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Study of Seasonal Heat, Freshwater, and Volume Transports in the Gulf of Thailand using an Ocean Circulation Model

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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 consist of bottom topography, current velocities, potential temperature, salinity, and seawater density, which are calculated from the primitive equations. 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 in 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. It can be summarized that the results of our research are on track.

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Keywords: Volume transport; Heat transport; Freshwater transport; Gulf of Thailand.

1. Introduction

The Gulf of Thailand (GoT) connected to the South China Sea (SCS) is situated approximately between longitudes 98°E to 107°E and latitudes 4°N to 14°N. As shown in figure 1, it is surrounded by the Kingdom of Thailand, the Kingdom of Cambodia, the Socialist Republic of Vietnam and Malaysia. The GoT is shallow with a mean depth of 45 meters and a maximum depth of about 85 meters. Since the GoT is shallow, it has phenomena such as tides, elevation of water mass, wind waves, storm, currents, and transports of properties in the sea. These phenomena are very important to our knowledge of how to manage natural resources, the marine environment, shipping, and tourism, which are advantageous for countries adjoining the GoT, but especially for Thailand.

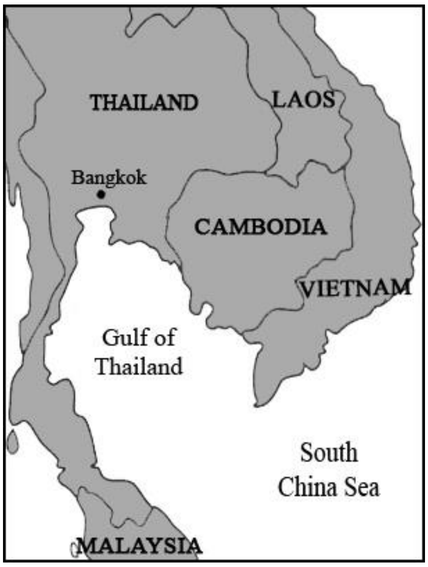


Figure 1: The Gulf of Thailand.

