf topography shown in Fig. 4.

Figure 5 shows the alongshore wind stresses calculated geostrophically from the pressure chart during the same period. Figure 6, 7 and 8 show, respectively, the observations, the model results with a straight coast lines, and the model results with a morerealistic coast lines. The top two panels

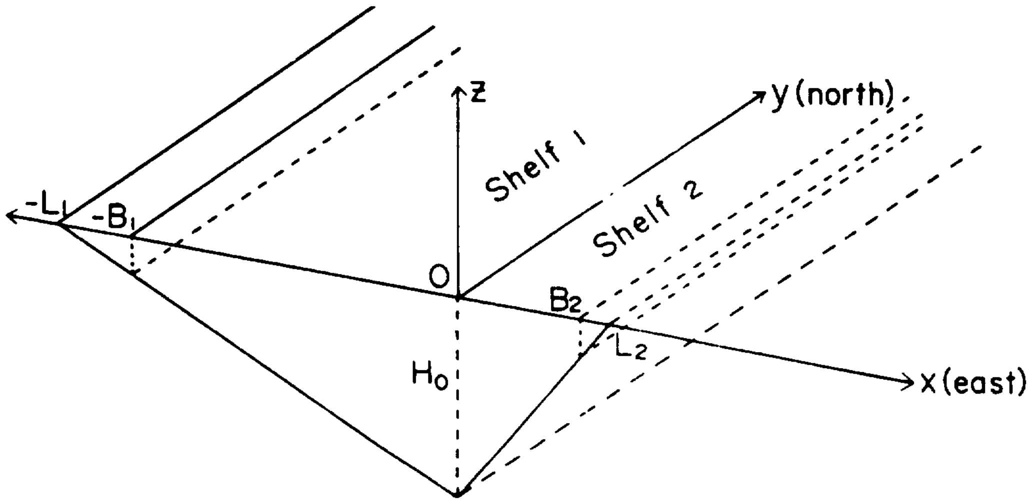

Fig. 4. Schematic representation of the geometry of double shelf of linear depth profile which represents the Yellow Sea topography best.

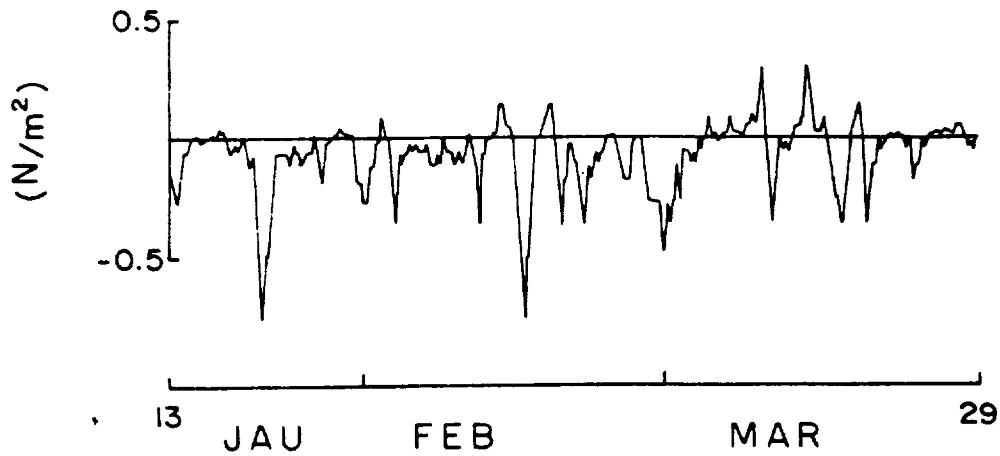

Fig. 5. Alongshore wind stresses calculated from the pressure chart during January 13 to March 29, 1986.

of each figure show the sea levels at data stations B and D and the lower 4 panels of each figure show the velocities at data stations B, D, F, and I during the same period. The data stations are shown in Fig. 1.

