A numerical study on the behavior of tidal waves in the Taiwan Strait

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Abstract

Results derived from recently observed sea level and velocity data suggest that the tidal waves behave as a Kelvin wave propagating southwestward by the west bank of the Taiwan Strait and a nearly standing wave in the eastern half of the strait. A numerical model with a larger computational domain compared to the existing ones was used to examine these findings. Conclusions from model results verified that the southwestward moving Kelvin wave starts from the Changjiang River mouth hugging the China coast, passes through the Taiwan Strait into the South China Sea, and ends at east of Hainan Island. As the Kelvin wave impeded by the Taiwan Banks, its reflections interact with the incident waves entering from the northeastern strait. The latter process favors the resonant-standing waves generated over the topography in the eastern strait.

1. Introduction

Tidal waves in the Asian marginal seas (see Fig. 1) have been extensively studied using numerical models. For example, Guo and Yanagi (1998), Kang et al. (1998) and Lefevre et al. (2000) investigated characteristics of tides for the Yellow Sea and the East China Sea; Fang et al. (1999) simulated tidal regime for the South China Sea. Their model successfully reproduced several tidal features found in these regional seas. However, propagation of tidal waves in the Taiwan Strait seems not to be properly resolved because the strait was one of their open boundaries. The computational domain nearby the open boundary is hardly free from artificially imposed boundary conditions. The numerical results more or less are also subjected to the coverage of modeling area especially for a smaller scale regional model. Therefore the need of establishing a larger domain numerical model for better examining the behavior of tidal waves in the Taiwan Strait is clear.

2. Observational data

It has long been believed that the tidal waves from the northwest Pacific diffract into the Taiwan Strait through both of its southern and northern openings and meet at about the central portion of the strait. However, results derived from recently measured velocity and sea-level data in the strait somewhat deviate from this previous conjecture. Analyses of these observational data suggest that the tidal waves behave as a southwestward propagating Kelvin wave and a nearly standing wave respectively in the west and east halves of the strait. The tidal wave energy fluxes mostly propagate southward in the strait and are nearly diminished in the area centered at the eastern strait, suggesting the progressive and standing wave systems co-exist in the strait. The complicated bottom topography (see the insert in Fig. 1) is speculated to modulate tidal characteristics in the strait. The present model work is to verify these inferences.

3. Model description

The modeling strategy in this study is essentially process-oriented. The numerical model described by Blumberg and Mellor (1987) is adopted to study characteristics of tidal waves in the Taiwan Strait. The tidal waves are essentially shallow water waves, justifying the use of a vertically averaged version of this model. The computation domain (Fig. 1) bounded by the 2°N and 41°N parallels and 99°E and 130°E meridians covers the northwest Pacific, the Bohi Sea, the Yellow Sea, the East China Sea and the South China Sea. The boundaries of the computation domain were opened along 130°E between 2°N and 31.5°N, and across the Korea Strait, the Makassar Strait and the Karimata Strait, which are sufficiently far from our study area. The horizontal grid spacing is one-eighth of a degree interval, which is fine enough to resolve essential tidal waves in the East Asia marginal seas. The bottom topography was established using ETOPO5 archives and a fine-resolution depth database for the Taiwan Strait and vicinity.

The model ocean was homogeneous and initially quiescent. Tidal forcing was subsequently imposed to drive the model to equilibrium. Different tidal constituents were separately imposed on the eastern open boundary for the simulation. Sea levels on the other open boundaries were determined using a radiation condition (Orlanski, 1976). The normal and tangential velocities on the open boundaries were extrapolated from interior by assuming zero normal gradients. Bottom stress was calculated using quadratic law. In a series of preliminary numerical experiments, the horizontal eddy viscosity and bottom drag coefficient had been varied and the amplitude and phase of calculated tidal constituents had been compared with the harmonic constants obtained from available coastal tide-gage stations. Conclusions from these side experiments suggest a better coefficient of horizontal eddy viscosity being 500 m^2/s and a non-dimensional drag coefficient being 0.0025. To avoid initialization shock, sea-level oscillations were ramped up to the given conditions within the first day of simulation. The model approached a cyclical equilibrium after about five days of integration. The simulated tidal regimes are consistent with those simulated by Guo and Yanagi (1998), Kang et al. (1998) and Lefevre et al. (2000) and Fang et al. (1999). This implies that the present model is reliable for resolving the behavior of tidal waves in the Taiwan Strait.