An important role of the ocean is transports of properties in the ocean which are the total flux of properties from one region to another. The transports of properties consists of volume, mass, heat, salt, and freshwater transports. These transports have been studied continuously by many investigators. It is important basic knowledge and very useful for managing resources in the ocean, which can lead to analyzing effects that may occur in the ocean after whatever property is transported in or out of the ocean. In calculating the transport of a property, it is determined from the integral of the property times current velocity on a cross-sectional area. Thus, before calculating the transport of the property, it has to have data used to be properties, such as potential temperature, salinity, seawater density, and current velocity. These data can be obtained from buoys, satellites, or the Ocean Circulation Model (OCM). It has to be noted that the use of buoys or satellites involves very high costs and a lot of time is expended for investigation, especially for the wide domain. A popular tool for investigation is the Ocean Circulation Model which is inexpensive and uses little time for computation. Examples of the Ocean Circulation Model are Modelo Hidrodinamico (MOHID), Geophysical Fluid Dynamics Laboratory Modular Ocean Model (MOM), Princeton Ocean Model (POM), and Parallel Ocean Program (POP), etc. In the present, there have been volumes of research done on transports of properties. Reference [11] studied mass transport in water waves. It was shown by Stokes that in a water wave the particles of fluid posses, apart from their orbital motion, a steady second-order drift velocity (usually called the mass-transport velocity). Reference [6] studied physical oceanography of Southeast Asian waters. He investigated the property of the water masses on the western side of the Luzon Strait and transport of surface water from the Pacific Ocean during the winter monsoon season. Reference [13] investigated mass transport in water waves propagated over a permeable bottom. Boundary-layer approximations are incorporated into the Lagrangian equations of motion, and the mass transport velocity is obtained for both monochromatic and random waves. Reference [8] calculated the heat transported meridionally in the Pacific Ocean from the surface heat budgets of Clark and Weare and others. Both budgets were based on Bunker's method, with different formulas. The meridional heat transport was also calculated from the surface heat budget of Esbensen and Kushnir, who used Budyko's method. Wijffels and his colleagues [17] presented the global distribution of freshwater transport in the ocean which is based on an integration point at the Bering Strait, which connects the Pacific and Atlantic oceans via the Arctic Ocean. Hernández-Guerra and his colleagues [1] presented 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 the water masses, geostrophic circulation and mass transport in the eastern most branch of the Canary Current. Reference [7] studied meridional heat transport across the Antarctic Circumpolar Current by the Antarctic Bottom Water overturning cell. The heat transported by the lower limb of the Southern Ocean meridional overturning circulation is commonly held to be negligible in comparison to that transported by eddies higher in the water column. They used output from one of the first global high resolution models to have a reasonably realistic export of Antarctic Bottom Water, the OCCAM one twelfth degree model. Reference [9] calculated meridional ocean freshwater transport and convergences from absolute geostrophic velocities and Ekman Transports. The freshwater transports are analyzed in terms of mass-balanced contributions from the shallow, ventilated circulation of the subtropical gyres, intermediate and deep water overturns, and Indonesian Through flow and Bering Strait components. Reference [3] studied water masses, mass transport and variability of the Canary Current in autumn. Conductivity-Temperature-Depth (CTD) casts from four separate autumn cruises in 1997, 2003, 2006, and 2009 sampled the Canary Basin in order to describe the autumn characteristics of the Canary Current. To calculate geostrophic velocities and transport, a reference level of no motion of y_n = 28.072 kg m^{-3} was chosen to integrate the thermal wind equation, as supported from LADCP data used from the ORCA 2009 campaign. Reference [14] studied water mass transport variability to the North Icelandic shelf, 1994-2010. Hui-Er and Yong-Qiang [10] evaluated volume and heat transport in the eddy-resolving model LASG/IAP Climate system Ocean Model (LICOM) using the observed meridional overturning circulation (MOC) and meridional heat transport (MHT) estimated from the Rapid Climate Change/Meridional Circulation and Heat Flux Array (RAPID/MOCHA) at 26.5°N. Most research has found that transports of properties have been studied at the surface or bottom only. Furthermore, it has also been found that most study regions are meridians of longitude or parallel of latitude in regions which may be quite unsuitable and useless for application. The volume, heat, and freshwater transports at all vertical plane sections in the GoT are investigated in this research. This research focuses on the transports of volume, heat, and freshwater for each season of Thailand. The values of properties and current velocities used in calculating the volume, heat, and freshwater transports are obtained from an Ocean Circulation Model. In order to validate our results for this research, we compare the results of other research in nearby regions. Although the locations of comparison are not the same points, at this time, it is the best method to look for corresponding tendencies.

2. Numerical ocean model

The data used for calculating the volume, heat, and freshwater transports are bottom topography, current velocities, potential temperature, salinity, and seawater density. Generally, the bottom topography is available but the current velocities, potential temperature, salinity, and seawater density are not. The current velocities, potential temperature, salinity, and seawater density have to be calculated from primitive equations. In this research, there are two main steps used to investigate the volume, heat, and freshwater transports. The first step is to simulate the currents' velocities, potential temperature, salinity, and seawater density from primitive equations using an Ocean Circulation Model (OCM) and the final step is to calculate the volume, heat, and freshwater transports from the simulated data.

2.1. Model description

The Princeton Ocean Model (POM) developed by [2] is modified in this research. POM model is the time-dependent, primitive equation model on a three-dimensional grid in Cartesian coordinates and vertical sigma coordinate. The model includes hydrostatic and Boussinesq approximations, realistic topography, a second-order turbulence closure model [4], horizontal diffusivity coefficients calculated by the Smagorinsky parameterization [5] and splitting modes. For the model grid, the orthogonal curvilinear grid is designed to match the problem domain, keeping the number of mesh identical to the rectangular grid.

