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EFFECTS OF WINDS, TIDES, AND STORM SURGES ON OCEAN SURFACE WAVES IN THE JAPAN/EAST SEA

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1. INTRODUCTION

Wind driven oceanic surface waves have a major impact on marine activity, especially near the coastal regions. Strong winds associated with winter storms induce storm surges along the west coast of Japan. Combined high wind conditions, tides, and storm surges can have a tremendous impact on the surface wave fields. Accurate wave forecast becomes an important issue at various operational forecast centers around the world. The physical processes governing the wind-wave and current-wave interactions, however, remain largely unknown in the Japan/East Sea (JES). Recent advancements in the numerical prediction of the atmospheric forcing using high-resolution atmospheric models and ocean surface wave modeling have made it possible to examine some of the scientific issues related to wind, wave, and current interactions. In this study, we use a wave model to investigate the impacts of variability of wind forcing, tides, and storm surges on the surface wave fields in JES where winter storm conditions are a perfect test bed for our modeling experiments.

2. MODEL DESCRIPTIONS

2.1 *Wave model*

The ocean surface waves are simulated using the third-generation wave model, WAVEWATCH III (referred to as WW3 in this study), developed by Tolman (1991) for wind waves on slowly varying, unsteady and inhomogeneous depths and currents. The model grid extends from 33°N to 52°N, 127°E to 143°E with a grid spacing of 1/12° (~7 km) in both latitude and longitude. Fig. 1 shows the WW3 model domain with the bottom topography of JES. The wind waves are described by using the action density wave spectrum based on 25 frequencies logarithmically spaced from 0.0418 to 0.41 Hz and 24 directional bands.

2.2 *Atmospheric Model*

We use the fifth generation of the Penn State University-National Center for Atmospheric Research atmospheric nonhydrostatic mesoscale model (MM5) (Dudhia, 1993) to characterize the mesoscale structures of atmospheric synoptic forcing, especially for wintertime Siberian cold-air outbreaks in JES. Detailed description of the MM5 simulations of the atmospheric surface forcing during January 1997 used in this study is given in Chen and Zhao, 2003.

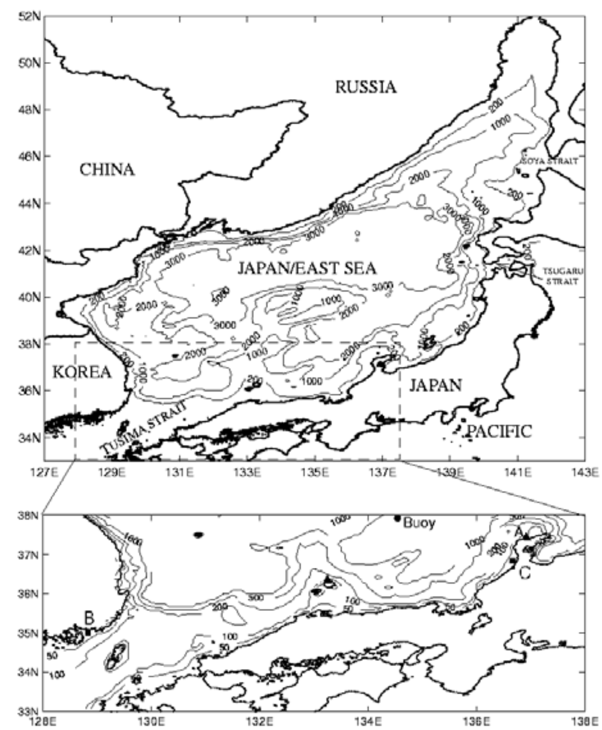

Fig. 1 WAVEWATCH III (WW3) model domain (over the oceanic region) and the Japan/East Sea bottom topography (contours, in meter). A, B, C, and D are selected locations where time series of model simulations will be shown.

To test the sensitivity of the wave fields to the atmospheric surface winds, we use two difference wind products to force the wave model. One is the operational ECMWF gridded global analysis wind field at 2.5° grid spacing. The other is the relatively high-resolution MM5 simulated wind at 15 km grid spacing.

