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Influence of local wind field on seasonal circulations in the upper Gulf of Thailand

Anukul BURANAPRATHEPRAT[1*], Tetsuo YANAGI[2], Pramot SOJISUPORN[3] and Chinorost BOONCHERM[4]

[1] *Department of Aquatic Science, Faculty of Science, Burapha University, T. Saensuk, A. Muang, Chonburi 20131 Thailand*
**E-mail: anukul@uvic.ca*
[2] *Research Institute for Applied Mechanics, Kyushu University, Kasuga 816–8580, Japan*
[3] *Department of Marine Science, Faculty of Science, Chulalongkorn University, Bangkok 10330 Thailand*
[4] *Geo-Informatics and Space Technology Development Agency, 196 Phahonyothin Road, Chatuchak, 10900 Bangkok Thailand*

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Abstract—Previous results of circulation in the upper Gulf of Thailand using a 2-dimensional model suggested counter-clockwise circulation and a clockwise gyre during the northeast and the southwest monsoons, respectively. A review of previous reports relevant to circulation, and the results of surface chlorophyll-a distribution estimated by OCTS (Ocean Color and Temperature Scanner) data support the results during the northeast monsoon. Anyway, residual circulation analyzed from oceanographic buoys deployed in the upper gulf illustrated both clockwise and counter-clockwise circulations during the southwest monsoon. Therefore, the objective of this study is trying to investigate the current patterns and their controlling factors especially during the southwest monsoon. The 2-dimenional circulation model is applied again but this time uses meteorological wind data from local stations around the study area as inputs. The experiments also include investigation of current patterns due to the difference of wind gradients in east-west and north-south direction. The results show that counter-clockwise circulation can be developed during the southwest monsoon when wind magnitude in the east or the south is significantly stronger than that in the west or the north, respectively, which possibly happens in the real situation. It can be concluded that the circulation patterns in the area are controlled by not only wind direction but also its gradient. We also found that external flows through the open boundary can change the patterns of circulation just in the southernmost area.

Key words: Upper Gulf of Thailand, circulation, seasonal variation

Introduction

The upper Gulf of Thailand is a semi-enclosed sea located in tropical zone at about 13°N and 100°E (Fig. 1). It has a square-like dimension with approximate area of $10^4\,km^2$ surrounded by land in all directions except in the south, which is open to the lower gulf. The averaged depth is 20 m with the deepest area of 48 m at the southeast close to Sattahip (Neelasri 1981). There are four main rivers emptying into the head of the gulf namely the Maeklong, the Thachin, the Chaopraya and the Bangpakong from the west to the east, respectively. Since the entire area is influenced by the reverse–monsoon system (the northeast and the southwest monsoons), the oceanographic conditions change seasonally due to variations in meteorological condition and prevailing wind.

The upper gulf has been intensively used for several purposes such as coastal fisheries, aquaculture especially mussel and oyster husbanding, maritime, and recreation. All of these activities together with expansion of municipalities and industries due to country development result in deterioration of the gulf condition. The Pollution Control Department (PCD) who has been conducting environmental monitoring program around the gulf found an increasing trend of pollution. Anyway, eutrophication is considered to be a serious problem in the inner gulf nowadays (Chongprasith and Srinetr 1998) because of excessive nutrient loads carried down by the major rivers. This situation encourages the increasing of phytoplankton bloom from 6 times a year during 1981–1989 to be 19 times a year during 1991–1993 (http://www.marinepcd.org/coastalwater/wq10year.html). Therefore, it is necessary to know physical characteristics, which is the first step, and other conditions relevant to eutrophication of the bay before over-utilizing it without good understanding. This study is concerning to seasonal variations in circulation and controlling mechanism related to the monsoon winds over the upper Gulf of Thailand.

Previous Investigations

NEDECO (1965) has conducted a study on the siltation on the Bangkok Port Channel and also investigated general circulation in the upper Gulf of Thailand. Circulation and water level were simply simulated assuming a rectangular basin with identical depth and steady wind field. The consequences indicated that the west and the south winds could