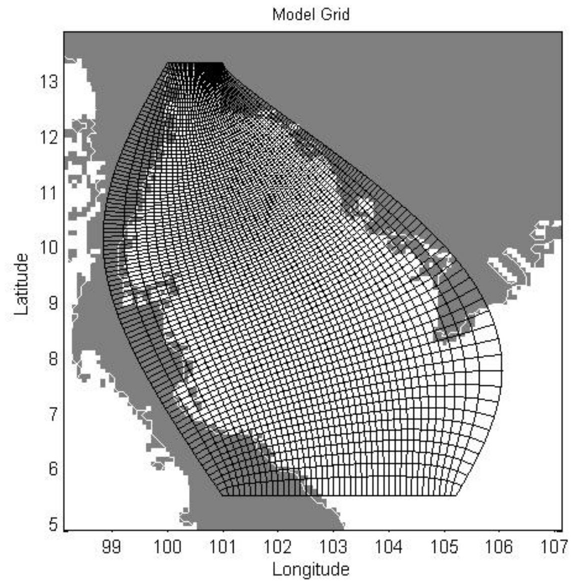


Figure 2: The model grid.

It is low cost and is computed in less time. In this research we specify the number of horizontal grid points as 43×97, as shown in figure 2. The grid spacing in direction is between 2-40 kilometers and the grid spacing in direction is between 5-35 kilometers. The number of sigma levels is specified as 9 levels. Aschariyaphotha and his colleagues [12] has described the techniques that generate the model grid and interpolate the initial data by using cubic spline and bilinear interpolations. A mathematical technique used to solve the primitive equations is the finite difference method. The study domain is discretized using a staggered grid. The C-grid is used in this research.

2.2. Initial conditions and initialization

The model was integrated with all three components of velocity initially set to zero. The initial data 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 the Levitus94 [15, 16] with 1 degree resolution between longitudes 97.5°E to 106.5°E and latitudes 4.5°N to 15.5°N. 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. The model was run until an ocean model reached an equilibrium state, or in other words, the time series of total kinetic energy (*EK*), total potential energy (*EA*) and total surface potential energy (*EAS*) reached a steady state under the applied force. The total energies [19] are monitored by the following:

$$EK = \frac{1}{2}\iiint \rho_0(u^2 + v^2)dxdydz \quad (1)$$

$$EA = -\frac{1}{2}\iiint \frac{(\rho-\tilde{\rho})}{g\frac{d\tilde{\rho}}{dz}}dxdydz \quad (2)$$

$$EAS = \frac{1}{2}\iint \rho_0 g\eta^2\, dxdy \quad (3)$$

where (u, v) is the components of the current along the x and y curvilinear coordinates, x, y, and z are eastward, northward, and upward directions, respectively, ρ_0 is a reference density for the ocean, η is the sea surface elevation, and $\tilde{\rho}$ is the mean density of the model domain calculated from the UNESCO equation of state [18], $\tilde{\rho}(x, y, z) \equiv \rho(\tilde{T}, \tilde{S}, z)$, $\tilde{T}$ and $\tilde{S}$ are observed temperature and observed salinity.

3. Transport equations

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

$$H_v = \int_0^L \int_{-H(x)}^0 v\, dzdx \quad (4)$$

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

$$F_Q = C_p \int_0^L \int_{-H(x)}^0 \rho VT \, dzdx \quad (5)$$

where C_p is the specific heat capacity.

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

$$F_W = \int_0^L \int_{-H(x)}^0 \rho v(1-S) \, dzdx \quad (6)$$

In this research, we use the value of the specific heat capacity, C_p, as 3898 J/(kg °C) [9].

4. Results

The volume, heat, and freshwater transports in the GoT 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 GoT are chosen from horizontal lines in x direction of the model grid because these regions help us identify the volume, heat, and freshwater transported in or out of the GoT. The study region and cross-section lines for this research are shown in figure 3. The results of the volume, heat, and freshwater transports yield positive and negative values. Positive values mean the moving from the SCS into the GoT. On the other hand, freshwater moving out of the GoT to the SCS produces negative values.

