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Impact of reclamation on monsoonal circulation changes in Jakarta Bay

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Abstract. The Jakarta Bay plays an important role in supporting maritime activities such as marine transportation, tourism, industry, and coastal communities. To meet the needs of the people in the future, it is planned to build islands (giant sea wall) through huge coastal reclamation. In oceanography-point-of-view, new islands formation is believed to modify natural coastal circulation in the region. Here, we investigated the impact of new islands formation on Monsoonal circulation and passive tracer distribution by performing a validated numerical model experiment with ROMS-AGRIF. The results show that natural Monsoonal circulation is characterized by eastward (westward) flow during the Northwest (Southeast) monsoon period, but mean circulation flows eastward. Water mass in the inner bay is flushed partially by water from western/eastern peninsula. With the presence of reclaimed islands, the Monsoonal surface flows are partitioned into channels in-between the islands. An intensification of the flows is found around a narrow channel. Furthermore, passive tracer of water, released in Ciliwung River estuary, indicated Monsoonal reversal spreading along the channels closed to the coastal mainland. Further experiment by changing channels width to be much smaller, the flows revealed are much weaker, was resulting in an accumulation of passive tracer around the estuary.

1. Introduction

The Jakarta Bay is a strategic area for fisheries, transportation, and tourism sector. This area is the central of coastal communities’ activity and produces economical profit to the surrounding regions. However, the number of human activities also generate a high environmental pollution. Based on previous research, Jakarta Bay has elevated contaminants of 537 tons per day [1]. Organic pollutants could cause an eutrophication that gives impact to the area ecologically. A study by [2] about the variability of Monsoonal currents in Jakarta Bay, showed that sea surface currents in June and September 2003 flowed broader from the southwest to northwest and from the near-bottom to the coastal area, except for towards the sea. Additionally, sea surface currents pattern in May 2004 generally came from northeast to northwest.

Based on [3], a giant sea wall (GSW) will be built in Jakarta Bay and the construction of the master plan will take one and a half year with the physical development takes about 10-25 years. Physical development is targeted to be complete in 2025. The presence of the GSW construction will presumably influence various aspects of ecology, including oceanographic aspect in Jakarta Bay that causes a controversial issue.

Numerical modeling method was used to assess possible changes of the structure of the coastal area that could be affected due to reclamation activities by indicating current circulation pattern changes. Numerical modeling and computational advance in oceanography have improved the capacity in oceanographic conditions prediction on the offshore and the onshore area. One of modeling tools that was already developed is Regional Ocean Modelling System (ROMS) with its nesting version ROMS-A
AGRIF. ROMS uses primitive equations (Navier-Stokes equation) for hydrodynamics model and can be applied in regional scale [4]. Certain numerical modeling using ROMS in Indonesian territory were also implemented, i.e. simulation of Monsoonal currents in Indonesian waters [5] and study of upwelling mechanism using numerical modeling in Southern Sulawesi [6].

As sea current acts as the carrier of sediments, nutrients, and pollutants, a study of current patterns in Jakarta Bay is needed. The pattern of flow was examined to explain the distribution of physical and chemical parameters as well as the distribution of marine organisms. Given the above context, we aim to investigate the annual cycle of sea surface currents pattern and its change as the impact of reclamation, as well as the distribution of passive tracer released from Ciliwung River.

2. Methods

2.1. The data

Data used for model were from research centers and World Database [7]. Atmospheric climatology (wind stress) was obtained from QuickSCAT, SST from AVHRR (Advanced Very High Resolution Radiometer)-Pathfinder Observations 1985-1997, bathymetry used ETOPO data with 0.5° resolution, the atmospheric flux used data from COADS05, the lateral boundary conditions (Drakkar Simulation of INDO-ORCA05), coastline (Coastline GHSS Folder), and seawater properties (World Ocean Atlas 2009).

Domain of model ranges from 106°18’E to 107°12’E and 5°18’S to 6°6’S. Domain for visualization was zoomed only between 106°40’E–107°5’E and 5°52’S–6°8’S. Jakarta Bay (visualization domain) consists of shallow water with average of depth approximately 32 m.

