Advances in Difference Equations
a SpringerOpen Journal

REVIEW Open Access

A numerical study of oil spill spreading in the Gulf of Thailand

Kittipong Srikhaetai[1], Kittisak Chayantrakom[1,2*] and Wattana Kanbua[3]

*Correspondence: kittisak.cha@mahidol.ac.th
[1]Department of Mathematics, Faculty of Science, Mahidol University, Bangkok, Thailand
[2]Centre of Excellence in Mathematics, CHE, Bangkok, Thailand
Full list of author information is available at the end of the article

Abstract

An oil spill is the release of liquid petroleum into the marine ecosystem leading to huge damages in the natural resources. Prediction of oil spill spreading can help in handling accidental oil spills. This study is to present numerical simulation to predict the movement of oil slicks in the Gulf of Thailand, based on the wind speed prediction obtained by an ocean wave model. The numerical results show that oil slicks can move toward different coastal areas.

Keywords: Linear geometric interpolation; Ocean wave model; Oil spill; Spreading

1 Introduction

In the past few decades, there have been nine oil spills in the Gulf of Thailand according to the Thai Marine Knowledge Hub (MKH). The effect of oil spill in the sea surface is represented by several factors including advection, biodegradation, dispersion, dissolution, evaporation, emulsification, sedimentation, and spreading [1]. The Gulf of Thailand is located on the east coast of Thailand and is very important economically for fishery, traveling, and ship transport [2]. It is also a crucially important tourist attraction and economic maritime. The forecast of wave height is very important to people living in the coastal areas. It affects the human activities in seas. The winds and waves are the two important factors for driving forces which generate several oceanic phenomena in the coastal area and open ocean. Waves are very essential for activities such as exploitation of natural resources, ship-routing, design of harbors, breakwaters and jetties, loading and unloading of ship's cargo, and estimation of sediment transport [3]. There are some research which used altimeter wind speed to provide information on the distribution of energy within the wave spectrum [4]. The wave data has been used to assimilate altimeter in a third generation wave model [5]. In 2000, Vethamony *et al.* [3] used winds from the model of the European Centre for Medium-Range Weather Forecast (ECMWF) to hindcast waves over the Indian Ocean and to compare with Geosat wave parameters. There were striking differences among the three sets of results, basically due to limitation of the model in shallow water and inaccuracy in the visually observed wave data. In 2004, Bhatt *et al.* [6] used winds from multi-frequency scanning microwave radiometer (MSMR) in the WAM model and compared the results with buoys and altimeter observations in the Indian Ocean. The result showed that ingestion of MSMR winds in the forecast model improves surface wind analysis and wave prediction. In 2005, Kanbua *et al.* [7] investigated the significant wave height in the Gulf of Thailand during Typhoon Linda in 1997 by using WAM and the general regression neural network model (GRNN). As a result, the GRNN model showed the better forecasting results compared with those obtained from the WAM model with RMSE < 0.15 m. In 2006, Sebastiao and Soares [8] presented the uncertainties in the predictions of oil spill trajectories using a classic oil spill model. The wind, wave, and current data were used in this model.

The objective of this paper is to predict oil spill movement in the Gulf of Thailand based on the ocean wave model. The ocean wave model, WAM, is chosen in this study because it is widely used to predict the transport of the two-dimensional wave spectrum [9]. The prediction data from WAM are selected on a fine weather day and on a day with the storm Pabuk, one of the severe cyclones in the Gulf of Thailand.

2 Mathematical model

The first generation wave models, developed in the 1960s and early 1970s [10], applied a simple model of spectrum for wind waves using the wave frequency in the equilibrium range based on wave breaking [11]. The second generation models were developed in 1970s based on some experiments [10, 12, 13] and the direct measurements of the wind input to the waves. In 1981, Snyder *et al.* [14] fundamentally changed the view of the spectral energy balance on the first generation model. This was the main reason for developing the second generation wave models. In this study, we use the ocean wave model which is a third generation wave model that solves the wave transport equation explicitly without any presumptions on the shape of the wave spectrum [15]. It represents physics of the wave evolution in accordance with full set of degrees of freedom of a two-dimensional wave spectrum. The model runs for any given regional or global grid system with a prescribed topographic data set. The grid resolution can be arbitrary in space and time. The propagation of waves can be done on a latitudinal–longitudinal or Cartesian grid [16]. In the present study, we use the ocean wave model to obtain wave prediction in the Gulf of Thailand, and we focus on the wave generation by wind and wave-wave interactions.