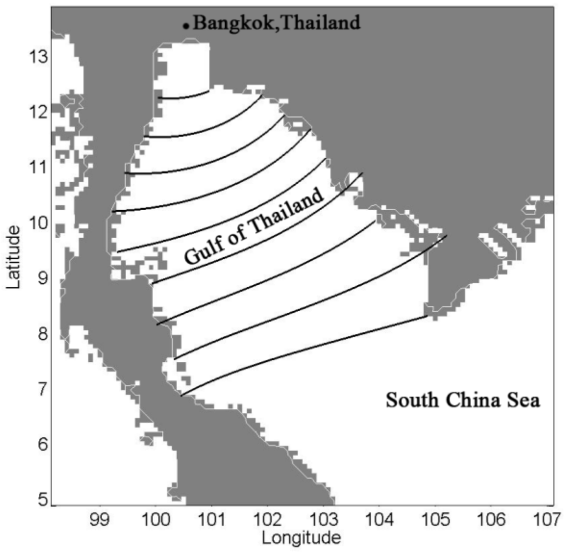
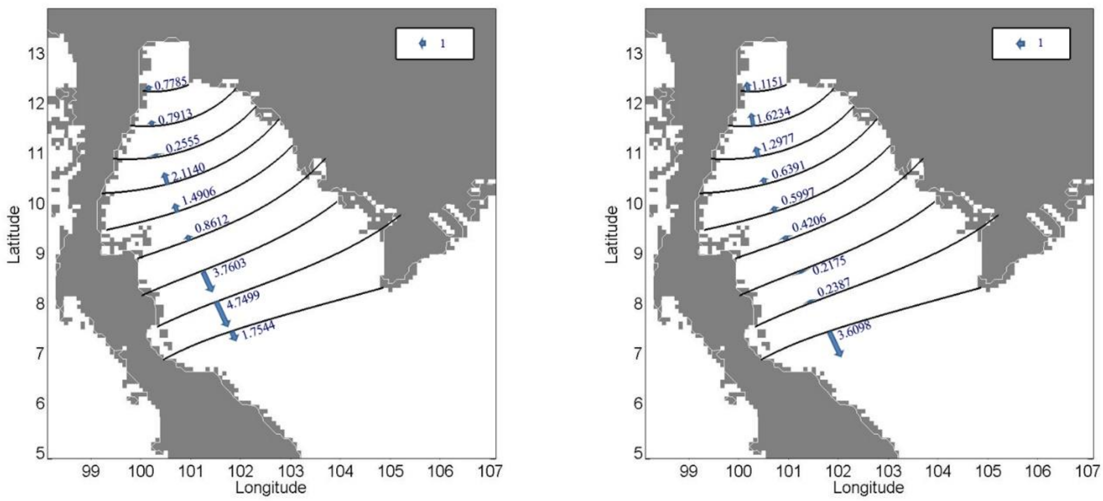
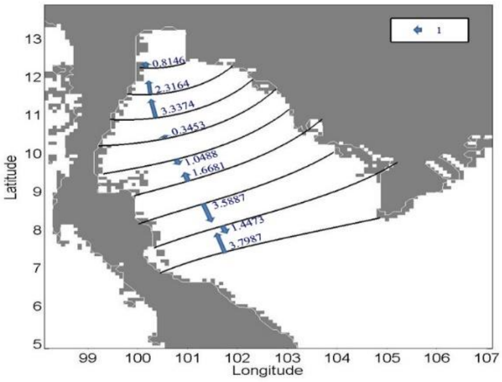


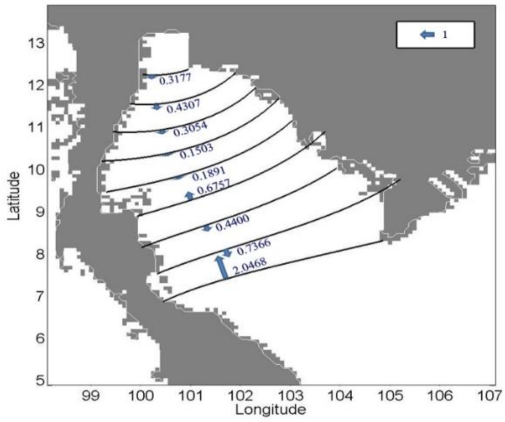
Figure 3: The study regions and cross-section lines in the GoT.

