Virtual Wave : an Algorithm for Visualization of Ocean Wave Forecast in the Gulf of Thailand

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ABSTRACT

In this paper, a case study of sea wave generated by tropical cyclone in the Gulf of Thailand is carried out by using the cycle 4 version of the WAM (Wave Model) model. The model domain currently covers from latitudes 5N -15N and longitudes 95E -105E, and the model spatial resolution reaches 0.25 degree. Comparisons among the model results, the platform demonstrate that the model can fairly reproduce the observed characteristics of waves and this paper presents a new method to simulate virtual ocean wave surface. One of the widely used methods for simulating ocean wave is making use of wind-wave spectrums. The ocean waves produced in this way can reflect the statistical characteristics of the real ocean well, they just look like superposition of significant wave height. In order to overcome this shortcoming of traditional method, the new method proposed in this paper take account of the effect of the 10 meters wind field over ocean surface. The virtual ocean wave simulated by this way is not only accord with statistical characteristics, but also looks like real ocean wave, it can be widely used in VR (Virtual Reality) applications.

KEYWORDS: WAM cycle 4, Significant wave height, Typhoon Linda 1997, Virtual Reality, Visualization, Virtual Wave

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1. INTRODUCTION

The WAM model, a third generation wave model developed by WAMDI-group [12] and improved by Komen et al. [5], is one of the best-tested wave models in the world. It is widely used for global and regional operational wave forecast in many marine and meteorological centers around the world. For representing the model output, visualization tools are important for showing all simulated data and can be used for validation the model. In this paper, Virtual Wave is an algorithm for visualizing the WAM model output in 3D Virtual Reality.

2. THE WAM MODEL

The WAM model is a state-of-the-art third-generation spectral wave model, which solves the wave energy balance equation without any priori assumptions on the shape of the wave energy spectrum. Denoting the two dimensional frequency (f)-direction (θ) wave variance spectrum by $F(f, \theta)$, the model equation reads:

$$\frac{\partial F}{\partial t} + \nabla \cdot (C_g F) = S \qquad \text{-----------------------(1)}$$

where C_g is the group velocity, and S is the net source function describing the rate of change of the wave spectrum, which includes wind input (S_{in}), nonlinear wave-wave interaction (S_{nl}) and energy dissipation functions due to white capping (S_{ds}) and bottom friction (S_{bt}), that is,

$$S = S_{in} + S_{ds} + S_{nl} + S_{bt} \qquad \text{-----------------------(2)}$$

The WAM model used here is the most recent version WAM Cycle 4 developed by Komen et al. [5]. There is an improvement in this cycle over the earlier cycles. It contains: (1) current-induced refraction (U=0 in this paper), (2) nesting, (3) the wind input term takes into account the feedback of the growing waves on the wind profile, (4) Dissipation due to the white capping, the least well-known source function, is clear now. There is some freedom in redefining the wind input and returning the dissipation constants, the only puzzle is the absolute magnitude of wind input and dissipation. By improving the wind input and dissipation term, the model gives more realistic growth rates of the waves.

The wind input source term represents the work done by the wind on the ocean surface to produce waves. The wind generation of waves takes place in the high frequency part of the spectrum, i.e. it produces the relatively short waves (the order of a few meters and less) which can be observed when wind is blowing on the surface. The basic theory behind wind input term was developed by Miles [6]. And it assumes a linear relationship between wave energy and the rate of change of energy,

$$\frac{\partial F}{\partial t} = S_{in} = \gamma \ F \qquad \text{---------------------- (3)}$$

which gives an exponential growth of wave energy with time

$$F \approx F_0 e^{\gamma t}$$

A realistic parameterization of the interaction between wind and wave was given by Janssen [3], a summary of which is given below. The basic assumption Janssen [3] made, which was corroborated by his numerical results of 1989, was that even for young wind sea,

the wind profile has a logarithmic shape, though with a roughness length that depends on the wave-induced stress. As shown by Miles [6], the growth rate of gravity waves due to wind then only depends on two parameters, namely