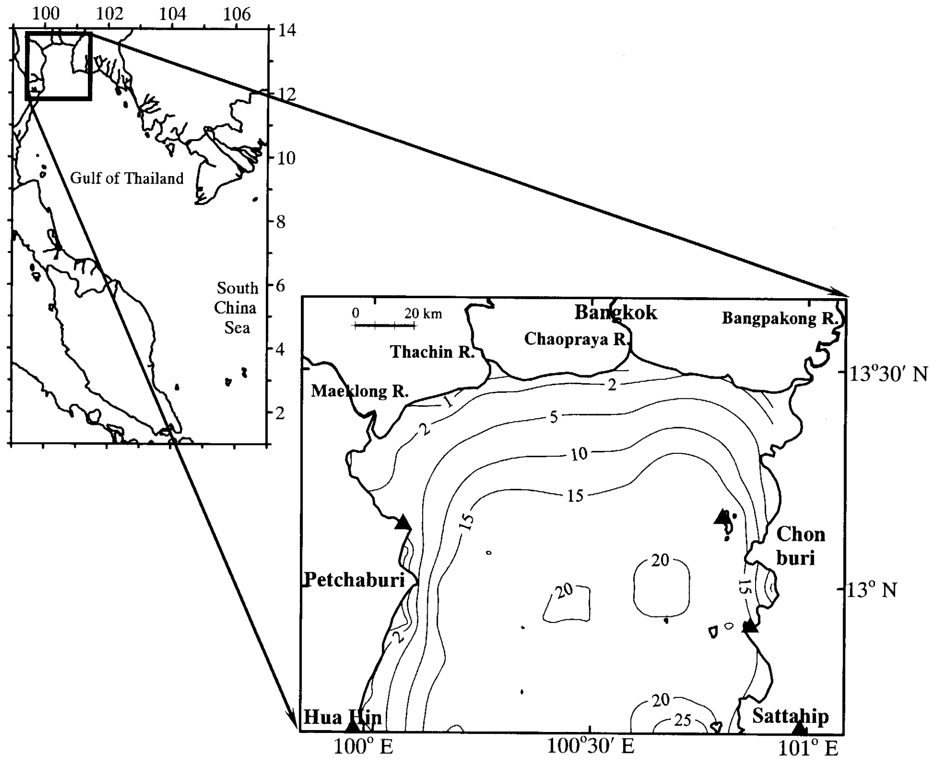

Fig. 1. The upper Gulf of Thailand. Contours show the depth in meters and solid triangles represent meteorological stations.

produce clockwise circulation. Furthermore surface salinity distributions from data collected by the Hydrographic Department of the Royal Thai Navy from 1956–1961 together with wind direction at the same period were analyzed for seasonal patterns of circulation. The distribution contours showed the response of surface salinity to changing in wind direction which could be concluded that counter-clockwise and clockwise circulations are generated during the northeast and the southwest monsoon, respectively.

Neelasri (1981) measured current profiles around the upper gulf in March and April 1979 which is the transition period from the northeast to the southwest monsoons. He found that surface current moved northeastwards into the bay which is the right direction of the southeastern wind due to Coriolis effect, and current at deeper layers has a trend to flow out of the gulf to southeast direction. The report also addressed the significant of pile up effect resulting from imbalance of relatively large surface inflow and small deep outflow that might occur along the northeastern coast where the wind blew to. Because current flows to the right direction of wind which is coming from the southeast into the bay, clockwise circulation consequently develops during this time.

Buranapratheprat et al. (2002) applied a 2-dimensional model to investigate seasonal variations in circulation in the upper Gulf of Thailand using wind and tide as significant inputs. Wind data at every computational domain were extracted and interpolated from long-time averaged ECMWF data while tidal elevations at the open boundary were calculated by employing harmonic analysis method. The authors also used computed current to simulate seasonal salinity distributions in order to compare them with the NEDECO results due to lacking of observed current data for verification. The models successfully reproduced salinity distributions during both monsoon peaks even though the model results represented depth-averaged salinities while those of NEDECO were the values at the sea surface. The results also confirm development of a clockwise gyre covering the northern part of the upper gulf during the southwest monsoon and counter-clockwise flow during the northeast monsoon.

Monthly distributions of chlorophyll-*a* (Fig. 2) which is a level 3 product of OCTS imageries (http://www.eorc.nasda.go.jp/SeaWiFS/imgcut/html) and residual circulation (Fig. 3) analyzed from current data in 1996–1998 measured by oceanographic buoys under SEAWATCH Thailand program (Booncherm 1999) also confirm the results of circulation during the northeast monsoon. Chlorophyll-*a* patchiness along northwestern and western coasts presumably arises because of westward circulation generated by the northeast wind. However, the distributions during the southwest monsoon are not clear enough to confirm the occurrence of clockwise circulation or a clockwise gyre. Booncherm (1999) showed some alternative consequences during the southwest monsoon period that counter- clockwise circulation is sometimes generated instead of the clockwise one such as the results in July (Fig. 3).

