Songklanakarin J. Sci. Technol.
44 (1), 169-175, Jan. - Feb. 2022

http://www.sjst.psu.ac.th

Original Article

Numerical studies of free convection in ocean using a 2D-model

Taufiq Iskandar[1*], Muhammad Ikhwan[2], Yudi Haditiar[3], and Syamsul Rizal[2, 3, 4]

[1] *Department of Mathematics, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Banda Aceh, 23111 Indonesia*

[2] *Graduate School of Mathematics and Applied Sciences, Universitas Syiah Kuala, Banda Aceh, 23111 Indonesia*

[3] *Department of Marine Sciences, Faculty of Marine and Fisheries, Universitas Syiah Kuala, Banda Aceh, 23111 Indonesia*

[4] *Research Center for Marine Sciences and Fisheries, Universitas Syiah Kuala, Banda Aceh, 23111 Indonesia*

Received: 8 September 2020; Revised: 9 June 2021; Accepted: 17 June 2021

Abstract

This study aimed to observe and simulate a process that releases heat from shallow and deep waters in the Aceh Waters. The simulations modeled vertical slice cases with varying seawater densities based on stability frequency. One transect was taken in shallow waters in Krueng Raba Bay, while the other two were taken in deep waters in Sabang Bay. This study used a 2D non-hydrostatic model with stratified densities from the sea surface to the specified depth. Seawater density changes increase in areas with shallow depth and leave low-density in the high depth area. The vertical current velocity or upwelling starts to strengthen in the sill area at two hours, in the simulation. The lighter fluid moves upwards, looking for a gap in the denser fluid on the surface, at a speed of 0.0042 m/s to 0.03 m/s. Areas with high depth have these speeds falling after about 3 hours in the simulation, but the surface layer shows seawater density stability. In general, the deep sea area is not affected by the convection process, and the sea surface area is well-mixed after 3 hours of simulation.

Keywords: ocean flux, mixed layer, heat convection, non-hydrostatic, numerical ocean model

1. Introduction

The convection flows dramatically affect the temperatures in the sea, both at the bottom and at the surface. Low density at a higher altitude means a decrease in convection (Doherty & Carter, 1924; Hoggard, Winterbourne, Czarnota, & White, 2017): then the surface of the water has a lower density than at the seabed, caused by forced convection. This convection is required in maintaining the climate on earth (Abbot & Tziperman, 2008; Cheon & Gordon, 2019) as heat fluctuations in high latitude areas with annual average sea surface temperature (SST). These will be much higher and the seasonal cycles will be dramatically reduced (Nuijens & Siebesma, 2019). Free convection is a way to stabilize the ocean temperature again after the forced convection. The free convection process occurs in the surface layer of the ocean with the division of layers to thermal boundary layer, free convection layer, and the layer with N_{th} uniform buoyancy loss (Marshall & Schott, 1999). The value of N is the stratification known as the frequency of stability (Kämpf, 2010).

The convective process increases surface roughness under free convection conditions (Huang, 2009, 2010). The convection process produces boundary layer convergence (Beare & Cullen, 2019). Boundary layer convergence occurs due to a layer that is continually changing due to convection, both in current velocity and density. In the case of fluid

*Corresponding author
Email address: tauis2005@gmail.com

convection, some boundary layers can be thick, but will be completely mixed in thin layers (Yunita *et al.*, 2021; Zhou, Dong, Li, & Chen, 2019).

This study explains the effects of the release of heat on density dynamics. We consider two depth cases, namely shallow and deep. The case built is only affected by the force that affects convection without the help of wind and tides.

2. Materials and Methods

Bathymetry data is used as the seabed boundary of the area given the free convection effect. The density stratification based on frequency stability follows the formula (Kämpf, 2010; Setiawan *et al.*, 2020):

$$\rho(z) = \rho_0\left(1 + \frac{N^2}{g}|z|\right) \quad (1)$$

where $p(z)$ is seawater density at z layer, p_0 is density at sea surface, g is gravity, z is depth in meters, and N is stability frequency.

