World Academy of Science, Engineering and Technology
International Journal of Physical and Mathematical Sciences
Vol:5, No:3, 2011

Three Steps of One-way Nested Grid for Energy Balance Equations by Wave Model

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Abstract—The three steps 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 takes a full advantage of the fine resolution of 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 the 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.

Keywords—energy balance equation, Gulf of Thailand, nested grid application, South China Sea, wave model.

I. Introduction

An 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) [15], [17], [16]. It uses a two–step one–way nested grid from a coarse grid domain (CGD) which covered the SCS and from a 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 meters respectively. Thus, it is important to study the wave dynamics in the shallow water conditions with a 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 South China Sea (SCS) and the Gulf of Thailand (GoT). The regional implementations of the third–generation WAve Model Cycle 4 (WAMC4) have been reported in several studies [5], [3], [7], [13]. The WAMC4 model has been carried out and tested with Typhoon Linda 1997 cases which entered into the GoT [19], [20], [21], [22]. The nested grid of the 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 [20], and the resolution is increased using the two–way nesting scheme developed at Puertos del Estado in the Spanish coast without resorting to the high resolution in the deep water [10]. The two–step application described by Wannawong et al. [20] is a simple scheme and less computational effort. In the present study, the three steps of the nested grids were studied and applied in two experiments as 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 [18]. The model description, one–way nesting procedure and model setting with the implementation are described briefly in Section II. The results The results of this study are presented in Section III. Finally, the discussions and conclusion are shown in Section IV.

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.
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II. Meteodology

A. A Description of Energy Balance Equations

The WAMC4 model solves the energy balance equations in the regional scale with the terms of the discrete energy density, $F(\theta, f; \mathbf{x}, t)$, where t represents time, $\mathbf{x}$ represents the geographical space in Cartesian (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. Excluding the intrinsic frequency, σ, as a coordinate allows the model to overcome the problem of high frequency waves propagating on strong opposite currents (e.g. the absence of diffraction and currents for the coastal scale).

The governing equation of the WAMC4 model on the spherical coordinates (λ, ϕ) reads,

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

where the propagation speed in the different spaces; $c_{g,\lambda}, c_{g,\phi}$, and c_θ are given by [12], [6],

$$c_{g,\lambda} = \dot{\lambda} = \frac{d\lambda}{dt} \quad = \quad (c_g \sin\theta)(R\cos\phi)^{-1}, \tag{2}$$
$$c_{g,\phi} = \dot{\phi} = \frac{d\phi}{dt} \quad = \quad (c_g \cos\theta)R^{-1}, \tag{3}$$
$$c_{\theta} = \dot{\theta} = \frac{d\theta}{dt} \quad = \quad (c_g \sin\theta\tan\phi)R^{-1}. \tag{4}$$

Here $c_g = g/2\omega = g/2(2\pi f) = g/4\pi f$ denotes the group velocity of the deep water condition, g represents the gravitational acceleration, ω represents the angular frequency, f represents the frequency, and R represents the radius of the earth. The detail of the energy balance equations on the Cartesian coordinates is shown in Appendix A.

On the right hand side of the equation (1), S_{tot} is the function representing the source and sink functions, and the conservative non–linear transfer of energy between wave components. For the present applications, the wave model included the standard WAMC4 formulations for the S_{tot} terms; wind input S_{in}, non–linear quadruplet wave–wave interactions S_{nl}, whitecapping dissipation S_{ds}, and bottom friction dissipation S_{bf}. For the complete explanation on the physics included in S_{tot}, the reader is referred to Komen et al. [3] and their references.

The wind input formulation is based on the resonant interaction between the wave induced pressure fluctuations and the waves of Miles' theory. This source of energy is represented as,

$$S_{in} = \gamma F \tag{5}$$

where γ is the growth rate of the waves, also called Miles' wave growth mechanism. In the WAMC4 model, this term is based on the theory proposed by Janssen [11]. According to Janssen [11], the interphase atmosphere–ocean represents a coupled system where the growth rate of waves depends on the wind, whose profile depends on the sea state. The term γ is expressed as below in the WAMC4 model.

