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# Simulated Ocean Circulation from INDESO data in the Region of the Gulf of Tomini

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### *Abstract*

*The Tomini is one of the largest gulf in Indonesia. The gulf also has a unique profile and adjacent to Maluku Sea which is the eastern route of the Indonesian Throughflow. The purpose of this research is to investigate and analyze the circulation patterns that occur inside the gulf of Tomini and Maluku Sea as well as the variability of physical parameters such as temperature, salinity and transport volume and to correlate the driving factors of ocean-atmosphere phenomena that affect these physical parameters using the INDESO model dataset from January 2008 to December 2014 (7 years). The results showed that the surface circulation in the gulf and Maluku Sea flows southeastward to the Lifamatola Strait during the northwest and 1st transition, during the southeastern season the circulation flows leaving Maluku Sea through the ITF entry to the Pacific and Sulawesi Seas, and then flows southeastward during 2nd transition. The seawater temperature in the study area ranges between 28.6 - 32.0 °C and the salinity varies between 32.2-34.4 psu. Vertical structure of zonal current in the gulf reveals velocity range from 0.02-0.3 Sv and the surface layer current is dominated by the westward flow, while at 20-60 m depth the flow is eastward. The mean transport volume at transects 123°E is about -0.028 (±0.2578) Sv. Variability of transport volume revealed spatial anomalies and periodicity on the intra-seasonal, semi-annual, annual, and inter-annual time-scales. Those are significantly coherence with zonal and meridional winds forcing in the Indo-Pacific region.*

***Keywords:*** *Indonesian Throughflow (ITF), INDESO, Maluku Sea, Gulf of Tomini, Ocean Variability*

## Introduction

The Gulf of Tomini is a semi-enclosed water in northern Indonesia with a total area of 59.500 km. It is considered as one of the largest gulf in Indonesia and is included in the Fisheries Management Area (WPP) of the Gulf of Tomini–Maluku Sea–Seram Sea. It has distinctive topography and bathymetry with an average depth of >1500 m and complex that is marked with geographical boundaries; i.e. coastline and highlands in the west, north, and south, and is adjacent to the Gulf of Tolo, Sulawesi Sea, and Maluku Sea in the east which is the Indonesian Throughflow (ITF) path. These geographical situation causes the circulation of water masses between the waters in the gulf and the surrounding waters (Setiawan and Habibi, 2011; Setyadji and Priatna, 2011; Sari *et al*., 2018). Maluku Sea is situated in the eastern Sulawesi Island and is bordered by the North Maluku Islands in the east part, connected respectively with the Celebes Sea, Gulf of Tomini, and Seram Sea in the north, west, and south side. It has maximum depth of 4,500 meters, different from shallow waters in the coastal of Banggai Islands in its west south side, and open its path to the Seram-Banda Sea in its southern border (Wirasatriya *et al*., 2017; Atmadipoera *et al*., 2018).

The east path of ITF passes through the Maluku Sea and Lifamatola strait and is originated from the North Pacific Ocean at the transport velocity near the bottom (2050 m) of as much as 2.5 Sv. It has an essential role within the global circulation, heat flux transfer, and sea surface temperature (SST) (Adhyatma *et al*., 2019) and ITF transport and circulation show the annual and interannual variability that is related to the seasonal wind variations and ENSO events. The combination of the complex topography of the Gulf of Tomini, seasonal variations of monsoon winds, local force, and interannual phenomena in the Pacific Ocean and Maluku sea contributes to the circulation pattern and profile of oceanographic parameters within the gulf.

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There are still few studies and observations in the Gulf of Tomini, especially pertaining to circulation patterns, physical parameters, and those that affect variability in the gulf. Observation and study are conducted in this area with hope that the results of this research can be developed and linked to research in other fields. Several modeling studies have been implemented to investigate seasonal and interannual variability in the gulf using realistic climatological and forcing data (Thoppil and Hogan, 2010; Yao and Johns, 2010; Pous *et al*., 2015) and numerical ocean modeling studies are needed to understand the main dynamics in the Gulf (Chao *et al*., 1992; Kampf and Sadrinasab, 2005). This study used INDESO model data to characterize the main features of circulation in the Gulf of Tomini, seasonal variability, and water mass transport and volume transport with surrounding waters.

## Materials and Methods

Data processing in this study used Ferret and Matlab software in a computer with a Linux operating system. Ferret software was used to analyze variability, validation, and visualization of physical model data, parameters, and time-series data. The INDESO (Infrastructure Development for Space Oceanography) output model data was obtained from the INDESO project held by the Ministry of Marine Affairs and Fisheries (KKP). The INDESO model uses the NEMO ocean general circulation model with a specific configuration with domains in the Indonesian sea area and surrounding waters (90°E-145°E; 25°S-20°N) (Figure 1.), including detailed bathymetry, parameterization of tidal explicit forcing and mixing. The configuration of the model is described in Tranchant *et al*. (2015). The model data output includes the zonal and meridional flow components, time series of sea temperature, and salinity from January 2008 to December 2014 (7 years). Data can be accessed through the INDESO page (http://www.indeso.web.id). The output of INDESO data is daily average simulation data with a horizontal resolution of 1/12° (9.25 km) and 50 depth levels.