The volume transports in the GoT for January, April, October and July are shown in figure 4. The heat transports in the GoT for January, April, October and July are shown in figure 5. The freshwater transports in the GoT for January, April, October and July are shown in figure 6. 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 move in the same directions, while freshwater transport moves in the opposite direction. During winter in Thailand, January, the values of volume, heat, and freshwater transports (figure 4(a), figure 5(a) and figure 6(a)) are between 0.2 to 4.8 Sv, 1×10^7 to 5.3×10^8 W, and 9×10^3 to 1.6×10^5 kg/s, respectively. Their highest values occurred in the middle GoT, between latitudes 7°N to 8°N, are 4.75 Sv, 5.25×10^8 W, and 1.56×10^5 kg/s, respectively, and their lowest values occurred at latitude 11°N are 0.26 Sv, 1.92×10^7 W, and 9.43×10^3 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). During summer in Thailand, April, the values of volume, heat, and freshwater transports (figure 4(b), figure 5(b) and figure 6(b)) are between 0.2 Sv to 3.7 Sv, 1×10^7 W to 4×10^8 W, and 3×10^3 kg/s to 1.2×10^5 kg/s, respectively. Their highest values occurred at the connection section between the GoT and the SCS, and are 3.61 Sv, 3.9×10^8 W, and 1.12×10^5 kg/s, respectively, and their lowest values occur between latitudes 8°N to 9°N and are 0.22 Sv, 1.68×10^7 W, and 3.49×10^3 kg/s, respectively. For the upper GoT, the volume and heat transports move northward, while they move in and out of the GoT alternately to the lower GoT. During rainy season in Thailand, July, the values of volume, heat, and freshwater transports (figure 4(c), figure 5(c) and figure 6(c)) are between 0.3 Sv to 3.8 Sv, 4×10^7 W to 4.3×10^8 W, and 1×10^4 kg/s to 1.3×10^5 kg/s, respectively. Their highest values occurred at the connection section between the GoT and the SCS, and are 3.80 Sv, 4.29×10^8 W, and 1.29×10^5 kg/s, respectively, and their lowest values occurred between latitudes 10°N to 11°N, and are 0.35 Sv, 4.030×10^7 W, and 1.29×10^4 kg/s, respectively. For the upper GoT, the volume and heat transports move northward, while they move in and out of the GoT alternately in the lower GoT. During the end of the rainy season in Thailand, October, the values of volume, heat, and freshwater transports (figure 4(d), figure 5(d) and figure 6(d)) are between 0.1 Sv to 2.1 Sv, 1×10^7 W to 2.5×10^8 W, and 3×10^{13} kg/s to 7.5×10^4 kg/s, respectively. Their highest values occurred at the connection section between the GoT and the SCS, and are 2.05 Sv, 2.42×10^8 W, and 7.48×10^4 kg/s, respectively, and their lowest values occur between latitudes 10°N to 11°N, and are 0.15 Sv, 1.60×10^7 W, and 3.06×10^3 kg/s, respectively. For the upper GoT, the volume and heat transports move southward, while they move in and out of the GoT alternately in the lower GoT.