This study used the Navier-Stokes equation to obtain numerical solutions of the horizontal velocities u and w. Non-hydrostatic model can be used to solve the Navier-Stokes equations (Kämpf, 2010). Momentum and energy were described with nonlinear differential equations under appropriate similarity transformations (Farooq & Xu, 2014). The system of differential equations used is (Kämpf, 2010):

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho_0}\frac{\partial(p+q)}{\partial x} + \text{Diff}(u) \quad (2)$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho_0}\frac{\partial q}{\partial z} + \text{Diff}(w) \quad (3)$$

where u and w are current velocities in zonal and vertical term, p is sea water density, η is sea level elevation, and h is total depth added to sea elevation. The parameters used are p as hydrostatic pressure and q as non-hydrostatic pressure. Parameterization of free convection over the ocean is quite crucial for the atmosphere, so the values of thermal expansion α, heat flux Q, and heat capacity C_p, and surface density must be observed (Beljaars, 1995). These parameters describe the changes in the density of the surface water with dρ/dt equivalent to $\alpha Q/C_p\Delta z$. The parameters are presented in Table 1.

The Navier-Stokes equations can be solved as follows:

1. Separate the pressure into several parts.
2. Execute momentum Equations (2) and (3)
3. Use finite difference scheme.
4. Use successive over relaxation (SOR) iterations.
5. Determine the boundary conditions for the bathymetry variable.
6. Determine the values of the stability criteria.
7. Numerical stability is achieved with Δt obeying the condition (Haditiar *et al.*, 2020; Kämpf, 2010):

$$\Delta t \le \frac{\Delta x}{\sqrt{g h_{max}}} \quad (4)$$

Table 1. Convection parameters

Parameter	Symbol	Value	Unit
Sea surface salinity	p_0	1021	psu or kg/m^3
Thermal expansion coefficient	α	2.5x10^{-4}	1/K
Stability frequency	N	0.001	1/s
Heat flux	Q	600	Watt/m^2
Heat capacity	C_P	4000	J/ (kg^{3}K)
Initial horizontal velocity	u_0	0	m/s

For comparison, the shallow coastal bathymetry uses the topography in Krueng Raba Bay with less than 30 meters depth. On the other hand, the deep bay bathymetry in Sabang Bay is used for simulations in the deep sea. Krueng Raba Bay is an open beach area and slightly protrudes into the mainland. This bay is influenced by the Indian Ocean in the west and Aceh waters (Irham, Miswar, Ilhamsyah, & Setiawan, 2018; Rizal *et al.*, 2018). It is crowded with tourists starting from the white sand beach in the north to the middle of the domain. Economic activities run very densely in this area. To the south on the coast there is one cement factory that carries cargo by sea transportation. This dense activity is a significant disturbance for the free convection process. The base and surface of the bay determine the momentum and velocity of the vertical current. Sabang Bay has a depth of up to 340 meters at map coordinates of about 5.75º-5.82º N and 95.3833º - 95.3458º E (Iskandar *et al.*, 2018). With comparatively insignificant depth, Sabang bay is strongly influenced by the surrounding oceans such as the Indian Ocean, the Andaman Sea, and the Malacca Strait (Seo, Xie, Murtugudde, Jochum, & Miller, 2009; Setiawan, Alfawirsa, Haditiar, & Rizal, 2018). SST is a physical property that can be affected by the oceans around Sabang bay.

This study used open source software, such as Fortran and Scilab. Bathymetry data were obtained from the Shuttle Radar Topography Mission with 15-minute resolution SRTM15 for specific and narrow areas such as the Sabang Bay study (Rasyidi *et al.*, 2019; Wahyudi *et al.*, 2019), and SRTM30 for larger areas such as the Andaman Sea, Gulf of Thailand, and Makassar Strait (Anwar *et al.*, 2019; Ardila *et al.*, 2019; Mahfud *et al.*, 2019). Meanwhile, the density data were generated from formula (1) without using other secondary data. According to Irmasyithah *et al.* (2019), the western waters of Sumatra, specifically in Aceh, have a thicker thermocline layer than the Andaman Sea, which is deeper. This implies that temperature can have an impact on density dynamics and heat loss.

