

Regional Ocean Tide Simulator: Applications to Adjacent Seas of Korea and Japan

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Abstract

A regional ocean simulation system for tides, wind and ocean circulation in the seas bordering the Korean Peninsula and Japan is designed to cover an area that is broad in scope and size, yet provide a high degree of resolution in the area of scientific and engineering interests. With this simulation system, tidal distribution of the modeled regional seas and changes occurred in tidal regime due to coastal dikes as exemplified for Isahaya Bay in the Ariake Sea, Japan and Saemangeum Sea area, Korea are firstly estimated and further improvement and implementation of the simulation system are also discussed.

1. Introduction

The necessity of predicting changes in tidal regime caused by large coastal engineering developments has led to increased numerical modeling of ocean tides on the continental shelf since the 1970s (Flather, 1976; Choi, 1978; Greenberg, 1979). In view of practical concerns related to pollutants, oil spill dispersal, search and rescue operations at sea, and navigation, demands for accurate tidal predictions with respect to both time and space are increasing. The aim of this study is to predict how the construction of tidal barriers in the interior region of the Ariake Sea (the Isahaya dike) in Japan and another long dike on the west coast of Korea (the Saemangeum dikes) would disturb and/or alter the system's natural tidal state. Because of the possible environmental consequences, it is important that correct evaluations are made. The only practical way of obtaining effective solutions is to construct a mathematical model that simulates the behavior of the tidal system, which plays a central role in the shelf sea, involving a set of equations of motion for the sea that are solved numerically to yield the tidal variation. The proposed changes in boundary configuration due to barrier schemes can then be inserted in the model and the resultant effects on the system can be estimated. The degree of confidence of these approximations is a function of accuracy with which the model reproduces the real system. During the past years, this approach has been widely used for the studies of barrier schemes in the Bristol Channel (Heaps, 1972; Miles, 1979; Owen and Heaps, 1979), the Bay of Fundy (Garrett, 1972; Duff, 1979; Greenberg, 1979), the west coast of Korea (Choi, 1978; 1981; 2001), and Isahaya Bay in the Ariake Sea (Kim and Yamashita, 2002; Kyojuka, 2002; Nadaoka, 2002; Takikawa and Tabuchi, 2002). One of the most difficult and important tasks in this approach is that a sufficiently large region should be considered in the mathematical modeling, since good results may only be expected by locating the open boundaries sufficiently far from the barrier sites, beyond the barrier's influence. Some previous studies (Heaps and Greenberg, 1974; Garrett and Greenberg, 1977; Garrett and Toulany, 1979) indicate that unreasonable results may be obtained if too small a sea area is considered in the computations. However, the open boundaries of the models reported for estimating tidal changes in the Ariake Sea and the Saemangeum Sea area have been chosen arbitrarily in the previous studies. In this paper, an ocean tide simulation system for accurate modeling of the ocean tides in the regional seas of bordering the Korean Peninsula and Japan is introduced. We briefly describe the possible applications of this system for the simulation of barrier effects perturbing the tidal regime due to the construction of tidal dikes in the eastern Yellow Sea and Isahaya Bay in the Ariake Sea.

2. Modeling system

2.1. Geographical setting

2.1.1. The Saemangeum Sea area in Korea

The Mangyong-Geum (Mangeum) estuary is a relatively shallow macrotidal embayment (the average tidal range is 5.7 m on springs and 2.8 m on neaps) located at latitude 35°N on the western coast of the Korean Peninsula in the eastern Yellow Sea. Its maximum depth is 10 m (below Indian Spring Low) at the mouth of the Geum estuary; it also has a broad intertidal zone exposed during low tide. Similar to other estuaries on the western coast of Korea, tidal currents have a profound influence on sediment dynamics in the area. The severe winter storms arising from northwesterly winds also create strong currents. Therefore, tide and wave conditions of sufficient intensity categorize this area as a high-energy environment. The Saemangeum tidal barrier was constructed in this sea area in 1991, connecting offshore islands from the Bieung and Osic Islands in the southern Geum estuary to Daehangri in the southern Mangyong estuary, forming a 40,100 ha reclamation area and freshwater reservoir. In April 2003, the barrier of 28.5 kilometers was constructed, yielding a total of 33 kilometers, leaving openings of 1.1 kilometers at the Sinsi Island gate construction area, 1.6 kilometers near Garyuck Island, and about 1.8 kilometers between Yami and Bieung

Islands. These openings were built for the sake of convenience, and the entire construction was classified as the Number Four dike. The final closure operation was then completed after completion of the sluice gates, in April 2006 and details will be reported under separate papers. Locally significant bed changes due to sand movement have been reported previously for the area along the dike alignment between Osic and Yami Islands (Choi, 2001). The sandbank-like deposition occurred at the originally-planned closure site at the Number Four dike between Yami and Bieung Islands; the researchers recorded rapid sand deposition of 6-7 meters over a period of 9 years along the dike alignment (spanning about 2 kilometers). Choi (2001) reported that this bottom evolution with sand deposition is somewhat faster than the hydrodynamic interpretation of Huthnance (1982). Thus, the region exhibits not only remarkable features with regard to turbid suspended sediment movement as manifested in the satellite images, but also long-term bed morphological changes due to bedload (sand) transport that may play an important role in sediment dynamics in the region. In the northern portion of the Saemangeum dikes, extensive port development has involved the construction of parallel dike and quay walls at the Keum estuary. Although the project was started with the optimistic view that sediment supply from the upstream river would significantly decrease by damming the upstream river, a considerable amount of siltation has been observed in the channel. This siltation is possibly due to redistribution of sediment within the estuary from the continuous suspended sediment supply from the outer estuary along the coast, especially during winter monsoon.

2.1.2. The Ariake Sea in Japan

The Ariake Sea includes a long inner bay, 90 km in length, 17 km average width, 1,700 km² in area, 20 m average depth, with a tidal flat area. Notably, the tidal range in Japan is the largest documented (Osamu, 2001). The sea connects with the East China Sea through the Hayasaki Straits. Vast tidal land, formed in its innermost part by sediments from many small rivers such as Chikugo-gawa, Yabe-kawa, Shira-kawa, Midori-kawa, Rokkaku-gawa and Honmyo-gawa, has a width of about 6-10 km from the coast during the ebb stage of spring tide (Isozaki and Kitahara, 1977). The Ariake Sea is the largest cultivating ground of laver (seaweed), providing about two-fifths of the laver in Japan. In recent years, environmental problems have become serious in this area, including frequent red tide and decreased fish catches. The laver plants in the Ariake Sea were seriously damaged in the winter of 2000. It is not yet clear exactly what caused such damage to the laver in the Ariake Sea. It has been suspected that the reclamation project (construction of tidal barriers) in Isahaya Bay in the inner part of the Ariake Sea is a major contributing factor.