2.2. Model configuration

Ocean circulation model was built using ROMS-AGRIF configuration. ROMS uses primitive equations and free surface (short time-step for barotropic dynamics and long time-step for baroclinic dynamics) to calculate atmospheric or oceanic state at the initial time and after.

ROMS requires horizontal grid data input (position of grid point, size of grid dimension), topography of sea floor, addition of surface forcing (wind stress, heat flux, surface freshwater flux), initial (temperature, salinity, currents, sea level height) and lateral (temperature, salinity, currents, sea level height) boundary conditions.

Equation of motion in ROMS applies the second Law of Newton where the change of momentum against time equals to the total forcing [8]. [9] describe the equation of motion of water in 3D form and Cartesian coordinates:

\[
\begin{align*}
\frac{du}{dt} + \bar{U} \cdot \nabla u - f v &= -\frac{1}{\rho} \frac{dp}{dx} + k \frac{d^2 u}{dz^2} + A_h \Delta u \\
\frac{dv}{dt} + \bar{U} \cdot \nabla v + f u &= -\frac{1}{\rho} \frac{dp}{dy} + k \frac{d^2 v}{dz^2} + A_h \Delta v \\
\frac{dw}{dt} + \bar{U} \cdot \nabla w + g &= -\frac{1}{\rho} \frac{dp}{dz} + k \frac{d^2 w}{dx^2} + A_h \Delta w
\end{align*}
\] (1.a) (1.b) (1.c)

Where \( u, v, w \) are the velocity of fluid at x, y, z axes; \( t \) is time; \( f \) is Coriolis parameter \((=2\Omega\sin\phi)\); \( \bar{U} \) is the angular velocity of the Earth rotation; \( \Phi \) is latitude coordinate; \( \frac{1}{\rho} \) is specific volume; \( p \) is pressure; \( k \) is vertical Eddy viscosity coefficient; \( A_h \) is horizontal Eddy viscosity coefficient; \( \Delta = \frac{d^2}{dx^2} + \frac{d^2}{dy^2} \); \( \nabla = \hat{i} \frac{d}{dx} + \hat{j} \frac{d}{dy} + \hat{k} \frac{d}{dz} \) (del operator); and \( g \) is Earth gravity.
Figure 1. (a) Domain of model and bathymetry and (b) Domain of visualization and bathymetry of Jakarta Bay.

ROMS uses Navier Stokes primitive equations and ignores the acceleration among vertical speeds \( w = 0 \) \cite{10}, thus, the equation of momentum conservation is simply referred as momentum conservation on the direction of x-axis and y-axis:

\[
\begin{align*}
\frac{du}{dt} + \vec{U} \cdot \nabla u - fv &= - \frac{1}{\rho_0} \frac{d\rho}{dz} + \nabla_h (K_{Mh} \cdot \nabla_h u) + \frac{d}{dx} (K_{Mu} \frac{du}{dx}) \\
\frac{dv}{dt} + \vec{U} \cdot \nabla v + fu &= - \frac{1}{\rho_0} \frac{d\rho}{dz} + \nabla_h (K_{Mh} \cdot \nabla_h v) + \frac{d}{dx} (K_{Mu} \frac{dv}{dx})
\end{align*}
\]  

(2.a)

(2.b)

where the parameter \( k \) is transformed into \( K_{Mu} \) and \( A_h \) is replaced by \( K_{Mh} \) as the vertical and horizontal mixing water mass coefficient.

