Australian Journal of Basic and Applied Sciences, 5(3): 75-80, 2011
ISSN 1991-8178

The Application of One-way Nested Grid for the Energy Balance Equation by Wave Model

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Abstract: The application of the standard one–way nested grid for a regional scale of the third generation WAve Model Cycle 4 (WAMC4) is scrutinized. The model application is enabled to solve the energy balance equation on a coarse resolution grid in order to produce boundary conditions for a smaller area by the nested grid technique. In the present study, the model is to take full advantage of the fine resolution wind fields in space and time produced by the available U.S. Navy Global Atmospheric Prediction System (NOGAPS) model with 1 degree resolution. The nested grid application of the model is developed in order to gradually increase the resolution from the open ocean towards the South China Sea (SCS) and the Gulf of Thailand (GoT) respectively. The model results were compared with buoy observations at Ko Chang, Rayong and Huahin locations which were obtained from Seawatch project. In addition, the results were also compared with Satun based weather station which was provided from Department of Meteorology, Thailand. The data collected from this station presented the significant wave height (Hs) reached 12.85 m. The results indicated that the tendency of the Hs from the model in the spherical coordinate propagation with deep water condition in the fine grid domain agreed well with the Hs from the observations.

Key words: Energy balance equation; Gulf of Thailand; Nested grid application; South China Sea; Wave model

INTRODUCTION

The operational wave forecasting system has been developed by the Thai Meteorological Department and Royal Thai Navy since 1997. The system is designed to provide the ocean wave forecasting for the Gulf of Thailand (GoT). It uses the two–step one–way nested grid from the coarse grid domain (CGD) which covered the South China Sea (SCS) and the fine grid domain (FGD) which covered the GoT. The deep water conditions are applied in both domains. The maximum depth of the SCS and GoT is approximately 4,000 and 85 m respectively. Thus, it is important to study the wave dynamics in the shallow water conditions with the new operation and the new nested grid windows in both domains. The intermediate grid domain (IGD) (Figs. 1(a) and (b)) in the three nested grid windows is designed to be a new domain and located between the CGD and FGD. The modeling technique is applied to obtain the storm wave predictions in the regional seas such as the SCS and GoT. The regional implementations of a third–generation WAve Model Cycle 4 (WAMC4) have been reported in several studies (Hasselmann, 1988; Gunther, 1992; Komen, 1994). The WAMC4 model has been carried out and tested in the GoT with Typhoon Linda 1997 cases (Vongvisessomjai, 2007; Vongvisessomjai, 2009). The nested grid of two–step application of the WAMC4 model has been developed in order to gradually increase the resolution from the open sea towards the GoT region (Wannawong, 2010), and the resolution is increased using a two–way nesting scheme developed at Puertos del Estado in the Spanish

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coast without resorting to high resolution in deep water (Gómez Lahoz, 1997). The two–step application of the previous work (Wannawong, 2010) is a simple scheme and less computational effort. In the present study, the three steps of the nested grids in two experiments are shown in Fig. 1(a). The objective of this work is to take the full advantage of the fine resolution wind fields in space and time produced by the available U.S. Navy Global Atmospheric Prediction System (NOGAPS) model with 1 degree resolution (Hogan, 1991). The model description, one–way nesting procedure and model setting with the implementation are described briefly in Section II. The results and discussion are presented in Section III. Finally, the conclusion is shown in Section IV.

II. Meteodology:

Description of Energy Balance Equations:

The energy balance equation is the wave transport equation which is solved by the numerical methods in the WAMC4 model (Hasselmann, 1988; Gunther, 1992; Komen, 1994). The model can be used in the global, regional and coastal scales with terms of the discrete energy density (Wittmann, 1997) $F(t, \mathbf{x}, f, \theta)$, where t represents time, $\mathbf{x}$ represents the geographical space in Cartesian coordinates (x,y) and spherical coordinates (λ,ϕ) and (θ, f) represent the spectral space (direction and frequency) respectively. The wave direction θ represents the wave direction measured clockwise from the true north. In the absence of diffraction and currents, the governing equations of WAMC4 model are

$$\frac{\partial F}{\partial t}+\frac{\partial(c_x F)}{\partial x}+\frac{\partial(c_y F)}{\partial y}+\frac{\partial(c_\theta F)}{\partial \theta}=S_{tot} \qquad (1)$$

and

$$\frac{\partial F}{\partial t}+\frac{\partial(c_\lambda F)}{\partial \lambda}+(\cos\phi)^{-1}\frac{\partial(c_\phi \cos\phi)F}{\partial \phi}+\frac{\partial(c_\theta F)}{\partial \theta}=S_{tot} \qquad (2)$$