2.2. Regional Ocean Tide Simulator

Investigation of the tides in the East Asian Seas started during the late 1970s with the formulation of a two-dimensional model for basic studies of tidal propagation in the Yellow Sea and the East China Sea continental shelf (Choi, 1980). This has been followed by a series of studies (Choi, 1981; 1989; 2001; Choi and Lee, 2003; Choi and Yuk, 2003) aimed at predicting tidal changes due to tidal barriers for potential tidal power exploitation, land reclamation, and port development using a combination of the Yellow Sea model and estuarine tidal models. In this study, a modeling technique that converts the model equations to a discrete form and allows computation over spatially unstructured meshes has been used as a primary component of the regional ocean tide simulator, allowing more accurate representations of the coastlines, man-made dikes, coastal structures, and topographic features. Rather than refining dynamic grid nesting technique retaining the finite difference scheme, we decided instead to adopt the finite element technique. This method permits more flexibility in fitting irregular coastlines and allows bathymetry to be fitted with elements of an arbitrary size, shape and orientation (in particular, barrier positioning). We made our own version of GUI based code for partitioning of unstructured meshes in semi-automatic manner to resolve the detailed variation of bottom topography and coastline topography. It permits easy editing of the unstructured meshes and merging them into larger domain of base models, of which the open boundary conditions were prescribed previously with a series of

adjustment runs. A dataset we created is detailed coastline data for Korean Peninsula comprising over million points and implemented on GUI based code for modification of coastline, updating and coordinate conversion. Considering the importance of setting up an appropriate model area, two versions of base models were created: one covering the Yellow Sea and the East China Sea (YS/ECS) continental shelf; and the YS/ES/NWP (the Yellow Sea, the East (Japan) Sea and the Northwestern Pacific) extending to the outer eastern Japanese coast. These models were helpful for focusing on different coastal regions of interest, as seen in Figures 1 and 2. With this simulator design, detailed meshes in the coastal and estuarine regions can be resolved and computations can be managed with parallel structures, demonstrating the ease of relocatability within the base model regions. By taking a time-step approach (Luettich et al., 1992), the method can accommodate the transient response to non-periodic (e.g., wind) forces in addition to tides, contrasting with the harmonic approach. This technique can also be extended to three-dimensional flow computations. We have started external mode equations using parametric relationships for bottom friction and momentum dispersion. Key features of the external mode solution include the use of a generalized wave-continuity equation formulation (Lynch and Gray, 1979; Kinmark, 1985) using finite element discretizations. The details are published widely (<http://www.nd.edu/~adcirc/manual.htm>) and will not be restated here.

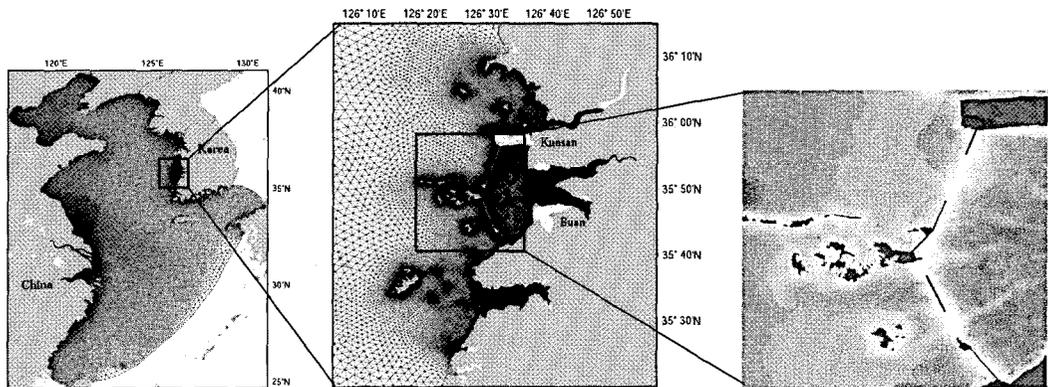


Figure 1: Overall and details of meshes over the Yellow Sea and at the location of Saemangeum barriers.

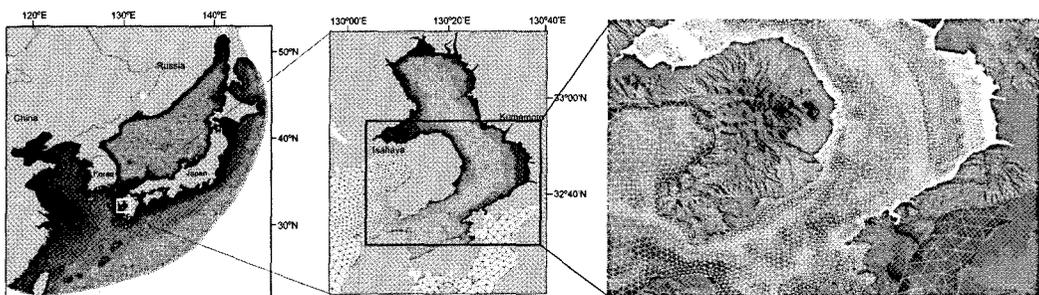


Figure 2: Overall and details of meshes over the Yellow and East China Seas and at the location of the Isahaya barrier in the Ariake Sea.

The simulation system for tides, wind, and ocean circulation in the neighboring area of the Korean peninsula was designed to cover an area that is broad in scope and size, yet provide a high degree of resolution in the nearshore area. Figure 1 shows the mesh system used for Saemangeum. Regionally, 200,000 refined elements were patched over 70,000 coarser elements of the large area system, thus totaling 270,000 elements. A series of simulations have been performed to reproduce the tidal regimes of eight major tidal constituents, taking the open boundary values from a larger domain tidal model. Here we mainly refer to the Japanese NAO (National Astronomical Observatory) database (Matsumoto et al., 2000) and use land-, as well as island-based, tidal observations. Figure 2 shows the mesh system used for Isahaya Bay simulation; 61,000 regionally refined elements were patched over 195,000 coarser elements from the larger area system, thus totaling 257,000 elements. Approximate mesh sizes in the region of interest were formulated as a few tens of meters and the bathymetry of the tidal flat area was described, thus enabling a detailed evaluation of changes in the tidal regime.

Figures 3 and 4 show the partitioned domains of the two base models used for detailed simulation of Saemangeum Sea area and Isahaya Bay in the Ariake Sea, respectively. It is based on PC-clustered Linux OS system (Beowulf) which can be set up easily for intensive computational task.

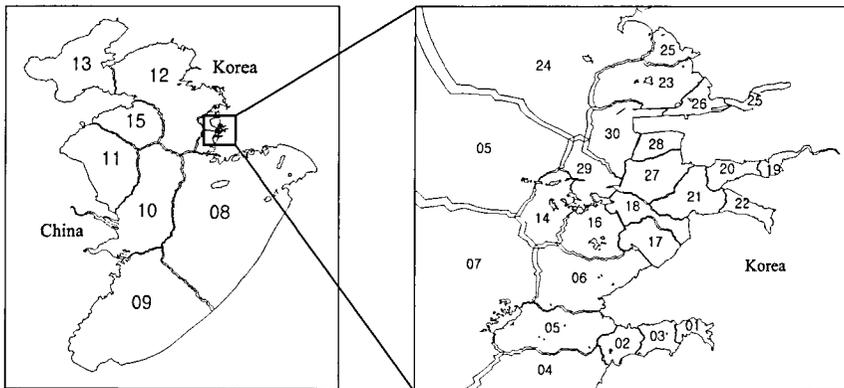


Figure 3: Partitioned domain for parallel computations showing details of domains at the Saemangeum