\( \rho \) is the density function of the temperature (T), salinity (S), and pressure gradient (P). However, density component is ignored in advection of equation (2) (the fluid is incompressible) so that on the equation of vertical hydrostatic equilibrium, the value of density can be described in equation (3) with the value of pressure on the depth equals to the negative of density and gravity:

\[
0 = - \frac{d\rho}{dz} - \rho g
\]

(3)

Change of horizontal density in continuity equation was neglected or fluid is incompressible (\( \rho = \rho_0 \)) (Boussineq approximation) so that density value is constant for horizontal pressure gradient. Continuity equation for incompressible fluid can be written as:

\[
0 = \frac{du}{dx} + \frac{dv}{dy} + \frac{dw}{dz}
\]

(4)
ROMS can analyze fluid movement due to the advection and mixing of water masses. The equation used is tracer conservation, with temperature and salinity are included. Conservation equations of temperature (5) and salinity (6) can be written mathematically as:

\[
\frac{dT}{dt} + \bar{u} \cdot \nabla T = \nabla_h (K_{Th} \cdot \nabla_h T) + \frac{d}{dz} (K_{Tv} \frac{dT}{dz}) \tag{5}
\]

\[
\frac{dS}{dt} + \bar{u} \cdot \nabla S = \nabla_h (K_{Sv} \cdot \nabla_h S) + \frac{d}{dz} (K_{sv} \frac{dS}{dz}) \tag{6}
\]

where \(\frac{dT}{dt}\) and \(\frac{dS}{dt}\) show the transform rate of temperature and salinity over time, \(\bar{u} \cdot \nabla T\) and \(\bar{u} \cdot \nabla S\) are advection, \(K_{Th}\) is horizontal mixing coefficient and \(K_{Tv}\) is vertical mixing coefficient. In this model, passive tracer calculates the debit of river in arbitrary unit.

Forcing of fluid on the surface and bottom are described using surface and bottom boundary conditions [11]. Surface waters are driven by kinematic (high sea level), surface wind stress and temperature-salinity flux. Mathematically, the driving force of the fluid in the surface boundary conditions can be written as:

\[
\frac{dn}{dt} = w \tag{7.a}
\]

\[
K_{Mv} \frac{du}{dz} = \frac{\tau_x}{\rho_0} \tag{7.b}
\]

\[
K_{Mv} \frac{dv}{dz} = \frac{\tau_y}{\rho_0} \tag{7.c}
\]

\[
K_{Tv} \frac{dr}{dz} = \frac{g}{\rho_0 c_p} \tag{7.d}
\]

\[
K_{sv} \frac{ds}{dz} = \frac{S(E-P)}{\rho_0} \tag{7.e}
\]

Equation 7.a shows driven fluid by transforming sea level elevation \(\frac{dn}{dt}\). Wind as forcing is figured by equation 7.b in x-axis and 7.c in y-axis. The equations describe mixed fluid \(K_{Mv}\) driven by a stretch of wind \((\tau_x\) and \(\tau_y\)) through the coastal area. Equation 7.d describes the change in temperature due to heat flux \(Q\) on a mixed layer and heat transfer coefficient is \(c_p\). Equation 7.e is the change of salinity due to evaporation-precipitation \(S(E-P)\) on a mixed layer.

Bottom force on the boundary condition waters consists of basic kinematic, friction (friction) and bottom temperature and salinity flux. Mathematically it can be written as:

\[
\bar{u} \cdot \nabla (-H) = w \tag{8.a}
\]

\[
K_{Mv} \frac{du}{dz} = -\frac{c_d ||u|| u}{\rho_0} \tag{8.b}
\]

\[
K_{Mv} \frac{dv}{dz} = -\frac{c_d ||v|| v}{\rho_0} \tag{8.c}
\]

\[
K_{Tv} \frac{dr}{dz} = 0 \tag{8.d}
\]

\[
K_{sv} \frac{ds}{dz} = 0 \tag{8.e}
\]

Equation 8.a describes the fluid motion due to advection process in bottom layers. Equation 8.b and 8.c explain the friction on x-axis and y-axis where the linear drag coefficient \((C_d)\) has a value of \(3 \times 10^{-4}\) m/s. Thus, the temperature and salinity flux in the bottom is zero.

2.3. Description of experiment

Model was made in three scenarios. Scenario 1 is the normal condition of Jakarta Bay which is exist before reclamation, scenario 2 is the condition of Jakarta Bay after reclamation with GSW blueprint modified, and scenario 3 is the condition of Jakarta Bay including reclaimed artificial islands in
accordance with the original GSW blueprint plan. The addition of reclaimed land of artificial islands in
scenarios 2 and 3 was performed by masking technique on the grid of model for scenario 1.