$$x = \frac{u_*}{C} \cos(\theta - \phi)$$

$$\Omega_m = \frac{g z_0}{u_*^2}$$

---------------------- (4)

with u_* the friction velocity, θ the direction in which the waves propagate, ϕ the wind direction, C the phase speed of the waves and z_0 the roughness length. Thus, through Ω_m the growth rate depends on the roughness, which on its turn depends on the sea state. The growth rate, normalized by angular frequency ω, is given as

$$\frac{\gamma}{\omega} = \varepsilon \; \beta x^2$$

---------------------- (5)

where γ is the growth rate, ω the angular frequency, ε the air-water density ratio and β the so-called Miles' parameter. In terms of the dimensionless critical height $\mu = k z_c$ (with k the wave number and z_c the critical height defined by $u_0 (z = z_c) = c$) Miles' parameter. becomes

$$\beta = \frac{\beta_m}{k^2} \mu \ln^4(\mu), \; \mu \le 1$$

---------------------- (6)

where k is the von Kármán constant and β_m a constant. In terms of wave and wind quantities μ is given as

$$\mu = (\frac{u_*}{kc})^2 \Omega_m \exp(\frac{k}{x})$$

---------------------- (7)

For positive values of the growth rate the wind will give at net input of wave energy to the ocean. In the wave model WAM this growth rate is always either positive or zero. It is important to note that in the real world, the growth rate may also have negative values. This means that the flow of energy is from the waves to the wind, i.e. that waves may generate wind. An example of this is very long waves or wind blowing in the opposite direction of the wind.

Wave energy may be lost from the ocean in two different ways; wave breaking and frictional dissipation caused by velocity differences. White capping and breaking of waves takes energy from the waves and transfers some of it into current, the rest is dissipated, which means that mechanical energy is lost and water is heated up. The physical process that takes place during wave breaking and white capping is extremely difficult to model. And in wave models, these processes are parameterized by using data from several measurements.

The dissipation source term is based on K. Hasselmanns [2] white capping theory according to Komen et al. [4]. In order to obtain a proper energy balance at high-frequencies the dissipation by white capping was extended by adding a k^2 term, thus

$$S_{ds} = (-\gamma_d) F$$

-------------------- (8)

$$\gamma_d = \frac{1}{2} C_{ds} <\omega>(<k>^2 m_0)^2 (\frac{k}{<k>}+(\frac{k}{<k>})^2) \quad \text{-------------------- (9)}$$

where C_{ds} is constants, m_0 is the total wave variance per square meters, k the wavenumber and $<\omega>$ and $<k>$ are the mean angular frequency and mean wavenumber, respectively.

On the other hand, the dissipation of energy that takes place within the fluid because of velocity differences may by modeled in a way similar to that of wind input, as a linear relationship between the wave energy and the rate of change of energy.

If wind input and frictional dissipation was the only process that was acting to change the energy spectrum, ocean waves would consist of only short surface waves. Apparently, the ocean also consists of long swells, which could not be generated by the wind directly. Such long waves are the result of energy cascades that takes energy from the short wind waves and feeds the longer waves with energy. When the wave amplitude becomes large, three waves with different wavelengths may interact through mechanical resonance and create a fourth wavelength. Only a limited combination of waves makes this possible.

Evaluating the functional derivative of the energy of the wave F with respect to a^* then gives the deterministic evolution equation for a .

$$\frac{\partial}{\partial t}(a_1 + i\omega_1 a_1) = -i \int dk_2 \, dk_3 \, V_{1,2,3} a_2 a_3 \delta(k_1 - k_2 - k_3)$$
$$+ ... + -i \int dk_2 dk_3 dk_4 W_{1,2,3,4} \delta(k_1 + k_2 - k_3 - k_4) a_2^* a_3 a_4 \tag{10}$$