2.1 Ocean wave model

In ocean wave modeling, wave prediction can be described by the wave energy balance equation [17] as follows:

$$\frac{\partial E(f,\theta;x,y,t)}{\partial t} + \nabla \cdot (c_g E) = S_{\text{in}} + S_{\text{wc}} + S_{\text{nl}}, \tag{1}$$

where E is the wave energy density, θ is the wave propagation direction, c_g is the group velocity, S_{in} is the process of wave generation by wind, S_{nl} is the processes of nonlinear-transfer, and S_{wc} is the processes of white capping dissipation. The last three terms are source terms. The input source term S_{in}, adopted from Snyder *et al.* [14], is given by

$$S_{\text{in}} = \beta F, \tag{2}$$

where $\beta = \max\{0, 0.25\frac{\rho_a}{\rho_w}(28\frac{u_*}{c}\cos\theta - 1)\}\omega$, F represents the ocean wave spectrum, u_* denotes the friction velocity, c is the phase speed of the waves, $\omega = 2\pi f$, ρ_a and ρ_w are the density of air and water, respectively. The dissipation source function S_{wc}, proposed by

Komen *et al.* [17], is defined as

$$S_{\mathrm{wc}} = -2.33 \cdot 10^{-5}\hat{\omega}\left(\frac{\omega}{\hat{\omega}}\right)^2\left(\frac{\hat{\alpha}}{\hat{\alpha}_{\mathrm{PM}}}\right)^2 F, \tag{3}$$

where $\hat{\alpha} = E\hat{\omega}^4 g^{-2}$, and $\hat{\omega}$ is an inverse of the mean frequency, $\hat{\alpha}_{\mathrm{PM}} = 3.016 \times 10^{-3}$ is the theoretical value of $\bar{\alpha}$ for a Pierson–Moskowitz spectrum [15]. The nonlinear source function S_{nl} is in the form [10, 15]

$$\begin{aligned} S_{\mathrm{nl}}(k_4) = \int & \omega_4 \sigma(\mathbf{k_1} + \mathbf{k_2} - \mathbf{k_3} - \mathbf{k_4}) \times \delta(\omega_1 + \omega_2 - \omega_3 - \omega_4) \\ & \times \left[n_1 n_2 (n_3 + n_4) - n_3 n_4 (n_1 + n_2)\right] d\mathbf{k_1}\, d\mathbf{k_2}\, d\mathbf{k_3}, \end{aligned} \tag{4}$$

where $n_j = F(\mathbf{k}_j)/\omega_j$ is the action spectrum and the coefficient $\sigma(\mathbf{k_1} + \mathbf{k_2} - \mathbf{k_3} - \mathbf{k_4})$ describes the coupling strength of resonantly interacting wavenumber quadruplet $\mathbf{k_1}, \mathbf{k_2}, \mathbf{k_3}, \mathbf{k_4}$. The nonlinear source function S_{nl} was presented by Hasselmann *et al.* [10]. The ocean wave model is formulated in circular latitude–longitude coordinates. A numerical technique, based on a finite difference method, is used for wave computation in an arbitrarily specified global or regional grid areas. The wave energy density can be used to derive the significant wave height H_s as follows [17]:

$$H_s = 4\left[\int E(t)\, df\right]^{\frac{1}{2}}. \tag{5}$$

2.2 Oil spill model

The oil spill can be modeled as the diffusion of oil in water, and the concentration of oil over time can be determined based on the diffusivity of oil in water. In this paper, the model of oil spill includes spreading and the movement model of oil slick processes. When an oil spill occurs in the ocean, it initially spreads in the water surface, depending on its relative density and composition. Wind, water current, and wave forces are affected to drift the oil slick over the large areas. Wind and wave data used in the model are generated by the ocean wave model in Equation (1).

2.2.1 Movement of oil slick

In this section, the mathematical model for the oil slick movement into the area of the Gulf of Thailand is presented. The shape of oil slick is assumed to be circular. The seabed area of the Gulf of Thailand is approximately 304,000 km^2 ranging from latitude 5°N to 15°N and longitude 95°E to 105°E. The northern part of the Gulf of Thailand is at the estuary of Chao Phraya River [18]. The Gulf of Thailand is a shallow sea which has 58 m in mean depth and the maximum depth is only 85 m [2]. We assume that the oil droplets can be neglected. The position of the oil slick can be determined by

$$\begin{aligned} \frac{dX}{dt} &= U, \qquad X(t_0) = X_0, \\ \frac{dY}{dt} &= V, \qquad Y(t_0) = Y_0, \end{aligned} \tag{6}$$

where U and V are the predicted wind velocity components in x and y directions, respectively, which can be obtained by an ocean wave model. The coordinate (X, Y) is the center of the circular oil slick and (X_0, Y_0) is the position of oil spill at the initial time.

