Wave – tide – surge coupled model simulation for Typhoon Maemi

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Abstract
Reasonably accurate predictions of wave heights, current and elevations during storm events are vital information for marine operations and design of offshore and coastal structures in the surrounding seas of Korea Peninsula. Ocean circulation and wind-wave models have traditionally been run separately but recent researches have identified potentially important interactions between current and wave motions. The coupled tide-surge and the WAM wave models at the atmospheric boundary layer and bottom boundary layer around the Korea Peninsula are applied for the Typhoon Maemi 0314 event. Communication between the models is achieved using MPI. Results are compared with coastal tide gauges and moored wave buoys and comparisons are also made between wave computations from the coupled model and the independent third generation wave models. Results suggest that applying the tide-surge-coupled model can be an effective means of obtaining wave and storm surge predictions simultaneously.

Key words: wave-tide-surge coupled simulation, Typhoon Maemi, wave models

1 Introduction

The main reason for coupling the tide and surge hydrodynamic model with a surface wave model can be found in the physical interactions taking place in the surface and bottom boundary layers. During the severe storm conditions such interactions among tide, wave and storm surge processes are pronounced in the shallow sea area around the Korea Peninsula. Previous studies of Zhang and Li 1996, Li and Zhang 1997, Moon 2000, Ozer et al. 2000, Moon et al. 2003, Moon 2005 for the synchronous coupling of the wave model and the storm surge model had not explored the wave-induced enhancement of bottom stress generated by the tidal and surge induced currents. Choi et al. 2003a, b and Kim 2003 showed that it is important to incorporate surface wave effects into the coastal storm surge model and incorporating the wave-induced bottom stress into the coupled wave-current model further improves the storm surge prediction. Welsh et al. 1999 also studied the coupling of advanced wave circulation and sediment transport models using a physically realistic combined bottom boundary layer model with parallel-processing strategies.

In this study the dynamically coupled wave-tide-surge model of Choi et al. 2003a, b based on the theory of wave-dependent surface roughness for the upper surface condition Janssen 1991 and simplified bottom boundary layer model of Grant and Madsen 1986 for the bottom boundary condition.
are used for the surrounding seas of Korea Peninsula with some improvements including recompiled depth fields\footnote{Choi et al. 2002} and modified open tidal boundary conditions taking NAO tide \footnote{Matsumoto et al. 2000}. The coupled model was used to simulate a typhoon surge and wave\footnote{Choi et al. 2002} which devastated Korean coasts extensively in 2003. Some of the results are presented and discussed.

## 2 Typhoon Maemi

Typhoon Maemi\footnote{Typhoon Maemi (0314)} was the most powerful typhoon to hit the Korea Peninsula in a century which was named after the Korean word for cicada. It landed on the coast of southern Kyongsang Province on 12 August with the sea level atmospheric pressure dropping to 950 hPa\footnote{Korea Meteorological Administration} breaking the previous record of 952 hPa set by Typhoon Sarah\footnote{Sarah} in 1959. Typhoon Maemi also created a new record in terms of wind speed\footnote{WAMDI Group 1988} by blowing winds of up to 60 m/s\footnote{Korea Meteorological Administration} while passing through Jeju Island on 12 August. It is the highest figure since the country started to record weather data in 1904\footnote{Korea Meteorological Administration} surpassing Typhoon Prapiroon\’s maximum speed of 58. 3 m/s in 2000. And the South Sea of the Peninsula recorded the heaviest amount of precipitation with 452. 5 mm. According to the report by the National Disaster Prevention and Countermeasures Headquarters the number of causalities was estimated at 130\footnote{National Disaster Prevention and Countermeasures Headquarters} with 117 announced dead and 13 missing. The amount of property damage caused by the typhoon is reported at 4. 8 trillion won\footnote{National Disaster Prevention and Countermeasures Headquarters} USD 4. 1 billion\footnote{National Disaster Prevention and Countermeasures Headquarters}. Nearly 9 000 lost their homes\footnote{National Disaster Prevention and Countermeasures Headquarters} while hundreds of households continued to suffer from blackouts as officials scrambled to restore the nation’s power lines severed in the strong winds. It was reported that the typhoon also damaged 873 roads\footnote{National Disaster Prevention and Countermeasures Headquarters} 30 bridges\footnote{National Disaster Prevention and Countermeasures Headquarters} wrecked 489 vessels and 15 158 hectares of allotments.

