A Numerical Study of The Outflow of Makassar Strait Using Regional Ocean Modelling System (ROMS)

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Abstract. In the Makassar Strait, upwelling occurred by wind-driven current and complexity of bottom topography. Analysis of upwelling phenomena could be determined by salinity, temperature and three-dimensional current value which happened in a year as a climatology change. Regional Ocean Modelling System (ROMS) is a terrain-following three-dimensional model to calculate a numerical value which needs stability for long-duration simulation. The model has been simulated for 1 year from 1 January 2017 to 31 December 2017 and verified by tidal data. Horizontal Boundary Condition which contains u-v velocities, salinity and temperature, is a climatology data from GLBa0.08 HYCOM. Atmospheric forcing was calculated from ERA-INTERIM ECMWF. The verification uses RMSE and RRE methods and showed good result between model and observation data with RMSE=0.1454 meter and RRE=6.5806%. The result was analysed from twelve sampling points, six points on the outflow of the Makassar Strait which generated upwelling and the six others on the canal that connect to the Flores Sea and the Java Sea. The model gave a good result on January, and indicate average w-velocity of 9.1183 m/day.

1. Introduction

Indonesian throughflow (hereafter referred to ‘ITF’) is a circulation which connects the Pacific Ocean into the Indian Ocean. Makassar Strait, located between Borneo and Sulawesi Islands, is known as one of the main pathways of ITF [1]. The total amount of 10 Sv of water mass was transported throughout the water column of the Makassar Strait [1]. In the year of 1997, volume transport is determined to be ~8 Sv with an uncertainty of 2 Sv (Sv=106 m3/sec) [1]. The volume transport of the Makassar Strait encounters a sill depth of ~680 m and has two branches; through the Lombok Strait with a sill depth of ~300 m and the other throughflow to the Banda Sea through the Flores Sea [2]. The freshwater and heat budget are observed between Indonesian throughflow and sea temperatures [3].

Many studies on upwelling have been done [3 4], the classic Ekman described a relation between wind and upwelling [5], and also the complexity of topography and mixing on the shallow area [6]. Upwelling phenomena occurred for a long duration; in a period over a month in a year [6]. Gordon [2] described correlations between ITF, that has a major contribution to sea temperature, and salinity over thermohaline circulation [7] with upwelling phenomena. ITF is mostly composed by the contribution of Pacific thermocline and intermediate water that flows through the Makassar Strait [8]. A previous study
[9] showed that the variance of temperature in the Makassar Strait is related to the variability of temperature in the atmosphere and heat budget that comes across the Pacific over Indian Oceans [9]. The observation shows that temperature variability on the Makassar Strait was nearly 3.72°C, while internal energy that passes it was 0.39 PW [9]. The observation also found the relation between heat budget with water discharge that crosses over the Indonesian throughflow [9].

Indonesian seas are mostly located in the tropical climate and have two seasonal monsoon wind patterns (ref). The wind blows mostly change over the season. In April to October, the wind blows from Australia. During this season, another wind comes from the Pacific and Indian Oceans carrying vapour over the atmosphere [10, 11]. The wind also drives current which creates seasonal Ekman transport over upwelling phenomena.

2. Data

Data come from the model, including several inputs that are handled differently on the model.

2.1. Atmospheric Forcing

Input data from atmosphere is used as forcing. The file containing parameters that would require to calculate bulk-flux formula [12], such as; surface 10 meters above sea level wind, heat flux components, surface freshwater flux, also climatology cloud cover and dewpoint. All data is accessed from ECMWF (European Centre for Medium-Range Weather Forecast) ERA-Interim dataset, which are analysis products of forecasting results owned by ECMWF. Bulk-flux product impact surface salinity, temperature and momentum. Each time step data is available in 3 hours, and initial time 00:00, covered over the year of 2017.

The input data converted into ROMS format from ECMWF GRIB format before use. The input data does not need to be the same grid as ROMS actual grid and would internally be interpolated as the model running.

