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# Storm Surge in the Gulf of Thailand Generated by Typhoon Linda in 1997 Using Princeton Ocean Model (POM)

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## ABSTRACT

Princeton Ocean Model (POM) was applied to simulate tidal circulation in the Gulf of Thailand. The model grid space was 0.1° × 0.1° (11×11 $km^2$). The model was forced by eight tidal components ($M_2$, $K_1$, $O_1$, $S_2$, $Q_1$, $P_1$, $K_2$, and $N_2$) at the open boundary. The model results were verified using tidal data from 23 tide gauges in the Gulf of Thailand. The results showed that the calculated values from POM corresponded well with the observed ones. Then, the model was used to simulate sea level fluctuation in response to typhoon Linda which entered the Gulf in November 1997. In addition to tidal forcing at the open boundary, 12-hours predicted atmospheric pressure and wind field from Navy Operational Global Atmosphere Prediction System (NOGAPS) were forced above the model surface. The model results showed that POM can simulate Linda's storm-surge even though the model underestimated the peak rise and sea level fluctuation was out of phase by approximately 1 hour sometimes. The reason for this might be that coarse grid, average atmospheric and wind fields were used in this study. In addition, the unreal of land-sea boundary and depth value from ETOPO5 might give rise to abnormal high sea level at some area in the model.

**Key words:** Princeton Ocean Model (POM), storm surge, Typhoon Linda

## INTRODUCTION

Storm surge, an abnormal high sea level phenomenon, is generated by very low pressure accompanied with very strong wind (tropical storm). Naturally, the water can flow freely in the open sea during the occurring of tropical storm, but not on land. Therefore, water is piled-up at the shore and spilled over lands. This causes serious hazards to coastal regions, such as flooding, coastal erosion, etc., and devastating the properties of people who live in those areas.

There were 6 severe storms (typhoons) that previously crossed over the Gulf of Thailand, namely typhoon "Harriet" (1962), typhoon "GAY" (November,1989), typhoon "BECKY" (August, 1990), typhoon "FRED" (August, 1991), typhoon "FOREST" (November, 1992), typhoon "LINDA" (November, 1997) (Lekphiphol,1998). Typhoon "GAY" hit Changwat Chumporn causing serious disaster, such as destroying the agricultural lands (about 183,000 ha), killing over 400 people, and directly affecting 154,000 people. In 1997 typhoon Linda striked at Thupsake, Changwat Prachuapkirikhan, resulting in 30 people dead, 102 people missing, and more than 400,000 Rai of agricultural land destroyed.

Thus, the warning system is needed for

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people who live in risking coastal areas. But, at present, there is no such warning system of storm surge for coastal region in Thailand. The aim of this research is to examine how storm surge affect sea surface elevation and to predict the sea surface elevation disturbed by tropical storms in the Gulf of Thailand. In this study, Typhoon Linda was used because we have sufficient data not only to serve as inputs in the model, but also to verify the model results. In the future, this information can then be useful in developing the warning system.

There are two and three dimensional models for storm surge simulation. For the coastal area, both models solved the shallow water equations to simulate the current, sea surface elevation, and significant wave height disturbed by storm. Princeton Ocean Model (POM) which was developed by Blumberg and Mellor in 1987 is a three-dimensional and fully non-linear ocean circulation model using realistic topography. It was used to simulate the circulation at various places such as the Straits of Florida (Mooers et.al., 1996). Moreover, these models were applied to investigate the other phenomena. POM was also implemented to study the effects of storm in many countries, for instance, South China Sea (Chu *et al*., 1996), hurricane Andrew in the Gulf of Mexico (Keen, 1998), and hurricane Fran in 1996 at North Carolina (Wu *et al*., 2002).

## METHODOLOGY

Princeton Ocean Model (POM) is the 3-dimensional ocean model which can simulate the flows and sea surface height for coastal ocean, estuaries and rivers. In the vertical coordinate uses sigma coordinate instead of z-coordinate with conservation equations for momentum, temperature, salinity and turbulence variables. In ordinary, z-coordinate system, water is divided to a number of equal-spaced layers while that of sigma coordinate system is divided into equal numbers of layers which are scaled to local depth.