2.3 *Hydrodynamic model*

The fully nonlinear, two-dimensional conservation-based, barotropic hydrodynamic model ADCIRC-2DDI (Luettich et al. 1992) is used to simulate tides and storm

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surges in JES. In this study, the model domain includes the Japan/East Sea, the Yellow Sea and extends into the deep waters of the northwest Pacific Ocean. The spatial resolution of this finite element model varies from 3 km in the coastal areas to 70 km in the deep ocean. The hydrodynamic model, ADCIRC-2DDI, is forced at the surface by wind stresses derived from the MM5 wind field using the drag law of Garrett (1977). Tidal forcing is derived from the tidal potential and tidal elevation specified at the open ocean boundary. Boundary values for eight constituents (M2, S2, N2, K2, O1, K1, P1, Q1) are extracted from the Grenoble FES95.2.1 global database (Le Provost et al., 1994). The model produces sea surface height (SSH) and depth-averaged current fields, which are used as input fields for WW3 to investigate wave-current interactions in JES.

3. SURFACE WAVE FIELDS

During the winter season, the atmospheric forcing in JES region is dominated by storms associated with cold air outbreaks with strong surface wind gusts every 3-7 days. The storm conditions induce large ocean surface waves that can be hazardous, especially near the west coast of Japan. Observed surface waves can reach a SWH close to 10 m in storm conditions in JES (Fig. 2). We first perform a month long WW3 control simulation with the MM5 surface wind during January 1997. WW3 is integrated for a 12 h spin-up period (from 1200 UTC, 31 December 1996 - 0000 UTC, 1 January 1997) before the month long simulation. The model results are validated against the wave measurements from the JMA buoy 21002 (marked in the enhanced map in Fig. 1). Both the MM5 simulated surface wind and the WW3 simulated SWH match the observations remarkably well. The high wind waves are associated with seven storm events. The model tends to under estimate SWH slightly in two extreme events on 1 and 21 January 1997.

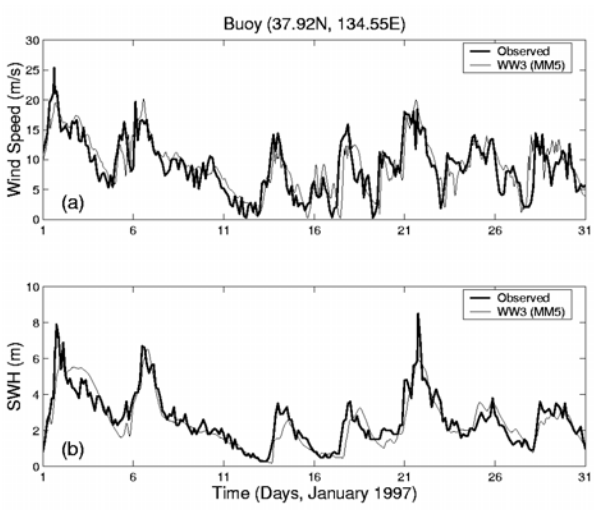

Fig. 2 Time series of (a) observed (thick solid line) and the MM5 simulated (thin solid line) surface winds, and (b) same as in (a) except for SWH at the JMA moored buoy 21002 (37.92N, 134.55N).

4. SENSITIVITY TO DIFFERENT WIND FORCING

Ocean surface waves vary with wind conditions. However, the model sensitivity to different wind forcing fields has never been tested in JES. One of the important issues related to surface wave forecast is whether the current global model wind forecasts are good enough for accurate wave forecasts, especially for the coastal regions. In this study, we examine the sensitivity of WW3 simulation to different wind forcing fields, namely the ECMWF global analysis and the high-resolution MM5 simulated surface winds. The main differences are in temporal and spatial resolutions. The ECMWF field is in 2.5° grid spacing with 12 h interval, where MM5 15 km with 1 h interval. Both forcing fields are interpolated to the WW3 grids. The temporal variations are linearly interpolated to the WW3 time step of 5 min. Because of the relatively low spatial and temporal resolutions, the ECMWF wind field cannot resolve the fine structure of the winter storms, especially many of them develop mesoscale cyclones and enhanced surface frontal zones over the relatively warm water in JES. Strong surface wind gusts and rapid wind directional changes are often observed to be associated with these mesoscale features that are simulated quite well in MM5.