Figure 1 shows the depth profile of the research domain. Sabang Bay (T_2 and T_3) has the location of convection at a fairly deep elevation, as illustrated in Figure 1, while it is only described as the difference in water height from a rough bottom to the sea surface with a total depth of 30 meters in the Krueng Raba Bay (T_1) domain.

3. Results and Discussion

3.1 Shallow depth simulation

Meridionally, heat loss takes place gradually and

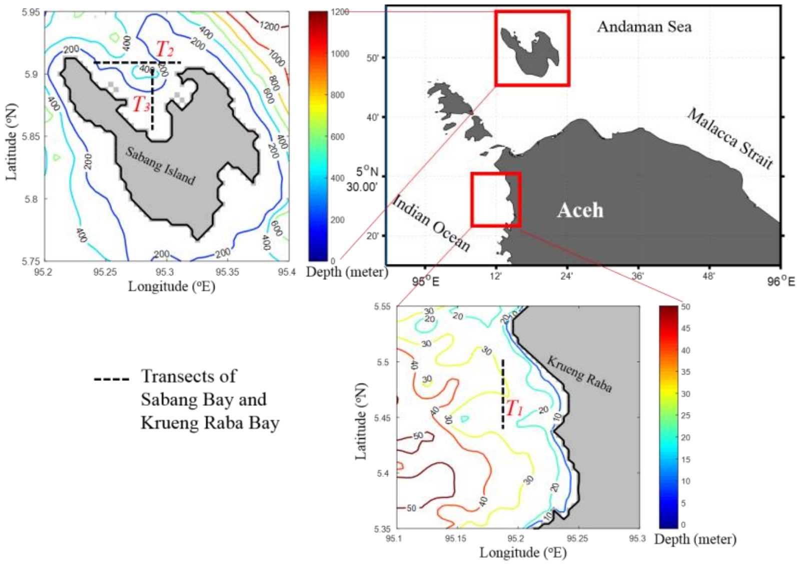


Figure 1. Profile of depth, T_1 is meridional transect in Krueng Raba Bay, T_2 and T_3 are zonal and meridional transects in Sabang Bay

starts at the surface layer, which is characterized by a high density in the surface layer compared to the lower layer. Figure 2 shows the current profile and density of at energy loss rate of 600 W/m^2 in all fluid columns.

In the first five minutes, fluid in the surface layer between 0-6 meters experienced stronger and heavier stratification while the lower layer was lighter and mixed well. This condition then causes interference with the vertical current after 35 minutes and horizontal current after 45 minutes. At 1 hour of simulated time, the light and heavy density have begun to mix. This is followed by vertical turbulence.

At two hours of simulation, the vertical current velocity or upwelling starts to strengthen in the sill area (around 5.44 °N) where the lighter fluid moves upwards, looking for a gap between the denser fluid on the surface with a maximum speed of 0.03 m/s as examples of internal wave and sill interactions in the ocean. Upwelling in the sill region after 3 hours of simulation is followed by the emergence of slightly clarified density. When this disturbance originates from the east, the domain begins to form.

At four and five hours of simulation, current disturbances from the east contribute to downwelling and upwelling on the right side of the sill (5.4546 - 5.4792 °N). The speed of upwelling and downwelling at that time is quite strong and these are almost equal. However, after 6 hours of the simulation, the downwelling speed was reduced quite quickly while the upwelling speed was still the same. In the upwelling zone (5.4628 - 5.471 °N), the density is greater than that of the sill or the surrounding part. Based on the simulation results for 6 hours, current and density conditions have not reached stability, the upwelling is still formed, and the density at the surface layer is still higher than in the part under the sea.