Development of counter-clockwise circulation during the southwest monsoon is very interesting and becomes the objective of this study which focuses on wind as the most

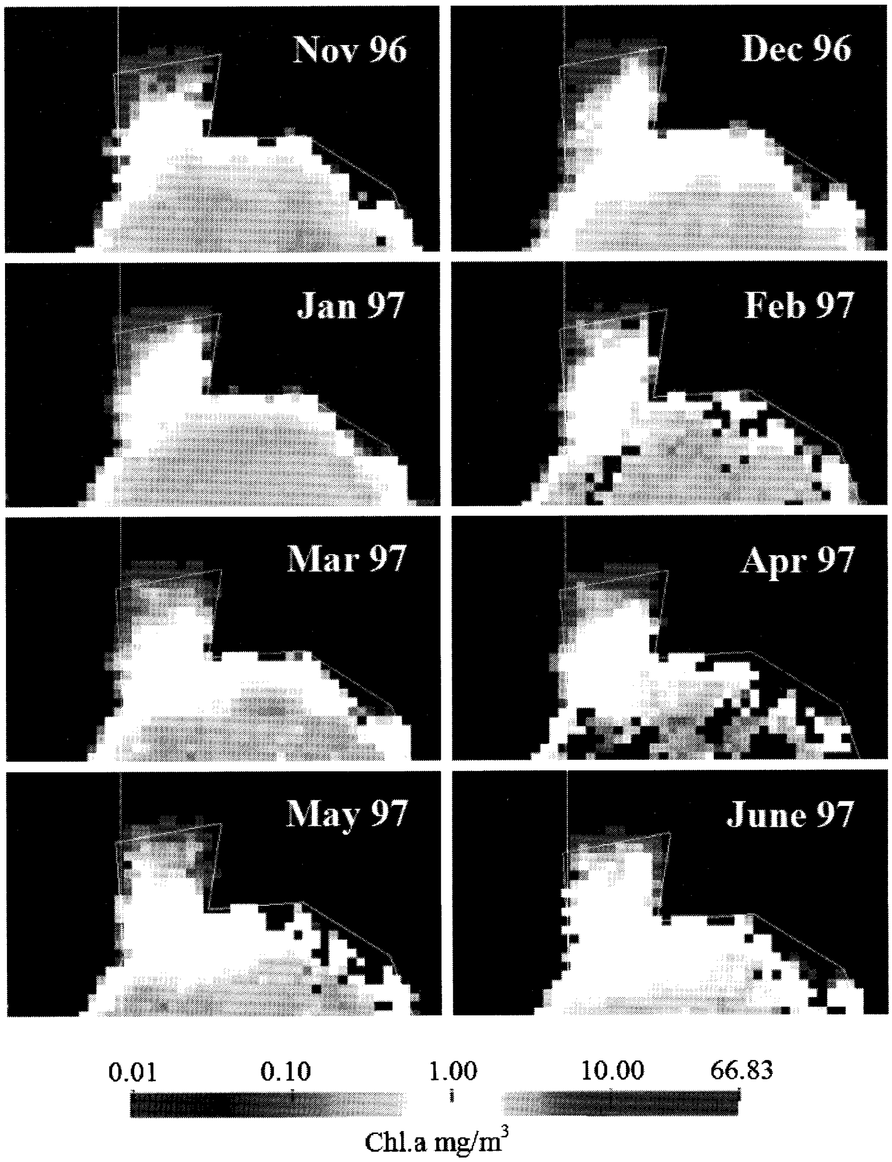

Fig. 2. Monthly averaged chlorophyll-*a* distributions derived from OCTS images.

significant driving force to the seasonal variations in circulation of the study area (Buranapratheprat et al. 2002). Applying interpolated ECMWF wind from coarse-grid data might not represent the local wind condition. Therefore, a 2-dimensional hydrodynamic model will be applied to investigate the patterns of circulation yet again but this time using wind data derived from meteorological stations located around the upper Gulf of Thailand as a major forcing. The purpose is to reproduce counter-clockwise circulation during the southwest monsoon and investigate factors controlling such a phenomenon.