Parameters used in this study were described below:

| Domain | Latitude 3°-14° N and |
|---|---|
| | Longitude 99°-109°E |
| Horizontal grid resolution | 0.1 ° (111 × 101 grid) |
| Vertical resolution | 21 levels |
| Density of water | 1025 kg/m3 |
| Density of air | 1.03 kg/m3 |
| Bottom Roughness | 0.01 |
| Internal time step | 10 minutes |
| External time step | 10 seconds |

Bathymetry was extracted from ETOPO5 publicly accessible ocean bottom database. Salinity and temperature data from Levitus 1994 to each model grid point.

Wind and pressure data were obtained from the U.S. Navy Global Atmospheric Prediction System (NOGAPS), a global atmospheric forecast model with approximately 1° (about 110 km) grid spacing. The forcing fields were obtained from the Master Environmental Library (MEL). But these data are not available on the model grids, so the bilinear interpolation was used to interpolate the data set of 1°×1° grid to 0.1° × 0.1° grids.

Tidal elevation and current at the East and South boundaries were derived from Oregon State University (OSU) Tidal Inversion Software (OTIS) regional scale (1/6 ) model of Indonesian Seas (Egbert and Erofeeva, 2002) in form of harmonic constants. Eight principal tidal constituents were used in this model composed of four diurnal tides ($K_1$, $O_1$, $Q_1$, $P_1$) and semi-diurnal tides ($M_2$, $S_2$, K2, $N_2$) were used to compute tidal elevation by following equation (Pugh, 1987):

$$h(t) = \sum A_i \cos[(V_o + u)_i + \sigma_i t - \kappa_i]$$

where is the amplitude of constituent

$K_i$ : the phase lag behind equilibrium for constituent

$(V_o+U)_{pi}$ : nodal factor

$\sigma_i$ : phase increment per mean solar hour of constituent

The purpose of this experiment is to examine the interaction between tide and surge, and simulate the sea surface elevation disturbed by tropical storm "Linda" in 1997. The model was driven by the combination of the meteorological data (wind and pressure), which were exerted on the surface of the model, and co-oscillation tide at the open boundaries. Wind and pressure data came in the form of 12-hours forecast starting from 21$^{st}$ October to 10$^{th}$ November 1997. The hourly time series of calculation of sea surface height were compared with the observed values at the tide gauges.

Experiment was designed into 4 sub-experiments using different surface drag coefficients.

| Experiment | Drag coefficient |
|---|---|
| A | $C_w = (0.63 + 0.066*W)*10^{-3}$ |
| B | $C_w = 0.0011$ for W < 6 m/s |
| | $C_w = (0.61 + 0.063*W)*10^{-3}$ for 6≤W≤22 m/s |
| | $C_w = (1 + 0.07*W)*10^{-3}$ for W >22 m/s |
| C | $C_w = 1*10^{-3}$ for W < 7 m/s |
| | $C_w = (0.1923 + 0.1154*W)*10^{-3}$ for 7≤W≤20 m/s |
| | $C_w = 2.5*10^{-3}$ for W>20 m/s |
| D | $C_w = (0.63 + (0.066 * W^2)^{1/2}) * 10^{-3}$ |

**Statistics**

The accuracy of a model for this purpose could be assessed by calculating the differences between the model and observed elevation and timing.

The goodness-of-fit between the time series of the model and observed elevations could be described by the following reliability index, RI (Keen *et.al.*, 1998)

$$RI_i = \frac{1 + \sqrt{\frac{1}{T}\sum_{t=1}^{T}\left[\frac{1 - Y_{ti} / X_{ti}}{1 + Y_{ti} / X_{ti}}\right]^2}}{1 - \sqrt{\frac{1}{T}\sum_{t=1}^{T}\left[\frac{1 - Y_{ti} / X_{ti}}{1 + Y_{ti} / X_{ti}}\right]^2}}$$

where $i$ is the mooring number; $T$ is the total number of pairs of data points in the time series; $Y_{ti}$ is the observation at mooring $i$ for time t ; $Xti$ is the model result at the same location and time.

