Final Report

Project Title A Study of Seasonal Water Mass Transports in the Gulf of Thailand using an Ocean Circulation

By Asst.Prof.Dr. Nitima Aschariyaphotha

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This project granted by the Thailand Research Fund

Executive Summary

Objective

This research aim to investigate volume, heat, and freshwater transports in the Gulf of Thailand for each season.

Research Methodology

The Gulf of Thailand (GoT) connected to the South China Sea (SCS) situates between longitudes 98°E to 107°E and latitudes 4°N to 14°N approximately. It is surrounded by the Kingdom of Thailand, the Kingdom of Cambodia, the Socialist Republic of Vietnam and Malaysia. The Gulf of Thailand is shallow with mean depth of 45 meters and maximum depth about 85 meters. Since the Gulf of Thailand is shallow, it has phenomena such as tide, elevation of water mass, wind wave, storm, current, and transports of properties in the sea. These phenomena are very important knowledge to manage natural resources, marine environment, shipping, and tourism, which are advantages for countries adjoined the Gulf of Thailand, especially with Thailand.

The data used for calculating the water mass transports is bottom topography and current velocities. Generally, the bottom topography is available but the current velocities are not. The current velocities have to be calculated from primitive equations. There are two main steps used to investigate the water mass transports. The first step is to simulate the currents velocities from primitive equations using an Ocean Circulation Model (OCM) and the final step is to calculate the water mass transports from simulated data.

The orthogonal curvilinear grid designed to match the problem domain, keeping the number of mesh identical to the rectangular grid is used in this research with 43×97 grid points. In order to separate water in the Gulf of Thailand into several layers, the vertical sigma coordinate is used. In the sigma coordinate system the density in each contour of vertical layers is quite constant. In this research, the number of sigma levels is specified as 9 levels. A mathematical technique used to solve the primitive equations is the finite difference method. The study domain is discretized using a staggered grid, which is C grid.

The Princeton Ocean Model (POM) is applied in this research. The model is run until the time series of total kinetic energy (*EK*), total potential energy (*EA*), and total surface potential energy (*EAS*) reach a steady state.

Initial data are prepared for solving the primitive equations. They consist of bottom topography derived from Digital Bathymetric Data Base 5-minute (DBDB5), climatological monthly mean wind derived from the European Centre for Medium-Range Weather Forecasts (ECMWF), and climatological monthly mean temperature and salinity. These data have to be applied to calculate the current velocities, potential temperature, salinity, and seawater density in the Gulf of Thailand. Since these data are not on all grid points of the model grid, they have to be interpolated into the model grid using bilinear interpolations.

Simulated current velocity, potential temperature, salinity, and seawater density are used to calculate the volume, heat, and freshwater transports in the Gulf of Thailand. The mean horizontal transport of volume across an ocean basin of width *L* and depth *H(x)* is

$$H_v = \int_0^L \int_{-H(x)}^0 V dz dx.$$

The integrated heat transport across an ocean basin of width *L* and depth *H(x)* is

$$F_Q = c_p \int_0^L \int_{-H(x)}^0 \rho V T dz dx$$

where c_p is the specific heat capacity.

The integrated freshwater transport across an ocean basin of width *L* and depth *H(x)* is

$$F_W = \int_0^L \int_{-H(x)}^0 \rho V (1-S) dz dx .$$

In this research, we use the value of the specific heat capacity, c_p, as 3898 J/(kg $^{\circ}$C) (Murray, 2004).

Results

The volume, heat, and freshwater transports in the Gulf of Thailand are calculated for each season of Thailand. The months January, April, July, and October represent the winter, summer, rainy season, and end of the rainy season of Thailand, respectively. The study regions in the Gulf of Thailand are chosen from horizontal lines in x direction of the model grid because these regions make us know that the volume, heat, and freshwater are transported in or out of the Gulf of Thailand. The results of the volume, heat, and freshwater transports yield positive and negative values. Positive values mean the moving from the South China Sea into the Gulf of Thailand. On the other hand, the moving out of the Gulf of Thailand to the South China Sea produces negative values.

For winter of Thailand, January, the values of volume, heat, and freshwater transports are between 0.2 to 4.8 Sv, 0.1×10^8 to 5.3×10^8 W, and 0.9×10^4 to 1.6×10^5 kg/s, respectively. Their highest values occurred in the middle GoT, between latitudes 7°N to 8°N, are 4.7499 Sv, 5.2461×10^8 W, and 1.5604×10^5 kg/s, respectively, and their lowest values occurred at latitude 11°N are 0.2555 Sv, 0.1921×10^8 W, and 0.9430×10^4 kg/s, respectively. For the upper GoT (upper than 9°N), the volume and heat transports move northward, while they move southward out of GoT in the lower GoT (lower than 9°N).

For summer of Thailand, April, the values of volume, heat, and freshwater transports are between 0.2 Sv - 3.7 Sv, 0.1×10^8 W - 4.0×10^8 W, and 0.3×10^4 kg/s - 1.2×10^5 kg/s, respectively. Their highest values occurred at the connection section between the Gulf of Thailand and the South China Sea are 3.6098 Sv, 3.9031×10^8 W, and 1.1188×10^5 kg/s, respectively, and their lowest values occurred between latitudes 8°N to 9°N are 0.2175 Sv, 0.1676×10^8 W, and 0.349×10^4 kg/s, respectively. For the upper GoT, the volume and heat transports move northward, while they move in and out of GoT alternately the lower GoT.

For rainy season of Thailand, July, the values of volume, heat, and freshwater transports are between 0.3 Sv - 3.8 Sv, 0.4×10^8 W - 4.3×10^8 W, and 0.1×10^5 kg/s - 1.3×10^5 kg/s, respectively. Their highest values occurred at the connection section between the Gulf of Thailand and the South China Sea are 3.7987 Sv, 4.2883×10^8 W, and 1.2920×10^5 kg/s, respectively, and their lowest values occurred between latitudes 10°N to 11°N are 0.3453 Sv, 0.4030×10^8 W, and 0.1285×10^5 kg/s, respectively. For the upper GoT, the volume and heat transports move northward, while they move in and out of GoT alternately in the lower GoT.

For the end of rainy season of Thailand, October, the values of volume, heat, and freshwater transports are between 0.1 Sv - 2.1 Sv, 0.1×10^8 W - 2.5×10^8 W, and 0.3×10^4 kg/s - 7.5×10^4 kg/s, respectively. Their highest values occurred at the connection section between the Gulf of Thailand and the South China Sea are 2.0468 Sv, 2.4200×10^8 W, and 7.4792×10^4 kg/s, respectively, and their lowest values occurred between latitudes 10°N to 11°N are 0.1503 Sv, 0.1603×10^8 W, and 0.3060×10^4 kg/s, respectively. For the upper GoT, the volume and heat transports move southward, while they move in and out of GoT alternately in the lower GoT.