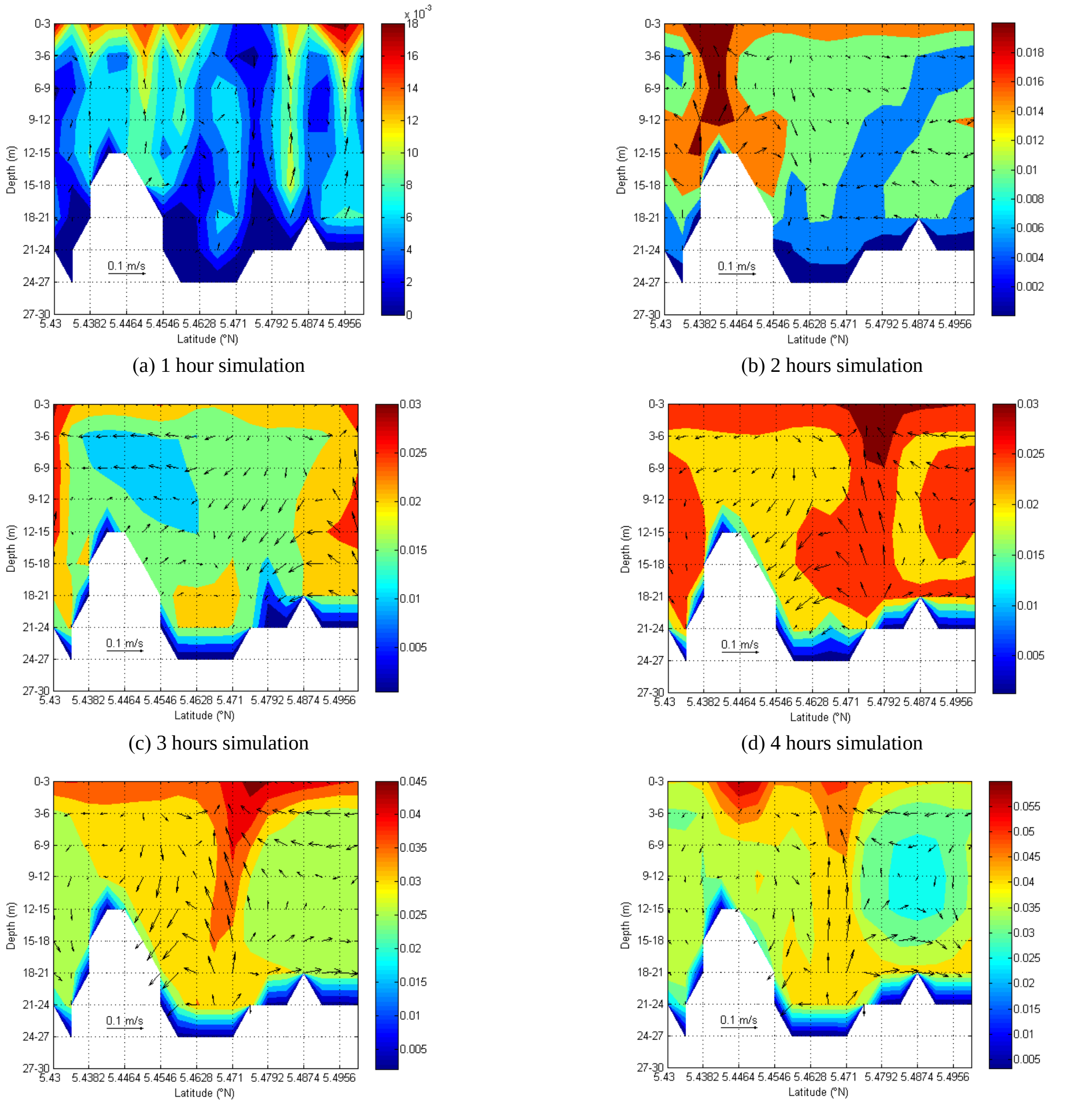
3.2 Deep sea simulation

This study took two vertical slices from the Sabang bay domain. For zonal vertical slice, the grid formed is 99x32 with a maximum depth of 490 meters. Zonal vertical slice stretches for 14.5 km. The simulation was run for 6 hours and produced a current and density profile that can be seen in Figure 3.

At the start of the simulation, both horizontal and vertical velocity are 0 initially. The stratification of the layers is still visible with small disturbance at the top layer. In the first hour, the surface layer undergoes cooling with changes in surface density. Some of these surface cells begin to sink when 35 minutes of simulated time is reached. The segment that undergoes a cooling and sinking process is at a depth of 0 - 50 meters. Horizontal current velocity has not been seen, but the vertical velocity is clearly visible in the sinking cell with speed of 0.0042 m/s.