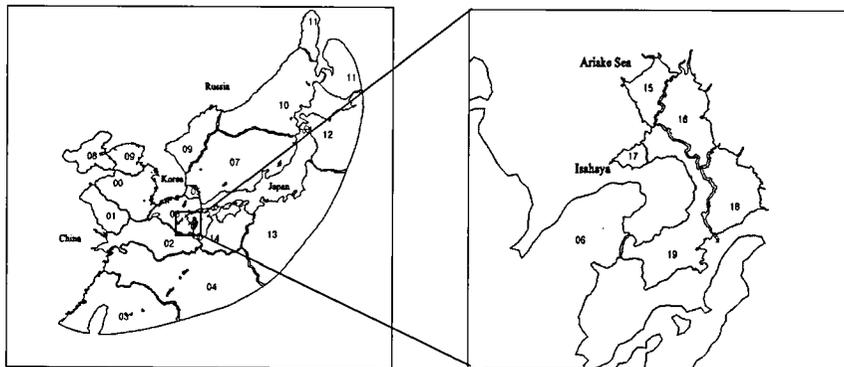


Figure 4: Partitioned domain for parallel computations showing details of domains at Isahaya Bay

3. Numerical simulation

3.1. Tidal computations

Figure 5 shows the tidal distributions of major M_2 , S_2 , K_1 and O_1 constituents, which are predominant in the East China and Yellow Seas. Figure 6 shows the tidal distributions of K_2 , N_2 , P_1 and Q_1 constituents. The simulations, together with these tidal charts, provide the general characteristics of tides throughout the whole system; the simulations are in general agreement with coastal observations (See Figures 7 and 8) and empirical co-tidal charts from satellite altimetry analysis (Fang et al., 2004). It has been observed that tides propagating from the Pacific Ocean and entering the Ryukyu Islands arc and the South China Sea through the strait form very complex tidal systems. A portion of the tides entering across the shelf rotates counter-clockwise with its center at the northern end of Taiwan (the degenerated amphidromic points shown in the M_2 tidal chart), moves counter-clockwise to the southwest, and then propagates to the Taiwan Strait. On entering the Yellow Sea, the tide propagates to the north along the west coast of Korea, and, after reaching the north shore of the Yellow Sea, the tide turns to the west and propagates to the Strait of Bohai. Then the tide progresses in a counter-clockwise direction along the coast in the Gulfs of Liaodong and Bohai and to the east along the south shore of the Bohai, making a complete revolution within the Gulfs of Liaodong and Bohai. The tides, after coming out from Bohai, progress first to the southwest and then to the southeast along the coast of China. Thus, the wave characteristics in the Yellow Sea correspond approximately to the tide propagation in a rotating channel in the northern hemisphere, as described by Hendershott and Speranza (1971).

Throughout the entire modeling area, tides have been changed locally due to the continuous development of coastlines, i.e., heavy siltation in the mouth of the Yellow River and damming of the estuarine region by building many tidal barriers at the Daedong River (in North Korea at $38^\circ 40'$ North latitude, Kyeonggi Bay, Keum River at 36° North latitude, the Yongsan River, and the Nakdong River). However, it seems that the degree of coastline modification at Saemangeum is the most extensive throughout the Yellow Sea system. The barrier schemes in the Bay of Fundy, Asan Bay and Bristol Channel represent modifications of the characteristic length of quarter-wavelength resonators, with their funnel-shaped or rectangular basins. Related tidal changes have been explained by a simple analytic model along with numerical simulations. However, the Saemangeum barriers are positioned offshore, protruding from the coastline and modifying only the progression of Kelvin waves propagating along the coast of the Korean Peninsula in the eastern Yellow Sea. Thus, it is of interest to see how the tidal system will change, utilizing the conventional hydrodynamic model used for forty years for engineering applications.

In the Ariake Sea, the strongest current is seen near the Hayasaki Straits; the current flows parallel to the meridional axis of the Ariake Sea (Isozaki and Kitahara, 1977). Tidal elevation amplitude and phase were calculated by the harmonic decomposition from the elevation results of each tide run. Figure 9 (right) shows the co-amplitude and co-phase charts of the M_2 tide in the model domain and the major straits in Japan. In Figure 10, similarly, the tidal charts of the S_2 and K_1 tides are shown. The results calculated from simulations in the Yellow Sea and the East China Sea are similar to the observed tide, while near the Ariake Sea, the calculated phases of some positions do not correlate easily with the observed positions.

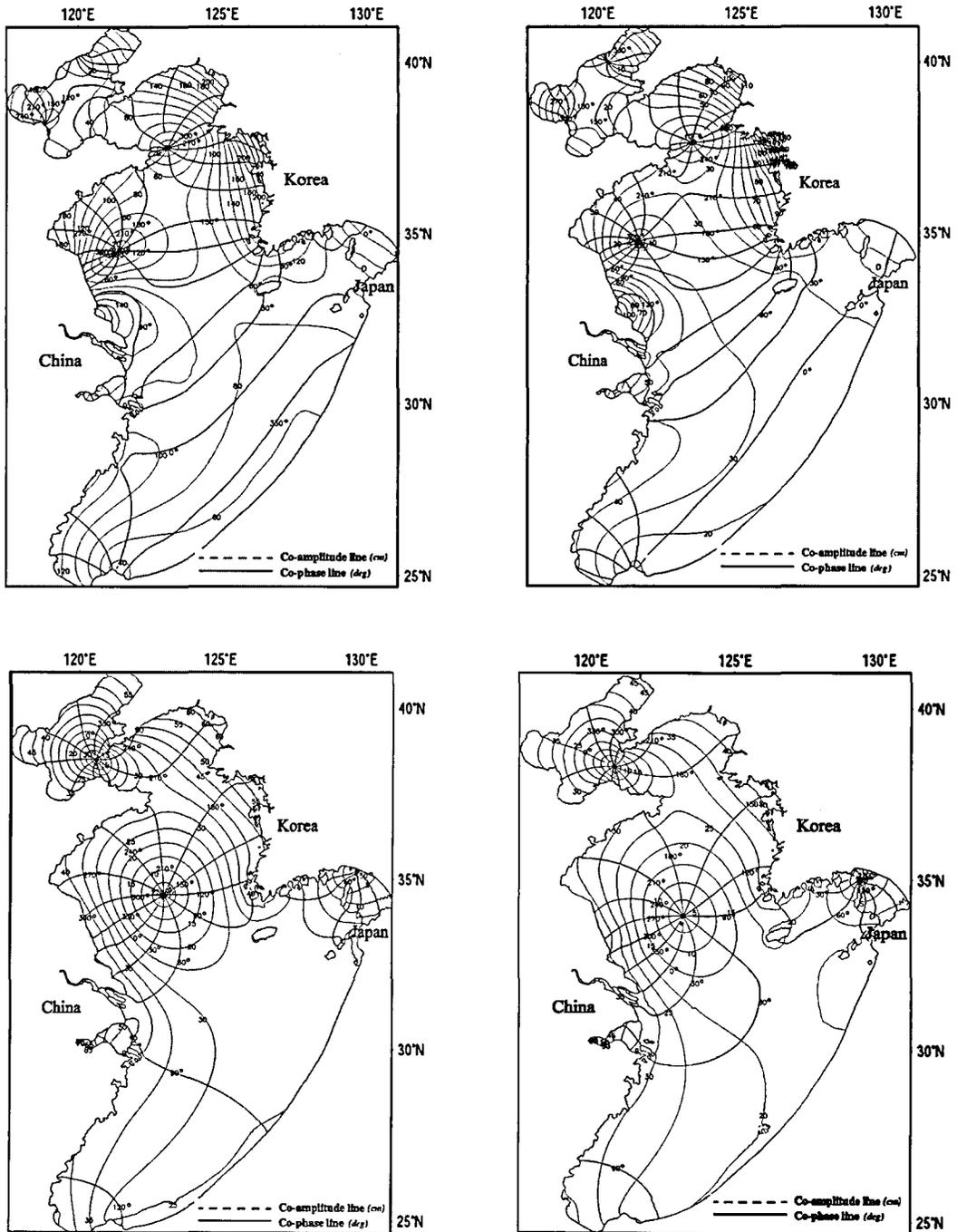


Figure 5: Reproduced tidal distributions (upper left plate - M_2 tide; upper right plate - S_2 tide; lower left plate - K_1 tide; lower right plate - O_1 tide).