The change of coast lines improves little the model reproductions of sea levels. Sea levels are mainly determined by the Kelvin waves and the Kelvin waves are affected little by the change of bottom slope in the China shelf. Thus, sea levels are almost not improved. Both of the model reproductions of sea level are by and large good in phase but not so good in amplitude. This is probably

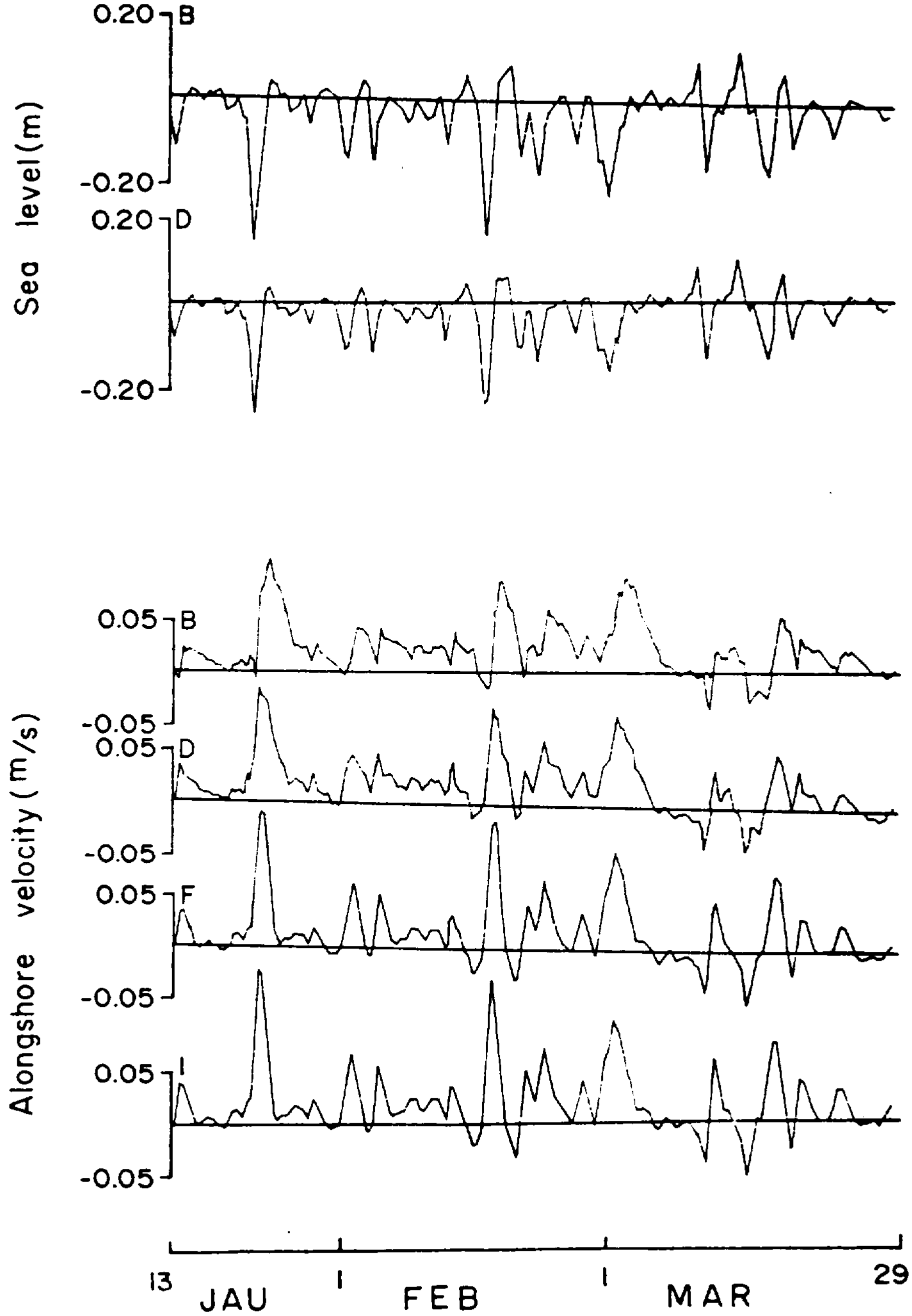

Fig. 6. Observed sea levels at stations B and D and alongshore velocities at stations B, D, F, and I during January 13 to March 29, 1986.