In order to validate the results, the volume transports for this research are compared with the volume transports obtained from Wyrtki (1961), who studied volume transport of the Southeast Asian Waters. Although he did not study in the Gulf of Thailand directly, his research is enough to compare with our results because it is the nearest region. His research investigated the direction of volume transports of the Southeast Asian Waters for June and December and the values of volume transports near Vietnam coast in February, April, June, August, October, and December. It can be seen that the volume transports in June and December have the same directions which is moving in and out of the GoT, respectively. For the values of the volume transports, our values and Wyrtki's values have similar tendencies.

Conclusions and Discussions

It can be summarized that the directions and magnitudes of volume, heat, and freshwater transports depend mainly on the current. The direction of transport arise from most current moving in a region greatly. While the magnitude of transport depends on the direction and speed of current. The high magnitude of transport results from the current has high speed and move in that region. On the other hand, the low magnitude of transport arise from the current at the region which has low speed. The results are very useful to manage fisheries and resources in the sea. Each species of life needs a different livelihood. Some kinds live in warm water, and some kinds live in cool water. The research also points out that various species of life move into or out of the Gulf of Thailand, depending on its need.

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บทคัดย่อ:

งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษาการถ่ายเทปริมาตรของน้ำ การถ่ายเทความร้อนของน้ำและการถ่ายเทน้ำจืด แต่ละฤดูกาลในอ่าวไทย โครงข่ายที่ใช้ในการวิจัยนี้เป็นโครงข่ายโค้งเชิงตั้งฉากที่สร้างขึ้นด้วยวิธีการประมาณค่าในช่วงแบบเส้นตรงและการแก้สมการของลาปลาซ สำหรับโครงข่ายในแนวตั้งเป็นระบบพิกัดซิกม่าซึ่งสามารถจัดการกับความแปรปรวนของภูมิประเทศได้ ข้อมูลที่ใช้ในการคำนวณประกอบด้วยระดับภูมิประเทศ ความเร็วกระแสน้ำ อุณหภูมิ ความเค็ม และความหนาแน่นของน้ำทะเล ซึ่งคำนวณมาจากสมการพื้นฐาน และวิธีผลต่างอันตะในการแก้สมการ ผลการวิจัยพบว่าค่าสูงสุดและต่ำสุดของการถ่ายเทปริมาตร การถ่ายเทความร้อนและการถ่ายเทน้ำจืดในแต่ละฤดูกาลที่เกิดขึ้นในบริเวณเดียวกัน การถ่ายเทปริมาตรและการถ่ายเทความร้อนในอ่าวไทยมีทิศทางเดียวกัน แต่การถ่ายเทน้ำจืดมีทิศทางตรงกันข้าม ค่าสูงสุดของการถ่ายเทปริมาตร การถ่ายเทความร้อนและการถ่ายเทน้ำจืด ในฤดูหนาวเกิดขึ้นระหว่างละติจูด 7 ถึง 8 องศาเหนือ ส่วนในฤดูร้อน ฤดูฝนและปลายฤดูฝนนั้นเกิดขึ้นที่บริเวณรอยต่อระหว่างอ่าวไทยและทะเลจีนใต้ สำหรับค่าต่ำสุด ในฤดูหนาวเกิดขึ้นที่ละติจูด 11 องศาเหนือ ในฤดูร้อนเกิดขึ้นระหว่างละติจูด 8 ถึง 9 องศาเหนือ ในฤดูฝนและปลายฤดูฝนเกิดขึ้นระหว่างละติจูด 10 ถึง 11 องศาเหนือ การตรวจสอบความแม่นยำของผลการวิจัยนั้นได้ทำการเปรียบเทียบผลที่ได้กับผลของการวิจัยของ Wyrtki ซึ่งหาการถ่ายเทปริมาตรน้ำในบริเวณเอเชียตะวันออกเฉียงใต้ สามารถสรุปได้ว่าผลการวิจัยนี้เป็นไปในทางเดียวกัน

คำหลัก : การถ่ายเทปริมาตร; การถ่ายเทความร้อน; การถ่ายเทน้ำจืด; อ่าวไทย; โครงข่ายโค้งเชิงตั้งฉาก

Abstract

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Project Period : July 2012 – June 2014

Abstract:

This research aims to investigate volume, heat, and freshwater transports in the Gulf of Thailand for each season. The Model grid used in this research is the orthogonal curvilinear grid which is constructed via cubic splines and solving Laplace's equation. For the vertical grid, the sigma coordinate is introduced to deal with significant topographical variability. The data used for calculating the volume, heat, and freshwater transports consist of bottom topography, current velocities, potential temperature, salinity, and seawater density, and are calculated from the primitive equations. A numerical method used to solve the primitive equations is the finite difference method. The results show that the highest and lowest values of volume, heat, and freshwater transports in each season occur at the same region, and the direction of volume and heat transports are all same in the Gulf of Thailand, but the freshwater transport is the opposite direction of volume and heat transports. The highest values of volume, heat, and freshwater transports occur between latitudes 7°N to 8°N in the winter and at the connection section between the Gulf of Thailand and the South China Sea in the summer, rainy season, and the end of the rainy season. Their lowest values occur at latitude 11°N in the winter, between latitudes 8°N to 9°N in the summer, and between latitudes 10°N to 11°N in the rainy season and the end of the rainy season. In order to validate the results, a comparison was made with the results of Wyrtki's research which investigated the volume transports of Southeast Asian Waters. In a comparison of the results, it can be summarized that the results of our research are on track.

Keywords : Volume transport; Heat transport; Freshwater transport; Gulf of Thailand; Orthogonal curvilinear grid

1. Objective

To investigate volume, heat, and freshwater transports in the Gulf of Thailand for each season.

2. Research Methodology

    - Study Area

The Gulf of Thailand (GoT) connected to the South China Sea (SCS) situates between longitudes 98°E to 107°E and latitudes 4°N to 14°N approximately. It is surrounded by the Kingdom of Thailand, the Kingdom of Cambodia, the Socialist Republic of Vietnam and Malaysia, as shown in Fig. 1. The Gulf of Thailand is shallow with mean depth of 45 meters and maximum depth about 85 meters. Since the Gulf of Thailand is shallow, it has phenomena such as tide, elevation of water mass, wind wave, storm, current, and transports of properties in the sea. These phenomena are very important knowledge to manage natural resources, marine environment, shipping, and tourism, which are advantages for countries adjoined the Gulf of Thailand, especially with Thailand.