For the ocean simulation\footnote{Regional Data Assimilation and Prediction System} we received the RDAPS\footnote{Regional Data Assimilation and Prediction System} dataset with 30 km intervals over the northeast Asian seas from KMA\footnote{Korea Meteorological Administration}. This dataset was interpolated to the dense\footnote{Regional Data Assimilation and Prediction System} 1/12° grid resolution at 1 h interval from 3 h dataset for the coupled model. Figure 1 shows the study area with bathymetry including wave and tidal observation points and the track of Typhoon Maemi selected for the simulation.

## 3 Simulation model

### 3.1 Wave models

The third generation wave model\footnote{WAM-cycie 4} WAM-cycie 4 model\footnote{WAMDI Group 1988} is one of the most sophisticated and validated models in the world\footnote{WAMDI Group 1988} and integrates the basic transport equation describing the evolution of a two-dimensional ocean wave spectrum without additional assumptions with respect to the spectral shape. The three source functions describing the wind input\footnote{WAMDI Group 1988}, nonlinear transfer\footnote{WAMDI Group 1988}, and white-capping dissipation are prescribed explicitly. In addition to the source functions\footnote{WAMDI Group 1988}, bottom dissipation and refraction terms are incorporated into the model of the finite-depth version. The action density is chosen because it is conserved in the presence of time-dependent water depths and currents whereas the energy density spectrum is not.

#### 3.1.1 WAM

The WAM solves the energy balance form for no currents and fixed water depths for both deep and shallow waters in a spherical grid. WAMDI Group \footnote{WAMDI Group 1988} describes the Cycle-3 version of WAM in which the wind input source function and dissipation function\footnote{WAMDI Group 1988} $S_{in}$ and $S_{ds}$ are based on the formulations of Komen et al. \footnote{Komen et al. 1984}. In the current Cycle-4 version of WAM\footnote{WAMDI Group 1988} wind input source function\footnote{WAMDI Group 1988} $S_{in}$ and $S_{ds}$ are based on the formulations of Janssen \footnote{Janssen 1989, 1991} in which the winds and waves are coupled\footnote{Janssen 1989, 1991} that is\footnote{Janssen 1989, 1991} there is a feedback of growing waves on the
Fig. 1. Study area with bathymetry and track of the Typhoon Maemi [0314]. Codes shown in the upper plate are wave observation points and those in the lower plates tidal observation locations.
wind profile. The effect of the feedback is to enhance the wave growth of younger wind seas over that of older wind seas for the same wind. In most simulations for extreme weather conditions using the WAM-cycle 4 model the present state that the energy propagation is concentrating on the specific directionality is shown. This is a kind of numerical error and named garden sprinkler effect. For reducing this effect a shifting scheme has been used in which the computation direction is chargeable for the two-dimensional wave spectrum about 15°. In the present study an alternative scheme proposed by Lavrenov 2003 was used to avoid this numerical error still keeping the directional resolution of 30° for computational efficiency.

3.1.2 SWAN

The SWAN model solves the spectral action balance equation on a spherical grid as an option. Because of the assumptions of time-independent water depths and no currents the solution is equivalent to the solution of the energy balance equation as in WAM. However it uses an implicit scheme to propagate the wave action density which has the great advantage that the propagation time step is not limited by any numerical condition since the scheme is unconditionally stable in the geographic and spectral spaces. In the geographic space the scheme is first-order upwind and it is applied to each of the four directional quadrants of wave propagation in sequence. In the spectral space the scheme is variable between an upwind scheme and a central scheme. The numerical scheme used for the source term integration is chosen by the user and can be fully implicit semi-implicit or explicit scheme. SWAN has the option of using WAM Cycle-4 physics for wind input source function and $S_{w}$ source terms. The version of the SWAN model used in this study is the SWAN Cycle-4 version 40. 31 that contains the parallel MPI source.