Numerical Model Experiment

A 2-dimensional hydrodynamic model composing of momentum and continuity equations are used for investigation of horizontal circulation in this study. Temporal change of circulation, Coriolis acceleration, pressure gradient, and wind and bottom stresses are major forcing terms in the momentum equations. Tide is also included as water elevations along the open boundary calculated using harmonic analysis method. Based on finite difference approximation, all equations are transformed and solved with ADI (Alternating Direction Implicit) technique. Spherical coordinate is applied and the computational area is divided in several small grids with 1 minute grid spacing in both longitudinal and latitudinal axes. Monthly mean fresh-water discharges of the four main rivers from the Hydrographic Department are also conditioned at the river mouth boundaries. The model is initially run from resting stage with the time step of 30 minutes. A free run is set for 2 days, and then circulation results for 30 days long are extracted, averaged and plotted for residual current investigation. More details in terms of mathematic ex-

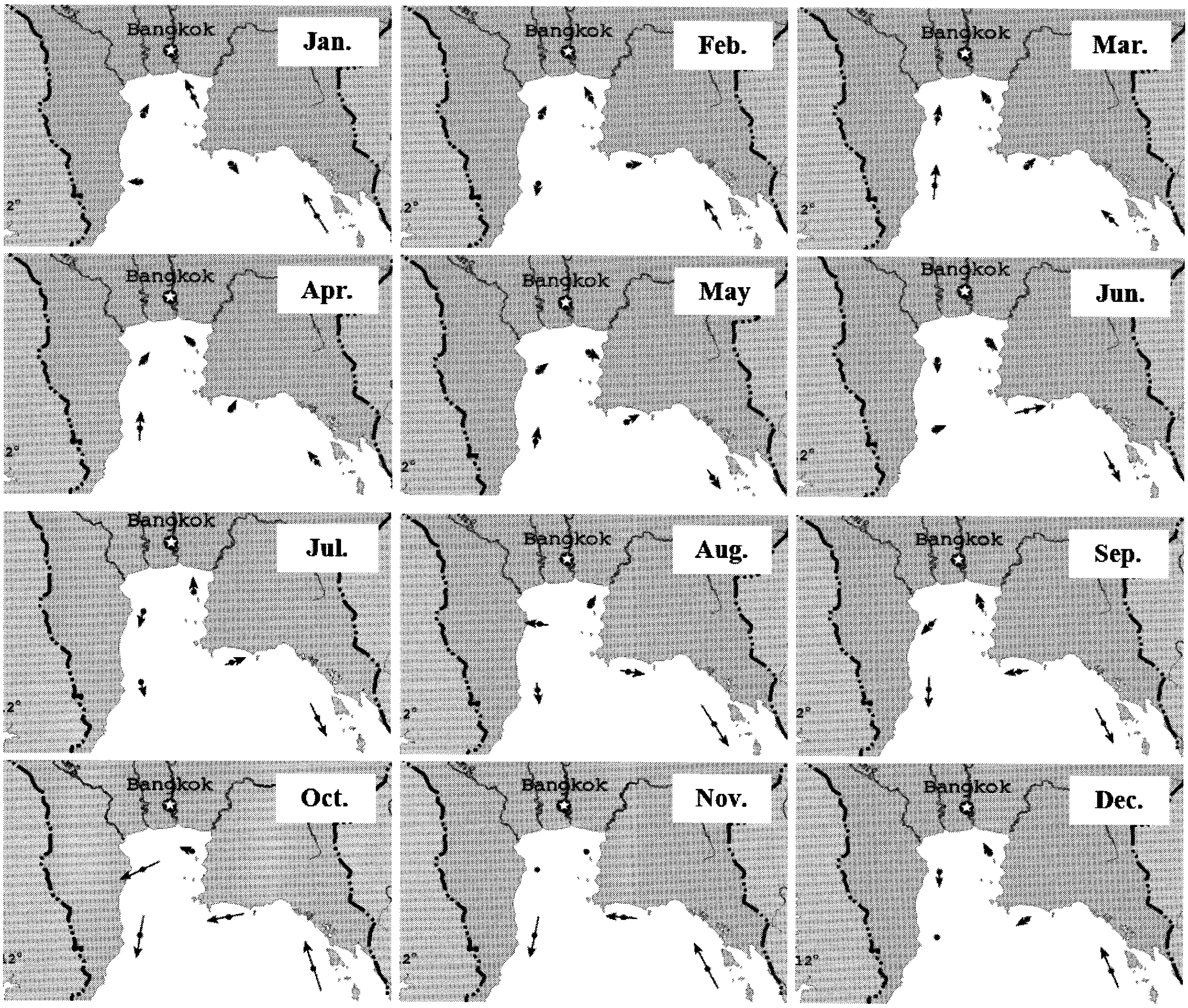

Fig. 3. Monthly mean surface residual current in 1996—1998 measured by oceanographic buoys under SEAWATCH program (Booncherm 1999).

pressions and explanation of the governing equations could be seen in Buranapratheprat and Bunpapong (1998); and Buranapratheprat et al. (2002).