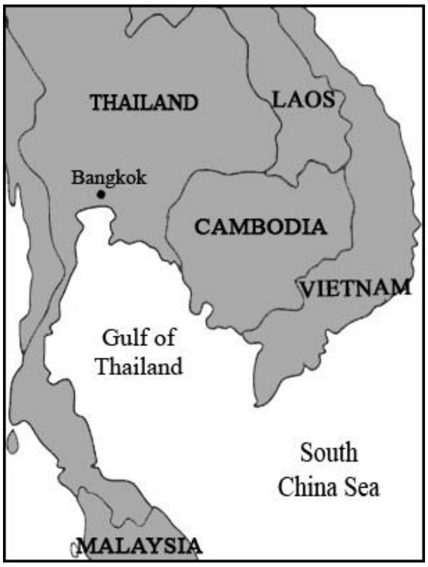

Fig. 1 The Gulf of Thailand.

    - Literature Reviews

Hern´andez-Guerra et al. (2001) studied the water masses, circulation and transport in the eastern boundary current of the North Atlantic Subtropical Gyre. Conductivity-temperature-depth (CTD) sections carried out in September 1998 are used to describe them. The surface water mass (<600 m) consists of North Atlantic Central Water (NACW) flowing south with a net mass transport of 2.3 × 109 kg s^{-1}. A tongue of relatively fresh water, consisting of Antarctic IntermediateWater (AAIW), was found approximately in the 600-1100 m depth layer. This tongue was 200-km wide, stretching from the African coast almost to Gran Canaria Island, and transported a net mass of 1.1 × 109 kg s^{-1} northward. This system of currents is what constitutes the real eastern boundary current of the North

Atlantic Subtropical Gyre.

Chu et al. (2001) reported the evaluation of the POM using SCS Monsoon Experiment (SCSMEX) data. A two-step technique is used to initialize POM with temperature, salinity, and velocity for 1 April 1998 and integrate it from 1 April 1998 with synoptic surface forcing for 3 months with and without data assimilation. Hydrographic and current data acquired from the SCSMEX from April through June 1998 are used to verify, and to assimilate into, POM. The mean SCSMEX data (Apr-Jun 1998) are about 0.58 ˚C warmer than the mean climatological data above the 50-m depth, and slightly cooler than the mean climatological data below the 50-m depth, and are fresher than the climatological data at all depths and with the maximum bias (0.2-0.25 ppt) at 75-m depth. POM without data assimilation has the capability to predict the circulation pattern and the temperature field reasonably well, but has no capability to predict the salinity field. The model errors have Gaussian-type distribution for temperature hindcast, and non-Gaussian distribution for salinity hindcast with six to eight times more frequencies of occurrence on the negative side than on the positive side. Data assimilation enhances the model capability for ocean hindcast, if even only CTD data are assimilated. When the model is reinitialized using the assimilated data at the end of a month (30 Apr; 31 May 1998) and the model is run for a month without data assimilation (hindcast capability test), the model errors for both temperature and salinity hindcast are greatly reduced, and they have Gaussian-type distributions for both temperature and salinity hindcast. Hence, POM gains capability in salinity hindcast when CTD data are assimilated.

Yaiprasert et al. (2005) studied the floating circle of objects simulation with the POM for the GoT. The motion of a group of particles floating on the sea surface was set up so that they formed a circle. The radius reflected uncertainties of longitude and latitude directions while the centre was set at the point of interest. POM was incorporated with tidal forcing on the boundary, which included used current forcing on the inflow by wind velocities, high resolution and realistic ocean bottom topography, temperature and salinity. The model domain for the Gulf of Thailand extended from latitude 3 ˚N-14 ˚N and longitude 99 ˚E-109 ˚E. A horizontal grid resolution of 0.1 degree (approximately 11.1 km) was used in the model. Therefore, the grids consisted of 101×111 cells. Twenty one levels in sigma coordinate were used in vertical resolution. The model results were verified using TOPEX/Poseidon and JASON satellite data. The results of the simulation were used to gain a better understanding of the sea current and object movement patterns in the GoT.

Phaksopa and Sojisuporn (2006) studied the storm surge in the GoT generated by Typhoon Linda in 1997 using the POM. The model was forced by eight tidal components (M2, K1, O1, S2, Q1, P1, K2, and N2) 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.

Alves et al. (2011) studied the hydrological structure, circulation and water mass transport in the Gulf of Cadiz. Hydrological and LADCP data from four experiments at sea (Semane, 1999; 2000/1; 2000/3; 2001) are used to describe them. These data were gathered on meridional sections along 8°20′W and 6°15′W and between these longitudes on a zonal section along 35°50′N. The mesoscale and the submesoscale structures (Mediterranean Water Undercurrents, meddies, cyclones) observed along these sections are characterized in terms of thermohaline properties and of velocity. The transports of mass and salt in each class of density (North Atlantic Central Water, Mediterranean Water, North Atlantic Deep Water) are computed with an inverse model. The model indicates a general eastward flux in the Central Water layer, and a westward flux in the Mediterranean Water layer, but there is also a horizontal recirculation and entrainment in these two layers, as well as strong transports associated with the meddy and cyclone found during Semane (1999).

J´onsson and Valdimarsson (2012) studied the water mass transport variability to the North Icelandic shelf, 1994-2010. In the Denmark Strait between Greenland and Iceland, the north-flowing warm, saline Atlantic Water (AW) of the Irminger Current meets the south-flowing cold, relatively fresh Polar Water (PW) of the East Greenland Current. A mixture of these two surface water masses then flows along the shelf north of Iceland. The mixture can vary from being almost pure AW to consisting, to a large extent, of PW. The relative quantities of each water mass to some extent determine the productivity and the living conditions on the shelf north of Iceland. The flow has been monitored with current meters on a section north of Iceland since 1994, and these measurements, together with hydrographic data, are used to study its structure and variability. The amount of AW carried by the flow is calculated along with the associated heat transport. In the period 1994-2010, the flow consisted on average of 68% of AW with a transport of 0.88 Sv and an associated heat transport of 24 TW. There is notable seasonal variation in the flow and strong interannual variability.

- Numerical Ocean Model

The data used for calculating the water mass transports is bottom topography and current velocities.

Generally, the bottom topography is available but the current velocities are not. The current velocities have to be calculated from primitive equations. There are two main steps used to investigate the water mass transports. The first step is to simulate the currents velocities from primitive equations using an Ocean Circulation Model (OCM) and the final step is to calculate the water mass transports from simulated data.