where c_x, c_y, c_λ and c_ϕ are the propagation velocities of the group velocity c_g in the geographical space and c_θ is the propagation velocity in the spectral space. The left hand sides of the Eqs. (1) and (2) are applied in the regional scale with the absence of diffraction and currents. The left hand sides of both equations represent the local rate of change of wave energy density in time, propagation in the geographical space, and shifting of frequency and refraction due to the spatial variation of depth and current. The right hand sides of both equations, (S_{tot}) show all effects of generation and dissipation of the waves in deep and shallow waters including wind input (S_{in}), white capping in dissipation (S_{ds}) and nonlinear quadruplet wave–wave interactions (S_{nl}). In addition, the shallow water in the regional domains such as the SCS and GoT need to be modified to include an additional source function (S_{bf}) representing the energy loss due to bottom friction and percolation. The bottom friction dissipation term (S_{bf}) represents the formulation under the Joint North Sea Wave Project (JONSWAP) (Hasselmann, 1973).

$$S_{bf}=-\frac{\Gamma}{g^2}\frac{\omega^2}{\sinh^2 kD}E \qquad (3)$$

where $\Gamma = 0.038$, g is the gravitational acceleration, ω is the angular frequency ($\omega^2 = gk\tanh kD$), k is the wave number and D is the finite depth dispersion relation.

B. the Standard One-way Nested Grid:

The standard one–way nested grid is the interested option in the WAMC4 model code. The option is enabled to apply the model on a coarse resolution grid in order to produce boundary conditions for a smaller area (Komen, 1994; Gómez Lahoz, 1997). In the present study, this section gives a briefly description of the algorithm which applied by the model to carry out the nesting windows and interpolation of boundary conditions (Figs. 1(a) and (b)). The interpolation technique for the boundary conditions which applied in the WAMC4 model is based on a linear interpolation of mean parameters (mean wave direction, mean frequency, and mean energy) along with a linear adjustment of the spectra to these parameters. Let $F_1(\theta, f)$ and

$F_2(\theta, f)$ be the wave spectra to be interpolated while Δ_{12} is the distance between them, and Δ_{1L} is the distance between spectrum number 1 and the new spectrum L to be generated by interpolation; $\bar{\theta}_1, \bar{\theta}_2, \bar{f}_1, \bar{f}_2, \bar{E}_1,$ and $\bar{E}_2$ are the mean direction, mean frequency, and mean energy respect of both spectra. The mean parameter obtained by linear interpolation, say for $\bar{E}$, is given by

$$\bar{E} = \frac{\Delta_{12} - \Delta_{1L}}{\Delta_{12}} \bar{E}_1 + \frac{\Delta_{1L}}{\Delta_{12}} \bar{E}_2 \tag{3}$$

The new spectra, $F_3(\theta, f)$ and $F_4(\theta, f)$ generated by linearly adjusting $F_1(\theta, f)$ and $F_2(\theta, f)$ so as to fit these mean parameters, are interpolated to obtain the desired new spectrum, given by

$$F_L(\theta_i, f_j) = \frac{\Delta_{12} - \Delta_{1L}}{\Delta_{12}} F_3(\theta_i, f_j) + \frac{\Delta_{1L}}{\Delta_{12}} F_4(\theta_i, f_j). \tag{4}$$

where i = 1, 2, 3, …,12 and j = 0, 2, 3, …, 24.