3 Numerical results and discussions

In this section, we present the numerical simulation to predict spreading of the oil slick in the Gulf of Thailand. In this study, their oil slicks, denoted by OS1, OS2, and OS3 are assumed to be originating at three drilling rigs, namely, Benchamas, Pathong, and Bongkot South, respectively. The locations of the three drilling rigs are at the following latitudes and longitudes: 10.42N 101.30E, 9.68N 101.40E, and 7.37N 102.60E, as shown in Fig. 1(a). The movement of oil slicks is based on Equation (6) which requires wind prediction, including wind speeds, and wind directions as input data. These data can be obtained from WAM, an ocean wave model. In our simulation, we present two study cases: a fine weather day on 6 December 2018 and a day with the tropical storm Pabuk on 4 January 2019. On the fine weather day, three snapshots of the three oil slicks are illustrated in Fig. 1. Table 1 shows the information of each snapshot in Fig. 1. The information includes the time duration between two snapshots, the positions of each oil slick, the distances that the oil slick can travel between two snapshots, the wind speed, and the significant wave height. Table 2 shows the significant wave height and the wind speed in the path that traveling each oil slick means along the total traveling distance, and the total traveling time of each oil slick. It can be seen that the oil slick OS3 moves relatively faster toward a coastal area compared to the oil slicks OS1 and OS2. This is because the averaged wind speed is higher. On the day with the cyclone Pabuk, similar snapshots are presented in Fig. 2. Tables 3 and 4 show similar information as in those for the fine weather day. A similar result is obtained as in the case of the fine weather day.

Comparing the averaged wind speeds and the averaged significant wave heights in Tables 2 and 4, it shows that the wind speed on the day with the storm Pabuk is roughly three times larger than that on the fine day. This leads to the larger value of the averaged significant wave height in the same order. Therefore, the wind is a major factor that affects the wave energy density which is represented by the significant wave height. It is also seen from Figs. 1 and 2 that the coastal areas with the three oil slicks moving toward them on

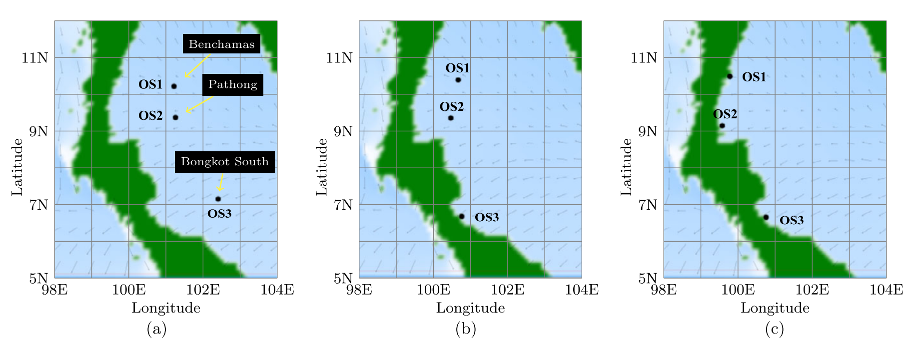

Figure 1 The movement of oil slicks. The simulation of the movement of three oil slicks, denoted by OS1, OS2, and OS3, originating from the different drilling rigs on 6 December 2018, a day with the fine weather. Three snapshots are illustrated: (**a**) when the oil slicks occur at the rigs, (**b**) when they drift to the sea surface, and (**c**) when they land on the coastal areas

Table 1 The positions and the traveling distances of each of the three oil slicks and their corresponding wind speeds and significant wave heights at the three different times on 6 December 2018, a fine weather day

Oil slick	Time duration (hh:mm)		
	Δt_1	Δt_2	Δt_3
OS1	00:00	05:34	10:38
Position	10.42N, 101.30E	9.43N, 100.57E	10.81N, 99.20E
Distance (km)	0	69.36	153.98
Wind speed (km h^{-1})	13.02	13.00	12.30
Significant wave height (m)	1.00	0.80	0.22
OS2	00:00	04:36	04:23
Position	9.68N, 101.40E	9.53N, 100.47E	10.22N, 99.78E
Distance (km)	0	85.55	76.31
Wind speed (km h^{-1})	19.83	18.53	13.29
Significant wave height (m)	1.00	0.80	0.70
OS3	00:00	06:08	00:00
Position	7.37N, 102.60E	8.57N, 101.43E	8.57N, 101.43E
Distance (km)	0	108.81	0.00
Wind speed (km h^{-1})	15.86	16.00	16.00
Significant wave height (m)	1.10	1.02	1.02