Monthly-mean winds of long-time averaged data during 1980–2000 from meteorological stations around the upper Gulf of Thailand (Fig. 1) are interpolated using Gauss's function to fit all computational domains. Figure 4 illustrates selected wind fields of the months that represent the monsoon wind in each season. Wind fields in December, March, July, and September stand for the monsoon winds during the northeast (October–January), transition from the northeast to the southwest (February–April), the southwest (May–August), and transition from the southwest to the northeast (September), respectively. Most of wind patterns in this study are quite similar to the monsoon winds interpolated from ECMWF data utilized in Buranapratheprat et al. (2002). Anyway, some parts of the former are different from the latter–larger magnitude of the northeastern wind, and non-uniform wind filed in every season especially in July (the Southwest monsoon) and September (transition from the southwest to the northeast).

Seasonal and Simulated Circulations

Seasonal circulations due to local wind are presented in Fig. 5. Monthly circulations in December, March, July, and September represent seasonal circulation in the same way as those of Fig. 4. Counter-clockwise circulation still develops in December which is the northeast monsoon period. A clockwise gyre near northern shore is also apparent during the southwest monsoon but the current magnitude is not so large. Current in March is rather complicated and weak. During this time, a clockwise and a counter-clockwise gyres rise up near the northern coast and the middle of the gulf, respectively. Although September is the transition period from the

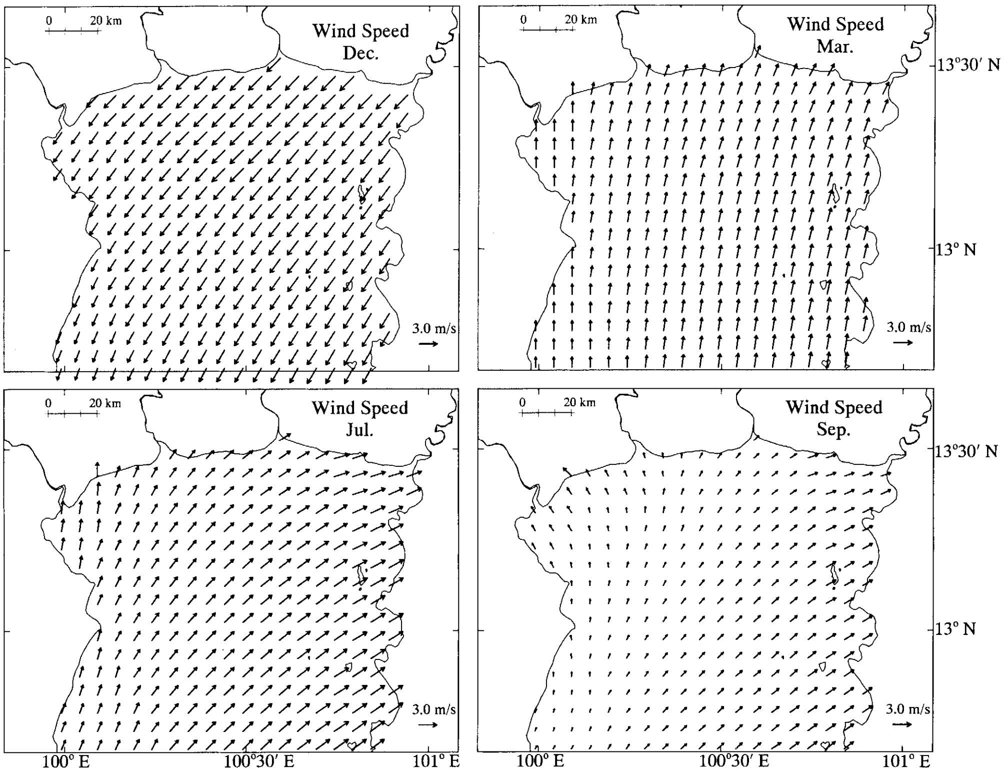

Fig. 4. Seasonal wind fields derived from data measured by meteorological stations around the upper Gulf of Thailand. December, March, July, and September represent the northeast, transition from the northeast to the southwest, the southwest, and transition from the southwest to the northeast monsoons, respectively.