Where V and W are known functions of wavenumber. To summarize, the evolution equation allows both three- and four-wave interactions, where for three-wave processes the resonance conditions in (11)

$$\omega_1 \pm \omega_2 \pm \omega_3 = 0, \quad k_1 \pm k_2 \pm k_3 = 0 \tag{11}$$

should be satisfied simultaneously, and for four wave processes the resonance conditions in (12)

$$\omega_1 + \omega_2 - \omega_3 - \omega_4 = 0, \quad k_1 + k_2 = k_3 + k_4 \tag{12}$$

where the components 1, 2 and 3 exchange energy with component 1. Expressions for the exchange of energy due to this mechanism, Pierson-Moskowitz spectrum is applied. This is a narrow-banded wave superposed on a Pierson-Moskowitz wave with the same peak frequency. As a representation of the JONSWAP spectrum however, this model is crude and the results are approximate only.

The bottom may induce wave energy dissipation in various ways: e.g. friction, percolation (water penetrating the bottom) wave induced bottom motion and breaking. Outside the surf zone, bottom friction is usually the most relevant. It is essentially nothing but the effort of the waves to maintain a turbulent boundary layer just above the bottom.

Several formulations have been suggested for the bottom friction. A fairly simple expression, in terms of the energy balance is due to Hasselmann et al. [2] in the JONSWAP project:

$$S_{bt}(\omega,\theta) = -\Gamma \frac{\omega^2}{g^2 \sinh kd} F(\omega,\theta) \qquad \text{---------- (13)}$$

Where Γ is an empirically determined coefficient. Tolman [11] shows that this expression is very similar in its effects to more complex expressions that have been proposed.

3. SETUP OF WAM MODEL CALCULATION

The system consists of two grids named coarse (Figure. 1(a)) and fine (Figure. 1(b)). The coarse grid has a grid size of 0.5 deg. by 0.5 deg. It covers from latitude 0 deg. N to 25 deg. N and from longitude 90 deg. E to 115 deg. E. The purpose of this grid is to simulate swell which may propagate to the area of interest from far north and far south in the model domain. It also provides boundary conditions for the fine grid. The fine grid extends from 95 deg. E to 105 deg. E and from 5 deg. N to 15 deg. N. It covers the east coast and the Gulf of Thailand. The purpose of the Gulf of Thailand is to simulate typhoon waves generated in the region entering the gulf through the Vietnam Cape. The grid size is 1/4 deg. by 1/4 deg..

Coarse grid resolutions are 0.5 x 0.5 degree latitude-longitude and subgrid squares can be run in a nested mode. In a course grid run the spectra can be outputted at the boundaries of a subgrid.
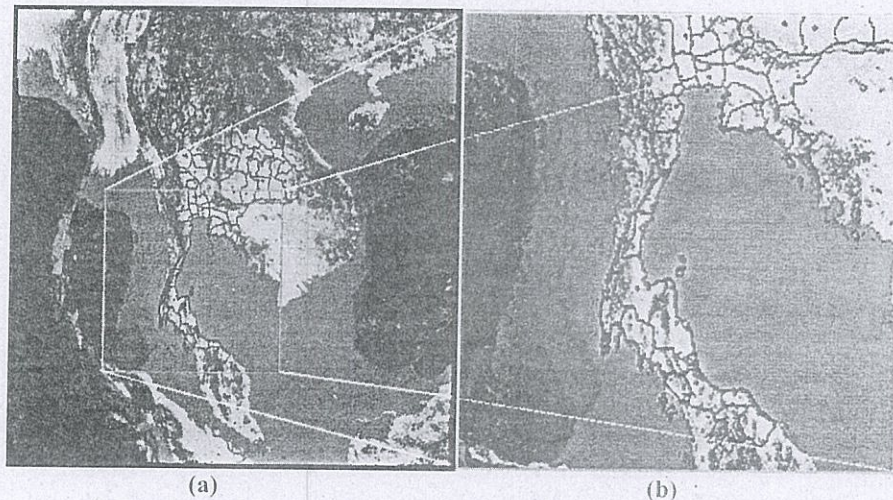

(a)   (b)

Figure 1. (a) Boundary of coarse grid, and (b) boundary of nested grid

They can then be interpolated in space and time to the boundary points of the fine subgrid and the model can be rerun on the fine mesh grid at resolutions are 0.25 x 0.25 degree latitude-longitude. The product generated is a gridded field that supplies wave height, period and direction. WAM requires surface wind (U_{10}) forcing from meteorological model output such as from NOGAPS, there is resolution of 10 meters wind at 1 x 1 degree latitude-longitude.