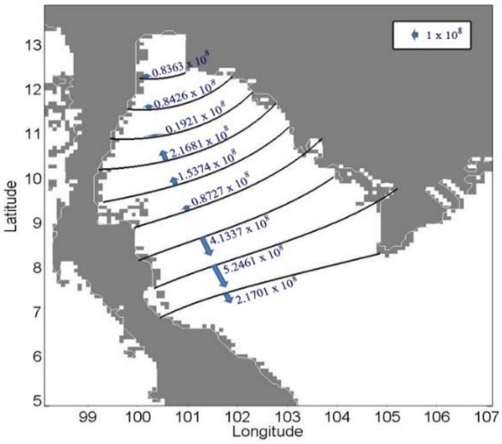
(a) (b)

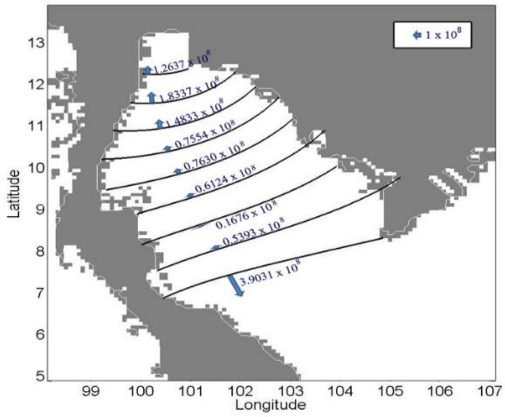




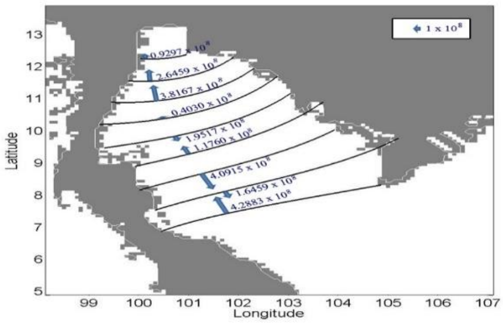
(c) (d)

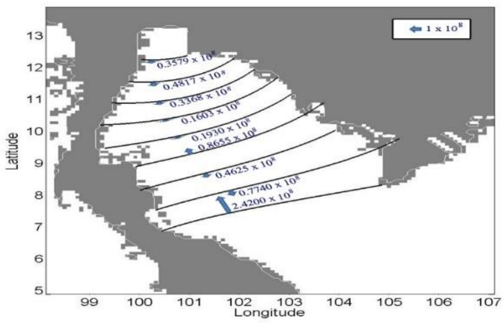
Figure 4: The volume transports (Sv) in the GoT for (a) January, (b) April, (c) July, and (d) October.





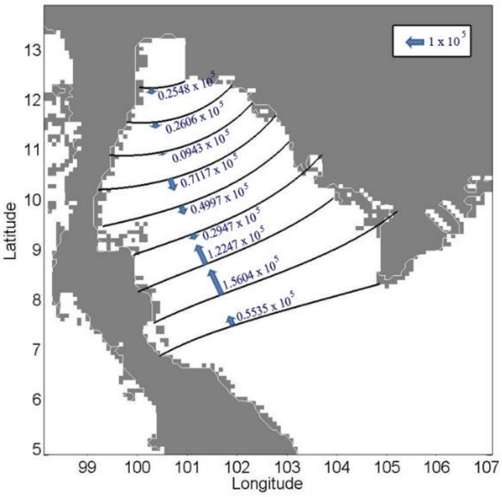
(a) (b)



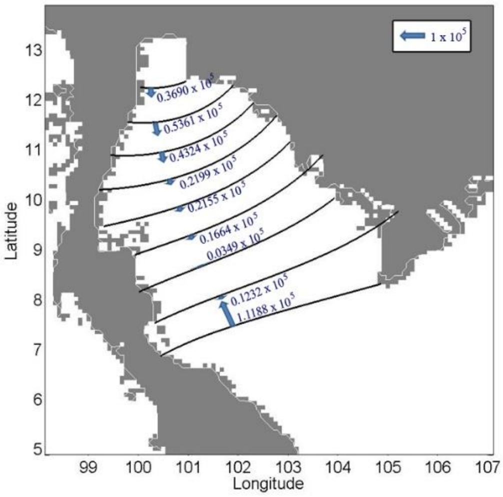


(c) (d)