- Governing Equations

The primitive equations are a system of equations used for calculating the current velocities, temperature, salinity, and density. It consists of the continuity equation, the momentum equations, the hydrostatic equation, the conservation equations of temperature and salinity, and the equation of state. These equations are expressed as

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}+\frac{\partial W}{\partial z}=0, \tag{1}$$

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}+W\frac{\partial U}{\partial z}-fV=-\frac{1}{\rho_0}\frac{\partial p}{\partial x}+\frac{\partial}{\partial z}\left(K_M\frac{\partial U}{\partial z}\right)+F_x, \tag{2}$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+W\frac{\partial V}{\partial z}+fU=-\frac{1}{\rho_0}\frac{\partial p}{\partial y}+\frac{\partial}{\partial z}\left(K_M\frac{\partial V}{\partial z}\right)+F_y, \tag{3}$$

$$\rho g=-\frac{\partial p}{\partial z}, \tag{4}$$

$$\frac{\partial T}{\partial t}+U\frac{\partial T}{\partial x}+V\frac{\partial T}{\partial y}+W\frac{\partial T}{\partial z}=\frac{\partial}{\partial z}\left(K_H\frac{\partial T}{\partial z}\right)+F_T, \tag{5}$$

$$\frac{\partial S}{\partial t}+U\frac{\partial S}{\partial x}+V\frac{\partial S}{\partial y}+W\frac{\partial S}{\partial z}=\frac{\partial}{\partial z}\left(K_H\frac{\partial S}{\partial z}\right)+F_S, \tag{6}$$

$$\rho=\rho(T,S,p). \tag{7}$$

Where U and V are the horizontal velocities in the x and y directions, respectively; W is the vertical velocity in the z direction; x, y, and z are the eastward, northward, and upward directions, respectively; t is the time; f is the Coriolis parameter, ρ_0 is the reference seawater density; p is the pressure; K_M is the vertical kinematic viscosity; F_x and F_y are the horizontal viscosity terms; ρ is the seawater density; g is the gravitational acceleration; T is the potential temperature; K_H is the vertical diffusivity; F_T and F_S are the horizontal diffusion terms, and S is the salinity.

- Model Grid

A grid type which is generally used for computing points in a problem domain is the rectangular grid. For more complex domains, the rectangular grid may not be as effective due to the nature of either the landscape or the coastal area. However, this difficulty can be overcome by increasing the number of mesh which in turn increases the number of generated points on boundaries of the domain. It is expensive to obtain this result, and it takes a lot of time to compute. For this reason, we use the orthogonal curvilinear grid designed to match the problem domain, keeping the number of mesh identical to the rectangular grid. It is low cost and uses less time to compute. In this research we specify the number of horizontal grid points as 43×97. The model grid for this research is shown in Fig. 2. The grid spacing in x direction is between 2-40 kilometers and the grid spacing in y direction is between 5-35 kilometers.

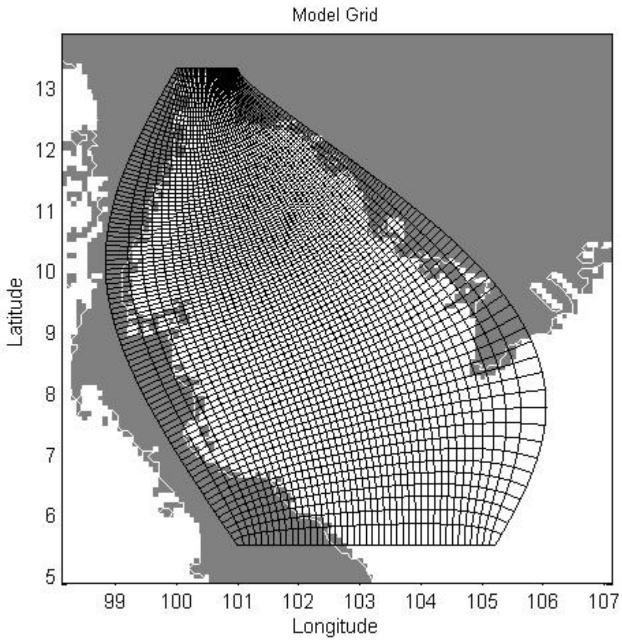

Fig. 2 The model grid.

- Sigma Coordinate and Staggered Grid

In order to separate water in the Gulf of Thailand into several layers, the vertical sigma coordinate is used. In the sigma coordinate system the density in each contour of vertical layers is quite constant. This is achieved by transformation of the governing equations from z-coordinate (x,y,z,t) to the vertical sigma coordinate (x^*,y^*,σ,t^*). The transformation from Cartesian to sigma coordinates is

$$x^* = x, \tag{8}$$

$$y^* = y, \tag{9}$$

$$\sigma = \frac{z-\eta(x,y,t)}{D}, \tag{10}$$

$$t^* = t\,. \tag{11}$$

Where $D = H(x,y)+\eta(x,y,t)$ is the seawater column depth; $H(x,y)$ is the bottom topography, and $\eta(x,y,t)$ is the surface elevation.

The value σ ranges from $\sigma = 0$ at the surface elevation, $z = \eta(x,y,t)$, to $\sigma = -1$ at the bottom topography, $z = -H(x,y)$.

In this research, the number of sigma levels is specified as 9 levels. The sigma levels are shown in Table 1.

The values $\Delta\sigma_k$ and $\Delta\sigma_{k+1/2}$ are obtained from

$$\Delta\sigma_k = \sigma_k - \sigma_{k+1} \quad \text{for } k = 1,2,\ldots,8 \tag{12}$$

and

$$\Delta\sigma_{k+1/2} = \sigma_{k+1/2} - \sigma_{k+3/2} \quad \text{for } k = 1,2,\ldots,7. \tag{13}$$

Table 1 Sigma levels for the research.

k	σ_k	$\sigma_{k+1/2}$	$\Delta\sigma_k$	$\Delta\sigma_{k+1/2}$
1	0.0000	-0.0357	0.0714	0.0653
2	-0.0714	-0.1010	0.0714	0.1010
3	-0.1429	-0.2020	0.1429	0.1551
4	-0.2857	-0.3571	0.1429	0.1429
5	-0.4286	-0.5000	0.1429	0.1429
6	-0.5714	-0.6249	0.1429	0.1551
7	-0.7143	-0.7980	0.1429	0.1306
8	-0.8571	-0.9286	0.1429	
9	-1.0000			

A mathematical technique used to solve the primitive equations is the finite difference method. The study domain is discretized using a staggered grid, which is C grid.

- Model Initialization

All above-mentioned methodologies are done using an Ocean Circulation Model (OCM). The Princeton Ocean Model (POM) is applied in this research. The model is run until the time series of total kinetic energy (*EK*), total potential energy (*EA*), and total surface potential energy (*EAS*) reach a steady state. The total kinetic energy (*EK*), total potential energy (*EA*), and total surface potential energy (*EAS*) (Aschariyaphotha et al., 2008) are

$$EK = \frac{1}{2}\iiint \rho_0 (U^2 + V^2)\,dxdydz, \tag{14}$$

$$EA = -\frac{1}{2} g \iiint \frac{(\rho - \tilde{\rho})^2}{\frac{d\tilde{\rho}}{dz}}\,dxdydz, \tag{15}$$

$$EAS = \frac{1}{2}\iint \rho_0 g \eta^2\,dxdy \tag{16}$$

where $\tilde{\rho}$ is the horizontal averaging of the density fields.

