Annual Meeting of Korean Society of Coastal and Ocean Engineers
Korea Ocean Research and Development Institute, 11-12 October 1996

Shallow Water Tides in the Seas around Korea

Lakshmi H. Kantha*, Inkweon Bang**, Jei-Kook Choi* and Moon-Sik Suk**

1. Introduction

Satellite-borne altimeters are one of the most important global ocean measurement and monitoring techniques available to modern oceanographers. While the U.S. Navy's GEOdetic SATellite (GEOSAT) mission in the mid-eighties firmly established its value, the full potential of satellite altimetry was not realized until the launch of the NASA/CNES TOPEX/Poseidon precision altimeter in 1992. The dual-frequency TOPEX altimeter, with a bore-sighted microwave radiometer, has enabled the sea surface topography to be measured and monitored to an unprecedented degree of accuracy (3-5 cm rms. overall, Fu et al. 1995). Since the ephemerides of the satellite can now be determined to an accuracy of a few centimeters by precision tracking/modeling, and other means such as GPS (Global Positioning System), the errors in orbit determination are no longer the major source of inaccuracy in determining the long-term sea surface height (SSH) variability in the global oceans. Instead, the residual errors due to inaccurate determination of the tidal SSH has become one of the three major remaining sources of error in modern altimetry, the other two being departures from inverse barometric response to atmospheric pressure fluctuations and the electromagnetic (EM) bias.

Errors due to inaccurate subtraction of tides are particularly serious in shallow water. While modern tidal models (and precision altimetry itself) can now provide tides in most of the global oceans quite accurately for altimetric analyses [Desai and Wahr, 1995 for example], it is still difficult to compute tides accurately in many shallow coastal and marginal seas around the world [see Le Provost et al., 1994 and Kantha, 1995 for example]. The principal problem is the inaccurate databases [see Kantha, 1995] and small spatial scales that require high resolution tidal models, and the importance of shallow water tides in many shallow water regions around the world. Shallow water tides are generated in shallow water by nonlinear interaction of primary tides, principally the semidiurnal M_2 and S_2 components. There are 6 shallow water tides of possible interest to altimetry, M_4, MS_4, M_6, $2MS_6$, $2SM_2$ and S_4. Of these M_4 and MS_4 are probably the most important. While in principle, it is possible to extract any shallow water tide from altimetric measurements themselves using along-track tidal extraction techniques, in practice, the high degree of spatial variability of shallow water tides near the coast, improper sampling and small amplitudes make this technique useful perhaps only for M_4. A high resolution nonlinear numerical barotropic model is a better alternative. This article addresses the problem of computing shallow water tides numerically in shallow coastal shelves and seas around the world, with the seas around Korea as an example.

---

* Department of Aerospace Engineering Sciences, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, CO 80309-0431

** Physical Oceanography Division, Korea Ocean Research and Development Institute

2. Tidal Model

A vertically-integrated, fully nonlinear barotropic data-assimilative tidal model, the global version of which is described by Kantha [1995] is used in this study to compute shallow water tides numerically. The model incorporates direct astronomical forcing and the regional version derives the conditions needed on open boundaries from global tidal models such as Desai and wahr [1995] and Kantha [1995]. The reader is referred to Kantha [1995] for a detailed description and Kantha et al. [1995] for some altimetric and geophysical applications (see also http://www.cast.msstate.edu/Tides2D). The model can simulate any combination of primary, long-term and shallow water tides and for this study, we have run the model for M_2 and S_2.

The tides are quite complex in the Korea Strait connecting the East Sea and the East China Sea. It is therefore preferable to model the entire Korea Seas region to avoid having to prescribe the needed boundary conditions in the region of the Strait. This is the strategy we have employed. While direct astronomical forcing is relatively unimportant in the Yellow Sea, it is retained in the model for accuracy and because of inclusion of the East Sea in the model domain, where directly forced tides are not much smaller than the co-oscillating tides. The model domain extends from Taiwan Strait near the South China Sea to Tatar Strait near the Sea of Okhotsk. The resolution is ~20 km. Bathymetry has been derived from a combination of 5′ DBDB5 global bathymetric data base and charts from local sources.