Data validation was carried out for model accuracy with satellite data. Taylor diagram is a graphical analysis diagram to summarize how close the pattern of model estimation and observation matches (Taylor, 2001) which describes 3 statistical parameters, namely Root Mean Standard Error (RMSE), correlation coefficient (r), and standard deviation (standard deviation) between the model and observation. Node fit stated that it good if r is close to 1 (positively correlated) and RMSE is close to 0. Calculation of correlation coefficient (*r*), RMSE (*E'*), standard deviation of model prediction results ($\sigma_f$), and standard deviation of actual data ($\sigma_r$) are as follows (Taylor, 2001).

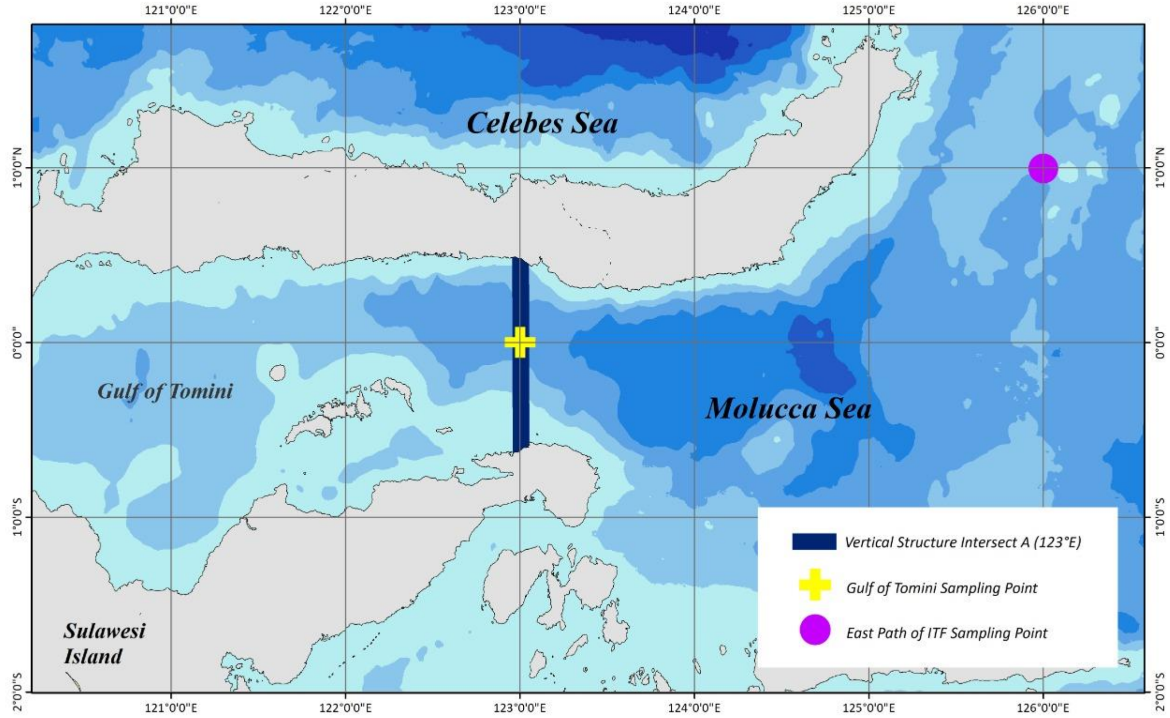

**Figure 1.** The research location in the Gulf of Tomini area, Sulawesi and Maluku Sea. The purple point indicates the sampling point in the east path of the ITF. The yellow cross indicates the sampling point in Gulf of Tomini. The dark blue line shows the pick-up point for the transport velocity and direction at coordinates 123°E

$$r = \frac{\frac{1}{N}\sum_{n=1}^{N}(f_n - \bar{f})(r_n - \bar{r})}{\sigma_f \sigma_r}$$

$$E' = \{\frac{1}{N}\sum_{n=1}^{N}[(f_n - \bar{f})(r_n - \bar{r})]^2\}^{1/2}$$

$$\sigma_f = \{\frac{1}{N}\sum_{n=1}^{N}(f_n - \bar{f})^2\}^{1/2}$$

$$\sigma_f = \{\frac{1}{N}\sum_{n=1}^{N}(r_n - \bar{r})^2\}^{1/2}$$

The annual cycle pattern at a certain time can be determined by averaging the temperature and salinity with the current velocity at the study site. The averaging is done monthly with average temperature and salinity values which are then overlapped with the current component through the Emery and Thomson (2014) equation:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} xi$$

where $\bar{x}$ is the average result of *N* data.

The analysis of estimated transport volume in the Gulf of Tomini aims to see the mass transport of water enters and leaves the study area. The amount of transport volume is calculated in units of Sverdrup at Sv (1 Sv = $10^6 m^3 s^{-1}$). This method is applied to the U component or zonal at the mouth of the Gulf (123°E).

$$Qu_{a-b} = \int_a^b \int_z^0 dx\, dz$$

where $Qu_{a-b}$ is the transport value from the integral result of the zonal flow component from depth *z* to surface depth along the transect at the mouth of the gulf (123°E)

Analysis of variability in a water area can be done using the EOF method. The concept of decomposing data into the main components of a variable into smaller values and containing independent information (Emery dan Thomson, 2014). EOF calculation is based on the equation according to Hanachi *et al.* (2007):

$$X(t,s) = \sum_{k=1}^{M} C_k(t)\, u_k(s)$$

Where *X(t,s)* is the function of time (*t*) dan space (s); *M* is the number of Mode; $u_k(s)$ is a function of space and $C_k(t)$ is the function of time (Principal Component).