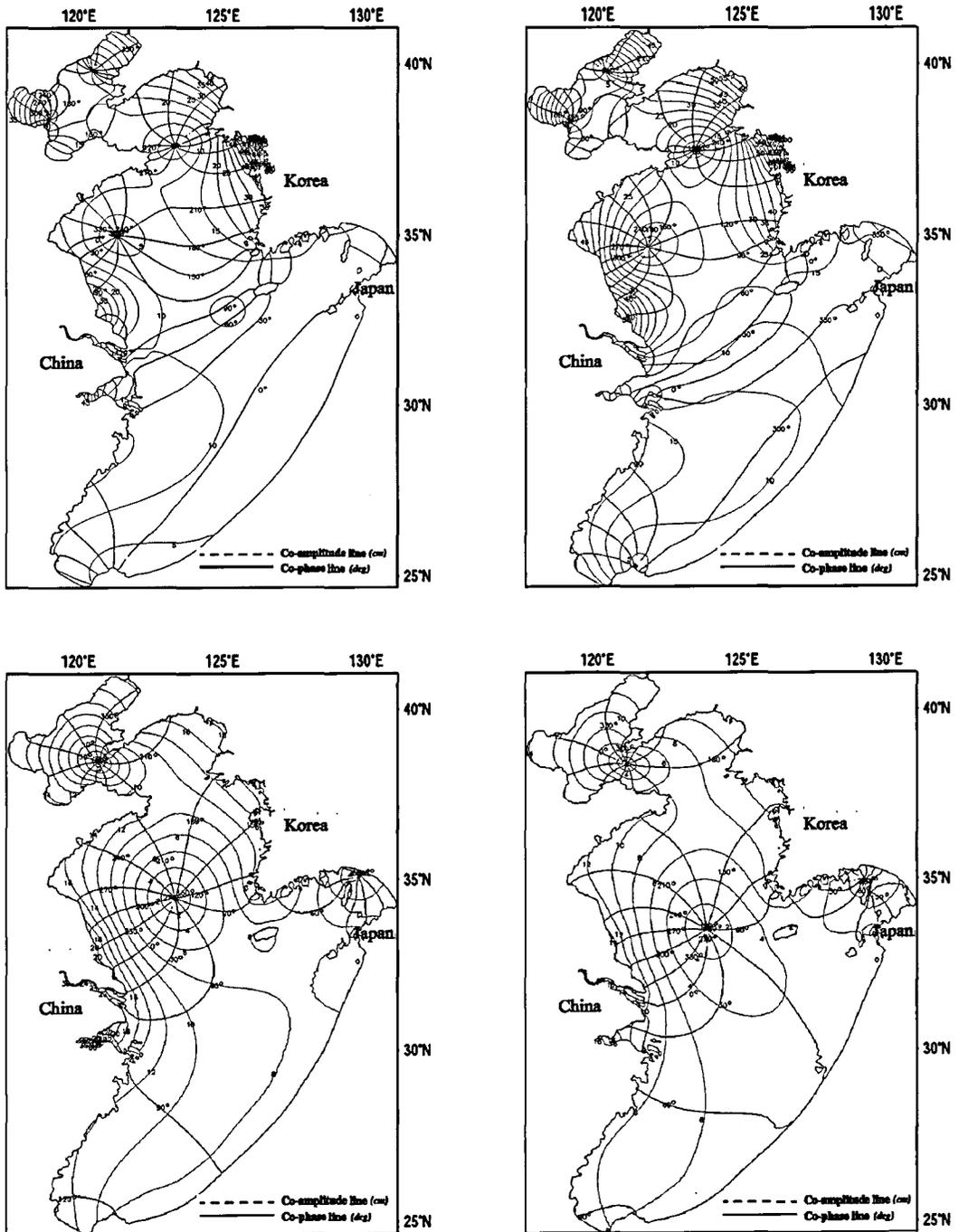


Figure 6: Reproduced tidal distributions (upper left plate - K_2 tide; upper right plate - N_2 tide; lower left plate - P_1 tide; lower right plate - Q_1 tide).