To examine our inferences about the process of tidal wave propagation, model topography in the Taiwan Strait and vicinity was varied so that the Luzon Strait was closed, the Taiwan Banks was removed, etc. Model results from the ninth to the tenth day are analyzed and only selected experiments are presented follow for brevity.

4. Numerical results and discussion

Fig. 2 shows calculated co-phase and co-range charts for the dominant M_2 waves in the strait. The co-phase lines suggest that, in the western strait, a progressive wave moves southwestward along the China coast. This southwestward propagating Kelvin wave starts around the Changjiang River mouth, passes through the Taiwan Strait and ends at east of Hainan Island. In the eastern strait the tidal phases vary slowly in space implying a nearly standing wave condition occurred here. Through the Luzon Strait, the westward incident M_2 waves mostly enter the South China Sea and partly diffract clockwise into the Penghu Channel. The amplitudes of simulated M_2 waves are significantly amplified by the west coast of Korea (not shown here), near the Changjiang River mouth (not shown here), and in the Taiwan Strait. It is noteworthy that the amplitudes nearby the northwest bank of the strait are increased about three fold of that of imposed sea level oscillations.

Fig. 3 shows tidal current ellipses and the tidal energy fluxes for the simulated M_2 waves. The tidal currents are quite strong over the Taiwan Banks and off the northwestern Taiwan and in the Penghu Channel. Tidal currents are relatively weak in the western strait and tend to be diminished in the area centered in the eastern reaches of the strait. The directions of energy fluxes in Fig. 3 indicate that the tidal energy be mainly from the East China Sea. The northward propagating tidal energy in the Penghu Channel is relatively minor compared to that from the East China Sea.

The model simulated tidal waves are in good agreement with the observed tidal charts and existing other model results, and lend support to the behavior of tidal waves in the Taiwan Strait inferred from the observational data. Numerical experiments with varied topography (results not shown here) further examined the role of the Taiwan Banks as a barrier partly blocking the southwestward propagating Kelvin wave from the East China Sea and guiding the westward propagating through the Luzon Strait into the South China Sea. The partly reflected waves north of the Taiwan Banks may interact with the incident waves diffracted from the northern tip of the Taiwan Island. Moreover, a zonal topography rise (the Changyun Rise) in the middle reaches of the strait also favors the existence of a co-oscillating tide north of it. Combination of these processes yields the resonant-standing condition in the eastern strait.

5. Concluding remarks

Analyses of recently observed sea level and current data suggest that the tidal waves behave as a southwestward propagating Kelvin wave and a nearly standing wave respectively in the west and east halves of the strait. Results from numerical experiments verified the physical process inferred from the findings. Conclusions derived from model results suggest that the Kelvin wave propagates southwestward along the China coast from the Changjiang River mouth, and passes through the Taiwan Strait into the South China Sea. As the Kelvin wave impeded by the Taiwan Banks, its reflections interact with the incident waves from the northeastern strait. The latter process favors the resonant-standing waves generated over the topography in the eastern portion of the strait.