2.2. Tidal

Tidal data is used as hydrodynamic forcing from water level elevation in the studied region. Data is obtained from harmonic tidal model data TPXO-ATLAS based on seawater level data observed from Topex-Poseidon satellite. Tidal components used in this model simulation are Q1, O1, P1, K1, N2, M2, S2, K2, and M4. Tidal data is a tide model with complex amplitude and harmonic constituents and used the Laplace Tidal Equations and along-track averaged data from TOPEX/Poseidon and Jason (on TOPEX/Poseidon tracks since 2002) [13, 14]. For the model verification, data used sea surface elevation from Compact TD instrument, and compared to the model result of January-February 2017.

2.3. Temperature, Salinity and Velocity

Temperature, salinity and u and v-velocity inputs are the inputs used as initial condition and horizontal boundary along with the model simulation data. The mentioned file is obtained from HYCOM (Hybrid Coordinate Ocean Model) model and NCODA Global 1/12° Reanalysis in spatial-temporal format (http://tds.hycom.org/thredds/catalogs/GLBa0.08/expt_91.2.html). The input was extracted from all layer into ROMS format and user-defined grid configuration. The data was analysed for every 3-days as an indexed lateral boundary condition. The time step was not covered but the data was calculated internally by ROMS using Radiation-Nudging boundary condition.

2.4. Bathymetry

Bathymetry was used by the model illustrated by Figure 1 below, and was sourced from ETOPO1. It was processed using GridBuilder v1.2 software, with grid dimension (lat_grid x lon_grid) 722 x 462, and grid resolution (lat_grid x lon_grid) by 1.6 km x 1.6 km. The masks used GSHHG (Global Self-consistent, Hierarchical, High-resolution Geography Database), and modified by user-defined. This is important to find a shallow channel or too large covered sea which caused over velocity for several areas, especially
coastal river run-off which is not used, small islands and narrow channel area.

The shallowest bathymetry is 15m below first initial sea level and smoothed by adjusting positive with target rx0 of 0.2, bathymetry is also divided into 20 layers, which is using stretched terrain-following coordinate layer by Shchepetkin and William [15]. The slope between layer is transformed by ROMS default transformation equation [16]. The properties of vertical transformation equation is defined by 2 and vertical stretching function is defined by 4, the function also used \( \theta_s \) 5.0 and \( \theta_h \) 0.4.

3. Methods
In the Makassar Strait over Lombok strait, phenomena upwelling would be hard to analyse. Many components were calculated and need better numerical treatment to get a realistic result. This model was adapted from a previous study [17, 18] and the result was smooth enough to be adapted from coastal studying to regional scale. These models include atmospheric model as a heat source, momentum-flux and salinity exchange over the air. This model also used Radiation-Nudging (RadNud) schema [19] to calculate momentum in the boundary area. RadNud schema made computation affected to become slower, but more accurate and nearly similar to the next time-step input data.

The goal is to model upwelling as climatology study, also to find upwelling on topography slope. In many trials, we found that fake upwelling found over the sloping area. Then, the grid has to be smoothed by decreasing the topography slope before simulation to avoid model to become unstable. The ROMS also calculated vertical velocity by using Arakawa “C” grid and stretched terrain-following coordinate layer, this will be a benefit on solving changing seal level over time [20]. The ROMS method also solved 3 Dimensional change with finite difference approximation of the Reynolds-averaged Navier-Stokes (RANS) [21, 22].