Time-series data analysis with power spectral density (PSD) was used to analyze the periodicity of energy fluctuations from time-series data, so that peaks of energy fluctuations used can be observed; i.e. zonal and meridional flow from EOF analysis and transport volume at a certain period or frequency at a 95% confidence interval with a data length of 2557 data, and a segment length of 512 data . PSD is calculated using the Bendat and Piersol equations on the Fourier transform component (FFT):

$$X_i(f_k) = \Delta t X_{ik} = \Delta t \sum_{n=0}^{N-1} X_{in}\ exp\left[\frac{-j2\pi kn}{N}\right]$$

where $X_i(f_k)$ is the fourier component; $X_{in}$ is the date value, $n$ = 0,1,...N-1, i=1,2,..., $n_d$ ; k = 0,1,...,N/2.

The cross-PSD is used to analyze the relationship between fluctuations of two time-series variables at the same frequency. The output of the cross-PSD analysis consists of a cospectrum energy, coherence, and phase difference. Based on Bendat and Piersol (2010), cospectrum value is calculated using the following equation:

$$G_{XY}(f_k) = \frac{2\Delta t}{T}\left|X(f_{(k)}) * Y(f_{(k)})\right|$$

where $G_{XY}(f_k)$ is the cross energy density spectrum at the k-th frequency $(f_k)$ ; $f_k = \frac{k}{Nh}; k = 0,1,2,\ldots,N-1$ ; $X(f_{(k)})$ is the fourier component from (*xt*); $Y(f_{(k)})$ is the fourier component from (*yt*); $\Delta t$ is the interval of data retrieval (1 day); *T* is the data period. The energy cospectrum shows the magnitude of the energy fluctuation at the same frequency between the two time-series data.
Coherence value can be calculated using the Bendat and Piersol equation (2010):

$$\gamma^2{}_{XY}(f_k) = \frac{\left|S_{xy}(f_k)\right|^2}{S_x(f_k)S_y(f_k)}$$

where $\gamma^2{}_{XY}(f_k)$ is the coherence value at the k-th frequency $(f_k)$; $S_x(f_k)$ is the cross energy density spectrum at the k-th frequency $(f_k)$; $S_x(f_k)$is the energy density spectrum *X*(*fk*); $S_y(f_k)$is the energy density spectrum *Y*(*fk*) at the k-th frequency (*fk*).

The value of phase difference is calculated using Bendat and Pierson question (2010):

$$\theta_{XY}(f_k) = tan^{-1}\left|\frac{Q_{xy}(f_k)}{C_{xy}(f_k)}\right|$$

where $\theta_{XY}(f_k)$ is the imaginary value of $Q_{xy}(f_k)$; $C_{xy}(f_k)$ is the real value of $Q_{xy}(f_k)$.

## Result and Discussion

The output data of the INDESO model were validated using satellite data, by comparing the Sea Surface Height (SSH) and Sea Surface Temperature

(SST) data from the model data with observation data from the Copernicus Marine Environment Monitoring Service with the same parameters. The SSH data (Figure 2a) between the satellite data and the model has a correlation coefficient of 0.8670 and RMSE 0.0277 at the sampling point at the mouth of Gulf of Tomini and 0.8811 and 0.0258 at the sampling point at the east entrance of the ITF which indicates a high degree of closeness between the two data. The SST data (Figure 2b.) has a correlation coefficient of 0.6157 and RMSE 0.5925 at the sampling point at the mouth of Gulf of Tomini and 0.7011 and 0.5277 at the sampling point at the east entrance of the ITF which indicates a fairly close relationship between the two data.

### *Annual cycle*

Annual cycle (Figure 3.) in the January (West Monsoon), the temperature values spread differently at a value of 30.2-31°C inside the Gulf of Tomini and lower temperature with 29°C at the Maluku Sea. The current in the January move leave the Gulf of Tomini and Maluku sea moving south. In April (First Transition), the temperature is 30-31.8°C, with the temperature in the gulf higher than in Maluku Sea. The temperature in the July (East Monsoon) shows a very striking temperature difference between Maluku Sea and Gulf of Tomini, with a value range of 28.6-31°C in the study area and the ocean current move to the north leave Maluku sea, but the temperature increases significantly in the gulf and the Maluku Sea during October (Second Transition) with the direction of the current move whirly inside gulf and the other hand in the Maluku sea the current whirly in the middle and some current leave the sea to the east. According to Tita *et al*. (2020), the average temperature value of above 30°C in the Gulf of Tomini is closely related to the strength of the wind and its pattern, while in Maluku Sea, it is also influenced by monsoon winds (Martono, 2016).