Comparing the two WW3 simulation using the MM5 and ECMWF wind forcing shown in Fig. 3, several contrasting features are worth noting. First, the frontal zones are much sharper in the MM5 winds (Fig. 3a) than in the ECMWF winds (Fig. 3b). Second, there is a closed circulation associated with a mesoscale low developed in the northeastern JES near the coast, which was observed by satellite cloud imagery shown in Chen and Zhao (2003). The ECMWF winds missed this feature completely. The difference in the two corresponding SWH fields forced by the MM5 and ECMWF winds are significant. The SWH forced by the ECMWF winds maximize in the middle of the ocean, whereas the MM5 forcing near the coastal regions. The latter is more close to reality. The SWH tends to be overly smooth in the ECMWF than in the MM5 wind forcing.

The two month-long WW3 simulations using difference wind forcing are compared with the observations at the JMA moored buoy 21002 (Fig. 4). Both wind fields capture the seven storm events well, partly because the buoy data has been assimilated into the ECMWF global analysis fields. The main difference between the two wind fields is that MM5 is able to produce the high frequency variability in the wind similar to the observations (Fig. 4a). Although both WW3 simulations underestimate the SWH, especially the peak values during the storms, the SWH using the MM5 winds is higher and closer to the observations than that using the ECMWF winds (Fig. 4b). The improvement using high-resolution MM5 winds in the WW3 simulated wavelength is clearly evident in Fig. 4c.

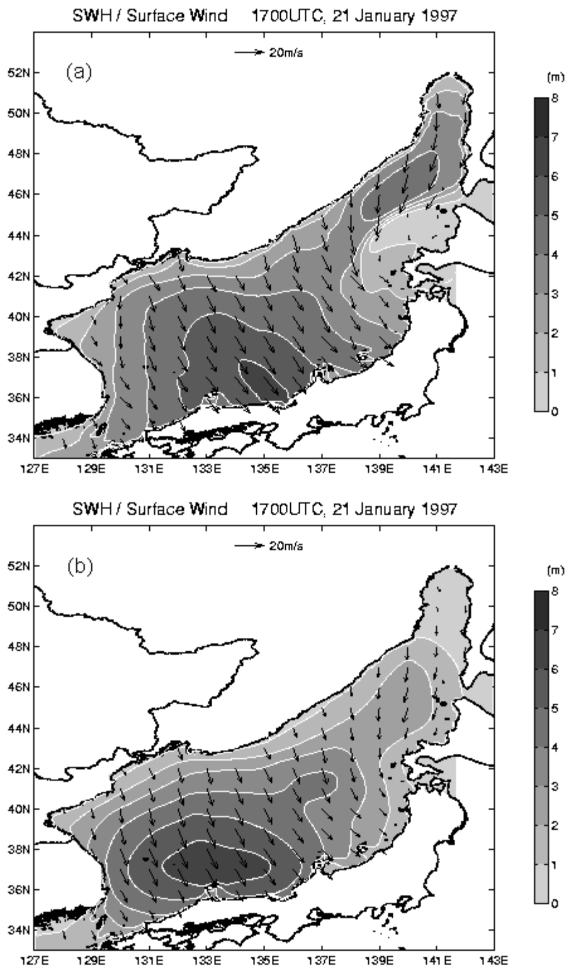

Fig. 3 MM5 simulated (a) and ECMWF (b) surface winds (arrows) and WW3 simulated significant wave height (SWH, shade) on 1700 UTC, 21 Jan.

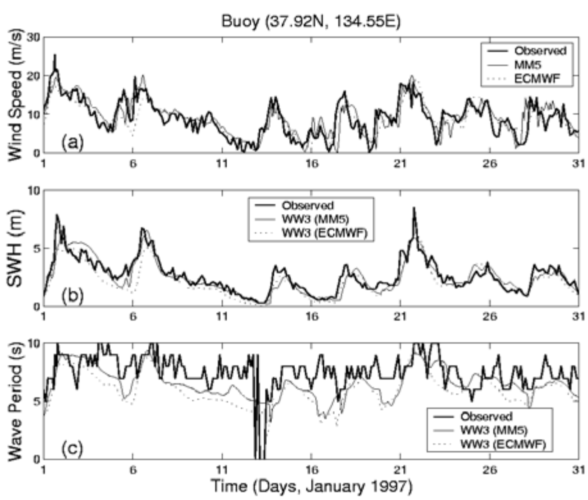

Fig. 4 Time series of (a) observed (thick solid line), MM5 simulated (thin solid line), and the ECMWF (dotted line) surface winds, (b) same as in (a) except for SWH, and (c) same as in (a) except for wave period, at the JMA moored buoy 21002 (37.92N, 134.55N).