$$\gamma = \max\Big[0, (\rho_a/\rho_w)\beta X^2\Big] \quad ; \quad X = (u^*/c)\cos\vartheta, \tag{6}$$

where ρ_a is the density of air, ρ_w is the density of sea water, ϑ is the relative direction between wind and waves, $u^* = \sqrt{\tau/\rho_a}$ is the friction velocity where τ is the wind stress, c is the phase velocity of the waves, and β is the Miles' parameter given by,

$$\beta = (1.2/\kappa^2)\nu\ln^4\nu \quad ; \quad \nu = \frac{gz_e}{(\kappa c_p)^2}\exp(\kappa/X). \tag{7}$$

where z_e represents the effective roughness length, c_p is the wave propagation speed and κ = 0.41 is the von Kármán constant. The nonlinear resonant interaction between the quadruplet of wave components is included in the WAM through an approximation to the exact expression,

$$S_{in}^{exact}(\mathbf{k_4}) = \int \omega_4\varsigma\delta(\mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}_3 - \mathbf{k}_4)\delta(\omega_1 + \omega_2 - \omega_3 - \omega_4) \times [n_1 n_2(n_3 + n_4) - n_3 n_4(n_1 + n_2)]d\mathbf{k}_1 d\mathbf{k}_2 d\mathbf{k}_3 d\mathbf{k}_4 \tag{8}$$

where $n_j = F(k_j)/\omega_j$ is the action density and the coefficient ς is the coupling coefficient. The approximation included in the WAM (DIA method, Hasselmann et al. [14]) reduces the space of resonant quadruplets to a two–dimensional plane where the discrete interaction of a symmetric pair of configurations is only used (see Figs. 3.1 and 3.2 in van Vledder [4]).

On the finite–depth waters, the computation of S_{nl} is carried out in similar way as on the deep waters, but including a scaling factor:

$$S_{nl} = \Upsilon(\bar{k}H)S_{nl} \tag{9}$$

In the equation (9), $\bar{k} = [E_{tot}^{-1}\int F(f,\theta)k^{-1/2}df d\theta]^{-2}$ is the mean of wave number, E_{tot} is the total of wave energy density and the scaling factor Υ reads,

$$\Upsilon(\chi) = 1 + \frac{5.5}{\chi}\Big(1 - \frac{5\chi}{6}\Big)\exp\Big(-\frac{5\chi}{4}\Big), \tag{10}$$

with $\chi = (3/4)\bar{k}H$.

The term representing the energy dissipation by wave breaking on the deep waters (also called the whitecapping) is based on the extension of the formulation proposed by Komen et al. [2]. In Komen's formulation, the existence of an equilibrium solution of the energy balance equation during fully developed sea condition is assumed. Once the Janssen's theory for the wave growth by sea–atmosphere coupling was implemented, the Komen's formulation had to be extended in order to obtain the proper balance during fully developed sea conditions. In the WAMC4 model, the term S_{ds} is evaluated as,

$$S_{ds} = -C_{d1}\bar{\omega}\bar{k}^4 E_{tot}^2\Big[(1 - C_{d2})(k/\bar{k}) + C_{d2}(k/\bar{k})^2\Big]F \tag{11}$$

where E_{tot} is the total energy, C_{d1} = 4.5, and C_{d2} = 0.5.

B. The three steps of the standard one–way nested grid

The standard one–way nested grid is an interesting option of the WAMC4 model code. The option is enabled to apply the model on the coarse grid resolution in order to produce the boundary conditions for a smaller area [10]. In the present study, this section gives a brief description of the algorithm which was applied by the model to carry out the nesting windows and the interpolation of the boundary conditions (Figs. 1(a) and (b)). The interpolation technique for the boundary conditions which was 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[1] 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; $\overline{\theta}_1, \overline{\theta}_2, \overline{f}_1, \overline{f}_2, \overline{E}_1$, and $\overline{E}_2$ are the mean direction, mean frequency, and mean energy respect of both spectra. The mean parameter obtained from the linear interpolation, say for $\overline{E}$, is given by

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

[1] It is worth to remark that the letter F is used to denote the discrete representation of the wave energy density, E.