3.1.3 Wavewatch – III

As in SWAN the wave model Wavewatch-III also solves the spectral action density balance equation but with a variable wavenumber coordinate $k = 2\pi/L$, $L$ being wavelength replacing the wave coordinate $\sigma$. The propagation velocity $c_k$ in the wavenumber space replaces the propagation velocity $c_\sigma$ in the frequency space with the former closely resembling the latter. With the assumption of no currents and fixed depths $c_k = 0$ as in the case of the propagation velocity. The solution therefore simplifies the solution of the energy balance equation as in the case of WAM and SWAN. The wind input source function and $S_{w}$ source terms are based on the formulations of Tolman and Chalikov 1996 and include also the option of using WAM Cycle – 3 physics for these source terms. In Wavewatch – III all the boundary points are set to land points. The version of Wavewatch – III model used in this study is the Wavewatch – III version 2. 23.

3.2 Tide and surge model

The vertically – integrated equations in spherical – coordinates for tides and storm surges incorporate a quadratic law of bottom friction with the nonlinear advective terms. The detailed equations and parameters are described by Choi et al. 2003a,b.

With the numerical models covering the northwest Pacific region the water movements associated with real time tides and actual storms can be reproduced. Reasonably well representative model simulations with the observed data in coastal areas can lead us to estimate the extreme condition of waves and currents for the design of coastal defense and offshore structures. The model employed here was developed originally at the Institute of Oceanographic Sciences IOS Choi 1980 to explore general tidal dynamics of the Huanghai Sea. This model was im-
proved and extended to cover the broad region from the previous model. Choi 1980 and to include additional major tidal components. Open boundary conditions were specified with 27 constituents Matsumoto et al. 2000 in addition to eight major constituents previously used Choi 2002 to produce more realistic real time tide predictions over the modeled area. The model is two-dimensional implementing nonlinear depth-averaged hydrodynamical equations in spherical polar coordinate. The model has the east and north components of current on the grid system of \( 1/12\,^\circ \) latitudes by \( 1/12\,^\circ \) longitudes utilizing detailed bathymetry recompiled Choi et al. 2002. The model has the 481 \times 361 grid elements with the selected time step of 40 s. Open boundary conditions of the model for tidal specifications were taken from 27 constituents Matsumoto et al. 2000 of which distributions of eight \( M_2 \), \( S_2 \), \( K_1 \), \( O_1 \), \( N_2 \), \( K_2 \), \( P_1 \) and \( Q_1 \) tidal charts are provided in Fig. 2.

3.3 Surface wind stress and simplified bottom boundary layer model

Janssen 1991 concluded that the growth rate of the waves generated by wind depends on a number of additional factors such as atmospheric density stratification wind gustiness and wave age and gave a more realistic parameterization of the interaction between wind and wave. Heap 1983 had already identified the need for a wave model to improve the specification of wind stress in surge models. Mastenbroek et al. 1993 clearly showed the influence of a wave-dependent surface drag coefficient on surge elevations. Even if these surge elevations can be reproduced with an appropriate tuning of this parameter in conventional wind stress formulations e.g. the dimensionless constant \( \alpha \) in the Charnock relation Charnock 1955 he argue that a wave-dependent drag is to be preferred for storm surge modeling. Davies and Lawrence 1994 notice a significant change of the tidal amplitude and phase in shallow near-coastal regions due to enhanced frictional effects associated with wind-driven flow and wind wave turbulence.

The total surface stress \( \tau \) consists of a turbulent stress \( \tau_t \) and a wave dependent stress \( \tau_w \) as follows

\[
\tau = \tau_t + \tau_w.
\]

The turbulent stress is explained as follows

\[
\tau_t = \rho_a \kappa z_e^2 \left( \frac{\partial U}{\partial z} \right)^2
\]

where \( \rho_a \) is the air density, \( \kappa \) is the von Karman constant, \( z_e \) is equal to 0.4 and \( z \) is the wind speed at height \( z \).