Table 2 The corresponding information of the three oil slicks on 6 December 2018, a fine weather day

Oil slick	Wind speed (km h^{-1})			Total distance (km)	Total time duration (hh:mm)	Significant wave height (m)		
	min.	max.	avg.			min.	max.	avg.
OS1	12.11	17.03	13.97	223.34	16:12	0.20	1.00	0.77
OS2	13.23	19.83	18.03	161.86	08:59	0.70	1.00	0.83
OS3	15.08	20.51	18.61	108.81	06:08	1.00	1.10	1.06

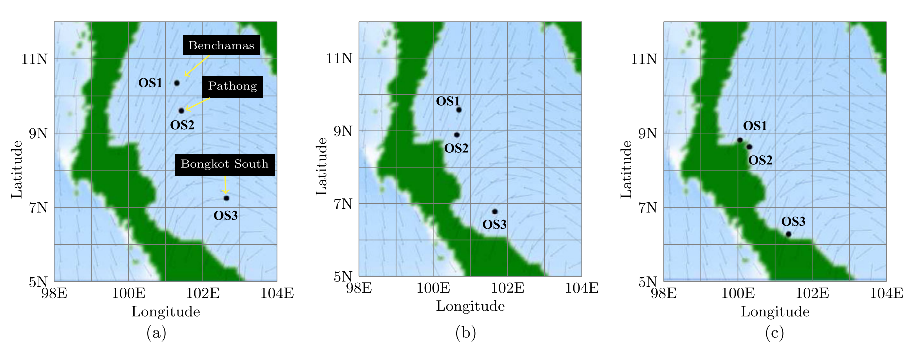

Figure 2 The movement of oil slicks. The simulation of the movement of three oil slicks, denoted by OS1, OS2, and OS3, originating from the different drilling rigs on 4 January 2019, a day with the tropical cyclone Pabuk. Three snapshots are illustrated: (**a**) when the oil slicks occur at the rigs, (**b**) when they drift to the sea surface, and (**c**) when they land on the coastal areas

the fine weather day are larger than those on the day with the cyclone Pabuk. This is because the wind direction varies in a great range. Therefore, a good management of oil spill would be greatly needed.

Table 3 The positions and the traveling distances of each of the three oil slicks and their corresponding wind speeds and significant wave heights at the three different times on 4 January 2019, a day with the tropical cyclone Pabuk

Oil slick	Time duration (hh:mm)		
	Δt_1	Δt_2	Δt_3
OS1	00:00	02:06	03:06
Position	10.42N, 101.30E	9.43N, 100.57E	10.14N, 99.86E
Distance (km)	0	81.89	108.36
Wind speed (km h^{-1})	46.72	49.94	32.71
Significant wave height (m)	5.86	3.55	2.30
OS2	00:00	01:51	01:47
Position	9.68N, 101.40E	9.53N, 100.47E	10.06N, 99.94E
Distance (km)	0	98.35	72.73
Wind speed (km h^{-1})	68.85	57.77	30.62
Significant wave height (m)	6.15	3.26	2.31
OS3	00:00	01:59	01:08
Position	7.37N, 102.60E	8.10N, 101.90E	8.24N, 101.76E
Distance (km)	0	72.55	28.88
Wind speed (km h^{-1})	61.05	47.61	38.04
Significant wave height (m)	4.76	6.35	6.77

Table 4 The corresponding information of the three oil slicks on 4 January 2019, a day with the tropical cyclone Pabuk

Oil slick	Wind speed (km h^{-1})			Total distance (km)	Total time duration (hh:mm)	Significant wave height (m)		
	min.	max.	avg.			min.	max.	avg.
OS1	32.36	51.24	47.45	190.25	05:12	2.30	5.86	3.53
OS2	30.28	68.85	55.86	171.08	03:38	2.31	6.15	3.61
OS3	36.05	61.18	51.07	101.43	03:07	4.76	6.77	5.91

4 Conclusions

In this paper, we present a numerical simulation to predict oil spill spreading in the Gulf of Thailand. In the simulation, we use the wind prediction, obtained from an ocean wave model, as the input to simulate the oil slick movement starting at three different drilling rigs. The results show that for a fine weather day the oil slicks land on larger areas compared to those on a day with the cyclone Pabuk.

Acknowledgements
We would like to thank the Marine Meteorological Center, Thai Meteorological Department for suggestion on WAM. We also would like to thank Nikita Savchenko for suggestion on the oil spread model.