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

$$F_L(\theta_i, f_j) = \frac{\Delta_{12} - \Delta_{1L}}{\Delta_{12}} F_3(\theta_i, f_j) + \frac{\Delta_{1L}}{\Delta_{12}} F_4(\theta_i, f_j). \quad (13)$$

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 was set to 0.25 degrees in the FGD.

The CGD was closed to cover the storm wave generation from $95°E$ to $155°E$ in longitude and from $20°S$ to $40°N$ in latitude ($0.5° \times 0.5°$ spatial grid size), which gave 121×121 points for both latitude and longitude. The IGD was opened to cover from $98°E$ to $125°E$ in longitude and from $2°S$ to $25°N$ in latitude ($0.375° \times 0.375°$ spatial grid size), which gave 109×109 points for both latitude and longitude. Finally, the FGD was opened to cover from $99°E$ to $111°E$ in longitude and from $2°N$ to $14°N$ in latitude ($0.25° \times 0.25°$ spatial grid size), which gave 49×49 points for both latitude and longitude. The propagation time steps of the CGD, IGD and FGD were 1,800, 1,200 and 600 s respectively while the source time steps of the CGD, IGD and FGD were also 1,800, 1,200 and 600 s 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 [9], [1]. 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 [20]. The wind fields at a height of 10 meters were obtained from the NOGAPS model with $1° \times 1°$ data resolution and the linear interpolation was used to generate the wind data to the grid points [18]. 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 observed 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.

III. Results of Experiments

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 to 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 (Figs. 5 and 6).

TABLE I
INFORMATION AND COMPUTATIONAL GRIDS OF EXPERIMENTS

Information	Numerical descriptions CGD	IGD	FGD
Grid size	$0.5° \times 0.5°$	$0.375° \times 0.375°$	$0.25° \times 0.25°$
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	Shallow water	Shallow water
2. Experiment II			
Geographical space	Spherical	Spherical	Spherical
Water flag condition	Deep water	Deep water	Deep water

IV. Discussions and Conclusion

The previous work [20] was 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 the present 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. The results also suggested that the three steps of the one-way nested grid of the WAMC4 model provided the similar values of Hs to that of the observational data. 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.

APPENDIX A
THE ENERGY BALANCE EQUATION ON THE CARTESIAN COORDINATES

The governing equation on the Cartesian coordinates (x, y) reads,

$$\frac{\partial F}{\partial t} + \frac{\partial c_{g,x}F}{\partial x} + \frac{\partial c_{g,y}F}{\partial y} + \frac{\partial c_{\theta}F}{\partial \theta} = S_{tot} \tag{14}$$

where the propagation speed in the different spaces; $c_{g,x}, c_{g,y}$, and c_θ are given by [12], [6],

$$c_{g,x} = \dot{x} = \frac{dx}{dt} = \sqrt{gd}, \tag{15}$$

$$c_{g,y} = \dot{y} = \frac{dy}{dt} = \sqrt{gd}, \tag{16}$$

$$c_{\theta} = \dot{\theta} = \frac{d\theta}{dt} = \frac{1}{k}\Big[\frac{\partial f}{\partial d}\frac{\partial d}{\partial m}\Big]. \tag{17}$$

For the shallow water condition, the right hand side of the equations (1) and (14) need to be extended to include the additional source function S_{bf} representing the energy loss due to bottom friction and percolation. The bottom friction dissipation term, S_{bf}, is represented according to the formulation proposed during the Joint North Sea Wave Project (JONSWAP) by Hasselmann et al. [8],

$$S_{bf} = -\frac{\Gamma}{g^2}\frac{\omega^2}{\sinh^2 kD}F \tag{18}$$

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

ACKNOWLEDGMENTS

The authors would like to acknowledge the Commission on Higher Education for kindly providing financial support to Mr. Worachat Wannawong under the Strategic Scholarships Fellowships Frontier Research Networks (CHE–PhD–THA–NEU) in 2007. The authors are grateful to the Geo–Informatics and Space Technology Development Agency (Public Organization) (GISTDA) for buoy data and documents. The authors also wish to thanks Cdr. Wiriya Lueangaram of the Meteorological Division, Hydrographic Department, Royal Thai Navy, Sattahip, Chonburi, Thailand, for providing laboratory space. Finally, the authors are greatly indebted to Mr. Michael Willing and Miss Donlaporn Sae–tae for helpful comments on English grammar and usage.