3.1. Governing Equations
The governing equations are as described [21, 16], which are used by the Regional Ocean Modelling System and were presented. The momentum equation in x and y-directions are:

\[
\frac{\partial H_u}{\partial t} + \frac{\partial(\rho H_u)}{\partial x} + \frac{\partial(\rho H_v)}{\partial y} + \frac{\partial(\rho H_t)}{\partial z} - f H_u = - \frac{H_z}{\rho_o} \frac{\partial p}{\partial x} - H_z g \frac{\partial \eta}{\partial y} - \frac{\partial}{\partial z} \left( \frac{\partial \bar{u} \bar{w}}{\partial x} - \frac{\partial \bar{v} \bar{w}}{\partial y} \right) - \frac{\partial(H_5 \bar{w})}{\partial x} - \frac{\partial(H_5 \bar{w})}{\partial y} - \frac{\partial(H_5 \bar{w})}{\partial z}
\]

(1)

\[
\frac{\partial H_v}{\partial t} + \frac{\partial(\rho H_v)}{\partial x} + \frac{\partial(\rho H_v)}{\partial y} + \frac{\partial(\rho H_t)}{\partial z} + f H_v = - \frac{H_z}{\rho_o} \frac{\partial p}{\partial y} - H_z g \frac{\partial \eta}{\partial x} - \frac{\partial}{\partial z} \left( \frac{\partial \bar{v} \bar{w}}{\partial x} - \frac{\partial \bar{v} \bar{w}}{\partial y} \right) - \frac{\partial(H_5 \bar{w})}{\partial x} - \frac{\partial(H_5 \bar{w})}{\partial y} - \frac{\partial(H_5 \bar{w})}{\partial z}
\]

(2)

\[- \frac{1}{\rho_o} \frac{\partial p}{\partial x} - \frac{\partial p}{\partial y} = 0
\]

(3)

The scalar transport:

\[
\frac{\partial(\theta C)}{\partial t} + \bar{v} \nabla C = - \frac{\partial}{\partial s} \left( \bar{v} \bar{w} \frac{\partial C}{\partial s} \right) + F_c + D_c
\]

(4)

While the continuity equation:

\[
\frac{\partial \eta}{\partial t} + \frac{\partial(\rho H_u)}{\partial x} + \frac{\partial(\rho H_v)}{\partial y} + \frac{\partial(\rho H_t)}{\partial z} = 0
\]

(5)

The equations above are described with parameterizing Reynolds stresses and turbulent tracer fluxes as:

\[
\bar{u} \bar{w}' = -K_M \frac{\partial u}{\partial z}; \quad \bar{v} \bar{w}' = -K_M \frac{\partial v}{\partial z}; \quad \bar{p} \bar{w}' = -K_H \frac{\partial p}{\partial z}
\]

(6)
The vertical condition is using data from satellite. The equation below was calculated by bulk-flux for atmosphere boundary layer and adapted to ROMS equation for vertical boundary layer \[22\]. The bed layer stresses are calculated internally by ROMS by using the default value. The top vertical boundary:

\[
K_M \frac{\partial u}{\partial z} = \tau_s^x(x, y, t) \tag{7}
\]

\[
K_M \frac{\partial v}{\partial z} = \tau_s^y(x, y, t) \tag{8}
\]

\[
K_C \frac{\partial C}{\partial z} = \frac{\partial C}{\partial \rho \phi \rho} \tag{9}
\]

\[
w = \frac{\partial \zeta}{\partial t} \tag{10}
\]

The bed vertical layer:

\[
K_M \frac{\partial u}{\partial z} = \tau_b^x(x, y, t) \tag{11}
\]

\[
K_M \frac{\partial v}{\partial z} = \tau_b^y(x, y, t) \tag{12}
\]

\[
K_C \frac{\partial C}{\partial z} = 0 \tag{13}
\]

\[-w + \ddot{v} \cdot \nabla h = 0 \tag{14}\]

where \(K_M\) is momentum viscosity Eddy \(K_c\) is Eddy diffusivity. They are calculated using one of five options for turbulence-closure models in ROMS: (i) BruntVäisälä frequency mixing in which mixing is based on the stability frequency; (ii) a user-provided analytical expression such as a constant or parabolic shape; (iii) the K-profile parameterization \[23\], expanded to include both surface and bottom-boundary layers \[24\]; (iv) Mellor-Yamada level 2.5 (MY2.5) method \[25\]; and (v) the generic length-scale (GLS) method \[26\]. The detail for each variable is listed in Table 1.