The model predictions are accurate within a factor of RI, that is the observed values fall within 1/RI and RI times the corresponding predicted values.

## RESULTS AND DISCUSSION

The interaction between tide and surge was carried out based on the occurrence of Typhoon Linda. The hydrodynamic model was executed covering the period from 20$^{th}$ October 1997 to 9$^{th}$ November 1997. Tide strongly affected the sea surface elevation. However, during strong wind condition (tropical storm), the sea surface elevation was also dominated by wind surge as depicted in Figure 1. Thus, it is necessary to combine the effect of tide and meteorological factors into the simulation of the sea surface elevation.

The results showed that POM could simulate Linda's storm-surge but the sea level was under estimated. Since the grid spacing of wind and pressure data from NOGAPS was too coarse to properly forecast weather features with scales of less than about 200 km. As a result, tropical storms are less intense in NOGAPS forecasts than observed, and might follow different tracks than real storms.

Especially Ko Prab station, the predictions were not clearly correlated with the observed sea level because the coarse and inaccurate bathymetry used for the simulation.

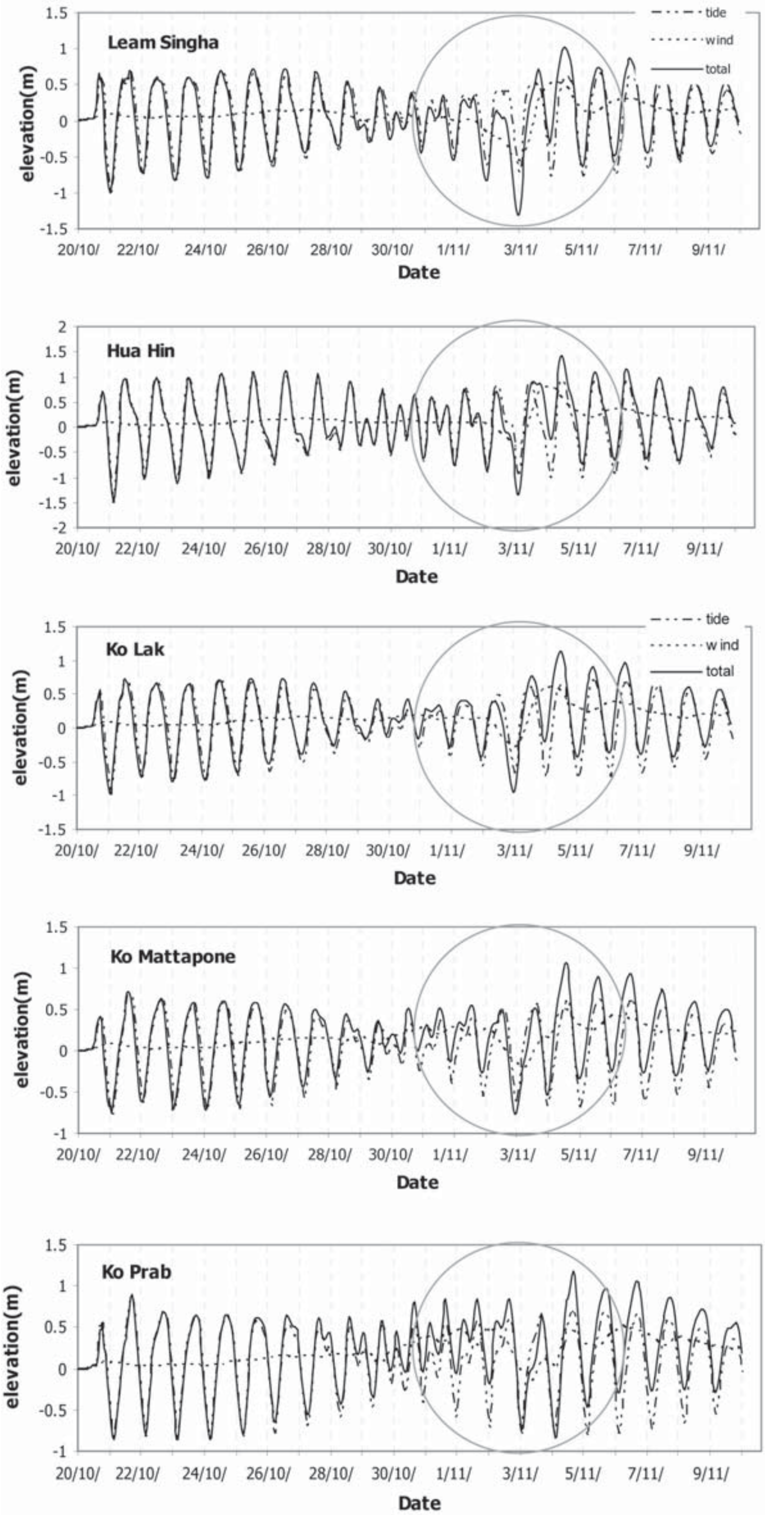


**Figure 1** Temporal variation of the total water level from the hydrodynamic model based on POM for the period 20th October to 9th November 1997 at 5 tide gauge stations.

There were only four tide gauge data available during this period, namely Leam Singha, Ko Lak, Ko Mattapone, and Ko Prab. Sea surface elevation from POM and from tide gauges fluctuated in similar pattern. These plots showed that the surface elevation from POM correlated with the observed elevation at almost all stations, except at Ko Prab station. They showed a sudden drop of sea level as Linda entered the Gulf. Then, when Linda approached, there was a rapid rise of sea level to the highest point on 4$^{th}$ November at 12.00 am. After that, the sea level gradually dropped to normal fluctuation.