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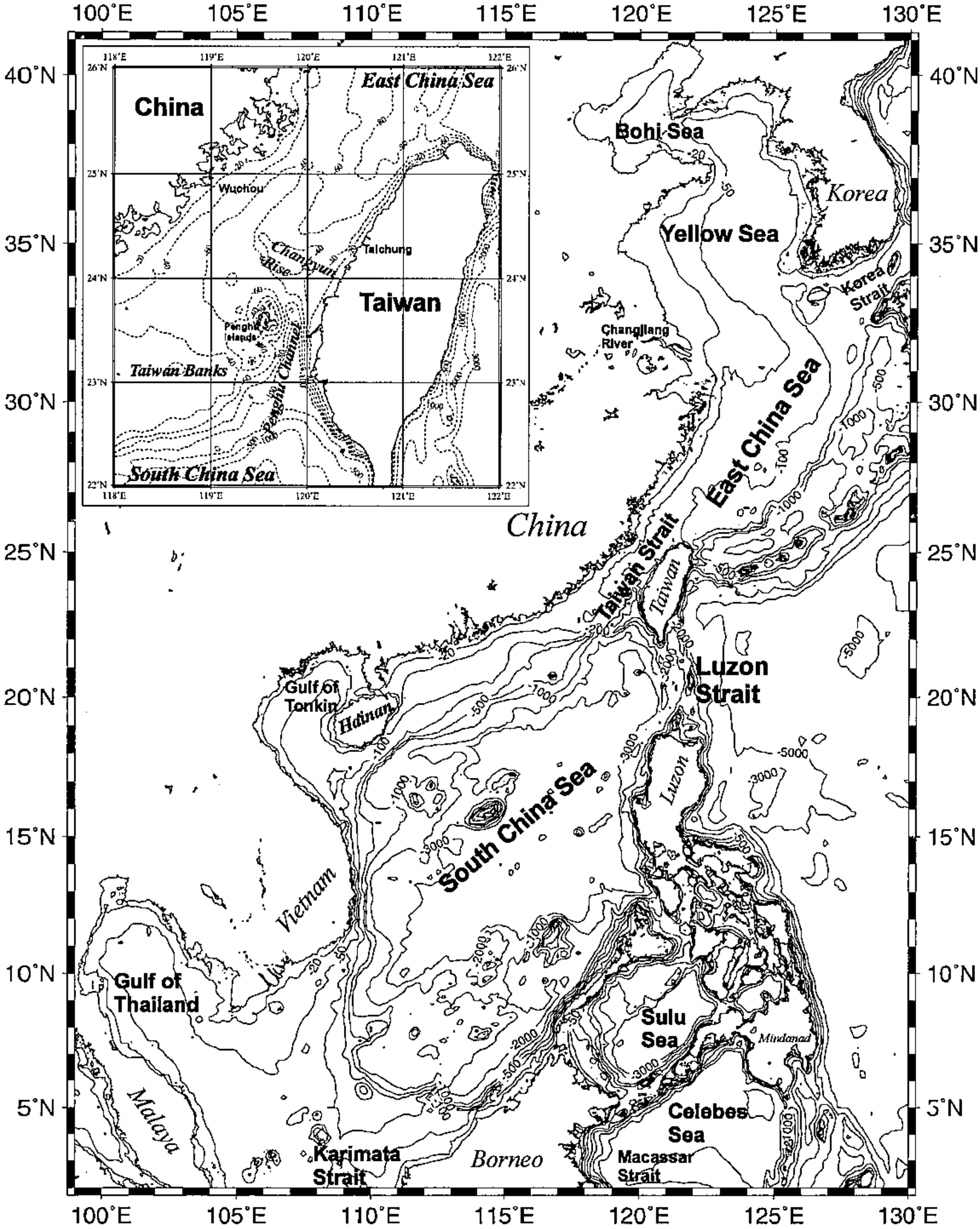

Fig. 1 Map and bathymetry charts (in meters) for the Asian marginal seas. The insert in the upper-left portion illustrates the topography in the Taiwan Strait.