The wave-dependent stress is very large at the initial stage of wave growth when the young wind-sea prevails in the wave field. This occurs immediately after an increase of the wind speed or change of the wind direction. Janssen 1991 derived the wave-induced stress using the following wind profile in the presence of waves

\[
\frac{u_* \ln \left( \frac{z + z_e - z_0}{z_e} \right)}{K} = \frac{u_* \ln \left( \frac{z + z_e - z_0}{z_e} \right)}{K}
\]

where \( u_* \) is the friction velocity, \( z_0 \) and \( z_e \) are the roughness length in the absence of waves and the effective roughness length a function of the wave-induced stress, respectively. For the turbulent term of the stress the mixing length hypothesis is assumed. If the wind profile described in Eq. 3 is differentiated squared and compared with the expression of the turbulent stress described in Eq. 2 at \( z = z_0 \) the relationship between \( z_0 \) and \( z_e \) is explained as

\[
z_e = \frac{z_0}{\sqrt{1 - \tau / \rho_a z_0 \gamma}}
\]

where Eq. 1 and the friction velocity \( u_* = \sqrt{\tau / \rho_a} \) are used.

Since the drag coefficient \( C_d \) depends on the roughness length \( \tau \) is written as

\[
\tau = C_d U^2 L
\]
Fig. 2. NAO-tidal charts of the $M_2$, $S_2$, $K_1$, $O_1$, $N_2$, $K_2$, $P_1$, and $Q_1$ tides. Matsumoto et al. 2000.
\[ C_d = \left( \frac{k}{\log L/z_0} \right)^2 \]

where \( L \) is the mean height above the wave. The wave-induced stress is given by

\[ \tau_w = \rho_w \int_0^\infty \sigma S f \theta |d\theta| \]

where \( \sigma \) is the angular frequency, \( f \) is the frequency, \( \theta \) is the direction, and \( \rho_w \) is the density of water.

The wave-dependent stress is computed from the wind input source function which is based on an analytical approximation of the results obtained from the quasi-linear theory of wave generation. Given the wind speed \( U(L) \) at \( L \) and \( \tau_w \) and the surface roughness is determined from an iterative solution of Eqs (4) through (7). The ratio \( \tau / \tau_w \) depends on the wave age and indicates the strength of the coupling between winds and waves. For the extreme young wind-sea the surface roughness can be enhanced by as much as a factor of ten.

Given \( L \) and \( \tau_w \), and the surface roughness are determined from an iterative solution using the set of equations with the algorithm provided within the WAM model. There are general discrepancies between the present approach and the conventional method.

The wave and bottom roughness conditions are considered in this study it is determined that the effect of the steady current on the oscillatory stress component could be neglected because it only influences the wave-dependent stress itself and not the steady stress component \( \tau_w \). The steady stress component on the other hand is a strong function representing both waves and currents. Therefore the effective drag coefficient can be determined from an iterative process followed by the method of Grant and Madsen 1986.

4 Simulation procedure

For the tide and surge simulation the vertically-integrated equations for the tides and storm surges in spherical coordinates were used while the WAM model was used for wave computations. The synchronous coupling scheme of the two models to explore the mutual interactions of wave-tide-surge processes is shown in Fig. 3 where exchange variables are \( U \) depth - mean current \( U_b \) is wave-induced bottom velocity \( H_s \) significant wave height and \( T \) wave mean period. As described in Section 3.3 the BBL model requires inputs from both tide-surge and wave models. Resolution of the two models is identical as in 1/12 in longitude and latitude covering the inner NW Pacific \( 20^\circ \sim 50^\circ \) N \( 115^\circ \sim 155^\circ \) E including the East China Sea continental shelf and the East Sea. Run time step is 120 s for the WAM model 10 s for the tide-surge model and 3600 s for the coupling simulations model. At this stage the direct transfer of surface momentum by means of radiation stress tensor has not been introduced and the stratification due to suspended sediment for both wave and current dominated conditions in BBL was not introduced either in the present paper yet.