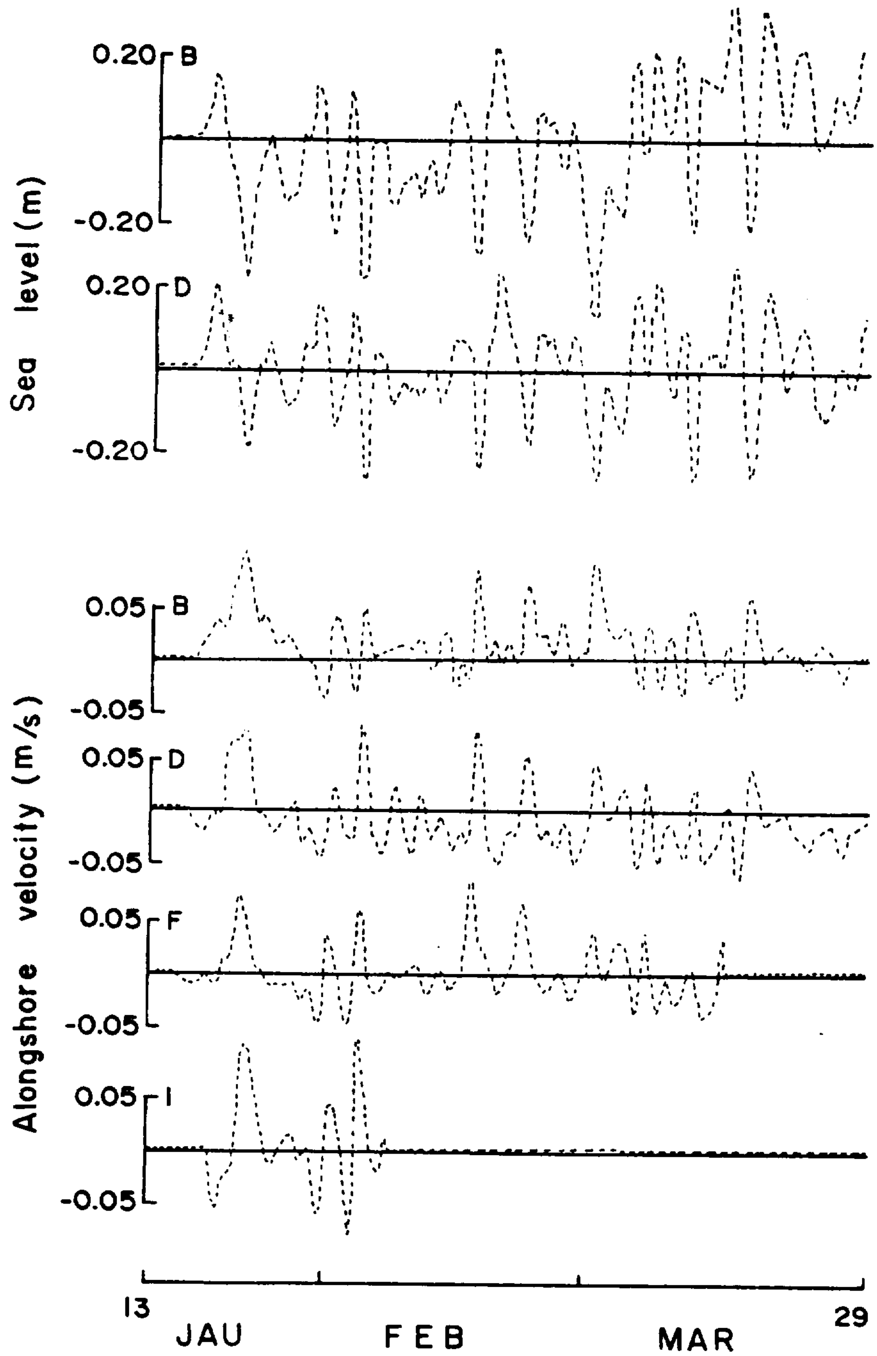

Fig. 7. Model results of sea levels at stations B and D and alongshore velocity at stations B, D, F, and I, with straight coast lines during January 13 to March 29, 1986.

due to the geostrophic wind calculated from the pressure chart. The geostrophically calculated wind stress is likely to be accurate in phase but not in amplitude. The sea level reproduction is also sensitive to the northern boundary since the northern boundary region transmits the Kelvin waves. For better sea level reproductions on the Yellow Sea area, we need eventually some modifications in modelling the northern boundary region.

The model reproduction of alongshore velocities is not improved at near the Korea coast by the change of coast lines. The change of bottom slope on the China shelf affects significantly the China continental shelf waves but only a little the Korea continental shelf waves. And the China continental shelves decay exponentially over the Korea shelf. Therefore, the alongshore velocities near the Korea coast, which are determined dominantly by the Korea continental shelf waves, are hardly improved by the change of bottom slope in the China shelf. Both models fail in reproducing alongshore velocity near the Korea coast. The strong density contrast between the coast and off-shore waters, which is not accounted in the model, might be the reason. The strong density contrast shown near the Korea coast will drive the coastal water northward in the real ocean, while the wind stress forces the water to move to downwind direction in the model.