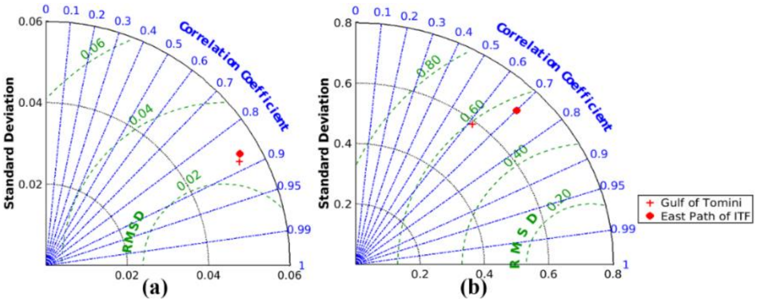

**Figure 2.** Taylor diagram for validation of model data and observations of the parameters of Sea Surface Height (a) and Sea Surface Temperature (b) in Gulf of Tomini (red cross) and the entrance of the ITF east line (red point) in 2008-2014

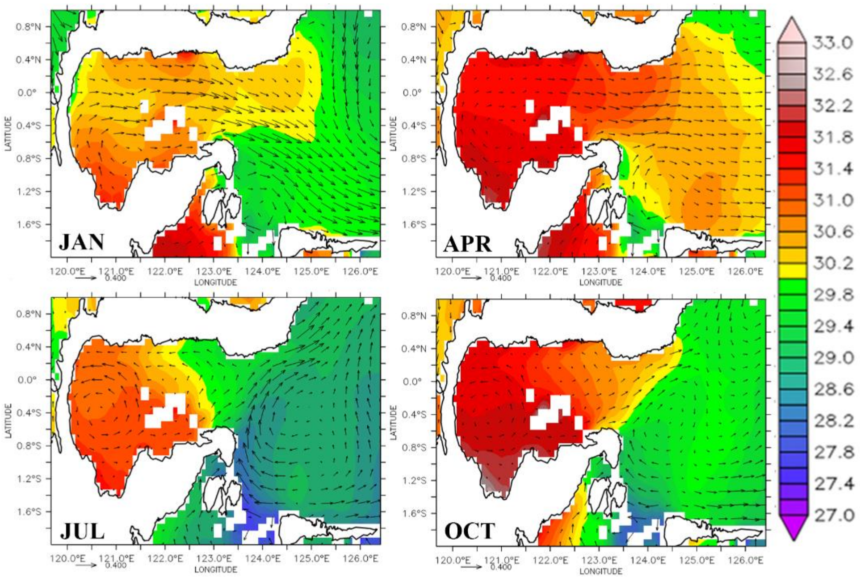

**Figure 3.** The annual circulation and sea surface temperature in peak month in each season

The salinity distribution (Figure 4.) during January (West Monsoon) in the gulf and the Maluku sea has a salinity range of 32.2–34.1 psu, with higher salinity distribution patterns found in the Maluku Sea compared with inside gulf. At the same time, the southern part of the gulf has a lower value. Salinity at April (First Transition) has a value range of 33.1-33.8 psu. The lowest values in April were found in the southern parts of Gulf. The salinity distribution observed on the July (East Monsoon) has a range of 33-34.2 psu, indicating a significant difference in salinity patterns and values between the gulf and Maluku Sea. The increasing and decreasing in salinity values in the gulf and Maluku sea continued until October, with salinity values in the gulf ranging from 33-34.4 psu. According to research by Rahma *et al*. (2020), the salinity value in the Maluku Sea is influenced by input from the ITF with water masses of South Pacific Subtropical Lower Thermocline Subtropical Water (SPSLTW) and North Pacific Water (NPSW). The salinity value in the Gulf of Tomini is assumed to be influenced by the input of the ITF water mass that enters the Maluku Sea and is partially passed into the gulf.

The annual cycle of the vertical structure of the zonal flow in the Gulf of Tomini (Figure 5.) shows seasonal variations, where in January, the outflow (Red) has a maximum velocity of 0.35 m.s$^{-1}$ and moves in the surface area to a depth of 20 m, while the inflow (Light Blue) moves at a depth of 20-60 m at a velocity of 0.05-0.20 m.s$^{-1}$, and the current velocity decreasing when it hits April. On the July, the current velocity ranges from 0.02-0.12 m.s$^{-1}$ with outflows of 0.04-0.12 m.s$^{-1}$ and inflow 0.02-0.06 m.s$^{-1}$. On October, outflow and inflow current velocity ranging from 0.02-0.10 m.s$^{-1}$ at the surface to a depth of 20 m for outflow and in the deeper depth for inflow. The current velocity on the transect is quite weak due to the effect of the weak wind blowing in the Gulf of Tomini. The current velocity will decrease along with increasing depth until the wind does not affect at depth of 200 m (Octavia *et al*., 2018). The current velocity will be strong during the west monsoon and weak in First Transition, while during the east monsoon, the current will get amplified and weaken again in Second Transition (Tita *et al*., 2020). Gordon *et al*. (2003) also conveyed the weakening of the current velocity, who stated that the current weakened during the Transition season due to the influence of changing seasons and changing wind direction.