In this research, the numbers of days used in the model run are shown in Table 2.

Table 2 Numbers of days used in the model run for each month.

Month	Days
January	9500
February	9900
March	8000
April	5000
May	7500
June	5000
July	2800
August	3000
September	6000
October	2500
November	5500
December	7500

- Initial Data

Initial data are prepared for solving the primitive equations. They consist of bottom topography derived from Digital Bathymetric Data Base 5-minute (DBDB5) with 1/12 degree resolution between longitudes 98.125°E to 107.125°E and latitudes 4.875°N to 14.875°N, climatological monthly mean wind derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) with 2.5 degree resolution between longitudes 95°E to 107.5°E and latitudes 2.5°N to 15°N, and climatological monthly mean temperature and salinity in 6 levels of the Cartesian coordinate derived from Levitus94 with 1 degree resolution between longitudes 97.5°E to 106.5°E and latitudes 4.5°N to 15.5°N. These data have to be applied to calculate the current velocities, potential temperature, salinity, and seawater density in the Gulf of Thailand. Since these data are not on all grid points of the model grid, they have to be interpolated into the model grid using bilinear interpolations.

- Transport Equations

Simulated current velocity, potential temperature, salinity, and seawater density are used to calculate the volume, heat, and freshwater transports in the Gulf of Thailand. The mean horizontal transport of volume across an ocean basin of width *L* and depth *H(x)* is

$$H_v = \int_0^L \int_{-H(x)}^0 V dz dx. \tag{17}$$

The integrated heat transport across an ocean basin of width *L* and depth *H(x)* is

$$F_Q = c_p \int_0^L \int_{-H(x)}^0 \rho V T dz dx \qquad (18)$$

where c_p is the specific heat capacity.

The integrated freshwater transport across an ocean basin of width *L* and depth *H(x)* is

$$F_W = \int_0^L \int_{-H(x)}^0 \rho V (1-S) dz dx \; . \qquad (19)$$

Since the values of bottom topography, current velocity, potential temperature, salinity, and seawater density depend on grid locations, calculating the volume, heat, and freshwater transports, Eqs. (17), (18), and (19) have to be discretized before calculation, which are expressed as

$$H_v = \sum_{k=1}^{kb-1} \sum_{i=1}^{im} \left(\frac{V_{i,j+1,k} + V_{i,j,k}}{2} \right) H_{i,j} \Delta\sigma_k \Delta x_{i,j} \; , \qquad (20)$$

$$F_Q = c_p \sum_{k=1}^{kb-1} \sum_{i=1}^{im} \rho_{i,j,k} \left(\frac{V_{i,j+1,k} + V_{i,j,k}}{2} \right) T_{i,j,k} \Delta\sigma_k H_{i,j} \Delta x_{i,j} \; , \qquad (21)$$

$$F_W = \sum_{k=1}^{kb-1} \sum_{i=1}^{im} \rho_{i,j,k} \left(\frac{V_{i,j+1,k} + V_{i,j,k}}{2} \right) (1 - S_{i,j,k}) \Delta\sigma_k H_{i,j} \Delta x_{i,j} \; . \qquad (22)$$

Where kb is the total number of levels in the sigma coordinate; im is the total number of grid points in x direction; Δx is the grid spacing in x direction; $\Delta\sigma$ is the difference of the value σ in the sigma coordinate.

In this research, we use the value of the specific heat capacity, c_p, as 3898 Joules per kilogram per degree Celsius (J/(kg °C)) (Murray, 2004).

3. Results

The volume, heat, and freshwater transports in the Gulf of Thailand are calculated for each season of Thailand. The months January, April, July, and October represent the winter, summer, rainy season, and end of the rainy season of Thailand, respectively. The study regions in the Gulf of Thailand are chosen from horizontal lines in x direction of the model grid because these regions make us know that the volume, heat, and freshwater are transported in or out of the Gulf of Thailand. The study region and cross-section lines for this research are shown in Fig. 3. The results of the volume, heat, and freshwater transports yield positive and negative values. Positive values mean the moving from the South China Sea into the Gulf of Thailand. On the other hand, the moving out of the Gulf of Thailand to the South China Sea produces negative values.

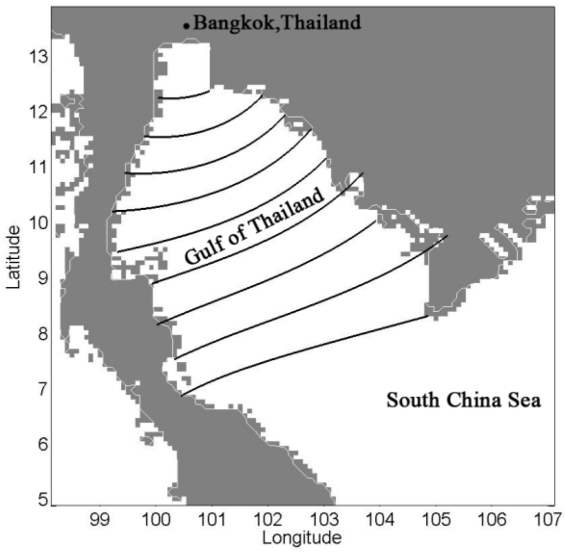

Fig. 3 The study region and cross-section lines in the Gulf of Thailand.

The volume transports in the Gulf of Thailand for January, April, October and July are shown in Fig. 4 – Fig. 7, respectively. The heat transports in the Gulf of Thailand for January, April, October and July are shown in Fig. 8 – Fig. 11, respectively. The freshwater transports in the Gulf of Thailand for January, April, October and July are shown in Fig. 12 – Fig. 15, respectively.

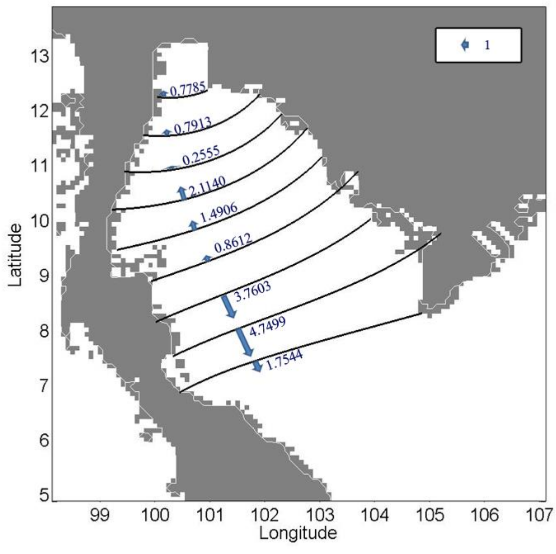

Fig. 4 The volume transports (Sv) in the Gulf of Thailand for January.