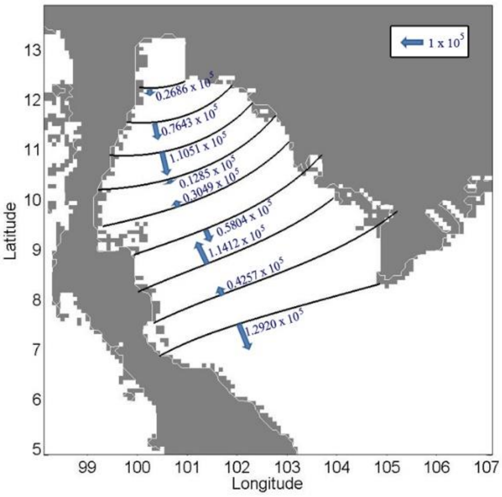
Figure 5: The heat transports (W) in the GoT for (a) January, (b) April, (c) July, and (d) October.



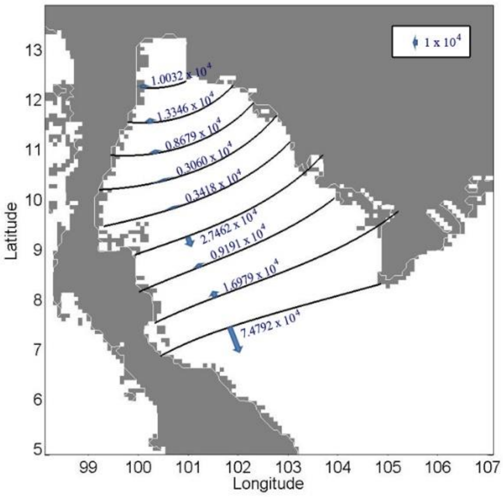
(a)



(b)



(c)



(d)

Figure 6: The freshwater transports (kg/s) in the GoT for (a) January, (b) April, (c) July, and (d) October.

It can be summarized that the directions and magnitudes of volume, heat, and freshwater transports depend mainly on the current. The direction of transport arises from most currents moving largely within a region, while the magnitude of transport depends on the direction and speed of current. The high magnitude of transport results from currents having high speed and moving in that region. On the other hand, the low magnitude of transport arises from currents in the region which have low speed. The volume transports across the connection section between the GoT and the SCS, which is connected from the point (100.448°E, 6.857°N) to the point (104.870°E, 8.297°N), for each month are shown in Table 1. It can be seen that volume of water is transported from the SCS into the GoT during May to October, while the rest of the year, volume of water is transported from the GoT into the SCS. In order to validate the results, the volume transports for this research are compared with the volume transports obtained from [6], who studied volume transport of the Southeast Asian Waters. Although he did not study in the GoT 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 the Vietnam coast in February, April, June, August, October, and December, as shown in Table 1. It can be seen that most of the volume transports from our values and Wyrtki's values have similar tendencies.

Table 1: The volume transports (Sv) at the connection section between GoT and SCS for each month and the volume transports (Sv) in Southeast Asian waters near the Vietnam Coast according to Wyrtki [6].

	Our results at the connection section between GoT and SCS	Wyrtki's results near the Vietnam Coast
January	-1.75	
February	-10.90	-5
March	-11.11	
April	-3.61	-1.5
May	0.67	
June	3.68	3.5
July	3.80	
August	3.75	3
September	3.31	
October	2.05	-2
November	-7.85	
December	0.89	-5

5. Conclusions

The POM 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 GoT 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 the same in the GoT, but freshwater transport is in 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 GoT and the SCS 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 (higher than 9°N) in the winter and summer move northward, and they move southward at the end of the rainy season. At the lower GoT (below 9°N), they move southward in the winter, and they move in and out of the GoT alternately in the summer and at 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 the lower GoT. These results are very useful in managing 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 GoT, depending on its need.