### *Transport volume variability and its coherence with Indo-Pacific Winds*

The transport volume time series from January 2008 to December 2014 on transects 123°E are shown in Figures 6. The fluctuations of transport volume on transect 123°E show a maximum transport value of +0.37 Sv and a minimum value of -0.36 Sv with a mean transport of -0.0152 Sv with a standard deviation of 0.10 Sv (Figure 6a.). The direction of movement of the transport volume on transect 123°E is predominantly westward, indicated by a negative sign. Transport fluctuations in transect 123°E dominantly occurred in the 140-346 days or intra-seasonal to annual period. The current that moves into the gulf is thought to be part of the ITF current from the Maluku Sea, where the velocity decreases due to the profile of the gulf.

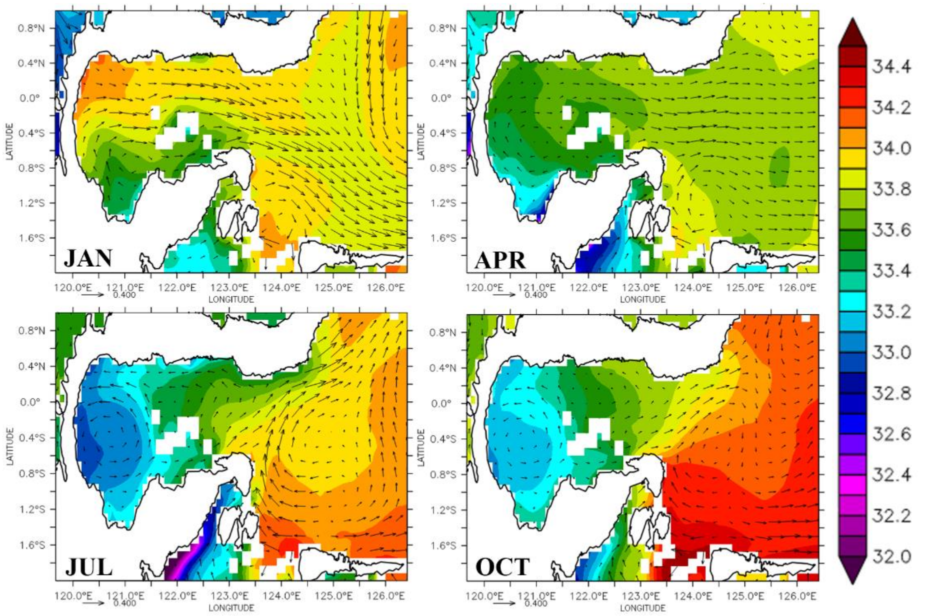

**Figure 4.** The annual circulation and sea surface salinity in peak month in each season

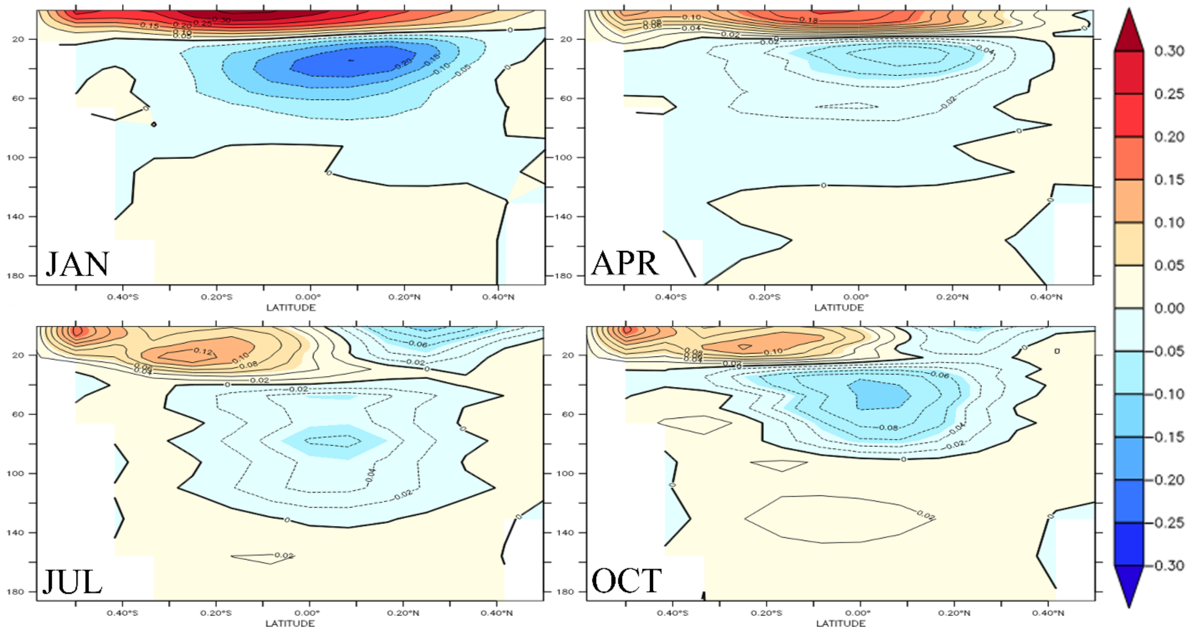

**Figure 5.** The annual cycle of the zonal flow component cross section at the 123° E transect in the peak of each Season