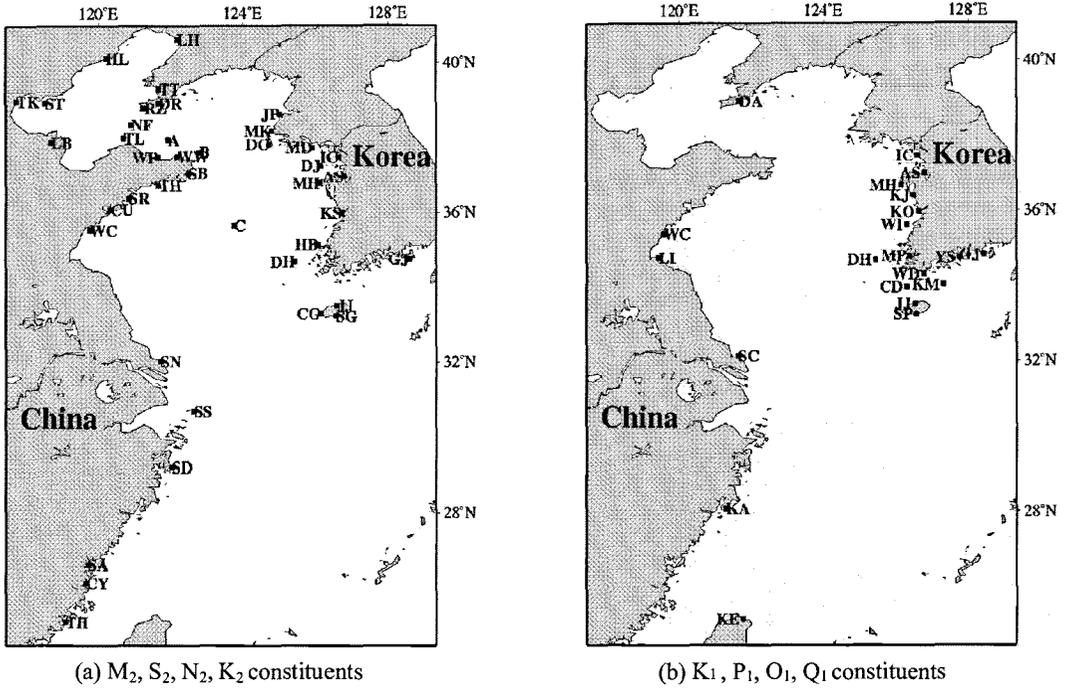


Figure 7: Positions of tidal stations in the East China and Yellow Seas

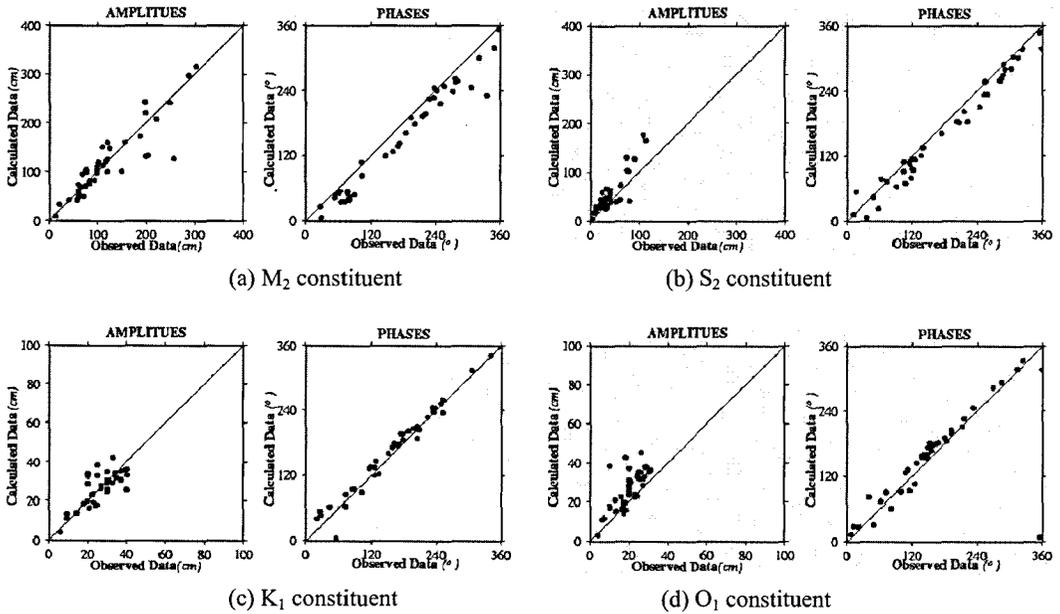


Figure 8: Comparison of amplitude and phase between calculated and coastal observation stations shown in Figure 7

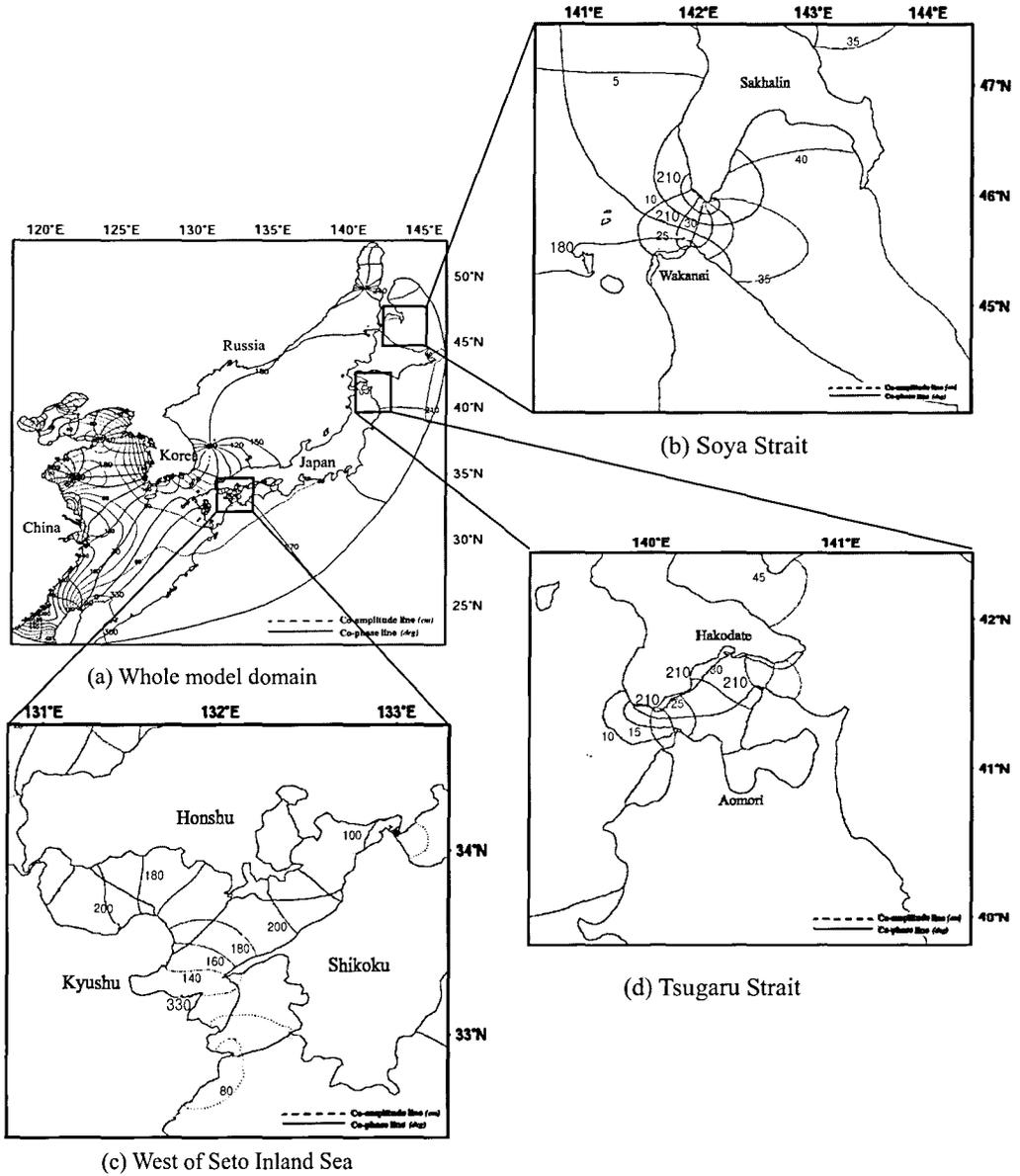


Figure 9: Reproduced M_2 tidal distributions over the whole modeled region showing detailed distributions at major narrow straits in Japan