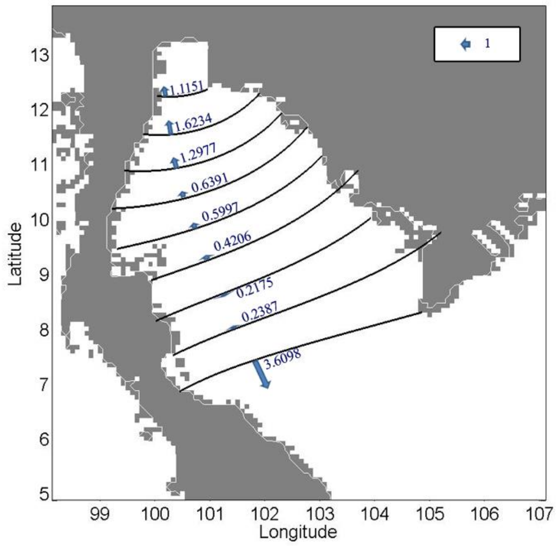

Fig. 5 The volume transports (Sv) in the Gulf of Thailand for April.

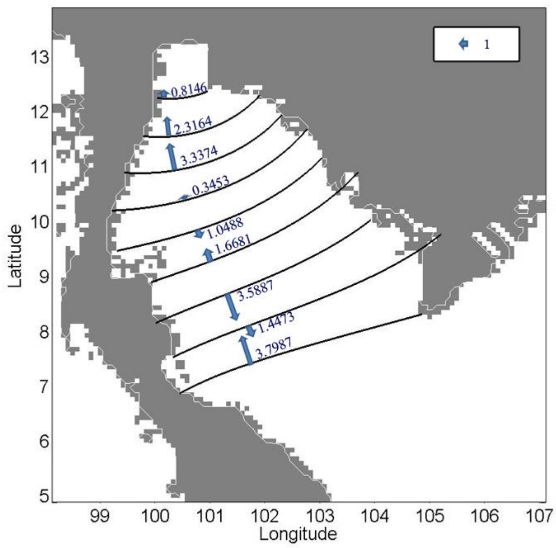

Fig. 6 The volume transports (Sv) in the Gulf of Thailand for July.

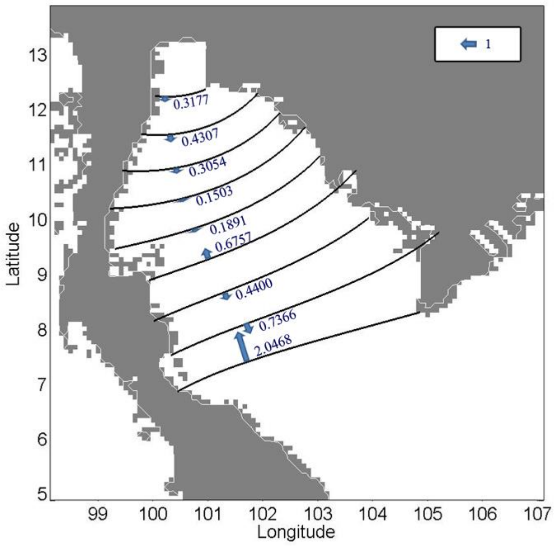

Fig. 7 The volume transports (Sv) in the Gulf of Thailand for October.

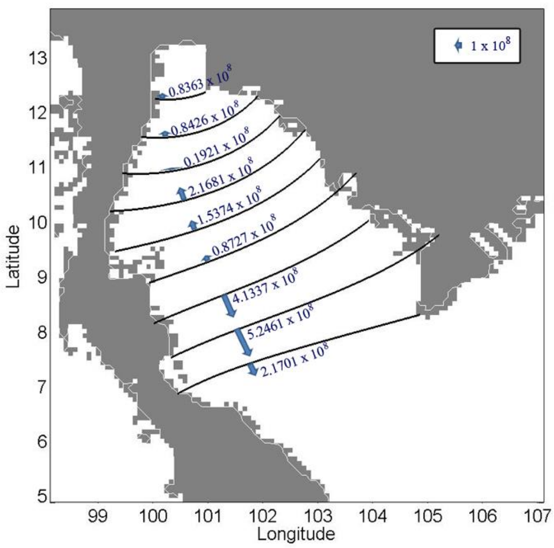

Fig. 8 The heat transports (W) in the Gulf of Thailand for January.

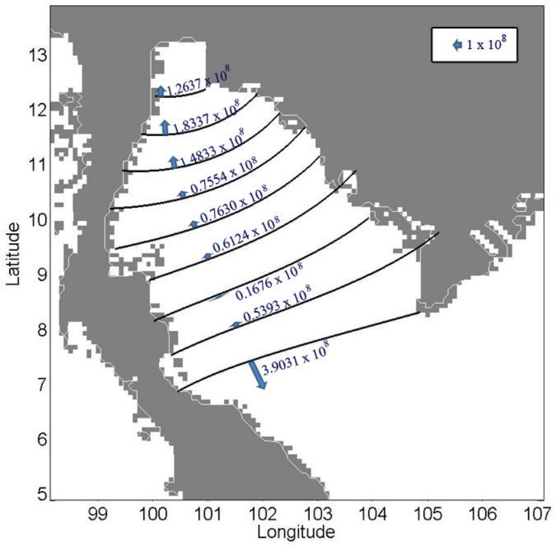

Fig. 9 The heat transports (W) in the Gulf of Thailand for April.

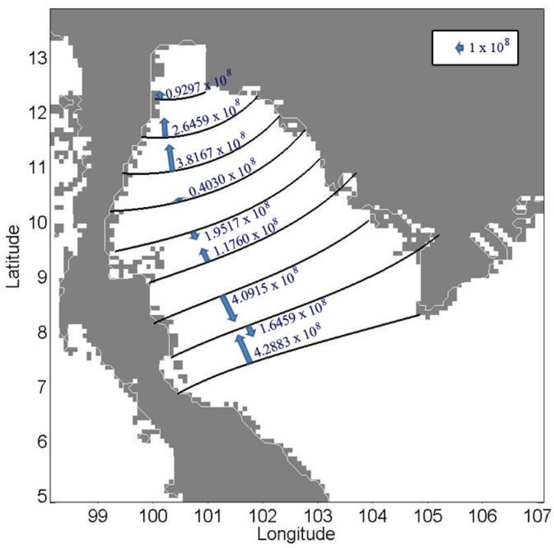

Fig. 10 The heat transports (W) in the Gulf of Thailand for July.