C. Model Setting and Implementation:

The operational ocean wave system contained three domain applications which covered the Pacific Ocean, SCS and GoT respectively (Figs. 1(a) and (b)). The one–way nesting scheme, mentioned earlier, the resolution of the Pacific application with closed ocean was increased from 0.5 degrees in the CGD of Typhoon Linda cases. The open sea of the SCS in shallow and deep waters modified in both experiments showed the resolution of 0.375 degrees in the IGD. The modeling system with the open sea condition of the GoT is set up to 0.25 degrees in the FGD. The CGD was closed to cover the storm wave generation from 95ºE to 155ºE in longitude and from 20ºS to 40ºN in latitude, which gave 121×121 points for both latitude and longitude. The IGD was opened to cover from 98ºE to 125ºE in longitude and from 2ºS to 25ºN in latitude, which gave 109×109 points for both latitude and longitude. Finally, the FGD was opened to cover from 99ºE to 111ºE in longitude and from 2ºN to 14ºN in latitude, which gave 49×49 points for both latitude and longitude. The new application also has variable grid spaces of 1800, 1200 and 600 s in the CGD, IGD and FGD which are shown in Figs. 1(a) and (b) with the typhoon track information. The experimental designs, computational grids and coordinate propagations with flag conditions in each experiment are shown in Table I. The WAMC4 model was required the bathymetry data and input wind field in each nested grid. The bathymetry data was obtained from ETOPO5 and ETOPO1 (Edwards, 1989; Amante, 2008). The ETOPO5 was updated in June 2005 for the acceptably deep water. It has been applied in the CGD. The latest version (on July 28, 2008), ETOPO1 (Bedrock version) was chosen to apply in the IGD and FGD. The details of the combination of both topographies and nested grid domains were described in the previous study Wannawong, *et al.,* (2010). The wind fields at a height of 10 m were obtained from the NOGAPS model with 1×1 data resolution and the linear interpolation was used to generate the wind data to the grid points (Hogan, 1991). The computational model of Typhoon Linda cases was started at 00UTC on October 20 and ended at 00UTC on November 10, 1997. The results of WAMC4 model were exposed in every hour from the typhoon wave generation in the Pacific Ocean through the GoT. The stability of model was computed according to the Courant–Friedrichs–Lewy (CFL) stability condition.

RESULTS AND DISSCUSION

The computations of typhoon wave and coordinate propagation with flag condition were analyzed from a set of model experiments: Experiment I and Experiment II as described in Table I. The numerical simulation of the significant wave height (Hs) which was generated by Typhoon Linda in Experiment I was firstly considered and then the strong wave was presented in Experiment II (Figs. 3 and 4). Both experiments were driven with the same wind field (wind speed), domain (wind fetch) and time (duration) but with the different coordinate propagation and flag condition in the IGD and FGD. The maximum Hs related with the maximum wind fields in the CGD, IGD and FGD of each experiment are shown in Figs. 2–4. The results of the

WAMC4 model showed that the Hs at Ko Chang (I), Rayong (II), Huahin (III) buoys and Satun based weather station (IV) (see Fig. 1(c)) of Experiment I and II were in ranges of 1.50–2.45 and 2.20–3.24 m respectively. The Hs of those stations in both cases were slightly different among the same case. For the comparison of the Hs of the WAMC4 model with the observation data (2.50–12.48 m), the results expressed that the Hs at Ko Chang (I), Rayong (II) and Huahin (III) bouys (2.50–4.06 m) were similarly different while Satun based weather station (IV) showed a markedly different Hs (12.48 m). However, the Hs shown in Experiment II were more similar to the observation data than that of Experiment I since the energy loss due to bottom friction and percolation.

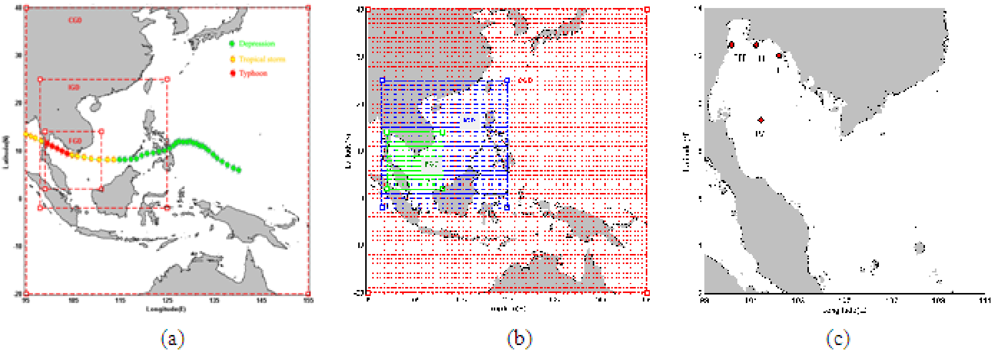


Fig.1: The nested grid windows with: (a) typhoon track, (b) structural resolutions and (c) observation points in the FGD.

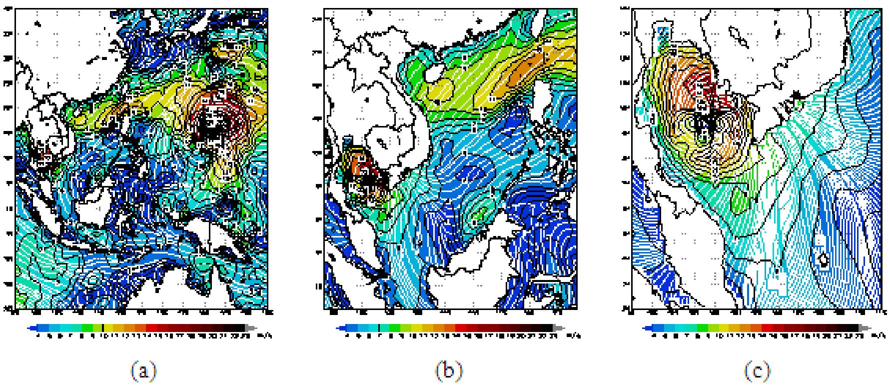


Fig. 2: Wind speed and streamline at 00UTC03NOV1997 in the: (a) CGD, (b) IGD and (c) FGD.