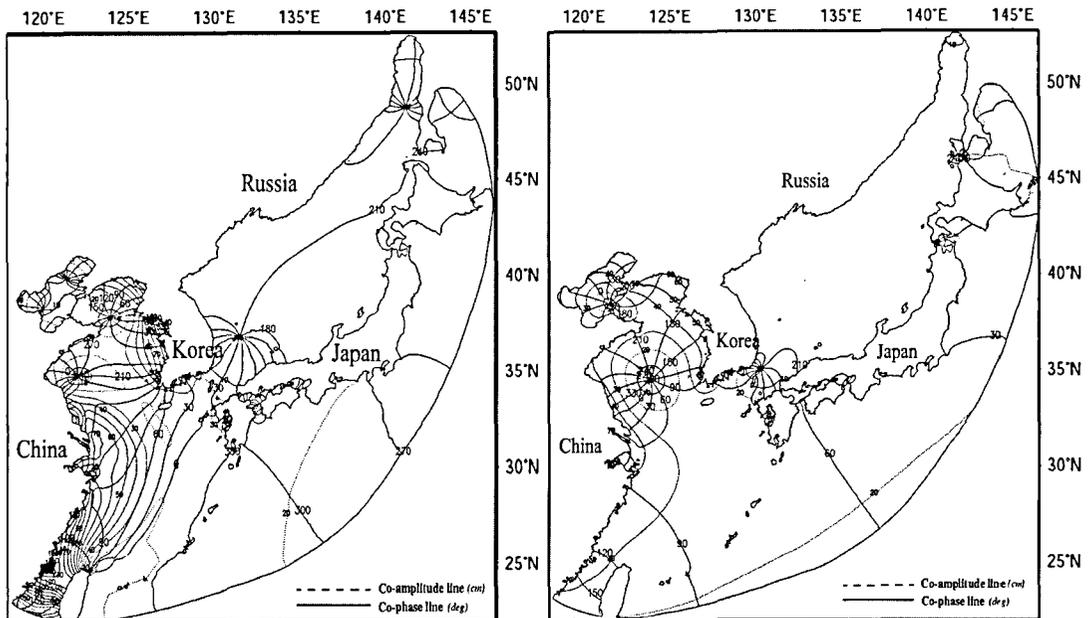


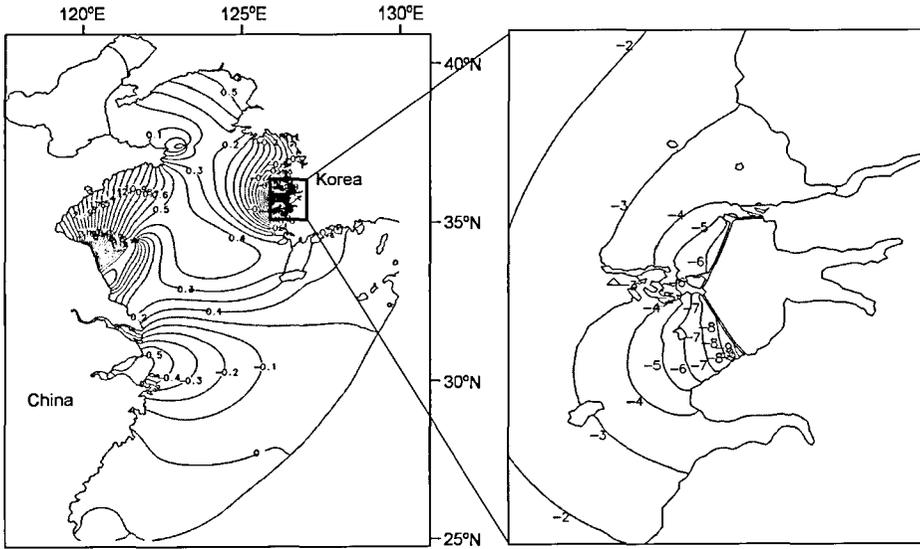
Figure 10: Reproduced tidal distributions (left plate - S_2 tide; right plate - K_1 tide)

3.2. Perturbation due to Saemangeum barrier construction in Korea

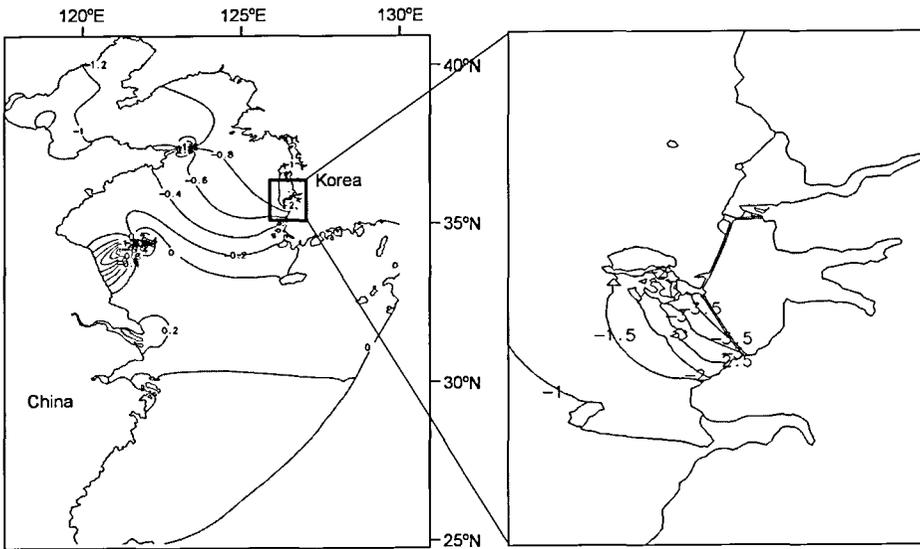
Primary results from the simulations of the effects of the completed Saemangeum dikes are provided in Figures 11 and 12 for the M_2 and S_2 tides respectively. As seen from these figures, perturbation in the tidal regime due to Saemangeum barriers for the M_2 tide occurs throughout the entire system, although the magnitude of vertical tides may be limited to barrier sites and may lack significance. Present estimates based on fine resolution models show that previous computations (Choi, 2001) were somewhat overestimated. However, velocity fields are often more sensitive than variations in elevations; thus careful examinations of changes in current intensity, tidal circulation, and bottom stress are necessary to understand tide-related processes.

The difference in simulated amplitude after the construction of Saemangeum dikes as provided in above figures show that perturbations occur throughout the entire system. Amplitudes increased from about 0.1 cm to 2.1 cm during the M_2 tide in the northern part of the eastern Chinese coast bordering the Changjiang River. Amplitude reductions of up to 0.5 cm were simulated for the M_2 tide in the southern part of the Chinese coastline. It is worth noting that the amplitude is reduced up to 8 cm during M_2 tide in the Saemangeum Sea area. In cases of phase disturbance, differences in M_2 tide of about 1 degree were found throughout the entire model region, except the river mouth area of the Yangtze River (including the northern part of the Saemangeum Sea area after dike construction). A phase difference of about 3.5 degrees characterized the M_2 tide after the construction of dikes at Saemangeum, as compared to the previous situation without dikes.

During the construction of Saemangeum dikes, the Number Four dike closure work was completed by June 10, 2003. Data collected subsequently demonstrated the pre-operational, real-tidal time simulation as an efficient and reliable approach. The final closure operation was performed with an operational forecast for the gradual closing to ensue during two fortnightly tides in March and April 2006 (http://wave.skku.ac.kr/SMG_FinalClosure_Forecast)



(a)



(b)

Figure 11: Difference of (a) amplitude and (b) phase of the M_2 tide due to the development of Saemangeum. Unit in cm and degree respectively indicating negative values as reduction in amplitude and phase.