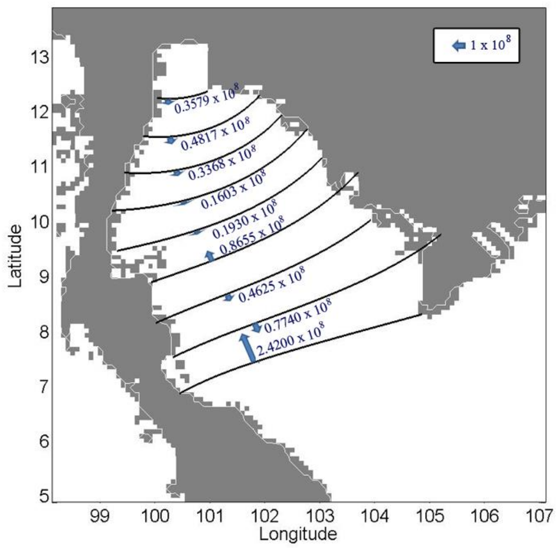

Fig. 11 The heat transports (W) in the Gulf of Thailand for October.

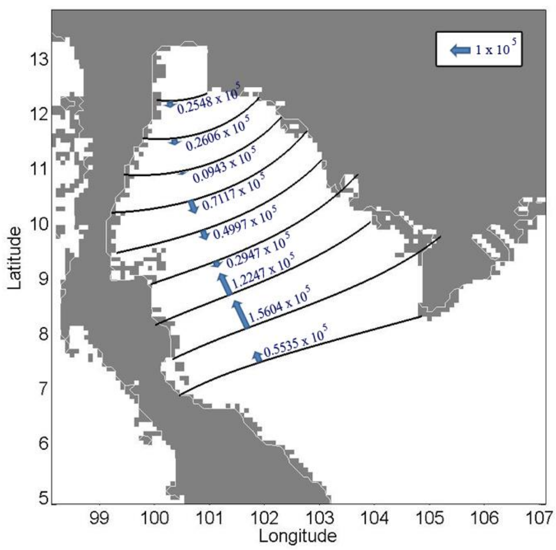

Fig. 12 The freshwater transports (kg/s) in the Gulf of Thailand for January.

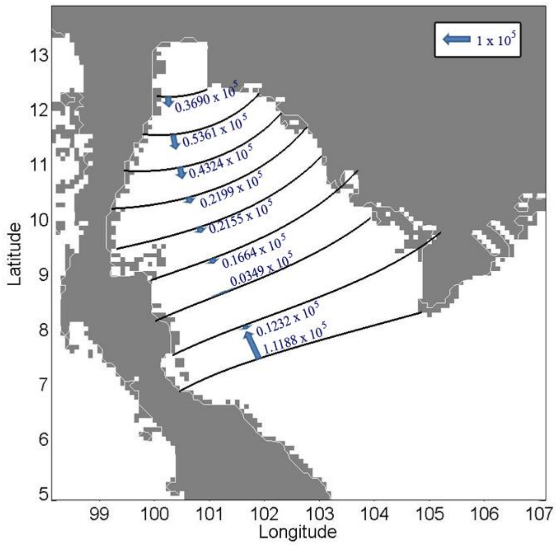

Fig. 13 The freshwater transports (kg/s) in the Gulf of Thailand for April.

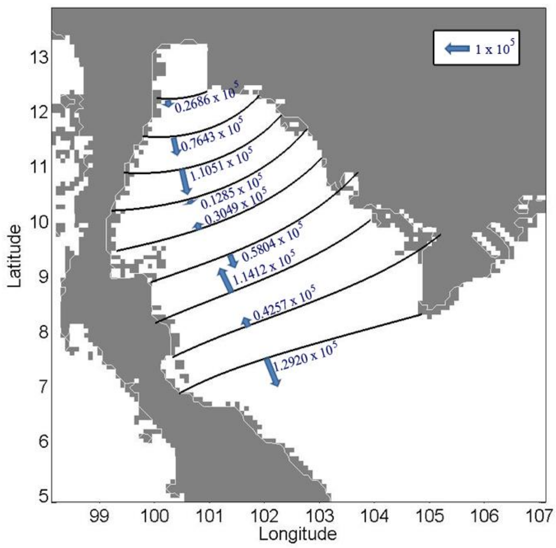

Fig. 14 The freshwater transports (kg/s) in the Gulf of Thailand for July.

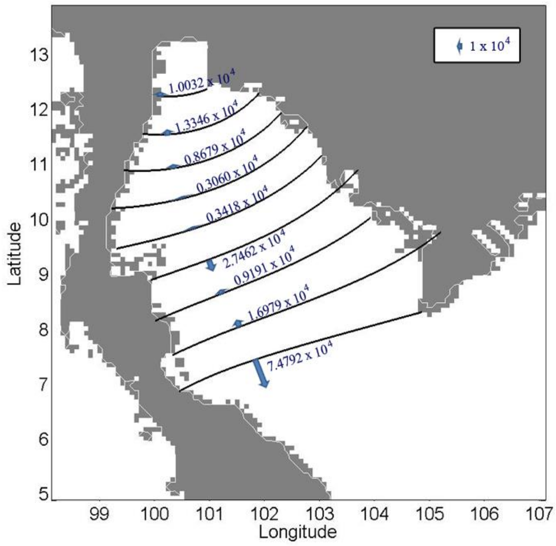

Fig. 15 The freshwater transports (kg/s) in the Gulf of Thailand for October.

It can be seen that the highest and lowest values of volume, heat, and freshwater transports in each season are at the same region. The volume and heat transports have the same directions, while the freshwater transport has the opposite direction.

For winter of Thailand, January, the values of volume, heat, and freshwater transports (Fig. 4, Fig. 8 and Fig. 12) are between 0.2 to 4.8 Sv, 0.1×10^8 to 5.3×10^8 W, and 0.9×10^4 to 1.6×10^5 kg/s, respectively. Their highest values occurred in the middle GoT, between latitudes 7°N to 8°N, are 4.7499 Sv, 5.2461×10^8 W, and 1.5604×10^5 kg/s, respectively, and their lowest values occurred at latitude 11°N are 0.2555 Sv, 0.1921×10^8 W, and 0.9430×10^4 kg/s, respectively. For the upper GoT (upper than 9°N), the volume and heat transports move northward, while they move southward out of GoT in the lower GoT (lower than 9°N).

For summer of Thailand, April, the values of volume, heat, and freshwater transports (Fig. 5, Fig. 9 and Fig. 13) are between 0.2 Sv - 3.7 Sv, 0.1×10^8 W - 4.0×10^8 W, and 0.3×10^4 kg/s - 1.2×10^5 kg/s, respectively. Their highest values occurred at the connection section between the Gulf of Thailand and the South China Sea are 3.6098 Sv, 3.9031×10^8 W, and 1.1188×10^5 kg/s, respectively, and their lowest values occurred between latitudes 8°N to 9°N are 0.2175 Sv, 0.1676×10^8 W, and 0.349×10^4 kg/s, respectively. For the upper GoT, the volume and heat transports move northward, while they move in and out of GoT alternately the lower GoT.