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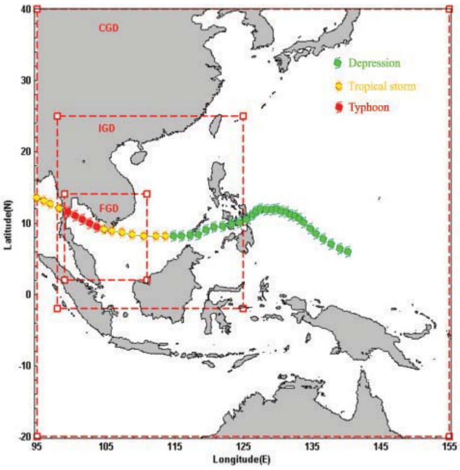

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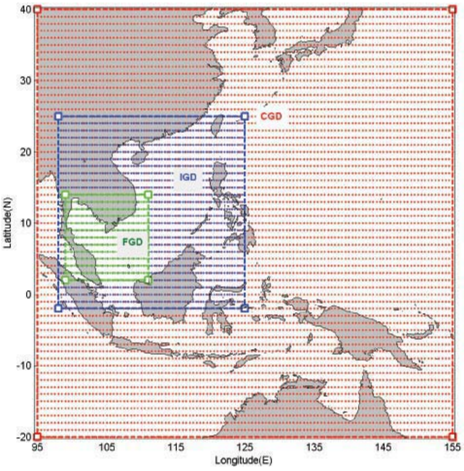

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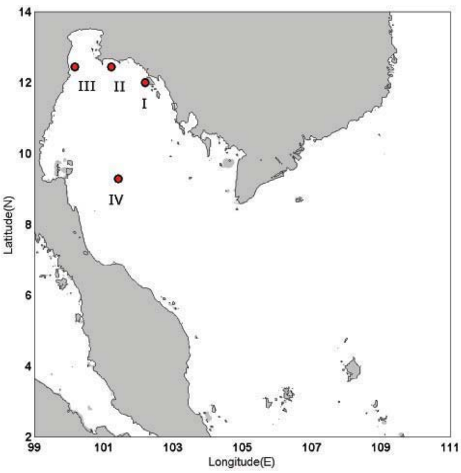
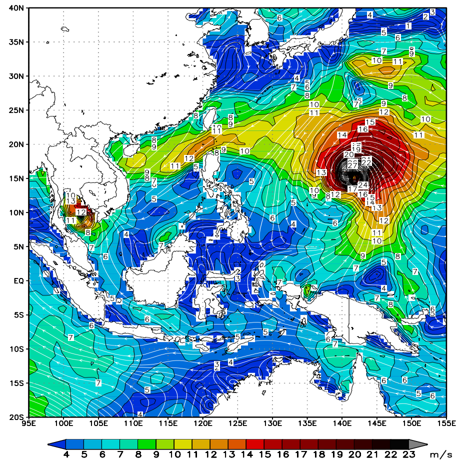


(c)

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



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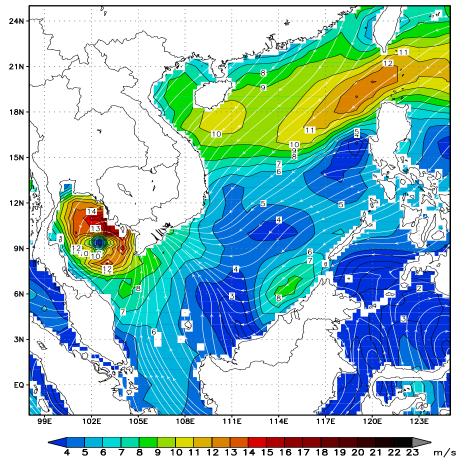
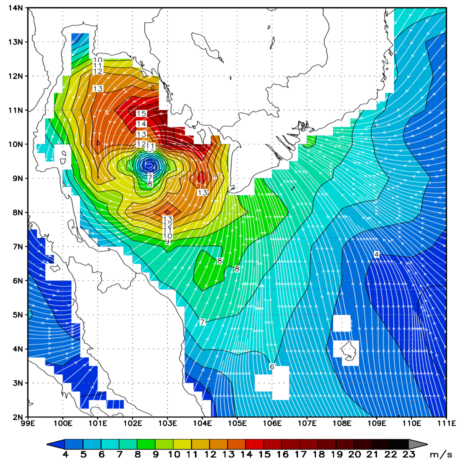
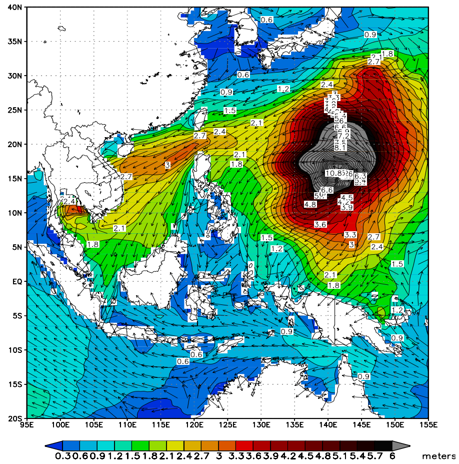