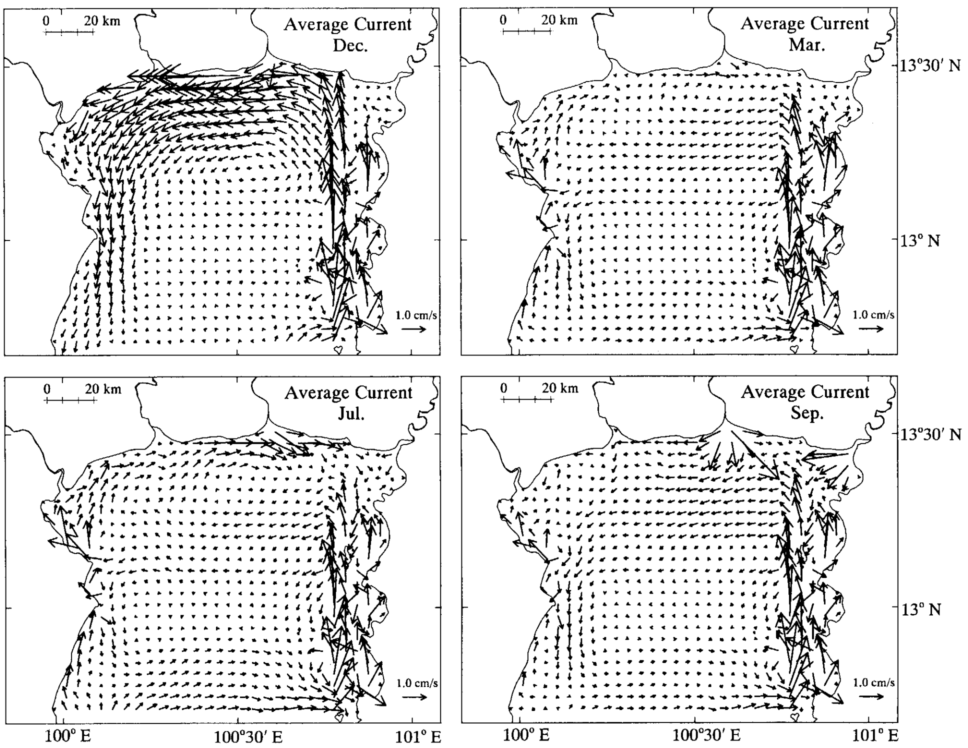

Fig. 5. Calculated seasonal circulations due to seasonal wind fields.

southwest to the northeast monsoons, counter-clockwise flow can develop in almost the same way as it happens during the northeast monsoon. This result is very interesting because wind fields in both seasons are completely unlike but can generate the same circulation pattern. Strong northward flow along the eastern islands appears in all seasons due to imbal-