4. A CASE STUDY

Typhoon Linda 1997

In 1997 Typhoon Linda occurred in the South China Sea and reached typhoon intensity shortly after entering the Gulf of Thailand. The cyclone turned northwestward following steering from the subtropical ridge. The impact of Typhoon Linda caused strong winds and heavy rainfall, there are moored buoys in the Gulf of Thailand, they measured meteorological oceanography data and Huahin buoy measured significant wave height about 3 - 4 meters, especially in the coastal zone of eastern part and east coast of southern part. After that the system weakened slightly to 50 knots (92.65 km/hrs) prior to striking Thabsakae district, Prachuap Khiri Khan province, Thailand at 1900Z on 3 November. Crossing the southern part of Thailand, Linda further weakened as it encountered the region's mountains.

Tropical depression 2003

This tropical cyclone is formulated from low pressure and then it reached tropical depression in evening of 22 October 2003 at lat. 10.2 N and long. 101 E. In the beginning the tropical depression did not move until 24 October 2003, it moved a little bit northward and closer the eastern shore of southern part of Thailand and in the afternoon of 24 October 2003, it struck Prachuap Khiri Khan province.

Tropical storm 2004

Tropical storm Muifa was born off the east coast of Leyte Island, Philippines as typhoon status. It was moving slowly across South China Sea to become a long-life typhoon and draw near to the southern part of Vietnam, Ho-Chi-Minh, and then was forecast to reach as far as Malay Peninsula. It passed near Vietnam and moving across Gulf of Thailand toward southern part of Thailand. It keeps westward track and the system weakened prior to striking the coastal of Surat Thani province.

5. WAM INPUT AND OUTPUT

The model can be integrated with independently chosen propagation, source term such as topographic data, wind input and wind output time steps. The following table shows the WAM output directories which used in Virtual Wave software.

Output Directory	Meaning	Symbol in the model
WAVEHGT	Significant wave height	Hs
WAVEDIR	Mean wave direction	θ
WAVESPD	Wave Speed	C
M_FREQY	Mean frequency	f
USTAR10	Friction velocity	u_*
WINDDIR	Wind direction	ϕ
WINDSPD	Wind Speed	U_{10}
P_FREQY	Wave peak frequency	f_p

6. VISUALIZATION ALGORITHM

For visualizing the tropical cyclone moving through the Gulf of Thailand, the output results from WAM model are needed. The algorithm for visualizing the ocean wave forecast is shown below.

Virtual Wave Algorithm

1. Read Topography (Earth grid points)
2. Read WAM Output of all time steps (every 3 hours, UTC-Time)
    2.1 Input the period of simulation given by user (starting date, ending date)
    2.2 Read Wave Height (WAVEHGT, Hs)
    2.3 Read Wave Direction (WAVEDIR, θ)
    2.4 Read Wind Speed (WINDSPD, U_{10}), Wind Direction (WINDDIR, ϕ)
    2.5 Read Wave Frequency (M_FREQY, f)
3. Calculate significant wave height (Hs) and surface elevation (η) of all points
    3.1 Significant wave height (Hs) and maximum wave height (H_{max})