The convection process continues until it reaches the third layer (based on the color of the segment). During the two-hour simulation, horizontal and vertical velocity emerged due to the momentum caused by the gulf base. On the right seafloor, the sinking cell has reached the bottom, then the mass of water was reflected. The disturbance is seen from the quivering form that moves away from the sea floor. In the middle of the domain, small disturbances are seen as biases from disturbances on both sides, left and right. The third color layer begins to mix with the layers that experience convection and the current velocity starts to look diverse.

The simulation has been running for three hours and stratification began to decrease. The third layer starts to get thin so that it can be said that the first three layers have reached stability. Vertical current continues to sink to a depth of 140 meters. Layers with a depth greater than 150 meters experience only a small amount of interference, not even being disturbed at all at the very base. After the simulation was run for more than 3 hours, steady conditions could be seen in 0 - 150 meters layers. Even though it looks like the convection is only in the surface layer, but, if it only the vertical velocity is accounted for, there are several cells of water mass sinking to a depth of 360 meters.



(a) 1 hour simulation

(b) 2 hours simulation

(c) 3 hours simulation

(d) 4 hours simulation

(e) 5 hours simulation

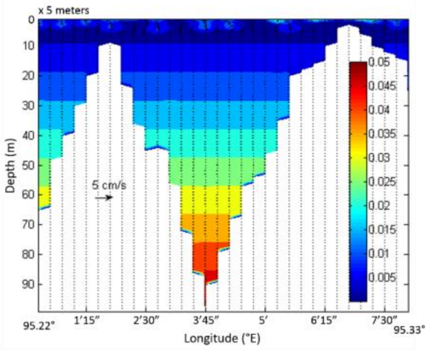
(f) 6 hours simulation

Figure 2. Profiles of free convection in a meridional shallow vertical slice (T1 see Figure 1), color bar indicates density levels (psu) and arrows indicate current direction and velocity (m/s).

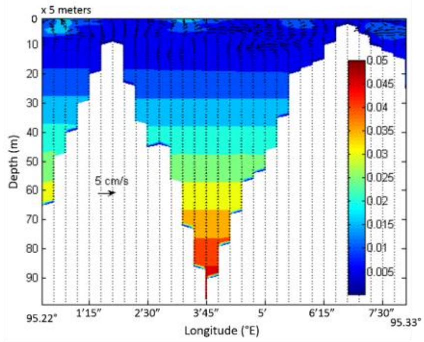
The second vertical slice had a 93x25 discretization grid. This domain is 11.7 km long starting from the beach to the middle of the bay. The depth observed was 470 meters with a small trough in the middle of the domain. Like the first case, the second domain was simulated for six hours. The results on free convection in this domain are in Figure 4.

Vertical current velocity is different from the previous case. The effect of the seabed on the momentum of the mass of water has been seen in one hour of simulation. In general, physical phenomena are generated are similar in zonal vertical slices, with the occurrence of vertical current velocity and the beginning of the presence of water cells that were sunk due to the cooling. The seabed in the second domain has a very sharp slope. Therefore, the momentum generated is also different. In the two-hour simulation, the vertical and horizontal currents are very solid. The first and second layers are even thoroughly mixed and begin to see a slight mass of water with a density like the third layer.

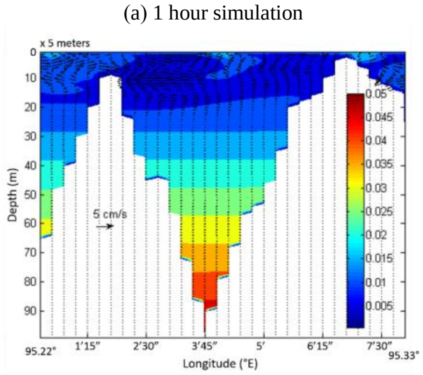
Stratification in the three-hour simulation has been reduced. With a domain in form of a trough, the vertical and horizontal flow velocities formed are very large. The horizontal velocity is evenly distributed on the surface layer. As in the first domain, this second domain began to reach steady conditions at 3 hours of simulated time. Vertical and horizontal current velocities only move in 0-150 meters layers. In the middle of the domain, the sinking cell reaches a depth of 360 meters. The mass of water in 150-360 meters only moves horizontally and is very slow. Significant horizontal speeds reach 5 cm/s on the surface, while vertical velocity is only 0.0042 m/s on the surface.