For rainy season of Thailand, July, the values of volume, heat, and freshwater transports (Fig. 6, Fig. 10 and Fig. 14) are between 0.3 Sv - 3.8 Sv, 0.4×10^8 W - 4.3×10^8 W, and 0.1×10^5 kg/s - 1.3×10^5 kg/s, respectively. Their highest values occurred at the connection section between the Gulf of Thailand and the South China Sea are 3.7987 Sv, 4.2883×10^8 W, and 1.2920×10^5 kg/s, respectively, and their lowest values occurred between latitudes 10°N to 11°N are 0.3453 Sv, 0.4030×10^8 W, and 0.1285×10^5 kg/s, respectively. For the upper GoT, the volume and heat transports move northward, while they move in and out of GoT alternately in the lower GoT.

For the end of rainy season of Thailand, October, the values of volume, heat, and freshwater transports (Fig. 7, Fig. 11 and Fig. 15) are between 0.1 Sv - 2.1 Sv, 0.1×10^8 W - 2.5×10^8 W, and 0.3×10^4 kg/s - 7.5×10^4 kg/s, respectively. Their highest values occurred at the connection section between the Gulf of Thailand and the South China Sea are 2.0468 Sv, 2.4200×10^8 W, and 7.4792×10^4 kg/s, respectively, and their lowest values occurred between latitudes 10°N to 11°N are 0.1503 Sv, 0.1603×10^8 W, and 0.3060×10^4 kg/s, respectively. For the upper GoT, the volume and heat transports move southward, while they move in and out of GoT alternately in the lower GoT.

It can be summarized that the directions and magnitudes of volume, heat, and freshwater transports depend mainly on the current. The direction of transport arise from most current moving in a region greatly. While the magnitude of transport depends on the direction and speed of current. The high magnitude of transport results from the current has high speed and move in that region. On the other hand, the low magnitude of transport arise from the current at the region which has low speed.

In order to validate the results, the volume transports for this research are compared with the volume transports obtained from Wyrtki (1961), who studied volume transport of the Southeast Asian Waters. Although he did not study in the Gulf of Thailand directly, his research is enough to compare with our results because it is the nearest region. His research investigated the direction of volume transports of the Southeast Asian Waters for June and December and the values of volume transports near Vietnam coast in February, April, June, August, October, and December, as shown in Table 3. The volume transports in the Gulf of Thailand for June and December are shown in Fig. 16 and Fig. 17, respectively.

Table 3 Values of the volume transports in the Southeast Asian waters at Vietnam Coast from Wyrtki (1961).

Month	Volume Transports (Sv)
February	-5.0
April	-1.5
June	3.5
August	3.0
October	-2.0
December	-5.0

It can be seen that the volume transports in June and December have the same directions which is moving in and out of the GoT, respectively. For the values of the volume transports, our values and Wyrtki's values have similar tendencies.

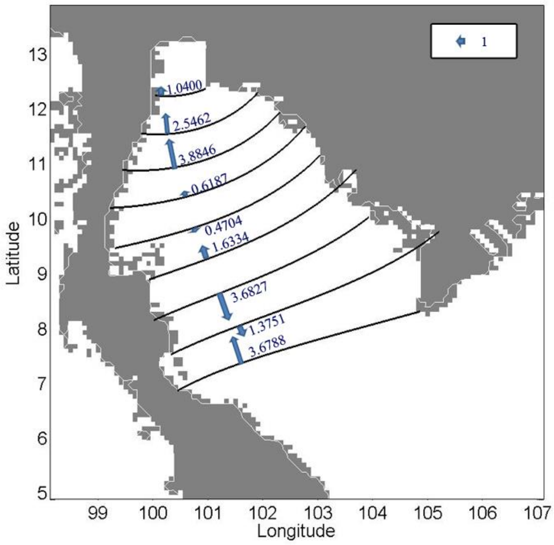

Fig. 16 The volume transports (Sv) in the Gulf of Thailand for June.

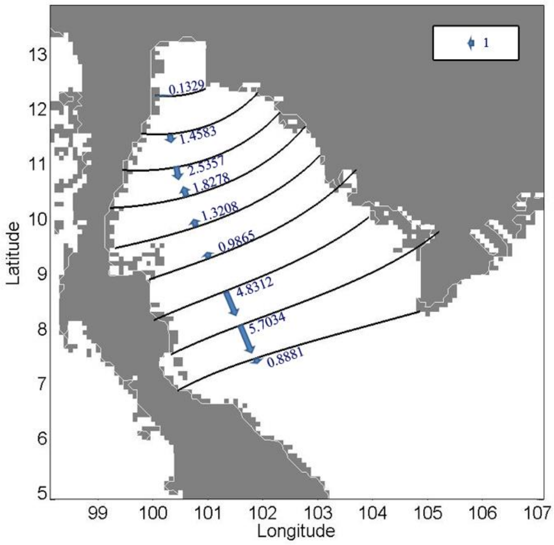

Fig. 17 The volume transports (Sv) in the Gulf of Thailand for December.

4. Conclusions and Discussions

In this research, we investigated the volume, heat, and freshwater transports in the Gulf of Thailand. The model grid is the orthogonal curvilinear grid and the vertical coordinate is the sigma coordinate.

Initial data have been prepared for solving the primitive equations. The initial data consists of bottom topography, wind, potential temperature, and salinity. The Princeton Ocean Model is applied in this research. It is used to solve the primitive equations in order to determine the current velocities, potential temperature, salinity, and seawater density. These data are used to calculate the volume, heat, and freshwater transports in the Gulf of Thailand for each season of Thailand. The results show that the highest and lowest values of volume, heat, and freshwater transports in each season occur at the same region, and the direction of volume and heat transports are all same in the Gulf of Thailand, but the freshwater transport is the opposite direction of volume and heat transports. The highest values of volume, heat, and freshwater transports occur between latitudes 7°N to 8°N in the winter and at the connection section between the Gulf of Thailand and the South China Sea in the summer, rainy season, and the end of the rainy season. Their lowest values occur at latitude 11°N in the winter, between latitudes 8°N to 9°N in the summer, and between latitudes 10°N to 11°N in the rainy season and the end of the rainy season. For the direction of volume and heat transports, the volume, heat, and freshwater at the upper GoT (upper than 9°N) in the winter and summer move northward, and they move southward in the end of the rainy season. At the lower GoT (lower than 9°N), they move southward in the winter, and they move in and out of the GoT alternately in the summer and the end of the rainy season. For the rainy season, they move northward at the upper GoT, and they move in and out of the GoT alternately at lower GoT. These results are very useful to manage fisheries and resources in the sea. Each species of life needs a different livelihood. Some kinds live in warm water, and some kinds live in cool water. The research also points out that various species of life move into or out of the Gulf of Thailand, depending on its need.

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Thailand using an Ocean Circulation Model” submitted to “The Arabian journal for Science and Engineering”.