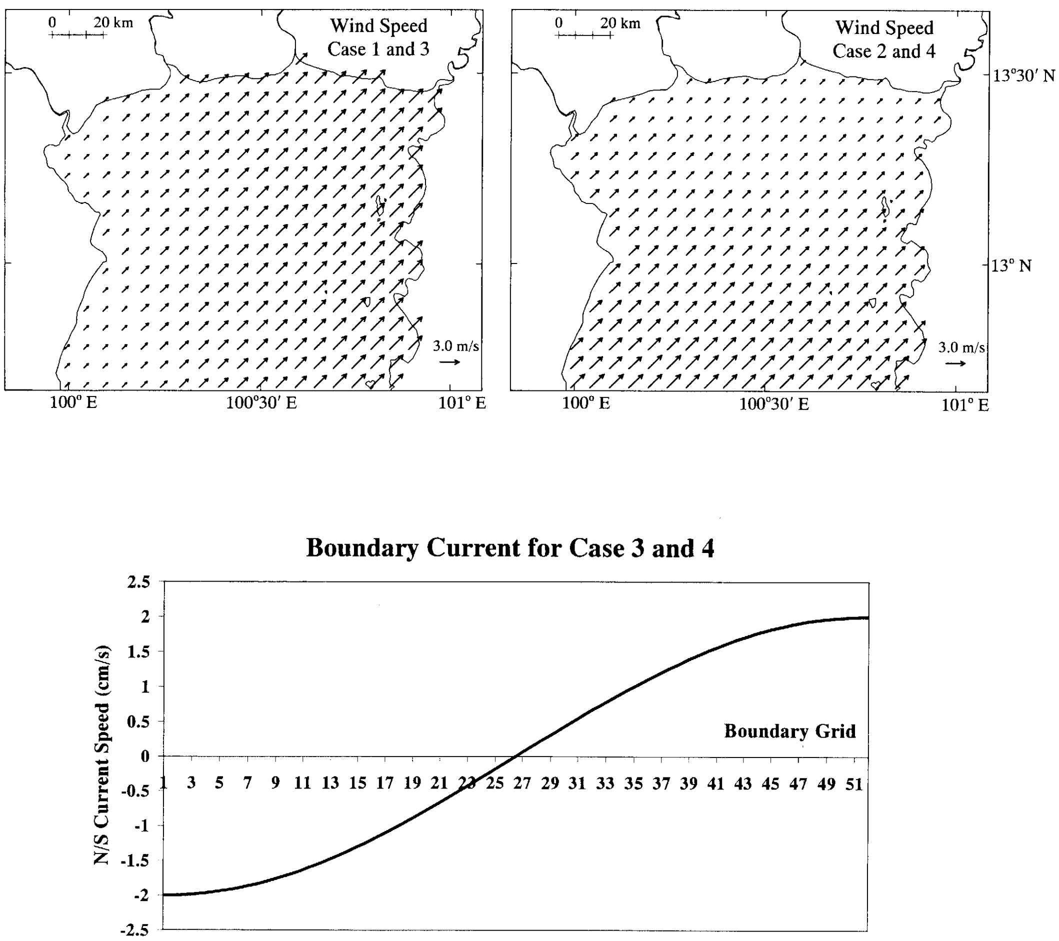

Fig. 6. Idealized wind fields during the southwest monsoon (upper panels), and external boundary current (lower panel) for case studies.

ance of tidal current around that area. This phenomenon happens due to the characteristic of tidal current in the upper gulf whose major flow is mainly in north-south directions (Neelasri 1981). The presence of island trend along the eastern coast probably disturbs the magnitude of calculated northward flow during flood tide to become larger than southward flow during ebb tide.

Up to now we can see that the southwest wind can generate just a clockwise gyre, and it seems impossible that counter-clockwise circulation could be generated likewise the circulation in July (Fig. 3) in the study of Booncherm (1999). We will do the experiments to investigate wind condition during the southwest monsoon that can produce counter-clockwise circulation. A possible case is when positive curl of wind fields generates in the area. Based on this assumption, we will conduct two more experiments—the first one is when the wind speed in the east is stronger than that in the west; and the other one is the case when the southern wind is stronger than the northern wind. Wind directions are all southwestern while the speed is selected to be 1 m/s and 3 m/s in the weak wind and the strong wind sides, respectively (Fig. 6 upper panels), which is considered from possible situations that might happen in the study area.

Table 1. Conditions of simulated wind and external flow through the open boundary for each case study.

Case	Wind gradient	External flow
1	E–W	No
2	N–S	No
3	E–W	Yes
4	N–S	Yes

Influence of external flow form the lower gulf through the open boundary on circulation are also tested by assuming inflow and outflow in north-south direction, which is generated by a cosine function (Fig. 6 lower panel), at the western and the eastern halves of the boundary, respectively. This condition likely happens during the southwest monsoon when southern or southwestern wind in the lower gulf is very strong that can generate flow up to southeastern area of the upper gulf (Buranapratheprat and Bunpapong 1998). Therefore, this experiment is separated into 4 cases as shown in Table 1.

Computed circulations due to idealized winds and boundary currents are presented in Fig. 7. Counter-clockwise