Funding
The first author would like to thank Panyapiwat Institute of Management for funding scholarship. The second author would like to thank the Centre of Excellence in Mathematics, Commission on Higher Education, Thailand, for financial support.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
KS simulated, analyzed simulation results, and wrote the research paper. KC designed the research work, analyzed and interpreted simulation results, and wrote the research paper. WK analyzed, interpreted simulation results, and revised the research paper. All authors read and approved the final manuscript.

Author details
[1]Department of Mathematics, Faculty of Science, Mahidol University, Bangkok, Thailand. [2]Centre of Excellence in Mathematics, CHE, Bangkok, Thailand. [3]Marine Meteorological Center, Thai Meteorological Department, Bangkok, Thailand.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Received: 9 February 2019 Accepted: 15 May 2019 Published online: 30 May 2019

References

1. Schramm, L.L.: Emulsions, Foams, and Suspensions: Fundamentals and Applications. Wiley, New York (2006)
2. Kompor, W., Tanaka, H., Ekkawatpanit, C., Kositkittiwong, D.: Application of simulating waves nearshore (swan) model for wave simulation in Gulf of Thailand. Northeast. Reg. Disaster Sci. Res. **52**, 139–144 (2016)
3. Vethamony, P., Sudheesh, K., Rupali, S., Babu, M., Jayakumar, S., Saran, A., Basu, S., Kumar, R., Sarkar, A.: Wave modelling for the North Indian Ocean using MSMR analysed winds. Int. J. Remote Sens. **27**(18), 3767–3780 (2006)
4. Francis, P., Stratton, R.: Some experiments to investigate the assimilation of SeaSat altimeter wave height data into a global wave model. Q. J. R. Meteorol. Soc. **116**(495), 1225–1251 (1990)
5. Lionello, P., Gunther, H., Janssen, P.A.: Assimilation of altimeter data in a global third-generation wave model. J. Geophys. Res., Oceans **97**(C9), 14453–14474 (1992)
6. Bhatt, V., Sarkar, A., Kumar, R., Basu, S., Agarwal, V.K.: Impact of Oceansat-I MSMR data on analyzed oceanic winds and wave predictions. Ocean Eng. **31**(17–18), 2283–2294 (2004)
7. Kanbua, W., Supharatid, S., Tang, I.-M.: Ocean wave forecasting in the Gulf of Thailand during typhoon Linda 1997: hard and soft computing approaches. J. Atmos. Ocean Sci. **10**(3), 145–161 (2005)
8. Sebastiao, P., Soares, C.G.: Uncertainty in predictions of oil spill trajectories in a coastal zone. J. Mar. Syst. **63**(3–4), 257–269 (2006)
9. Gelci, R., Cazale, H., Vassal, J.: Prévision de la houle. La méthode des densités spectroangulaires. Bull. Inf. Com. Oceanogr. Etude Côtes **9**, 416–435 (1957)
10. Hasselmann, K., Barnett, T., Bouws, E., Carlson, H., Cartwright, D., Enke, K., Ewing, J., Gienapp, H., Hasselmann, D., Kruseman, P., et al.: Measurements of wind-wave growth and swell decay during the joint north sea wave project (Jonswap) (1973). Ergänzungsheft 8–12
11. Phillips, O.M.: The equilibrium range in the spectrum of wind-generated waves. J. Fluid Mech. **4**, 426–434 (1958)
12. Mitsuyasu, H.: On the growth of the spectrum of wind-generated waves, I. Rep. Res. Inst. Appl. Mech. Kyushu Univ. **16**, 459–465 (1968)
13. Mitsuyasu, H.: On the growth of the spectrum of wind-generated waves, II. Rep. Res. Inst. Appl. Mech. Kyushu Univ. **17**, 235–243 (1969)
14. Snyder, R., Dobson, F., Elliott, J., Long, R.: Array measurements of atmospheric pressure fluctuations above surface gravity waves. J. Fluid Mech. **102**, 1–59 (1981)
15. Group, T.W.: The WAM model|a third generation ocean wave prediction model. J. Phys. Oceanogr. **18**(12), 1775–1810 (1988)
16. Samiksha, S., Polnikov, V., Vethamony, P., Rashmi, R., Pogarskii, F., Sudheesh, K.: Verification of model wave heights with long-term moored buoy data: application to wave field over the Indian Ocean. Ocean Eng. **104**, 469–479 (2015)
17. Komen, G.J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S., Janssen, P.: Dynamics and modelling of ocean waves p. 554. Cambridge University Press, Cambridge (1996). ISBN 0521577810.
18. Waewsak, J., Landry, M., Gagnon, Y.: Offshore wind power potential of the Gulf of Thailand. Renew. Energy **81**, 609–626 (2015)