![Fig. 3. Schematic diagram of synchronous coupling between wave model and tide-surge model.](image-url)
5 Simulation results

The main reason for coupling the tide and surge hydrodynamic model with a surface wave model can be found in the physical interactions taking place in the surface. The physical interaction is the effects of waves on currenting consists of wind input to the current field due to waves roughening the water surface plus the direct transfer of surface momentum and wave-induced enhancement of bottom stress generated by the tidal and surge-induced current. To investigate coupling effects of tides, storm surges, and wind waves, simulations have been performed with an additional independent numerical wave experiment along with synchronous coupling model runs. The independent wave model runs were performed with only meteorological wind fields. Figure 4 shows the distribution of differences in the maximum positive surge elevation by the synchronous coupled model which are higher than the non-coupled tide-surge model for about 10 ~ 15, 5 ~ 15 and 30 cm or more around the southern coasts of Shandong and the Hangzhou Bay in China and the western coasts in Korea respectively. Also distribution of difference in the maximum negative surge elevations by the synchronous coupled model are lower than non-coupled tide-surge model for about 5 ~ 20, -5 ~ -15 and -15 cm or more for the southwestern coasts in Korea the Hangzhou Bay and the Fujian coasts in China see Fig. 5.

Figure 6 shows the comparison between the computed elevation and coastal tide gauge at Masan MS in the southern coast of Korea. The synchronous coupled model predicts the peak surge arrival better than the non-coupled model. Still synchronous

![Fig. 4. Distribution of difference in the maximum positive surge height between synchronously coupled model run and tide - surge model run for Typhoon Maemi 0314.](image-url)
coupled model predicts the peak surge height almost 1 m less than observation. This difference may be due to coarse grid errors thus not yet reflect wave-current interaction and enhanced surface shear stress from wave. More detailed meteorological input considering local winds interacting with coastal topography with finer resolution model will be required.

Figures 7 and 8 show the maximum significant wave heights from the WAM and synchronously coupled model respectively both showing 8 ~ 10 m along the track of typhoon around the southeastern coasts of Korea, 4 m or more at the Changjiang Estuary in China and 8 ~ 10 m along the southwestern coasts of Kyushu in Japan. The mean periods are 10 ~ 14 s and 12 s around the southern coasts of Korea, the Hangzhou Bay in China and the southwestern coasts of Kyushu in Japan respectively.

Differences in the maximum significant wave
Fig. 7. Maximum significant wave height during Typhoon Maemi (0314) from WAM.

Fig. 8. Maximum significant wave height during Typhoon Maemi (0314) from the synchronously coupled model.
height and wave mean period between synchronous coupled model and the wave independent model are provided in Figs 9 and 10. These differences are localized at the southern coast and South Sea of Korea Peninsula along the typhoon track where waves are modified by the bathymetry and coastline of the Korea Strait.

The third generation ocean wave models, the Wavewatch-III and the near shore wave model SWAN are also used independently to simulate waves for Typhoon Maemi in addition to the synchronously coupled model and WAM. Significant wave heights off the port Pusan, PS during Typhoon Maemi, 0314 are shown in Fig. 11. Comparison between observation and wave models show the general agreement with observation despite the limitation of meteorological input in coarse grid resolution with insufficient interaction with coastal topography.

Generally results of the coupled and non-coupled model present noticeable differences in the Huanghai Sea and East China Sea continental shelves for storm surge computation thus justifying accommodation of the BBL model and incorporating the wave model into the storm surge computational system.

6 Concluding remarks

In this paper we have described continuing efforts for simulating the tide – surge and wind waves in the Huanghai Sea continental shelf via synchronously interacting models by accommodating the wave-induced stress to the total surface stress and a boundary layer model of bottom physics which takes inputs from both tide-surge and wind wave models respectively.

Fig. 9. Distribution of changes of significant wave height m between synchronously coupled model run and wave-independent model WAM run during Typhoon Maemi 0314.
Fig. 10. Distribution of changes of wave mean period (sec.) between synchronously coupled model run and independent wave model [WAM] run during Typhoon Maemi (0314).

Fig. 11. Significant wave height off the port of Pusan (PS) during Typhoon Maemi (0314).
The application of the model for the seas surrounding the Korea Peninsula and the hindcast results for Typhoon Maemi showed that the coupled process model reproduces reasonable wave hindcast as compared with independent third generation wave models along with storm surge information.

Detailed shallow water physics can be further pursued with the field verification experiment accommodating three-dimensional storm surge model enhanced bottom boundary layer physics and further mesh refinements with nested grids.

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