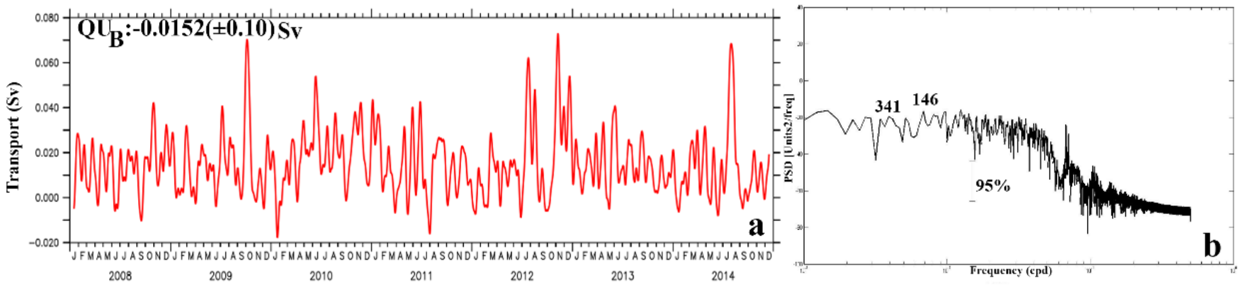

**Figure 6.** Transport volume time series with 31-days filter on transect 123E (a), and PSD analysis (b).

### *Spatial patterns and temporal variability of zonal and meridional flows*

The spatial-temporal variability of the zonal flow component is explained in the four highest modes in the EOF analysis with a total percentage of explained variance of 73.6%, shown in Figure 7. The spatial pattern of the zonal flow component in modes 1-4 is 45.20, 16.57, 7.61, and 4.22%, respectively, with positive values spread over the lower and upper part of the Maluku Sea with maximum positive values found in the south, near the Lifamatola Strait. The negative values is shown in the northern part of Maluku, and inside of the gulf in some modes. Temporal fluctuations and PSD results from modes 1-4 show the dominant periodicity; intra-seasonal, semi-annual, annual, and inter-annual periods. They can be seen in Figure 7b in each EOF mode figure.

Figure 8 shows the spatial-temporal variability of the meridional flow component in the four largest modes with a total value of the explained variance of 84.91%. The value of explained variance in 4 modes is 58.24, 17.11, 6.34, and 3.22% respectively. Negative values dominate the spatial pattern in the four most prominent modes covering the Maluku sea area, starting from ITF gateway to near the Lifamatola strait in mode 1. In modes 2-4, negative values are found in several different places, such as in parts of Maluku Sea and inside the gulf. At the same time, the positive values was found in the middle part of Maluku Sea and covered Maluku Sea in mode 2. The temporal variation from the EOF analysis of mode 1-2 meridional flow showed intra-seasonal, semi-annual, annual, and inter-annual variations reinforced by the PSD plot results.

The results of temporal variation show variability with intra-seasonal, semi-annual, annual, and inter-annual periodicity. The fluctuations that occur from the zonal and meridional flow are thought to be transport currents that called the Indonesian Throughflow (ITF). The transport volume of the ITF fluctuates under the influence of atmosphere ocean