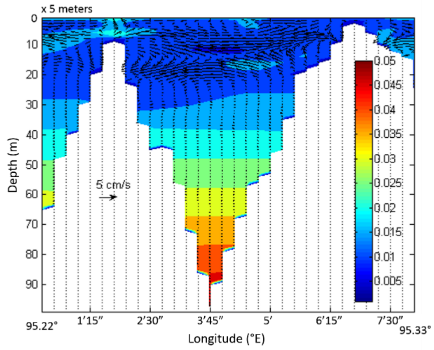
(a) 1 hour simulation



(b) 2 hours simulation

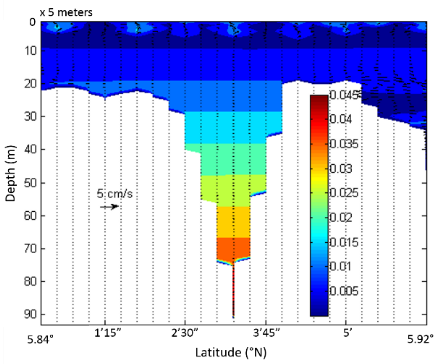


(c) 3 hours simulation

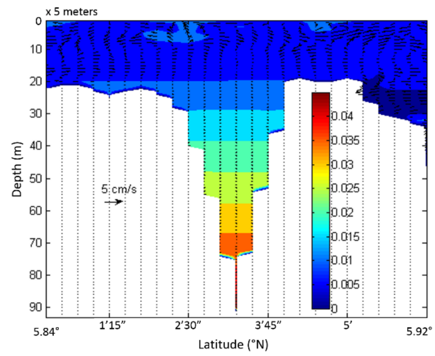


(d) 6 hours simulation

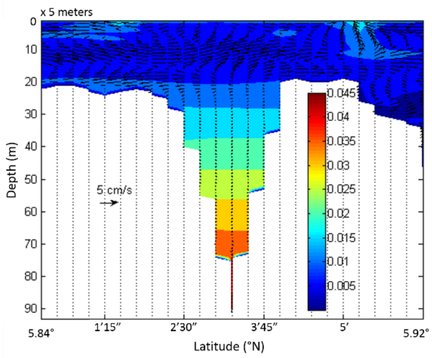
Figure 3. Profiles of free convection in deep zonal vertical slice (T2 see Figure 1), color bar indicates density levels (psu) and arrows indicate current direction and velocity (m/s).



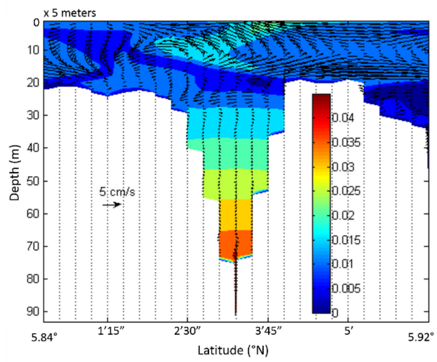
(a) 1 hour simulation



(b) 2 hours simulation



(c) 3 hours simulation



(d) 6 hours simulation

Figure 4. Profiles of free convection in deep meridional vertical slice (T3 see Figure 1), color bar indicates density level (psu) and arrows indicate current direction and velocity (m/s).

At a depth of more than 30 meters, other influences can no longer be seen. This force is like the influence of weather or surface currents. However, different things can be seen on the surface. The surface gets a direct effect from the atmosphere and the weather. The effect lasts for 5-30 minutes after exposure.

4. Conclusions

In the first hour of simulation, the vertical current velocity shows that water mass that has a higher density in the southern region of the shallow bay is characterized by mass of sinking water. The vertical current velocity or upwelling starts to strengthen in the sill area at two hours of simulation. The lighter fluid moves upwards, looking for a gap in the denser fluid on the surface with a maximum speed of 0.03 m/s. The speeds of upwelling and downwelling at four and five hours is quite strong and almost similar to each other.