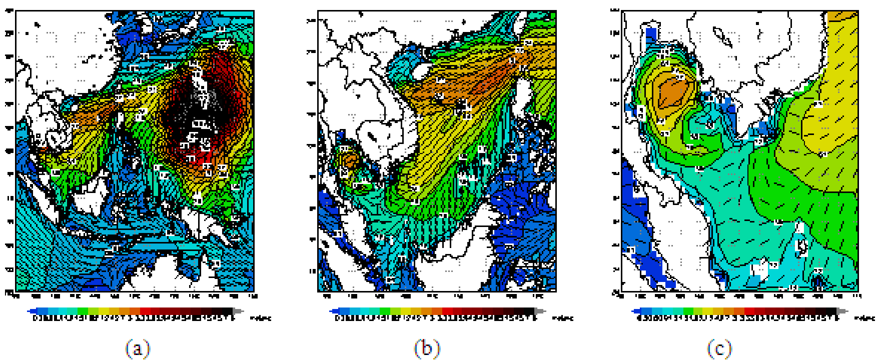
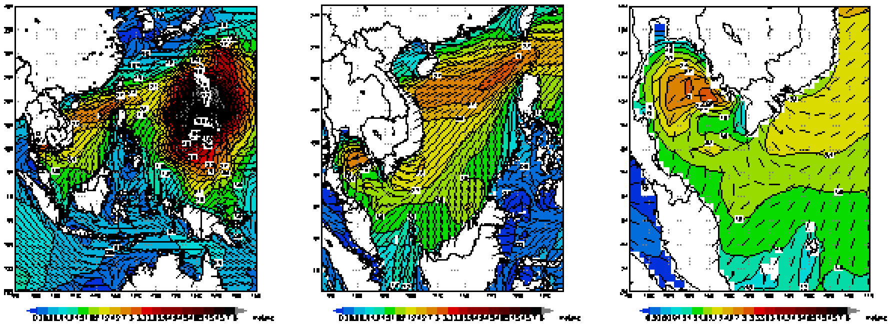


Fig. 3: The Hs and direction at 00UTC03NOV1997 of Experiment I in the: (a) CGD, (b) IGD and (c) FGD.



(a) (b) (c)

Fig. 4: The Hs and direction at 00UTC03NOV1997 of Experiment II in the: (a) CGD, (b) IGD and (c) FGD.

Table 1: Information of experiments and computational grid

Information	Numerical Descriptions		
	CGD	IGD	FGD
Grid size	0.5°×0.5°	0.375°×0.375°	0.25° ×0.25°
Grid point	121×121	109×109	49×49
Propagation time step	1800 s	1200 s	600 s
Source time step	1800 s	1200 s	600 s
	1. Experiment I		
Geographical space	Spherical	Cartesian	Cartesian
Water flag condition	Deep water	Deep water	Deep water
	2. Experiment II		
Geographical space	Spherical	Spherical	Spherical
Water flag condition	Deep water	Shallow water	Shallow water

IV. Conclusion:

The previous work (Wannawong, 2010) studied on the FGD showed that the storm waves significantly influence wave water. It is important to study the typhoon waves in the regional scales of the operational wave forecasting system. The results of this study confirmed that the effect of the maximum Hs must be investigated and developed simultaneously. The results of the WAMC4 model showed the slight difference of the Hs between Experiment I and II with typhoon distribution during Typhoon Linda entering into the GoT. Additional studies will be undertaken in the future with a focus on how storm wave affects other domains and the wave model should be coupled with the hydrodynamic models. The effects of storm wave on the sea surface layer should be more comprehensively examined with more typhoon case simulations.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Commission on Higher Education for giving financial support to Mr. Worachat Wannawong under the Strategic Scholarships Fellowships Frontier Research Networks in 2007. The authors are grateful to the Geo–Informatics and Space Technology Development Agency (GISTDA) for buoy data and documents. Finally, the authors are greatly indebted to Mr. Michael Willing for helpful comments on English grammar and usage.

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