The near surface winds interact strongly with the complex coastal topography that are not well-resolved by any of the current global models. The high frequency variability in both wind speed and direction is absent in the ECMWF winds. Figs. 5 shows one example, point A indicated in the enhanced map in Fig. 1, from many coastal stations on the west coast of Japan. The high frequency variability in the MM5 and observed wind fields tends to increase the SWH in WW3 by as much as 30 % in some storm conditions compared to the ECMWF wind forcing.

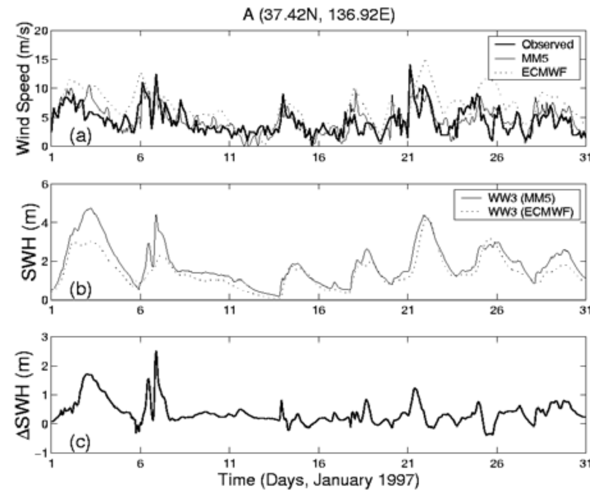

Fig. 5 Time series of (a) surface winds from the observed (thick solid line), the MM5 (thin solid line), and the ECMWF (dotted line) fields at a land based coastal station very close to point A indicated in the enhanced map in Fig. 1, (b) SWH fields with the MM5 (solid line) and the ECMWF (dotted line) surface wind forcing, and (c) difference in the SWH fields with the two difference wind forcing.

5. EFFECTS OF TIDES AND STORM SURGES

To explore the potential effects of the tides and storm surges on the surface waves in JES, we employ the hydrodynamic, ADCIRC-2DDI, to simulate the ocean current using the MM5 simulated atmospheric forcing. ADCIRC-2DDI is run for the entire month of January 1997 with imposed tidal potential and tidal elevations at deep open ocean boundaries. A 12- day period during which the applied wind and tidal forcing are ramped precedes computations for the month January. The model produces depth mean current and SSH. We then perform a month long wave model simulation using the same MM5 surface winds and adding the ADCIRC computed current and SSH as forcing fields. Wave-current interaction is a complex subject that is beyond the scope of this study. Our focus here is to examine the net impact of the tides and storm surges on model simulated surface waves in JES.

Because of the large water depth in JES, the mean current is relatively small over most of the JES basin, except in the Tusima Strait where the tides are a dominant feature. As shown in Fig. 2, the surface wind is relatively calm in between storms. The tidal range in this area is about 1-2 m, and the tidal current is about

0.5-1.0 m s^{-1}. Although the tides are weak in most of the interior of JES, there are clear tidal currents in the relatively shallow region near the coastal regions of Japan.

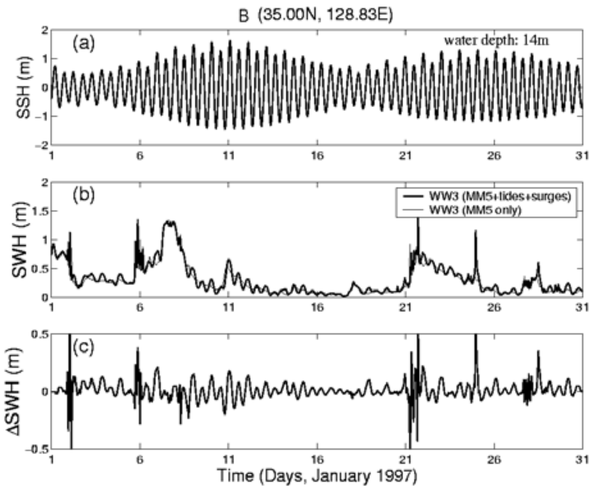

Fig. 6 Time series of (a) SSH, (b) SWH with only the MM5 surface wind forcing (thin solid line) and the combined forcing from the surface winds, tides, storm surges, and (c) the difference in SWH fields with the two forcing fields shown in (b), at a coastal location B near the south end of the Korea peninsula indicated in the enhanced map in Fig. 1.