(b)

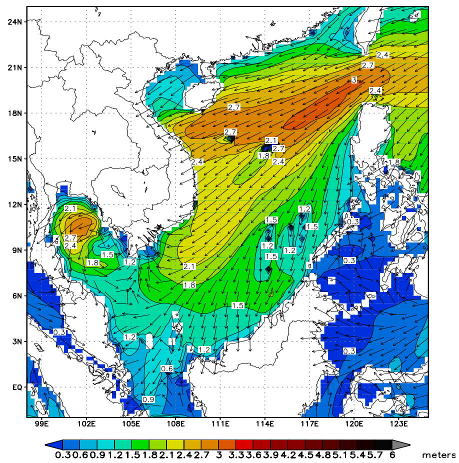


(c)

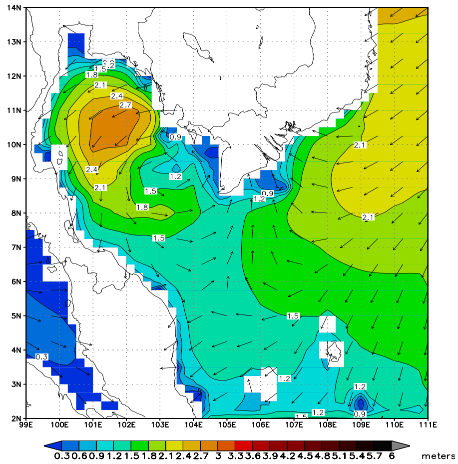
Fig. 2. Wind speed and streamline at 00UTC03NOV1997 in the: (a) CGD, (b) IGD and (c) FGD.



(a)

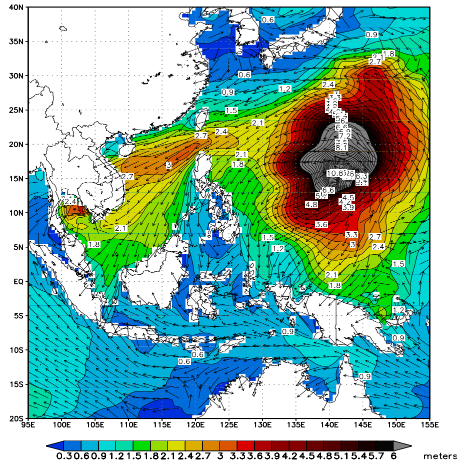


(b)

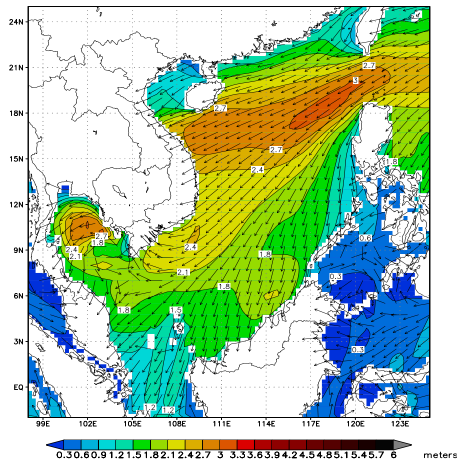


(c)