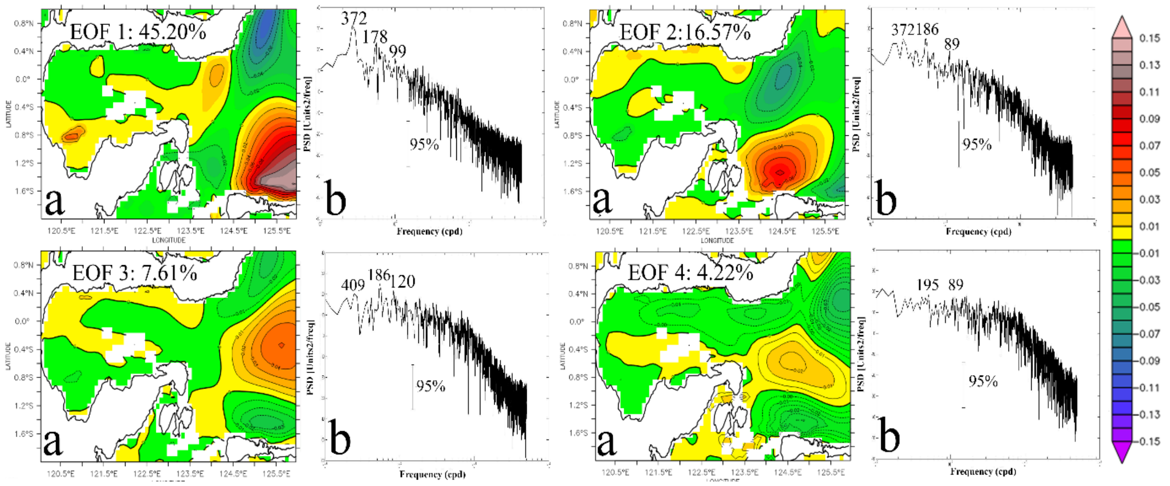

**Figure 7.** The results of the analysis of EOF mode 1-4 Zonal flow components (a) and PSD (b)

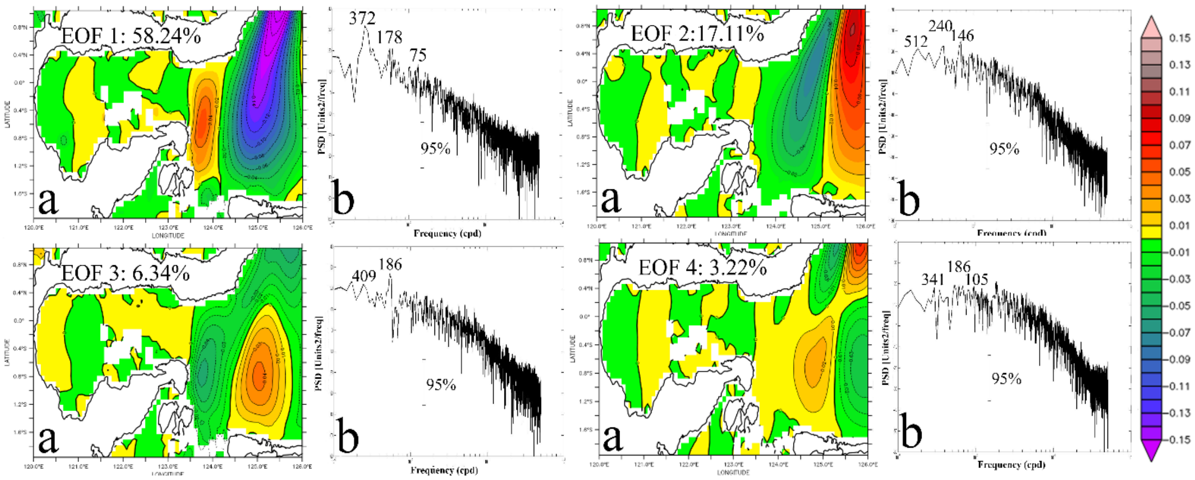

**Figure 8.** The results of the analyses of EOF mode 1-4 Meridional flow components (a) and PSD (b)

interactions such as the Asia-Australian monsoon, El Nino/La Nina Southern Oscillation (ENSO), and the Indian Ocean Dipole, which are 3 factors that affect the volume of ITF transport (Putriani *et al*., 2019). Holbrook *et al*. (2019) also explained that there are driving forces that affect ocean conditions such as local wind drives, ocean advection, and air-sea interactions or climate drivers via the atmosphere such as the Madden-Julian Oscillation (Intra-Seasonal), and Interannual modes such as ENSO and IOD and via ocean connections such as Kelvin waves that have a scale of several months or Rossby waves that occur on a scale of several months to years.

### *The coherence between current transport fluctuations and wind (Cross-PSD)*

The results of the cross-PSD analysis are shown in Figure 9-11 with 2 data between zonal transport and zonal winds whose results divided into 3 plots representing the annual (341 days, Figure 9), semi-annual (171 days, Figure 10.), and intra-seasonal (90 days, Figure 11.) timescale where the top row of plot showing the coherence and the bottom row showing the phase. Visually, the coherence of the cross-PSD results between the zonal wind and the zonal flow in the study area shows different values and color scales in each time scale. The coherence values obtained were 0.1039 (341 days), 0.2161 (171 days), and 0.6667 (90 days) while the phase plots showed values of 0.4258 (341 days), 0.3425 (171 days), and 0.0970 (90 days). This shows that the zonal wind and the zonal flow have a weak relationship in the annual and semi-annual periods. In contrast, in the intra-seasonal period, their relationship is quite strong. The phase value also shows that in the phase all time scale, the zonal transport precedes the zonal wind. ITF transport volume is related to sea-wind interactions