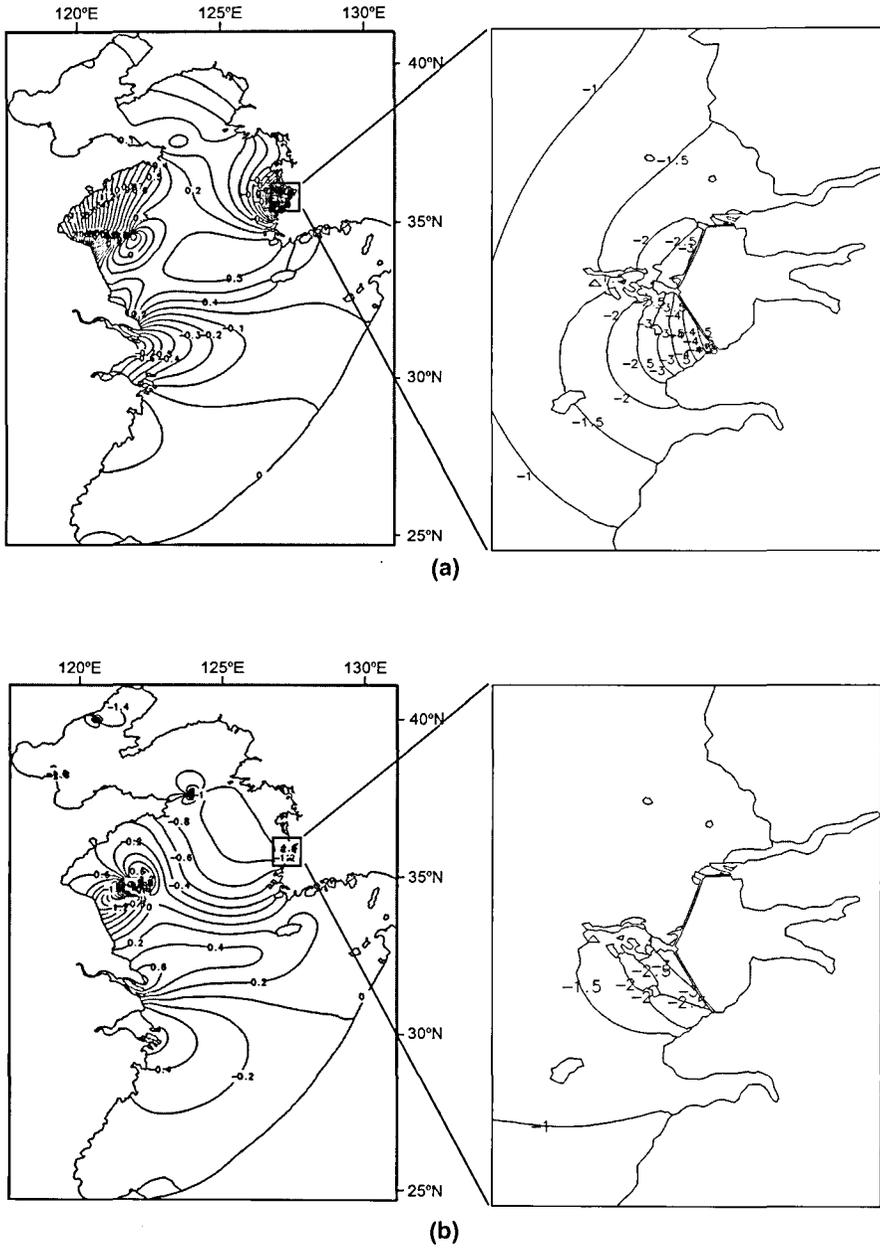


Figure 12: Difference of (a) amplitude and (b) phase of the S_2 tide due to the development of Saemangeum. Unit in cm and degree respectively indicating negative values as reduction in amplitude and phase.

3.3. Changes in the tide due to Isahaya barrier in the Ariake Sea, Japan

The primary results from the simulations for the effect of Isahaya dike on the tidal regime are provided in Figure 13. Figure 14 shows the domains of four previous models used for estimating tidal changes in Ariake Bay (A: (Kim and Yamashita, 2002); B: (Kyojuka, 2002); C: (Nadaoka, 2002); D: (Takikawa and Tabuchi, 2002)). In the four models, the model domains for estimating tidal perturbation in the Ariake Sea were confined to the Ariake Sea and the neighboring outer area, assuming tidal perturbation due to the Isahaya dike was negligible far out to the outer shelf sea. Figures 13 and 14 show that tidal changes of the M_2 due to the Isahaya dike are very small and not influenced by the Ariake Sea. Therefore, the model domains may be appropriate for estimating the tidal changes. Figures 15 and 16 show the difference in amplitude and phase of the S_2 and K_1 tides, indicating that tide disturbances due to the construction of barriers occur throughout the entire model domain and the Ariake Sea. As seen in these figures, tidal perturbation due to the impact of the Isahaya dike on the shelf system may be negligible in terms of magnitude and confined to the Ariake Sea, due to its contracted narrow opening. The decrease of amplitude is largest in Isahaya Bay in the case of the M_2 tide. Amplitude reduction progresses gradually in magnitude from Isahaya Bay to the mouth of the Ariake Sea.

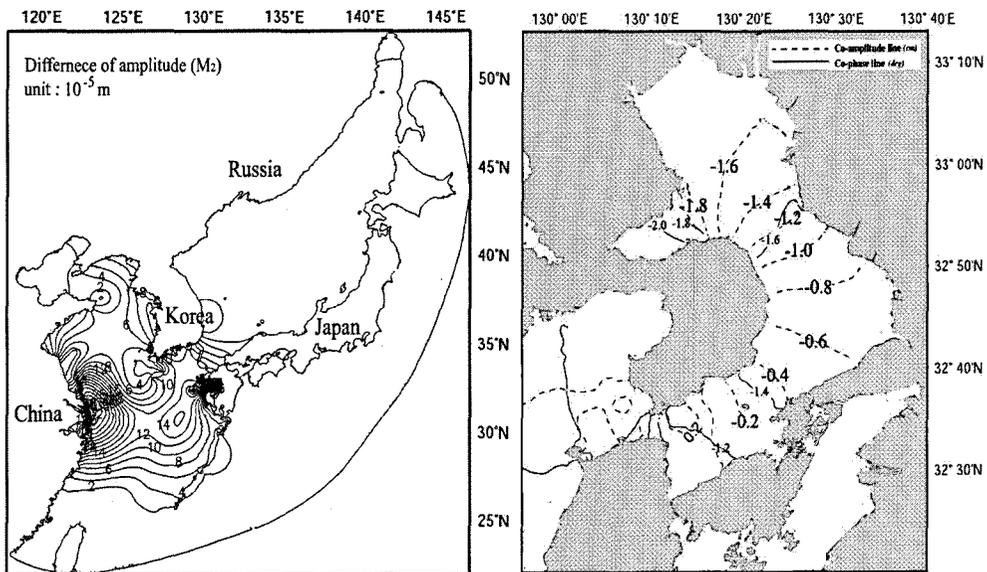


Figure 13: Difference of amplitude and phase of the M_2 tide due to the construction of Isahaya dike (left plate – amplitude in 10^{-5} m; right plate – amplitude in dotted line and phase in solid line, as unit in cm and degree respectively)

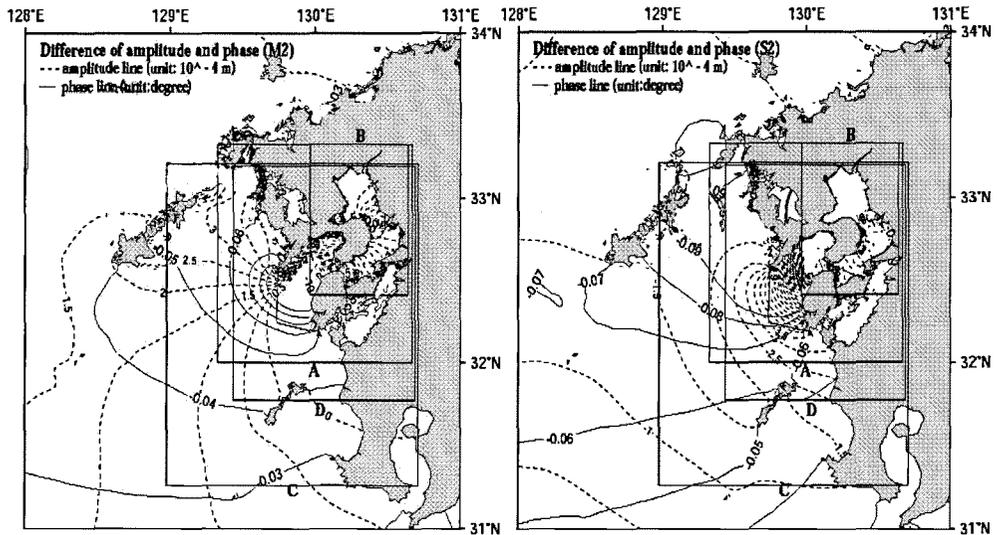


Figure 14: Difference of amplitude and phase due to the tidal barrier at Isahaya Bay at each boundary of four previous models (A: Kim and Yamashita, 2002; B: Kyozyuka, 2002; C: Nadaoka, 2002; D: Takikawa and Tabuchi, 2002)