The change of bottom slope also does not improve the alongshore velocity in the northern part along the Yellow Sea trough. However, the both models work quite well. We can see that for alongshore velocity, the northern part along the Yellow Sea trough, at station B, may be the best place to see how the model works since the flow is least affected by other dynamics. The area is far from the coasts and boundaries. The good agreement of the alongshore velocity at station B indicates that the wave model works fine basically for a double shelf topography and that the assumptions used in the model are by and large acceptable. One assumption is no incoming wave energy from the southern boundary. It turns out to be fine for velocity. It should be mentioned, however, that this assumption is not good for sea level. The tidal observations at the tip of the Korean peninsula show significant sea level fluctuatons. This means that the incoming wave energy from the southern boundary is probably in the form of the Kelvin waves. Another assumption is no incoming continental shelf waves from the northern boundary. It should be noted that the Kelvin wave transmits through the northern boundary region and comes back to the main region. The assumption is based on the fact that the perimeter of the northern boundary region is much longer than the decay distance of the continental shelf waves and much shorter than that of the Kelvin wave. In addition, the direction of the northern coast of the Shandon peninsula is in east-west direction, it is ineffective to generate continental shelf waves by the prevailing north-south wind. Under these assumptions, the wave model might work fine for velocity over a double shelf topography if water movements are not affected by the other dynamics.

However, the Yellow Sea shows a lot of variation in bottom slope, specially over the China shelf. The variation will affect the China continental shelf waves and therefore