Based on deep convection results, changes in density begin with an increase in density in areas with shallow depth and leave low-density in areas with high depth. Convection cells start to sink after 35 minutes of simulation with a vertical velocity of 0.0042 m/s on the surface and stop dropping at a depth of 360 meters. Areas with high depth indicate falling speeds after about 3 hours of simulation, but the surface layer shows density stability. At that depth, the mass of water only moves horizontally, and the magnitude is not significant. In general, the deep sea area is not affected by the convection currents, and the surface area is well-mixed after 3 hours of simulation.

Acknowledgements

Authors would like to express gratitude to the Ministry of Research, Technology and Higher Education of Indonesia for financial assistance in term '*Penelitian Lektor Kepala*' under contract number 121/UN11.2/PP/PNBP/SP3/2019. We also thank for facility support at Ocean Modelling Laboratory Universitas Syiah Kuala during the research.

References

Abbot, D. S., & Tziperman, E. (2008). Sea ice, high-latitude convection, and equable climates. *Geophysical Research Letters*, *35*(3), L03702. doi:10.1029/2007GL032286

Anwar, K., Haditiar, Y., Ikhwan, M., Wafdan, R., Setiawan, I., Marwan, . . . Rizal, S. (2019). Numerical study of M2 tide on the Gulf of Thailand. *IOP Conference Series: Earth and Environmental Science*, *348*, 012065. doi:10.1088/1755-1315/348/1/012065

Ardila, D., Haditiar, Y., Ikhwan, M., Wafdan, R., Muhammad, Sugianto, S., & Rizal, S. (2019). Ocean eddy detection in the Andaman Sea during April 2008. *IOP Conference Series: Earth and Environmental Science*, *348*, 012063. doi:10.1088/1755-1315/348/1/012063

Beare, R. J., & Cullen, M. J. P. (2019). A simple model of a balanced boundary layer coupled to a large-scale convective circulation. *Journal of the Atmospheric Sciences*, *76*(3), 837–849. doi:10.1175/jas-d-18-0189.1

Beljaars, A. C. M. (1995). The parametrization of surface fluxes in large-scale models under free convection. *Quarterly Journal of the Royal Meteorological Society*, *121*(522), 255–270. doi:10.1002/qj.49712152203

Cheon, W. G., & Gordon, A. L. (2019). Open-ocean polynyas and deep convection in the Southern Ocean. *Scientific Reports*, *9*(1), 1–9. doi:10.1038/s41598-019-43466-2

Doherty, R. E., & Carter, E. S. (1924). Effect of altitude on temperature rise. *Transactions of the American Institute of Electrical Engineers*, *XLIII*(12), 824–843. doi:10.1109/T-AIEE.1924.5061040

Farooq, U., & Xu, H. (2014). Free convection nanofluid flow in the stagnation-point region of a three-dimensional body. *Scientific World Journal*, *2014*. doi:10.1155/2014/158269

Haditiar, Y., Putri, M. R., Ismail, N., Muchlisin, Z. A., Ikhwan, M., & Rizal, S. (2020). Numerical study of tides in the Malacca strait with a 3-D model. *Heliyon*, *6*(9), e04828. doi:10.1016/j.heliyon.2020.e04828

Hoggard, M. J., Winterbourne, J., Czarnota, K., & White, N. (2017). Oceanic residual depth measurements, the plate cooling model, and global dynamic topography. *Journal of Geophysical Research: Solid Earth*, *122*(3), 2328–2372. doi:10.1002/2016JB013457

Huang, C. (2010). Sea surface roughness and drag coefficient under free convection conditions. *Latest Trends on Theoretical and Applied Mechanics, Fluid Mechanics and Heat and Mass Transfer*, 121–127. Retreived from http://www.wseas.us/e-library/conferences/2010/Corfu/HEAPFL/HEAPFL-20.pdf

Huang, C. H. (2009). Parameterization of the roughness length over the sea in forced and free convection. *Environmental Fluid Mechanics*, *9*(3), 359–366. doi:10.1007/s10652-009-9124-9

Irham, M., Miswar, E., Ilhamsyah, Y., & Setiawan, I. (2018). The northern tidal dynamic of Aceh waters: A 3D numerical model. *IOP Conference Series: Materials Science and Engineering*, *352*(1). doi:10.1088/1757-899X/352/1/012043