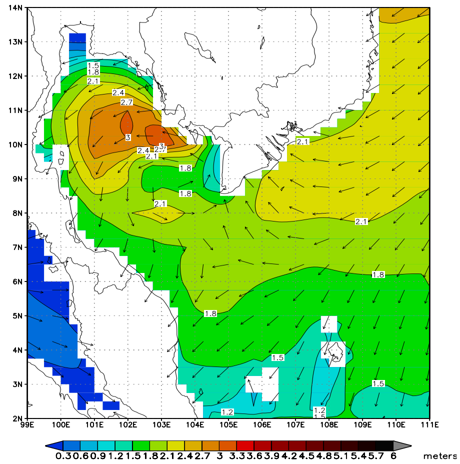
Fig. 3. The Hs and direction at 00UTC03NOV1997 of Experiment I in the: (a) CGD, (b) IGD and (c) FGD.



(a)

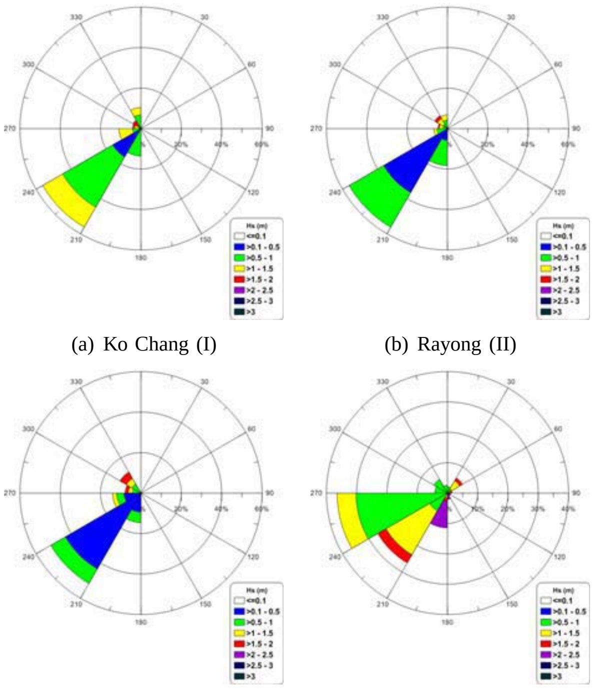


(b)



(c)

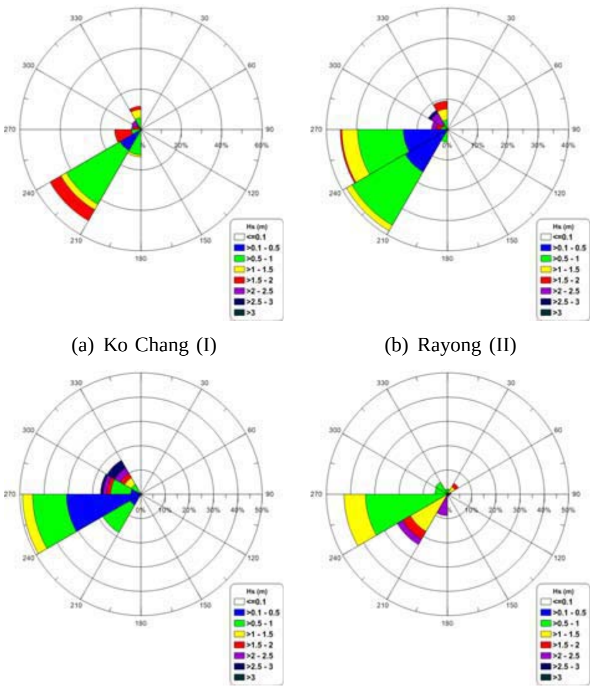
Fig. 4. The Hs and direction at 00UTC03NOV1997 of Experiment II in the: (a) CGD, (b) IGD and (c) FGD.



(a) Ko Chang (I) (b) Rayong (II)

(c) Huahin (III) (d) Satun based weather (IV)

Fig. 5. The summary of the Hs and direction simulations of Experiment I.



(a) Ko Chang (I) (b) Rayong (II)

(c) Huahin (III) (d) Satun based weather (IV)

Fig. 6. The summary of the Hs and direction simulations of Experiment II.