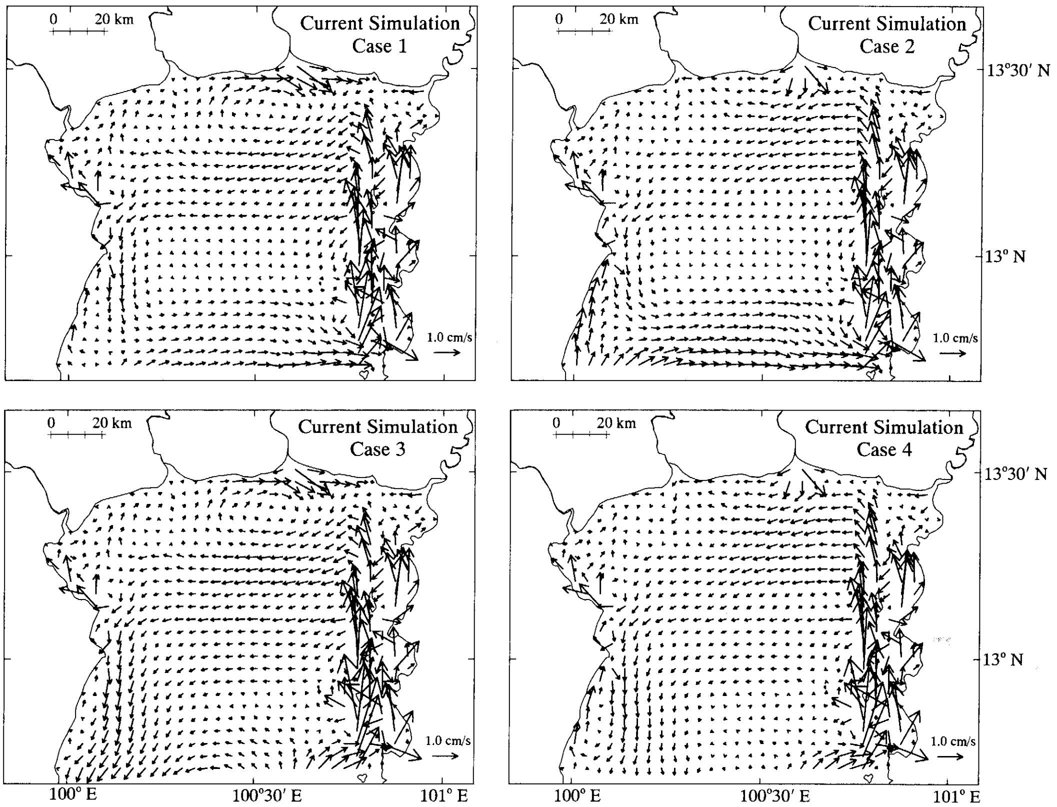

Fig. 7. Simulated circulation during the southwest monsoon of all case studies.

circulation develops in all cases. A small clockwise eddy appears near the Chaopraya river mouth in the cases of east-west wind gradients (case 1 and case 3). A flow from the west to the east along the open boundary is observed when the external flow is not taken into computation. It seems like the counter-clockwise flow is completely generated in almost the same way as those during the northeast monsoon after the external flow has been added in the experiments (case 3 and case 4).

Discussion

The results of seasonal circulation and all the previous researches confirm the occurrence of counter-clockwise circulation during the northeast monsoon. Anyway, the pattern of circulation during the southwest monsoon could not be fixed because it is very sensitive to characteristic of wind fields and external flow from the lower gulf. In general, uniform west or southwest wind induces clockwise circulation or gyre to be generated. However, complete counter-clockwise circulation can occur during this time in the case of strong southwest wind in the east or the south of the upper gulf with having appropriate flow from the lower gulf through the east of the open boundary. These situations could possibly happen in the real situation although all the results are created by a numerical model. The results also suggest the importance of not only wind direction but also the characteristic of wind field on circulation in the upper Gulf of Thailand.

Accuracy of computed circulation extremely depends on accuracy of wind data to be used as inputs. Reliability of wind data becomes very important since the circulation is very sensitive to wind patterns. We realized that using long-time averaged data might not good enough when comparing with employing instantaneous data. Unfortunately we cannot access the data during the experiments were done, but there are some significant advantages even the averaged data were used in the experiments. What we have learnt from the study is that using interpolated winds derived from meteorological stations around the study area can generate different patterns of circulation when compared to applying wind data from a climatorogical model (Buranapratheprat et al. 2002). These experiments consequently suggest the way how to deal with wind data to improve our circulation results in the near future. Using unrealistic wind might bring about circulation in alternative of actual situation such as in the case of the southwest monsoon. We can apply interpolated wind data from a meteorological model to simulate general circulation but the results might not represent the pattern in a specific time. Local wind data as accurate as possible should be considered to use in such a case.

External flow through the open boundary is influential to circulation in the southernmost area of the upper gulf. It helps to complete the counter-clockwise flow during the southwest monsoon if there is a flow coming through the east of the open boundary. In the experiments, we use just simulated data, however, which might be inaccurate, owing to lacking of those from observation. Investigation of seasonal variations in the net transport between the upper and the lower gulf should be conducted in the future.

The results of NEDECO (1965) showed obviously that river discharge cannot change the overall patterns of the salinity distribution and also horizontal circulation patterns, just generate the tongues of low salinity near the river mouths during the wet season. To apply a 2-dimensional model is consequently appropriate for investigation of seasonal variations in horizontal circulation patterns in the area which is the objective of this study. More accurate results can be achieved by using 3-dimensional model that considers other influences namely pile up effect due to the balance of wind force and water elevation near coastal area, and density-driven circulation especially during the wet season. Therefore, we will use a 3-dimensional model to investigate circulation profiles in the upper Gulf of Thailand in the near future.

Conclusions

The results of this study and previous investigations including chlorophyll-*a* distribution derived from OCTS imageries all confirm the development of counter-clockwise circulation during the northeast monsoon. However, both clockwise and counter-clockwise circulations may occur during the southwest monsoon depending on wind condition and external flow through the open boundary. It has been found that uniform southwest or west winds will generate a clockwise gyre, while the counter-clockwise circulation in almost the same way as that during the northeast monsoon can occur when the wind magnitude is significantly large at the east or the south of the upper gulf. External flow through the open boundary can change the patterns of circulation just in the southernmost area; however, it helps to complete the counter-clockwise circulation if there is a flow coming through the east of the open boundary.

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