Table 1. List of variables

| Symbol | Description                                      | Dimensions            |
|--------|-------------------------------------------------|-----------------------|
| \(C\)  | Tracer (temperature, salt, or suspended-sediment concentration) | \(^\circ\)C, salinity, or kg m\(^{-3}\) |
| \(H_z\) | Grid cell thickness                             | M                     |
| \(f\)  | Coriolis parameter                              | \(s^{-1}\)            |
| \(g\)  | Gravity                                         | \(m s^{-2}\)         |
| \(p\)  | Pressure                                        | \(N m^{-2}\)         |
| \(s\)  | Vertical sigma coordinate                       | –                     |
| \(u\)  | Velocity x-direction                            | \(m s^{-1}\)         |
| \(u'\) | Turbulent velocity x-direction                  | \(m s^{-1}\)         |
| \(v\)  | Velocity y-direction                            | \(m s^{-1}\)         |
| \(v'\) | Turbulent velocity y-direction                  | \(m s^{-1}\)         |
| \(w'\) | Turbulent velocity s-direction                  | \(m s^{-1}\)         |
| \(z\)  | Vertical elevation                              | M                     |
| \(\Omega\) | Vertical velocity s-direction                  | \(s^{-1}\) |
| \(\eta\) | Wave averaged free surface elevation            | M                     |
| \(\rho\) | Density                                        | kg m\(^{-3}\)        |
| \(\tau_b\) | Bottom stress                                  | m\(^2\) s\(^{-2}\)  |
| \(\tau_s\) | Surface stress                                  | m\(^2\) s\(^{-2}\)  |
3.2. Model Design
The model has 460 east-west grids and 720 north-south grids with 1.6 km spacing, with total wide of 1155 km and total length 739 km, and total area width of 853 923 km$^2$. The model cover area with latitude 0.9° north to -9.2° south and longitude 115.1°-121.7° east. We used masking to determine sea and land area. Criteria sea mask is filled by value 1 and the land area filled by value 0. The model has the lowest depth at 15m and the deepest at 5233.9m, with 20-layer sigma coordinate.

![Figure 1. Study Area of Model, Stations to be analysed is on Makassar Strait Outflow showed by the red circles, while the observation data is shown with the red square](image)

The CFL condition [27] is 81.1s, thus we tested on time-stepping 60 s and find an unstable solution. After that, we found the stable time step and easier to calculate time step at 30 s. On the boundary, we use radiation-nudging and data from HYCOM for every 3 days and 3 hourly data ERA-INTERIM from ECMWF for climatology as a forcing. We also added tidal data from TPXO8-atlas to change the analytic field for tidal on ROMS. This is important as we use tidal as compared data. We put 12 stations on the model to find w-velocity average depth. The exact location of each station is shown and listed in Table 2.

### Table 2. List of stations coordinate

| Location Name | Latitude (North-South) | Longitude (East-West) |
|---------------|------------------------|-----------------------|
| Observation data | 0.2241° | 117.42° |
| Station 1 | -4.7357° | 118.79° |
| Station 2 | -4.4817° | 118.13° |
| Station 3 | -4.1994° | 118.32° |
| Station 4 | -5.1450° | 118.46° |
| Station 5 | -5.6531° | 119.08° |
| Station 6 | -6.1470° | 119.42° |
| Station 7 | -5.2156° | 117.17° |
| Station 8 | -4.9051° | 117.48° |
| Station 9 | -4.9615° | 117.69° |
| Station 10 | -4.3264° | 119.50° |
| Station 11 | -3.7760° | 119.36° |
| Station 12 | -3.5784° | 119.20° |
4. Results

4.1. Verification Model

Figure 2 below shows the comparison between observation data with ROMS output. It seems ROMS model result still did not result in the same result as observation data. However, this verification is still good to be used. The observation data were calculated with root-mean-square (RMS) formula to find the difference with the physical unit scale. Relative-RMS-error (RRE) is also used to find percentage correlation.