$$Hs(x,t) = \frac{Hs}{10} \quad ; \quad H_{max} = 1.9 Hs(x,t)$$

    3.2 Surface elevation (η)

$$\eta(x,t) = \frac{Hs}{2} \sin(-2\pi f t)$$

4. Visualize and animate all data of all time steps
    4.1 For each time step (every 3 hours)
- draw topography using average normal vector for smoothing surface and texture mapping technique for realistic map
- draw significant wave height as color range (blue→ yellow→ red) or surface elevation as color range (blue→ sky blue) by toggle menu
- draw arrow of wave direction using wave speed represents the length
- draw arrow of wind direction using wind speed represents the length
- draw color map of significant wave height (Hs) or maximum wave height (H_{max})
- draw the Thailand flag for the interesting point from user and display the graph of wind speed, significant wave height, wind and wave direction and the period of the wave
- draw the center of storm (in case there is storm) which calculated from wind speed information
- display the date time

5. Output files of each frame can be captured to JPEG or GIF file, and automatically embedded to GIF animation file. The graph can be saved to JPEG or BMP file format. (This is only optional step by the end user.)

7. VISUALIZATION RESULTS

There are three cases for showing in this paper. There are Typhoon Linda 1997, Tropical depression 2003, and Tropical Storm 2004. Virtual Wave is 3D visualization tool for

WAM model, but the following results are shown by top view for easily understanding. The result of Typhoon Linda 1997 is shown in Figure 2. Figure 3 shows tropical depression 2003, and Figure 4 is tropical storm "Muifa" 2004.
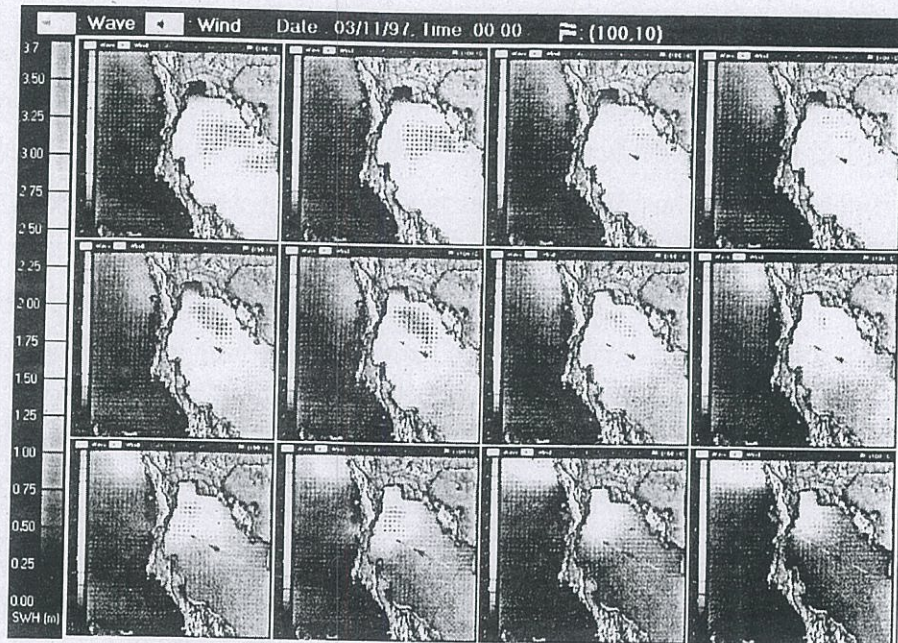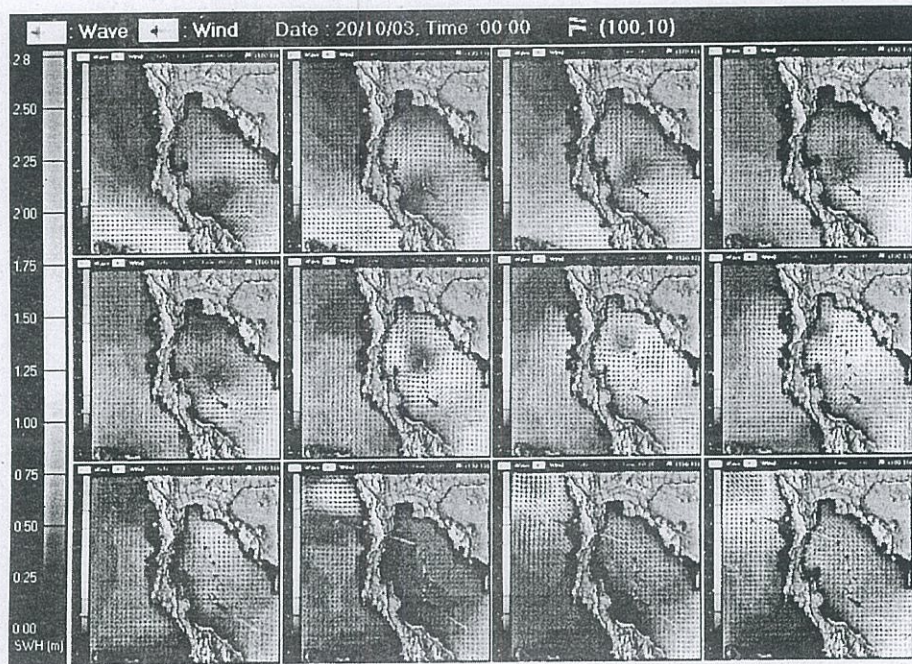