The results of sea surface elevations from each experiment were distinctive. At all stations, the model overestimated the sea surface elevation before the storm approached; in contrast, after the storm crossed over the Gulf, the model underestimated the sea surface elevation. During the storm surge, the peak sea surface elevation from POM was lower than the observed values. One reason was wind field which, for this study, was derived from global numerical weather prediction model with coarse resolution (1 degree), resulting in uniform wind field over the Inner Gulf. Moreover, the model only responded to prescribed tide, wind, and initial horizontal density gradient and stratification in the water column. The other governing processes were not considered by this model such as fresh water discharge.

In addition, the accuracy of a model for this purpose could be assessed by calculating the differences between the model and observed elevation and timing. The goodness-of-fit between the time series of the model and observed elevations can be described by the following reliability index, RI (Keen *et al.*,1998). The model predictions were perfect if RI equaled to 1 and no relationship when RI equadle to 0.

In summary, the best correlation between POM results and the observed values was found in experiment D by considering the correlation coefficients () and Reliability Index (RI) (see Table 1 and 2). Therefore,  in experiment D was used to calculate wind stress.

The wind stress and simulated currents from the model was illustrated in Figure 2 (selected scenes). The strong current was produced by strong wind, flowed from the South China Sea into the Gulf of Thailand. The pattern of circulation from the model agreed well with the best track data of Typhoon Linda.

**Table 1** The Correlation Coefficient ($R^2$) of each experiment.

| Experiment | RI | | | |
|---|---|---|---|---|
| | Leam Singha | Ko Lak | Ko Mattapone | Ko Prab |
| A | 0.84 | 0.83 | 0.79 | 0.63 |
| B | 0.84 | 0.84 | 0.84 | 0.73 |
| C | 0.83 | 0.84 | 0.80 | 0.64 |
| D | 0.84 | 0.84 | 0.83 | 0.64 |

**Table 2** The Reliability Index of each experiment.

| Experiment | RI | | | |
|---|---|---|---|---|
| | Leam Singha | Ko Lak | Ko Mattapone | Ko Prab |
| A | 1.11 | 1.10 | 1.10 | 1.17 |
| B | 1.13 | 1.14 | 1.12 | 1.20 |
| C | 1.11 | 1.10 | 1.10 | 1.16 |
| D | 1.11 | 1.10 | 1.10 | 1.16 |

The variation in currents and sea surface elevations could be divided into 3 stages: before the passage of storm surge, the existing of storm surge and after the passage of surge.