Irmasyithah, N., Haditiar, Y., Ikhwan, M., Wafdan, R., Setiawan, I., & Rizal, S. (2019). Thermocline studies using CMEMS data in the Andaman Sea during October 2017. *IOP Conference Series: Earth and Environmental Science*, *348*(October 2017), 012064. doi:10.1088/1755-1315/348/1/012064

Iskandar, T., Haditiar, Y., Setiawan, I., Fahmi, K., Muhammad, M., & Rizal, S. (2018). Simulation of long waves in a layered Sabang waters. *I IOP Conference Series: Earth and Environmental Science*, *216*, 012013.

Kämpf, J. (2010). *Advanced ocean modelling using open source software*. Berlin Heidelberg, Germany: Springer. doi:10.1007/978-3-642-10610-1

Mahfud, J., Haditiar, Y., Ikhwan, M., Wafdan, R., Setiawan, I., & Rizal, S. (2019). Numerical simulation of M2 tide in the Makassar Strait. *IOP Conference Series: Earth and Environmental Science*, *348*, 012095. doi:10.1088/1755-1315/348/1/012095

Marshall, J., & Schott, F. (1999). Open-ocean convection: Observations, theory, and models. *Reviews of Geophysics*, *37*(1), 1–64. doi:10.1029/98RG02739

Nuijens, L., & Siebesma, A. P. (2019). Boundary layer clouds and convection over subtropical oceans in our current and in a warmer climate. *Current Climate Change Reports*, *5*(2), 80–94. doi:10.1007/s40641-019-00126-x

Rasyidi, H. T. A., Haditiar, Y., Ikhwan, M., Wafdan, R., Setiawan, I., Sugianto, S., & Rizal, S. (2019). Effect of wind-driven currents circulation in Sabang Waters. *IOP Conference Series: Earth and Environmental Science*, *348*, 012094. doi:10.1088/1755-1315/348/1/012094

Rizal, S., Setiawan, I., Boihaki, B., Haditiar, Y., Iskandar, T., & Sugianto, S. (2018). Simulation of current using a two-dimensional numerical model in the Aceh Barat Daya waters, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *216*(1), 0–5. doi:10. 1088/1755-1315/216/1/012019

Seo, H., Xie, S. P., Murtugudde, R., Jochum, M., & Miller, A. J. (2009). Seasonal effects of Indian Ocean freshwater forcing in a regional coupled model. *Journal of Climate*, *22*(24), 6577–6596. doi:10.1175/2009JCLI 2990.1

Setiawan, I., Alfawirsa, M. A., Haditiar, Y., & Rizal, S. (2018). Simulation of tidal hydrodynamics in Sabang Bay , Indonesia. *IOP Conference Series: Earth and Environmental Science*, *216*, 012012.

Setiawan, I., Haditiar, Y., Ikhwan, M., Nufus, Z., Syukri, M., Ismail, N., & Rizal, S. (2020). Modeling of M2-Tide in the western waters of Aceh, Indonesia. *Journal of Sustainability Science and Management*, *15*(8), 122–135. doi:10.46754/jssm.2020.12.011

Wahyudi, H. A. A., Haditiar, Y., Ikhwan, M., Wafdan, R., Setiawan, I., Muhammad, M., . . . Rizal, S. (2019). Numerical study of tides in the Bay of Sabang. *IOP Conference Series: Earth and Environmental Science*, *348*, 012096. doi:10.1088/1755-1315/348/1/012096

Yunita, Ikhwan, M., Haditiar, Y., Wafdan, R., Setiawan, I., Muhammad, M., Jalil, Z., . . . Rizal, S. (2021). The influence of monsoon on mixed layer depth in the northern waters of Aceh in 2017. *IOP Conference Series: Earth and Environmental Science*, *674*(1). doi:10.1088/1755-1315/674/1/012055

Zhou, X., Dong, B., Li, W., & Chen, C. (2019). A 3D thermal LB model on non-orthogonal grid and its application for natural convection in irregular domains. *International Journal of Heat and Mass Transfer*, *136*, 223–234. doi:10.1016/j.ijheatmasstransfer.2019.02.069