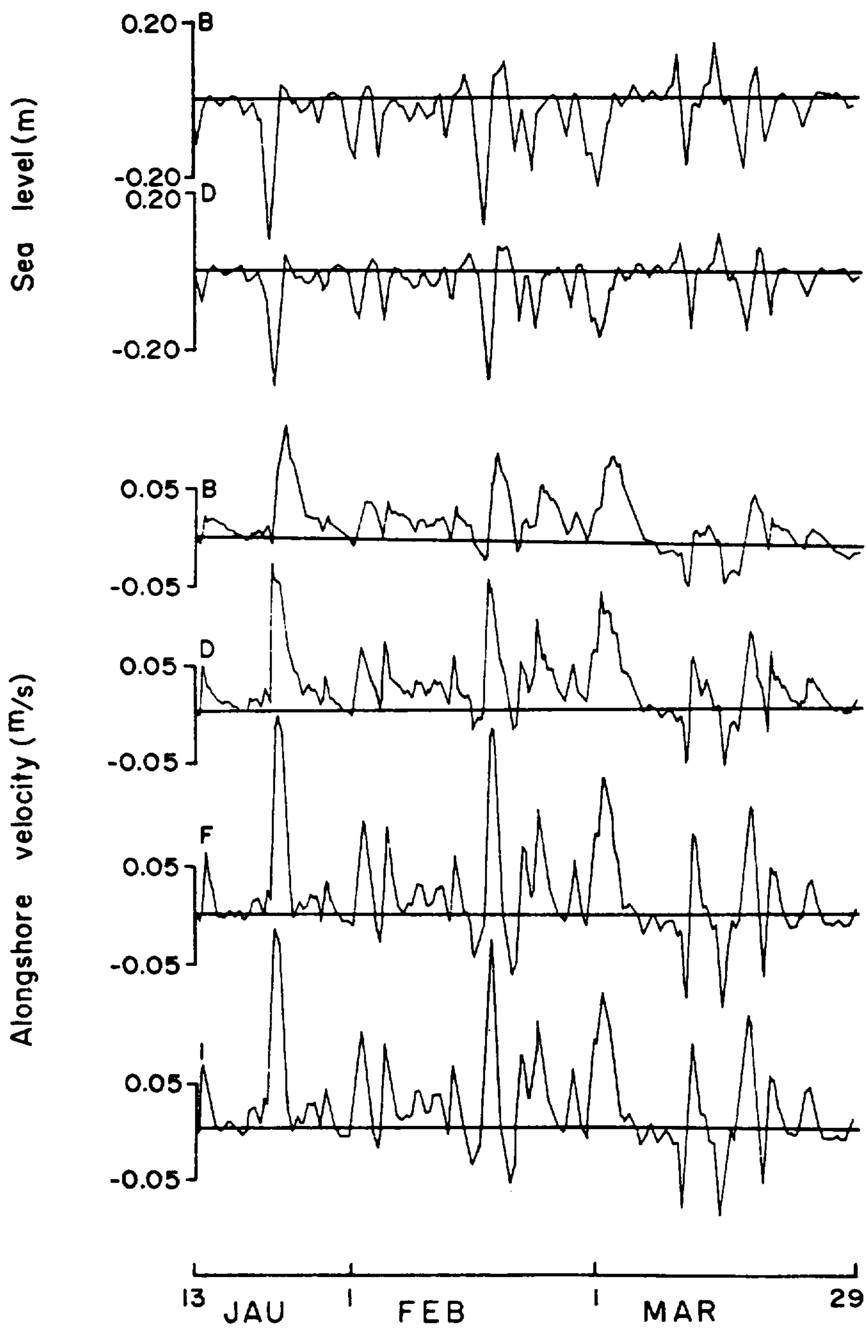

Fig. 8. Model results of sea levels at stations B and D and alongshore velocity at stations B, D, F, and I, with more realistic coast lines during January 13 to March 29, 1986.

the velocity near the southern boundary. The model results with straight coast lines shows a lot of discrepancies in the velocity near the southern boundary and the discrepancies have been reduced by using a more realistic coast lines. Thus, the best improvement occurs on the southern part along the Yellow Sea trough at stations F and I. As mentioned, this is because that the southern part is influenced more by the China continental shelf waves. Near the southern boundary, the China continental shelf waves are fully developed while the Korea continental shelf waves are not sufficiently developed yet.

The improvement by using a more realistic coast lines tells that the modifications of bottom slope is important for the water movement controlled mainly by the continental shelf waves. As expected, the modification of bottom slope does not improve the sea level reproductions. It tells that to improve the sea level reproductions, we need some modification of the boundary conditions and the northern boundary region. The wave model is shown not to be good for the coastal water movement controlled by other dynamics. To include the other dynamics in the wave model, we would need a baroclinic extension of the theory.

Through this study, we understand and also make sure what causes the discrepancies and how we can improve. With the other modifications, we need to use a more and more realistic bottom slopes.

Conclusion and Discussion

The long-period fluctuations of sea level and alongshore velocity in the Yellow Sea in winter time are basically due to the large-scale ocean response driven by winds. With a more realistic bottom topography for the China shelf, the model reproductions have been improved, specially near the southern boundary of the Yellow Sea.

This application shows that more modifications are necessary for better reproducations and that, nevertheless, some of our assumptions used in the wave model are acceptable. It shows possibilities of better reproductions only by using more realistic bottom topography.

Still there are discrepancies, specially in amplitudes. One of the reason why the model reproduce the phase well but not the amplitude might be due to the wind forcing used in the model. The geostrophically calculated wind stress is likely to be accurate in phase but not in amplitude. Another possible reason is because of the way that the wave model deals with the northern boundary region.

The model reproduces well up-wind flow events in the Yellow Sea trough. Continual up-wind flows events may result in a northward transport along the Yellow Sea trough in winter time by the typical strong southward winds in this area. This suggests that the northward intrusion of the Yellow Sea warm current along the Yellow Sea trough in winter time, which is suspected from the various hydrographic studies, is mainly caused by the typical wind system.

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〈摘要〉

바람에 의한 황해해수의 대규모반응과 해수순환

황해와 같은 양향성 대륙붕에서 장주기, 장파인 경우의 대륙붕파 이론이 발전되었다. 이 지형에서는 켈빈파가 해수면변화의 요인으로서 매우 중요하게 나타나며, 다른 파로는 해류변화의 요인인 대륙붕파가 있다.

양향성 대륙붕파 이론을 사용하여 양향성 대륙붕에서의 파동모델을 발전시켰으며, 황해에 적용하여 겨울철에 바람에 의해 발생하는 해수면과 해류의 변화를 계산하였다. 모델계산과 관측치와의 비교를 통해, 겨울철 황해에서 발생하는 해수면과 해류의 장주기 변화의 대부분이 바람에 의한 황해해수의 대규모 반응에 기인한다는 것을 발견하였다. 중국대륙 연안을 보다 실제적인 해안선으로 사용했을 때는 특히 황해남부해안에서 모델결과가 개선되었다.