The model was driven by tides derived from Desai and Wahr [1995] global model prescribed on the open boundaries. Taiwan Strait was assumed closed. While Kantha [1995] relied primarily on assimilation of altimetric and coastal tide gage data for accurate simulation of tides, we describe here runs both with and without data assimilation. The modeling strategy is to first simulate M_2 and S_2 individually to obtain the best possible results without assimilation and then in combination to derive shallow water tides. The former were run for 20 days and the last 10 days were used for estimating the coamplitude/cophase of the tidal sea level fluctuations. Residual currents were also derived, averaged over 10 tidal cycles. The shallow water tide simulations were done for a total of 40 days and the last 29 days of hourly data saved at all model grid points were used to derive the coamplitude/cophase of both primary and compound constituents by harmonic analysis. Model was ramped up over 5 days.

3. Model Results

The overall agreement is quite good, considering the ~20 km resolution of the model. For a quantitative comparison, the distance between the observed and modeled points in the complex plane as defined by Foreman et al. (1993) is used:

$$D=[(A_o\cos\phi_o-A_m\cos\phi_m)^2+(A_o\sin\phi_o-A_m\sin\phi_m)^2]^{1/2}$$

where A_o and A_m are observed and modeled amplitudes, ϕ_o and ϕ_m are the corresponding phases. Large differences are found at Stations 6, 13 and 14, located in and near the closed Taiwan Strait. Also the computed amplitudes for both M_2 and S_2 are smaller than observed because of the closed boundary. At some stations in the Gulf of Pohai and the Gulf of Liautung (stations 3, 4, and 7), the ratio is high and this is because their amplitudes are small and phase changes are large over short distance due to the proximity of the nearby amphidromic point. At stations 16 and 17 (Shanghai) both the distances and the ratios are large; however the quality of the observational data is uncertain. At almost all other points the distances are less than ~50 cm for M_2 and ~10 cm for S_2 and the ratio to the observed amplitudes are less than 0.5 for both M_2 and S_2.

We will now compare the horizontal patterns of M_2 coamplitudes and cophases to the numerical modeling results presented by Choi (1990) and Kang et al. (1991) and the observations of Fang (1994). Choi's results are only for the Yellow Sea and East China Sea, but the resolution is very high (1/15 degree), while Kang et al. included the East Sea and the resolution is 1/6 degree. The coamplitudes and cophase patterns are similar to these two previous modeling efforts, and the amphidromic points well-defined in the Yellow Sea.

However in the East Sea, only the amphidrome near Korea is reproduced whereas there exists another amphidrome near Tatar Strait. Our model domain includes only the southern part of the Tatar Strait, and the Soya and Tsugaru Straits are closed. The amphidrome north of Korea Strait in the East Sea is located a bit farther north than in Fang (1994), but is in agreement with the amphidrome of Kang et al. (1991). Cophase distribution of S_2 is similar to M_2 and the position of the amphidromes are almost the same as those of M_2. The magnitudes are only about one third of M_2 but the distribution is similar to M_2.

Dominant feature of M_2 residual current is the outflow from the Yellow Sea through the deep portion between Chinese coast and Cheju Island. This outflow is mainly supplied from the southward flow in the central Yellow Sea and it is connected to the southwestward flow in the East China Sea although the strength becomes very weak in this region. South of 34° N along the Chinese coast there is strong offshore flow and it changes direction to southeastward to join the outflow. In the S_2 residual current this offshore flow from the Chinese coast is the main source of outflow from the Yellow Sea. S_2 residual current pattern is similar to M_2 but the magnitude is much smaller than that of M_2 (about 1/5 of M_2).