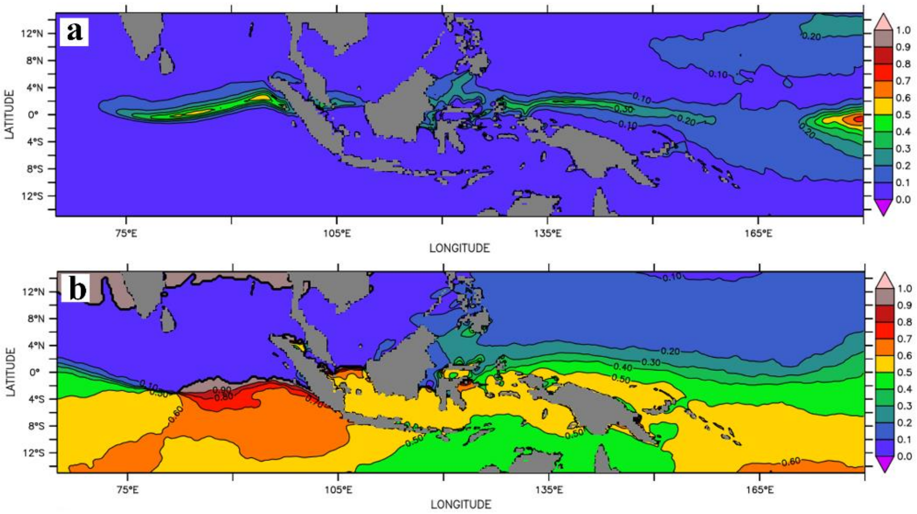

**Figure 9.** Coherence (a) and phase (b) relationship between zonal transport and zonal wind on an annual time scale

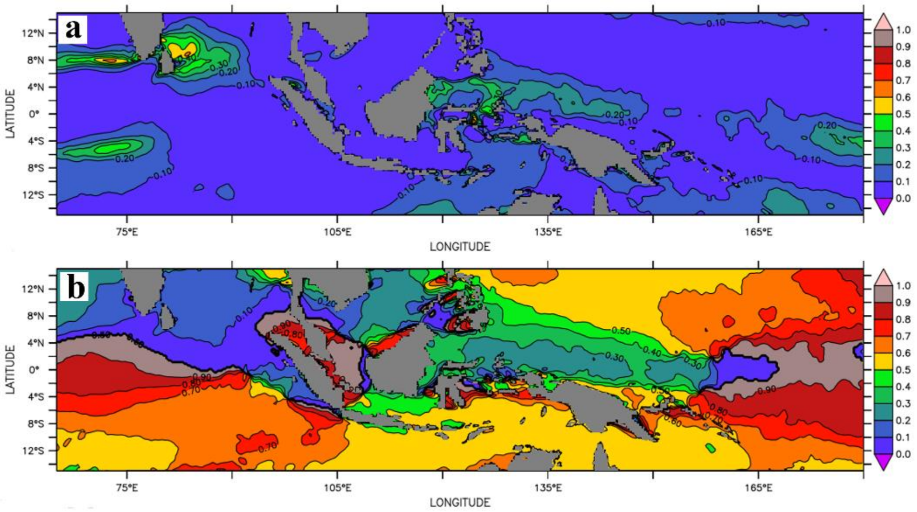

**Figure 10.** Coherence (a) and phase (b) relationship between zonal transport and zonal wind on a semi-annual time scale

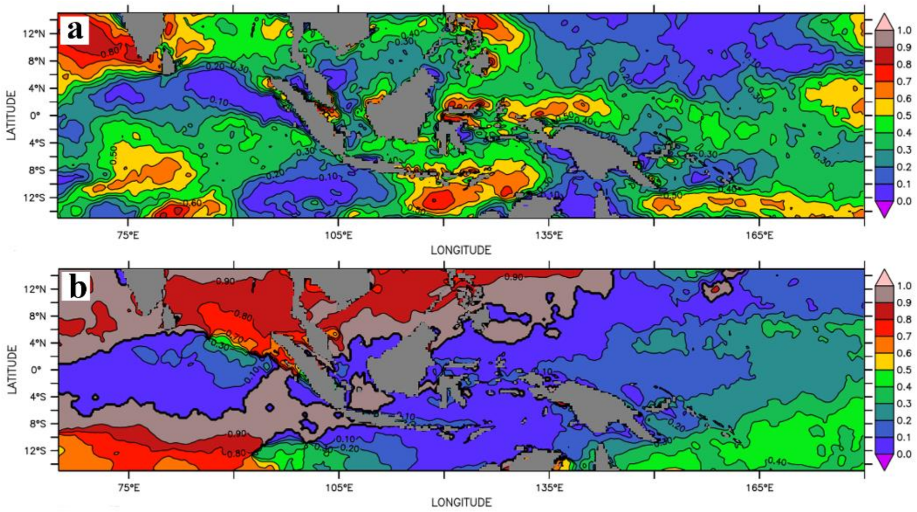

**Figure 11.** Coherence (a) and phase (b) relationship between zonal transport and zonal wind on the intra-seasonal time scal

that occur in the Pacific and Indian oceans and interannual phenomena. Winds was related to ENSO, Indian ocean variability, and local monsoon winds, which are important factors in ITF transport changes (Sen Gupta *et al.,* 2016).

## Conclusion

The current circulation in the study area varies in different seasons with the direction of the current. In the west monsoon, the current tends to move away from the gulf and Maluku Sea and move to the Lifamatola strait, while in the east monsoon, the current is partially trapped in the gulf moves northward, leaving the Maluku Sea. The range of temperature and salinity values between the Gulf of Tomini and the Maluku Sea also differs significantly during seasonal changes; SPSLTW water masses dominate the Maluku Sea and Gulf of Tomini water masses. Seasonal factors affect the pattern of wind movement and ITF input into the Maluku Sea. It affects physical oceanographic variables such as temperature, salinity, the current direction, and transport volume in the Maluku Sea and Gulf of Tomini. The variability and fluctuation of current transport in the Tomini Gulf and Maluku Sea are influenced by phenomena from intra-seasonal to interannual time scales based on EOF and cross-PSD analysis. Current fluctuations are influenced by Rossby waves propagating from the Pacific Ocean generated by zonal winds on the intra-seasonal scale, monsoon effects on the semi-annual time scale, and El Nino and La Nina's influence which affect the strength of the Pacific trade winds. This affects the ups and downs of pressure gradients and sea level levels in the west pacific, which results in the strength and weakness of the ITF entering the Maluku Sea and Gulf of Tomini.

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