The first stage (before the passage of storm surge), in general, the current in the Gulf were dominated by tide (see Figure 2(A) and (B)). The currents flowed out from the inner of the Gulf (ebb tide) into South China Sea; in simultaneously, the strong current flowed northwestward from South China Sea into the Gulf. It was divided the circulation into two parts at the South of Cape Camau of Vietnam, one moved westward into the southeastern part of the Gulf of Thailand along the coast of Cambodia and Vietnam, and the other moved southward along the coast of Malaysia. Twelve hours later, the currents flowed northward along the eastern and western of the Gulf into the Gulf (flood tide).

The second stage (during the occurring of storm surge), the developing of typhoon Linda starting on 2 November 1997 at 000 UTC to 4 November 1997 is depicted in Figure 3(C) to (G). On 2 November 1997 at 000 UTC, the typhoon wind was located at latitude 8.2 N and longitude 107.6 E. Its central pressure and maximum wind speed was 995 millibars and 45 knots respectively. Then, it moved northeastward to Cape Camau of Vietnam in twelve hours later. After that, it moved in the same direction into the Gulf, and hit the coast at Thupsake, Changwat Prachupkirikhun at 0.00 on 4$^{th}$ November 1997. These figures showed that the strong current from South China Sea flowed northwestward into the Gulf, and turned to the north along the eastern part of the Gulf. After that, it turned to the southern part of the Gulf. As a result, a counter-clockwise circulation was presented at southern part of the Gulf.

The final stage (after the passage of surge), the currents decreased in strength but the counter-clockwise circulation existed in the same location. The currents from the upper Gulf moved southward along the eastern part of the Gulf and the coast of Vietnam and Cambodia into South China Sea (Figure 2(H)).

The simulated sea surface elevations from the model were shown in Figure 4(A) to (D). Before the occurring the storm, sea surface elevation fluctuated with tide (Figure 4(A) and (B)). Before the surge hit the land, the entire sea surface elevation decreased to the lowest point, and then the sea surface elevations sharply rose to the highest peak as the storm entered the Gulf (see Figure 4 (C) to (G)). After that, the sea level gradually decreases to normal fluctuation. The storm strongly affected on the sea surface elevation especially in the upper part of the Gulf (upper of the track) due to the shape of this area.

## CONCLUSIONS

In this study, POM was modified and applied to investigate the effect of typhoon Linda on the sea surface elevation in the Gulf of Thailand. The model was driven by the combination of wind stress from numerical weather prediction (12 hourly), co-oscillation tide in terms of harmonic constants at open boundaries, and initial climatological horizontal density gradient and stratification during the period from 20$^{th}$ October 1997 to 9$^{th}$ November 1997.

The use of numerical experiments indicates that tide was the essential factor to simulate the sea surface elevation in the Gulf of Thailand. However, the interaction between tide and wind accounted for sea elevation during storm surge period. The model accurately generated sea surface fluctuation although at some points, the fluctuation was not in phase with the observed tide. In case of strong wind (typhoon Linda), the maximum predicted water levels were less than observed maximum surge due to various reasons. The first reason was that lower wind fields and atmospheric pressure and coarse resolution were used in this study. Second, the coarse and inaccuracy bathymetry for model simulations