Figure 2. Typhoon Linda 1997, from the date 03/11/1997 Time 00:00 to 04/11/1997 Time 09:00. The images show every 3 hours per frame from top-left to bottom-right. Maximum significant wave height is 3.70 meters.

The comparison of significant wave height and surface elevation is shown in Figure 5 (a) and (b), respectively.

Comparison of wave height and wave period time series at the Hua-Hin buoy (HHN) station is shown in Figure 6. In general, the modeled wave heights underestimate the observed wave heights especially in extreme cases. This amounts to an underestimation by as much as 20%. The wave buoy reported a maximum of 4.06 m significant wave height, whereas the simulated value is approximately 3.2 m at 06 UTC in November 3, 1997. Difference of nearly 1 m wave height can be attributed to: i) the limited "local" quality of the wind field (since the NOGAPS wind data correspond to a grid size of 1.0 deg. resolution while the WAM model grid size is 0.25 deg.) and ii) the enhanced energy dissipation due to the centered differences used in the model and the relatively close presence of a "diagonal" boundary. The comparison in term of the time series peak wave period also reveals that from the beginning of the simulation to 481 hours there were mainly sea waves. After this time the peak period increased to 6 seconds (Buoy data) and 7.4 seconds (WAM), denoting a clear effect of typhoon LINDA winds on swell waves.
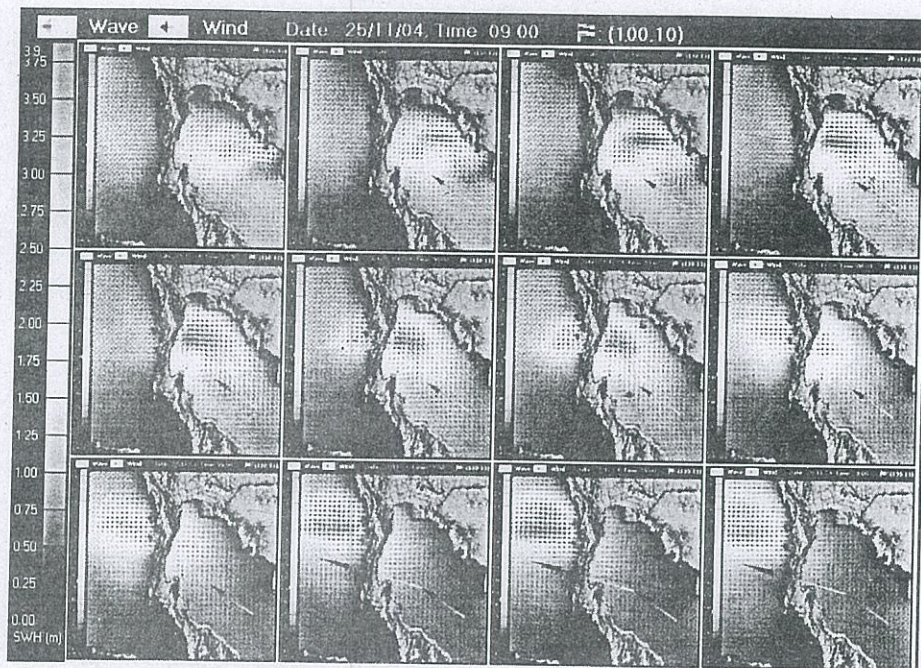
Figure 3. Tropical depression 2003, from the date 21/10/2003 Time 00:00 to 26/10/2003 Time 12:00. The images show every 12 hours per frame from top-left to bottom-right. Maximum significant wave height is 2.80 meters.