Acknowledgements

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References

[1]. A. Hernández-Guerra, F. López-Laatzen, F. Machín, D.D. Armas and J.L. Pelegrí. "Water Masses, Circulation and Transport in the Eastern Boundary Current of the North Atlantic Subtropical Gyre." Scientia Marina, vol. 65, pp. 177-186, 2000.

[2]. A.F. Blumberg and G.L. Mellor. "A Description of a Three-Dimensional Coastal Ocean Circulation Model. Three-Dimensional Coastal Ocean Circulation Models," in Heap N.S. (Ed.), American Geophysical Union, 1987.

[3]. C.A. Mock. "Water Masses, Mass Transport and Variability of the Canary Current in Autumn." Universidad de Las Palmas de Gran Canaria, Las Pal mas, Spain, 2011.

[4]. G.L. Mellor and T. Tamada. "Develop of a Turbulence Closure Model for Geophysical Fluids Problems." Rev. Geophys. Space Phys., vol. 20, 851-875, 1982.

[5]. J. Smagorinsky. "General Circulation Experiments with the Primitive Equations." Mon. Wea. Rev., vol. 91, pp. 99-164, 1963.

[6]. K. Wyrtki. "Physical Oceanography of the Southeast Asian Waters," in NAGA Report Vol 2, University of California, CA, 1961.

[7]. K.J. Heywood and D.P. Stevens. "Meridional Heat Transport across the Antarctic Circumpolar Current by the Antarctic Bottom Water Overturning Cell." Geophys. Res. Lett., vol. 34, pp. 1-5, 2007.

[8]. L.D. Talley. "Meridional Heat Transport in the Pacific Ocean." J. Phys. Oceanogr., vol. 14, pp. 231-241, 1984.

[9]. L.D. Talley. "Freshwater Transport Estimates and the Global Overturning Circulation: Shallow, Deep and Throughflow Components." Prog. in Oceanogr., vol. 78, 257-303, 2008.

[10]. M. Hui-Er and Y. Yong-Qiang. "Simulation of Volume and Heat Transport along 26.5°N in the Atlantic." Atmos. Oceanic Sci. Lett., vol. 5(5), pp. 373-378, 2012.

[11]. M.S. Longuet-Higgins. "Mass Transport in Water Waves." Philosophical Transactions of the Royal Society A, vol. 245, pp. 535-581, 1953.

[12]. N. Aschariyaphotha, P. Wongwises, S. Wongwises and U.W. Humphries. "Interpolation of Climatological Data to Numerical Ocean Modeling for the Gulf of Thailand," in Proceedings of the Joint International Conference on Sustainable Energy and Environment, 2004.

[13]. P.L. Liu. "Mass Transport in Water Waves Propagated over a Permeable Bed." Coastal Engineering, vol. 1, pp. 79-96, 1977.

[14]. S. Jónsson and H. Valdimarsson. "Water Mass Transport Variability to the North Icelandic Shelf, 1994–2010." ICES Journal of Marine Science, pp. 1-7, 2012.

[15]. S. Levitus, R. Burgett and T. Boyer. “World Ocean Atlas, Vol 3: Salinity,” in NOAA Atlas NESDIS 3, U.S. Government Printing Office, Washington D.C., 1994.

[16]. S. Levitus and T. Boyer. “World Ocean Atlas, Vol 4: Temperature,” in NOAA Atlas NESDIS 4, U.S. Government Printing Office, Washington D.C., 1994.

[17]. S.E. Wijffels, R.W. Schmitt, H.L. Bryden and A. Stigebrandt. “Transport of Freshwater by the Oceans.” J. Phys. Oceanogr., vol. 22, pp. 155-162, 1992.

[18]. UNESCO. “Tenth Rep. of the Joint Panel on Oceanographic Tables and Standards, UNESCO Tech.” in Marine Science, UNESCO, Paris, 1981.

[19]. X.H. Zhang and Q.C. Zeng. “Computational Design of the World Oceanic General Circulation Model.” Frontier in Atmospheric Sciences, pp. 188-207, 1993.