![Figure 2](image_url)

**Figure 2.** Model verification is tide elevation (meter), and showed a correlation between observation (blue line) data and the model (red dash line). The observation data is located on Pangempang, Muara Badak, Kalimantan Timur.

The formula of RMS [28] is given:

\[
RMS\ error = \left( \frac{1}{N} \sum_{n=1}^{N} (O^n - P^n)^2 \right)^{-2}
\]  

And RRE formula [29] is given:

\[
RRE = \frac{RMS\ error}{\text{observed change}} = \frac{\left( \frac{1}{N} \sum_{n=1}^{N} (O^n - P^n)^2 \right)^{-2}}{\frac{O_{\text{max}} - O_{\text{min}}}{2}} \times 100
\]

The verification model result shows good condition between ROMS output and the observation data located on Pangempang, Muara Badak, the exact location is shown in Table 2. The results show good condition with RMS error at 0.1454 meter. The ROMS output has a lower amplitude than the observation data. The result from RMS error is then calculated with RRE formula and gave small percentage error of 6.5786%.

4.2. Surface temperature and salinity

Surface temperature and salinity were averaged every three months from daily averaged ROMS output. On Figure 3 and Figure 4, each sub-figure is; (A) January, February, March (JFM), (B) April, May, June (AMJ), (C) July, August, September, and (D) October, November, December. Salinity in term of Practical Salinity Scale with no unit scale, where temperature is described in ℃.

We calculate the annual mean of sea surface salinity and found that SSS change periodically throughout the year. Figure 3 shows that; SSS at the beginning of the year is less saline, the average value for annual mean in January-March is 32.11 pss. With the exchange from the atmosphere, more saline water spread along April-June, the average value for annual means is 32.94 pss. July-September is the highest averaged value record for annual mean, the value is 33.85 pss. Surface salinity in October-December become fresher, the value is 33.79 pss.
Variability sea surface temperature is influenced by the atmosphere and changes periodically throughout the year. The sea surface is also gradually influenced by heat budget that comes with discharge from the Pacific current. The highest surface temperature has good result compared to model result from Qu T et al [30] and showed the variability of around 4.0°C. On the several station's areas, the surface temperature showed cooler temperature, it indicated that the upwelling process mixed potential temperature from the lower layer into the surface area. Average surface temperature in January-March is 29.62 °C and in April-June is 29.16 °C. Surface temperature becomes cooler in July-September with
the model result showing that the average value is 27.77 °C. In October-December, average surface temperature rises and become warmer along the year, the average value is 30.38 °C. The precipitation results from UKMO UM (UK Meteorological Office Unified Model) described anomaly around 1°C which contributes to temperature variability throughout the year [30].

**Figure 4.** Average surface temperature (°C) calculated in every 3 months from daily average ROMS output; (A) JFM, (B) AMJ, (C) JAS, (D) OND.
4.3. Variability of velocity near the surface

![Velocity data for various months](image)

**Figure 5.** Average monthly from 10 meters velocity. The pattern showed the direction of velocity, while the power of velocity is shown by colour.

The velocity component is velocity on 10 meters below sea level. It shows unsatisfied result caused by boundary condition criteria around Lombok Strait. However along the Makassar Strait to the Flores Sea, the velocity is still on normal value. As described by Gordon [2], Indonesia throughflow and shift with the sun, contribute variability mixed velocity around temperature further
north from July to September, further south from January to March. The seasonal swing of the surface temperature is accentuated by Ekman upwelling in the southeast monsoon of July to September. Near the station's area, phenomena of upwelling also caused velocity to mostly turned left and made spiral circulation. The result is caused by Coriolis effect on the southern hemisphere, and may make some Ekman transport.