8. CONCLUSION AND FURTHER WORK

From the simulation, the Virtual Wave is suitable algorithm for visualizing the ocean wave forecast from WAM model output in the Gulf of Thailand as a case study. The Virtual Wave can be used for other topographical grids. It is planed for combining ocean wave and weather forecast together. The Virtual Wave has nowadays been used for daily ocean wave forecast and four day in advance in the department of Meteorology, Bangkok, Thailand. Figure 5 (c) shows the Virtual Wave software. Virtual Wave software is programmed by using Delphi Borland 7 for user interface and OpenGL (Open Graphic Library) [10] for 3D graphic visualization. More information about Virtual Wave for ocean wave forecast, the web site is : http://www.tmd.go.th/~marine/
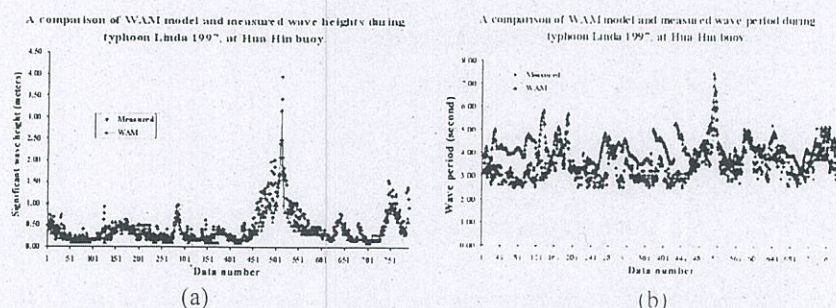
Figure 4. Tropical storm Muifa 2004, from the date 25/11/2004 Time 09:00 to 26/11/2004 Time 18:00. The images show every 3 hours per frame from top-left to bottom-right. Maximum significant wave height is 3.90 meters.

(a)   (b)   (c)
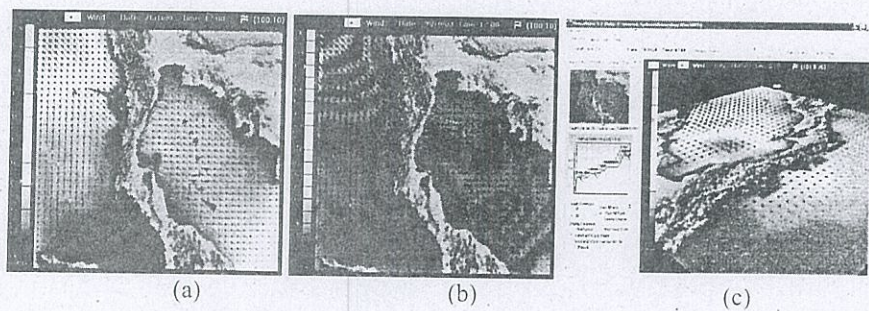
Figure 5. Comparison of (a) significant wave height and (b) surface elevation, (c) the 3D visualization tool namely Virtual Wave (perspective view)

Figure 6. Comparison of WAM model and measured wave height (a) and wave period (b) during typhoon Linda 1997, at Hua-Hin buoy.

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