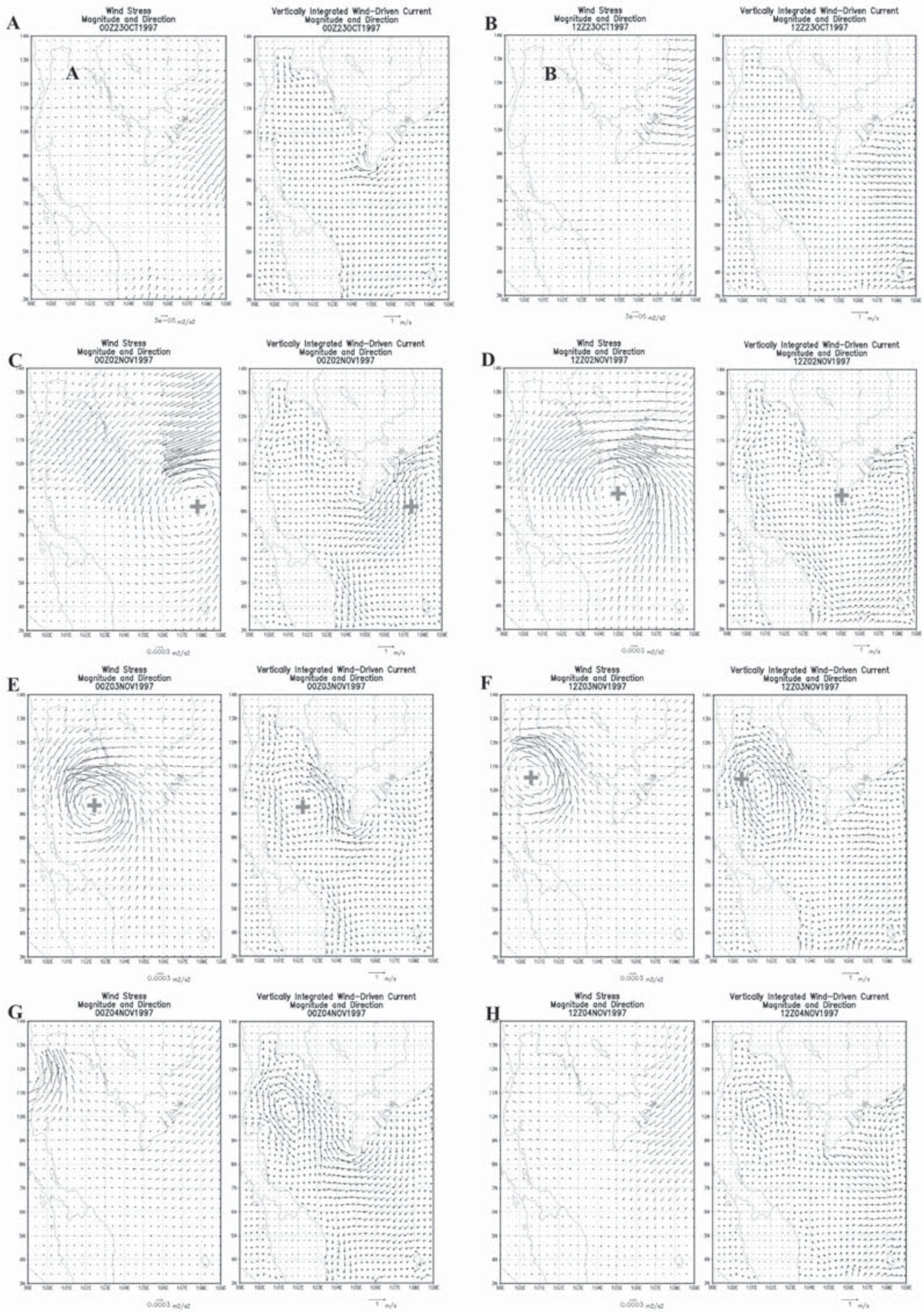


**Figure 2** The Simulated current (A) 23rd October 1997 at 00:00 (B) 23rd October 1997 at 12:00 (C) 2nd November 1997 at 00:00 (D) 2nd November 1997 at 12:00 (E) 3rd November 1997 at 00:00 (F) 3rd November 1997 at 12:00 (G) 4th November 1997 at 00:00 (H) 4th November 1997 at 12:00