4.4. Upwelling in the outflow Makassar Strait

4.4.1. Upwelling Area. Vertical velocity was calculated by transform-based layer into fixed depth, then calculating the average velocity from the surface to seabed. Figure 6 showed upwelling area divided into 2 areas; (1) the first location coloured by blue bars is located on station 1, station 2 and station 3 (coordinate in Table 2), (2) the second location coloured with red bars are located on station 10, station 11 and station 12.

In the first location, upwelling occurred not only caused by wind-driven, but also the water discharge which meets slope on the shallow area. In January, average vertical velocity started with 9.11 m/day, then decrease to near 6 m/day in February. Upwelling debit is also corresponded to water discharge from Makassar Strait. In April when the model showed water mass discharge increase, upward average vertical velocity value also gains a significant amount to 8.4 m/day. In July-August-September when water discharge from Makassar Strait is in stable condition, upwelling gains mostly high value for 3 monthly average over 7.5 m/day.

The bars with mostly red colour are located near coastal area Sulawesi. These locations are useful to track the correlation between Coriolis force and water mass which is deflected into the coastal area. On the area shown with red bars, upwelling is mostly constant over the year with the average value of 3.98 m/day. We found that wind come from south and southeast influenced the duration of upwelling. In April-September when monthly average wind speed from the south is more than 4 m/s, the value of vertical velocity is also above 4 m/day.

4.4.2. Downwelling Area. Water discharge from Makassar Strait branches into two part, first part mostly passed into Lombok strait and the other part passed the deeper area on the Flores Sea. The bars that are mostly coloured with yellow palette are located in the southern east pathway into the Flores Sea, while the bars that are mostly coloured with green palette are located in the southern west pathway which passes through the deeper area into Lombok Strait. The water discharge was discussed by Gordon [2] which seems has a correlation with downwelling in this area. The water mass from Makassar Strait encounter depth around ~680 m then fall into deeper area. While freshwater from Java Sea force water discharge from Makassar strait budge into a deeper area, the effect water mass bulk made downwelling vertical velocity. Figure 7 shows that throughflow from Makassar Strait budies which a greater amount of water
mass into Lombok Strait (green bars). Average downwelling has a higher value on April around -7.75 m/day and October around -11.83 m/day.

Figure 7. Sample points from station 4 to station 6 are located on the canal that connects Makassar Strait to the Flores Sea. Sample points from 10 to 12 are located Makassar Strait throughflow to Lombok Strait.

4.4.3. Upwelling due slope topography. Figure 8 is a cross-section from station 3 to station 2 when water mass from Makassar Strait encounter depth sill ~680 m. Water mass with higher negative zonal velocity value was found around the surface to ~500 m and lower negative zonal velocity was found in the deeper water column. ROMS output showed that on 15 April 2017 upwelling velocity has greater value than average monthly. Near the slope (>700 m) average depth upwelling velocity is more than 40 m/day, while the other days' value could be less than 5 m/day.

Figure 8. These figures are located between station 3 to station 2 on 15 April 2017, describe velocity between the variety of topography; (A) u-velocity, (B) v-velocity, (C) w-velocity.
Figure 9. The zoomed from Figure 8, vertical track from the surface to 550 m depth on 15 April 2017; (A) salinity, (B) temperature.

Figure 9 showed temperature and salinity over layers, near the sloping topography where upwelling happened. In the depth around 200 m, temperature change below 2°C. These figures showed that upwelling temperature and salinity mostly effect on shallower seas.

5. Conclusions

Upwelling can be considered to add an important role for understanding temperature and salinity variability. Atmospheric component influence period of upwelling especially on the shallow area. The result showed that upwelling occurs on coastal South Sulawesi on several months and created seasonal upwelling which dominantly occurs in April. The result was calculated by 3-Dimensional numerical model ROMS and showed good result between observation data and ROMS output.

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