We present next the coamplitudes and cophases of six shallow-water constituents arising from the interaction of M_2 and S_2. M_4 is the largest of them and we can compare our result with Choi's (1990) numerical computations. In his model, the M_4 amplitude is high, more than 5 cm, in the region where M_2 amplitude is high, i.e., along the west coast of Korea and the Chinese coast south of 34° N. Our results also show high values in the same region. One interesting feature that was not noted in Choi (1990) is the high value region south of Cheju Island. In this region, the water depth is relatively shallow compared to the northern and southern regions and the center of this isolated high amplitude region coincides with the region where a relatively large change in water depth occurs. This also agrees with the fact that topography is one of the factors for the generation of shallow water tides (Pugh, 1987). In most of Yellow and East China Seas, the amplitudes are higher than 2 cm and values higher than 10 cm are found along the west coast of Korea. M_4 is not generated from the tidal wave propagation from the Pacific as in the case of M_2, but from the nonlinear interaction of M_2 with itself. This is made clear by the lack of cophase lines that are parallel to the open boundary which are present in M_2 distributions. High amplitude regions of M_2 must also be those of M_4. From the phase distributions, we can say that in the Kyunggi Bay the M_4 tide generated near the coast propagates in the offshore direction and that generated near Kunsan propagates southward along the coast. Number of amphidromes are more than double those of M_2 because M_4 has half the period of M_2 and consequently shorter wavelengths. Some amphidromes have cophase lines rotating clockwise while all M_2 amphidromes have counterclockwise rotation.

Comparison of the computed values with the observed values shows good agreement of the amplitudes but not the phases. Even the assimilation of the limited coastal gage data into the model does not improve the agreement. It is likely that a higher model resolution and assimilation of data on shallow water tides at least at some points away from the coast might be necessary for improved results. It is possible to derive at least some shallow water tides from observations by accurate altimeters such as TOPEX. Disagreement of the computed phases with the observed phases was also noted in the northwest European continental shelf (Davis 1996) and he attributed it to the rapid change of phase from one grid point to the next due to its shorter wavelength than M_2.

MS_4 has the angular speed of sum of M_2 and S_2 and is a quarter-diurnal constituent. MS_4 is the most important of compound tides arising from M_2 and S_2 (Dronkers, 1964). MS_4 coamplitude pattern is similar to the pattern of M_4 but the magnitude is about half of M_4. Since M_2 is larger than S_2 it appears that M_2 affects the MS_4 distribution more than S_2. The next important compound tide is the six-diurnal constituent $2MS_6$. Its amplitude is smaller than 2 cm except along the west coast of Korea. M_6 is an overtide of M_2 and its amplitude is a bit larger than $2MS_6$ but smaller than the most important compound tide MS_4. Component $2SM_2$ has amplitudes less than 1 cm everywhere except in some coastal regions of Korea. The smallest of the six constituents is S_4 and its amplitude is about half that of $2SM_2$.

4. Conclusions

For the first time, shallow-water tidal constituents arising from the nonlinear interaction of M_2 and S_2 have been computed and presented in the Yellow Sea, the East China Sea and the East Sea. Our model adopted a rotated grid to include all the seas around Korea. Although the model is barotropic and the resolution is not as high as in other works (Choi 1990 and KORDI 1995), the agreement of the modeled M_2 and S_2 with observed data is fairly good.

The most important shallow-water constituent M_4 also shows a good agreement of modeled amplitudes with observed ones. M_4 amplitudes are larger than 2 cm in most of the Yellow Sea and East China Sea so that it cannot be excluded from the detiding process in the analysis of altimetry data in these regions. The modeled M_4 phase shows large differences with observed ones. The causes are two-fold: 1. The relatively poor grid resolution; a higher resolution is desirable for the quarter-diurnal and higher constituents because of their shorter wavelengths. Resolution is particularly critical near the coast because a large phase distortion can occur due to local geographic features, which are not resolved by a coarse resolution model. 2. Lack of shallow water tide data off the coast for assimilation. Altimetry itself holds the promise of deriving at least the major shallow water tides and at least at the crossover points, accurately, in regions like the Yellow Sea.

The other constituents (MS_4, $2MS_6$, M_6) also have amplitudes larger than 1 cm in wide areas of the Yellow Sea so that their exclusion can cause significant errors if sea-level change of a couple of centimeters is dynamically important. In fact, the dynamically important subtidal signals in the Yellow Sea are not expected to exceed several centimeters since the sea level anomalies do not exceed 10 cm in the East Sea (Bang et al. 1996). This makes it particularly important to derive accurate shallow water tides in the Yellow Sea.