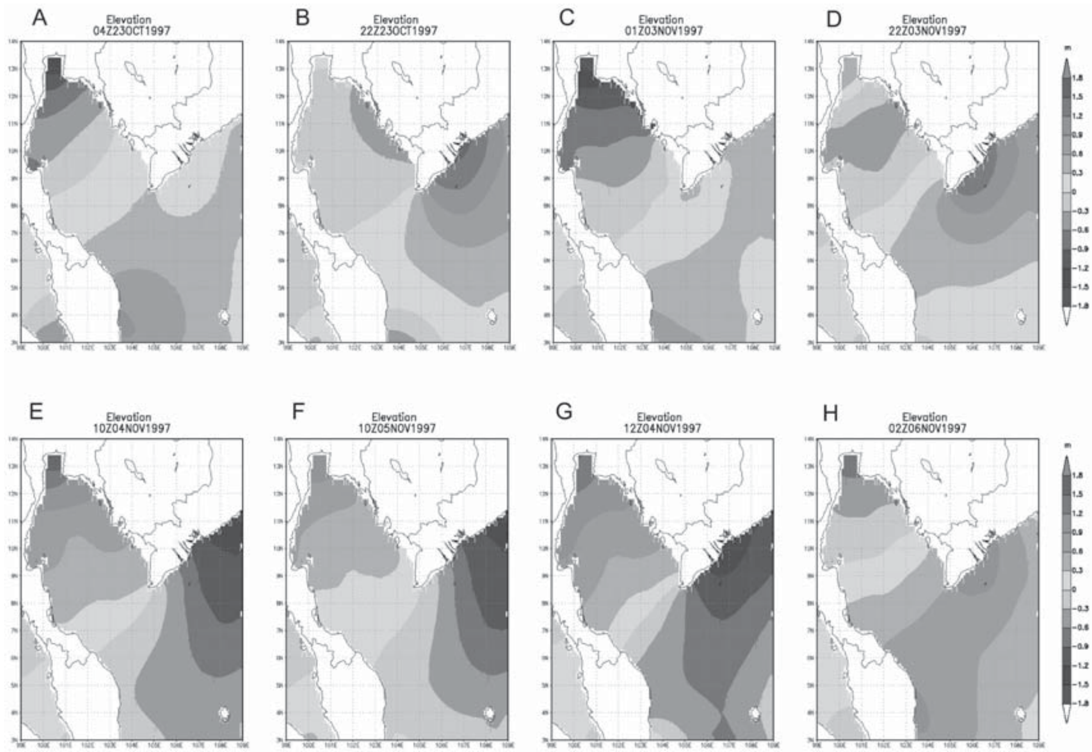


**Figure 3** Simulated sea surface elevation (A) 23rd October 1997 at 04:00 (B) 23rd October 1997 at 22:00 (C) 3rd November 1997 at 01:00 (D) 3rd November 1997 at 22:00 (E) 4th November 1997 at 10:00 (F) 4th November 1997 at 12:00 (G) 5th November 1997 at 10:00 (H) 6th November 1997 at 02:00

could cause the discrepancy in sea surface elevation between the model results and observed ones. For instance, Ko Prab located behind Ko Samui and Ko Pha-Ngan but the model couldn't account for the presence of island at Ko Samui. Finally, the other governing processes such as fresh water discharge which were not considered by this model could cause the discrepancy in sea surface elevation.

There were many issues that remain to be resolved in order to improve model performance. Wind field was an essential factor affected the sea surface elevation especially in the period of storm. The better accuracy and spatial resolution of local numerical weather prediction data needed for the model simulation. The accuracy of model results could improve in various ways: the model responses to co-oscillation tide of only eight principal constituents ($M_2$, $S_2$, $K_1$, $O_1$, $P_1$, $Q_1$, $N_2$, and $K_2$). Inclusion of other constituents such as $S_a$ in the Gulf of Thailand might improve the model accuracy, the effect of the freshwater discharged into the Gulf should be considered especially at estuary or river mouth.

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