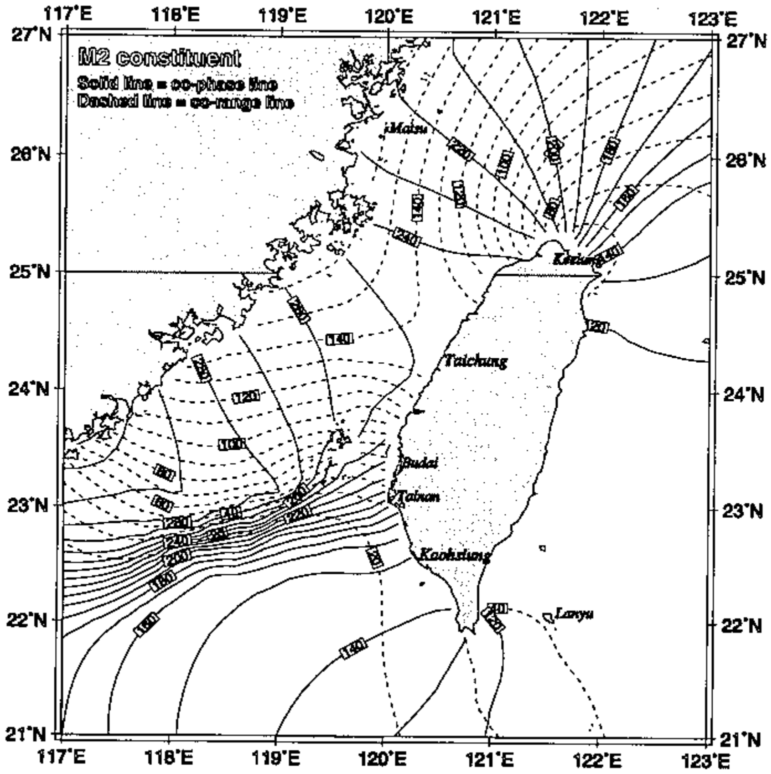

Fig. 2 Model calculated co-phase (solid line) and co-range (dashed line) charts for the M_2 constituent. The phase is in degrees and amplitude in cm.

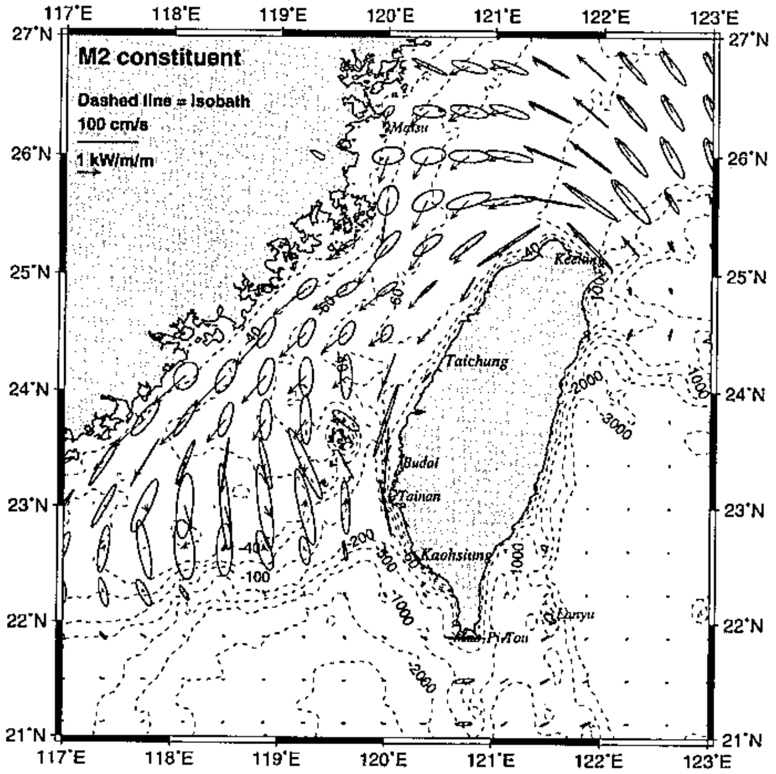

Fig. 3 Tidal velocity ellipses and energy fluxes for the simulated M_2 waves. Velocity and energy fluxes scales are appended in the upper-left corner. The dashed lines are isobaths.