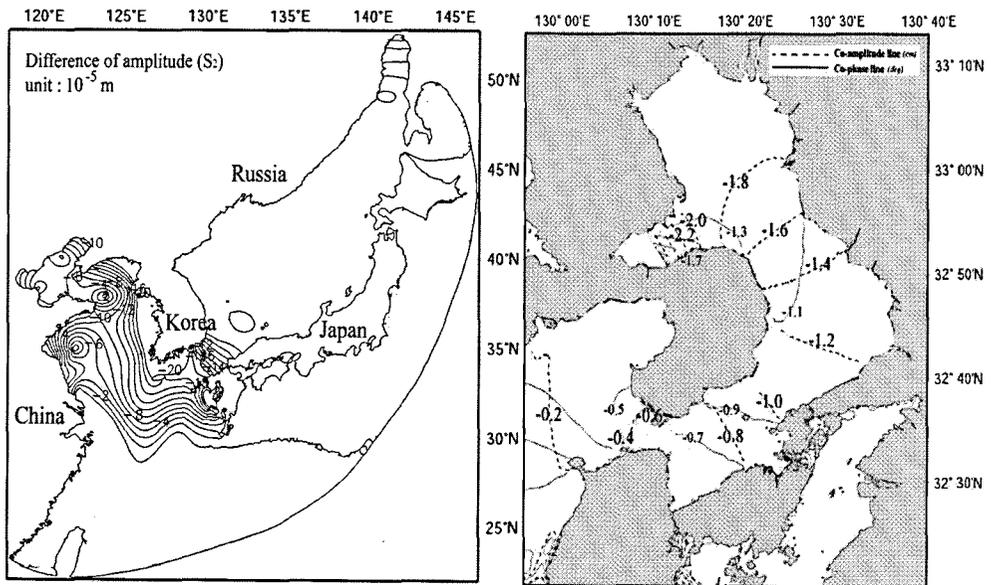


Figure 15: Difference of amplitude and phase of the S_2 tide due to the construction of Isahaya dike (Left plate – amplitude in 10^{-5} m; right plate – amplitude in dotted line and phase in solid line, as unit in cm and degree respectively)

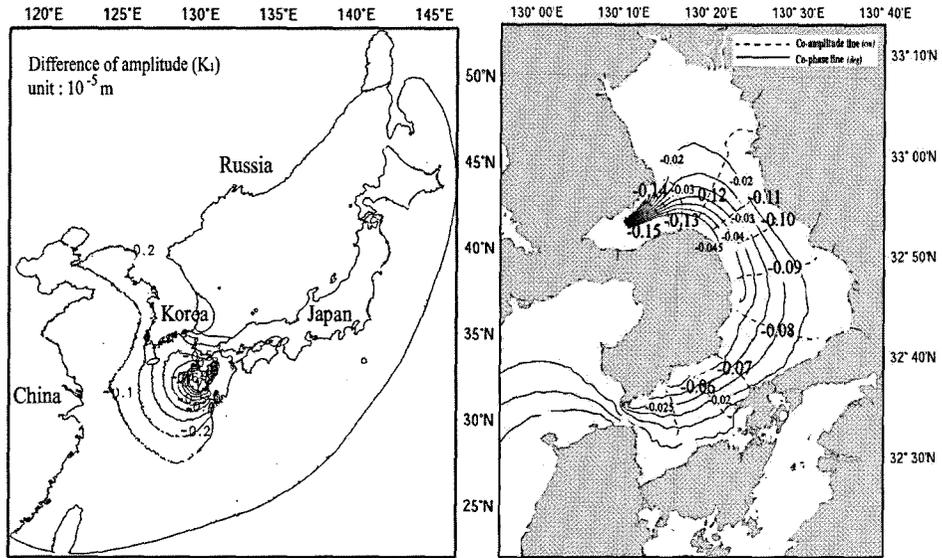


Figure 16: Difference of amplitude and phase of the K_1 tide due to the construction of Isahaya dike (Left plate – amplitude in 10^{-5} m; right plate – amplitude in dotted line and phase in solid line, as unit in cm and degree respectively)

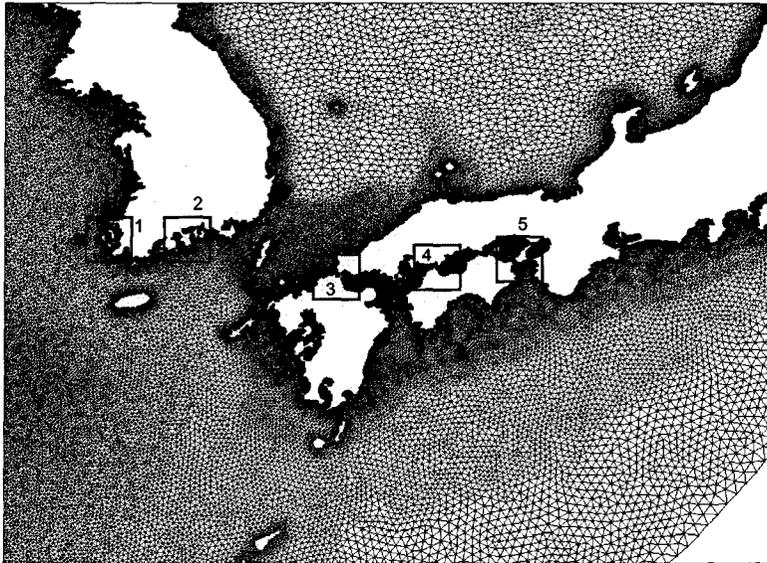


Figure 17: Areas of high potentials for tidal current power generation (1: Uldolmok, Jangjuk and Hoenggan Channels, 2: Noryang and Hodong Channels, 3: Kanmon Strait, 4: Kurushima Channel, 5: Naruto Channel)

4. Discussion and concluding remarks

The nearshore tidal regime within the entire shelf regime and offshore sea area bordering the Korea and Japan was satisfactorily reproduced. Then a barrier scheme for Saemangeum, the eastern Yellow Sea and Isahaya Bay, and the Ariake Sea is inserted to estimate range and intensity of tidal perturbation. It is believed that the present work also demonstrated the reliable tidal predictions over the large modeled sea area as well as detailed local tidal system. Simulation works on flow processes during the closure of dike operations based on this simulator can be provided as a preoperational sense; simulated information can be useful for in-situ decision-making as it relates to construction activities (http://wave.skku.ac.kr/SMG_FinalClosure_Forecast).

Another prospective application is to prepare tidal current maps from high resolution local meshes focusing on many narrow channels in Japan and Korea as seen in Figure. 17, so the tidal current energy estimates can be derived from them. At present significant developments are underway in Korea and Japan to develop machines and system that are able to convert the kinetic energy of strong tidal currents into electricity without resorting to building barrages. For this efficient parallel computing structures and three-dimensional simulations for modeling of local straits thus will be necessary for these tasks. Therefore several steps of improvement will be necessary in the forthcoming years as research collaboration efforts.

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