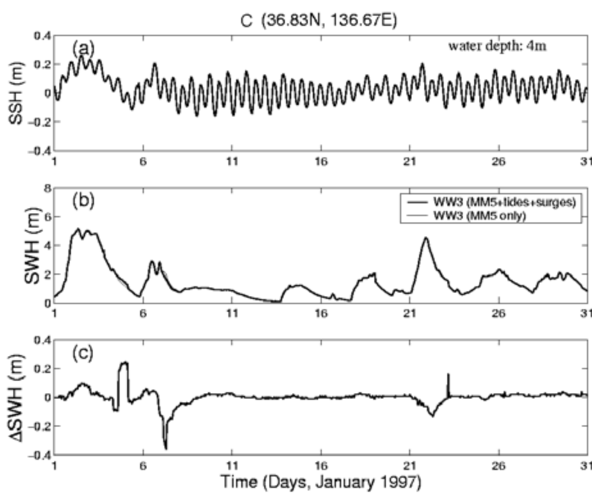

Fig. 7 Same as in Fig. 6, except for a coastal location C near the west coast of Japan indicated in the enhanced map in Fig. 1.

The month long evolution of the current and wave fields near the coastal regions can be best described at two locations, B and C indicated in the enhanced map in Fig. 1, which represent a range of general features in our simulations. The mean water depths for the two locations are 14 and 4 m for B and C, respectively. To examine the effects of tides and storm surges on the surface waves, we compare the results of the WW3 simulations with and without the ADCIRC-2DDI current and SSH fields. Both simulations are forced by the same MM5 surface wind field. As expected the tides dominate the SSH at the south end of the Korea Peninsula (point B, Fig. 6a). Fortnightly oscillation is clearly shown. The SSH oscillation varies from nearly 1.0 m at the spring to 2.0 m at the neap. Although the storm signals are not visible in SSH at point B, it shows clearly in the SWH field (Fig. 6b) at the same location. It suggests that the storm induced large surface waves are mainly forced by the wind. However, further comparing the two simulations we find a significant difference in the two wave fields. By subtracting the two SWH fields, Fig. 6c shows the net effect of the tides and storm surges on the wave field. The largest modulation of the SWH appears to be associated with the five winter storms in JES on 2, 6, 21, 25, and 28 of January, contributing 30-50% of the total SWH. The influence of the tides is also evident throughout the month, especially near the spring of the fortnightly oscillation.

In contract, away from the Tusima Strait, further to the north near the west coast of Japan (point C) the tides are weaker than at point B (Fig. 7a), but nevertheless exist there as well. The storm signals in SWH are clearly dominant at point C (Fig. 7b), again mostly from the wind forcing. The impact of the tides on the wave field is very small, but the influence of the storm surges is still visible, though only less then 10 % of the total SWH in most cases (Fig. 7c).

6. CONCLUSIONS

We conduct three month-long wave model simulations to examine the model sensitivity to variation in wind forcing, tides, and storm surges in JES during January 1997. The wave model, WW3, is able to re-produce the observed mean wave fields including the SWH and wavelength. Comparing with observed mean wave parameters (i.e., significant wave heights and wave periods), our results indicate that the variation in the wave fields is mainly caused by the variability of wind forcing. The operational ECMWF global wind analysis does not have an adequate spatial and temporal resolution to produce accurate wave forecast. Tides and storm surges seem to have a significant impact on the waves near shores when mean water depth decreases sharply from a few hundreds of meters to less than 10 m along the west coast of Japan. Improving surface wind forecasts will be crucial for the prediction of surface waves and storm surges in JES, especially near the coastal regions.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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http://orca.rsmas.miami.edu/jes/.