Tidal component was calculated as a forcing for the simulation model on the open boundary
condition. This was done since Jakarta Bay circulation is influenced by tides. However, the results of
the simulation were saved as daily average to focus on the annual cycle of circulation. Moreover, this
simulation model also set river discharge point to be made constantly. This parameter is required to
study Monsoonal pattern distribution based on passive tracer of Ciliwung River.

3. Results

3.1. Model validation
A numerical model of Jakarta Bay circulation on scenario 1 was validated using sea surface height (SSH)
data from altimetry satellite (AVISO) 2005-2010. Altimetry satellite data was averaged weekly in
monthly climatology. Sea level height data result in climatology (zeta) from ROMS model (scenario 1)
in the 5th year was also used as a comparison. Both of data was calculated for anomaly values (MSL
references) hence the sea surface height data could be compared. The following presented the result of
SSH data comparison between model and satellite altimetry (figure 2).

Correlation value between model data with the altimetry on the SSH is 0.7, which means that the
model represents allegedly against the data of observation. RMSE was neglected as the values of the
two signals are highly different, therefore the scale used were adjusted. Nevertheless, the patterns formed
in the time series were similar from one another. The value of altimetry data shows that the sea level is
below zero from January to March, and above zero from April to August. Sea level increases in
September and decreases significantly in December. Similar result is also shown on the model results.
Yet, model data was averaged daily which creates the sea level fluctuation was occurred more on the
model data. Generally, the increasing of sea level in monthly period follows the pattern of SSH data
altimetry.

![Figure 2. Annual cycle of sea level from satellite altimetry (black line) and model output (red line)
in the Northeast side of Jakarta Bay. Sea level correlation between data and model output is 0.7.](image)

3.2. Surface circulation pattern in Jakarta Bay
Simulation model in Jakarta Bay on scenario 1 (normal condition) was run for 5 years and averaged
daily; hence tide signal was already eliminated. Thus, the current pattern in Jakarta Bay is only affected
by wind with each grid on the model contains current vector. However, due to high resolution and very
small distance of each grid on the visualization, simplification is necessary. Display grid of flow vector
was given in every six grids with 0.1 m/s scale vector. Flow magnitude was not simplified or values are
displayed on the entire grid.

Highest current circulation takes place in February 16 (West Monsoon) where the water flows
eastward. Subsequently, sea current in May 16 (Transitional I Monsoon) moves slowly towards
westward likewise in August 16 (East Monsoon). In November 16 (Transitional II Monsoon),
transitional water flows from east to west and moves slowly until the West Monsoon sets in when the current speed increases eastwardly. Sea current pattern of the scenario 1 is presented in figure 3.

The development of the cape in Jakarta Bay causes the water flow from the western side is divided into two directions, into the bay area until near coastal and free flowing to the east or west. Then the two streams will converge in the eastern or western side of the mainland. Based on a research by [2] concerning the variability of currents in Jakarta Bay from field observation, the circulation pattern of model is less in accordance with the results of the study, most likely due to the current plot vector from field observation still consisted of tidal currents signal. However, different field measurement results show different circulation patterns, and it is indicated on the results of the model.

Simulation model of Jakarta Bay on scenario 2 (reclaimed GSW modified) has similar time step with scenario 1 (daily average). Current circulation pattern in Jakarta Bay on scenario 2 is also dominated by zonal components, but the presence of reclamation (mainland) configuration stimulates current partitions into the channels. Channels are the slits where increasing flow occurs in narrow gap. figure 4 is presented to describe the pattern of currents in Jakarta Bay on scenario 2.

Simulation model of Jakarta Bay on scenario 3 (reclaimed GSW blueprint) shows the current circulation pattern in Jakarta Bay is complicated and isolated, thus a small amount of water flows and enters the bay and turned over the GSW land reclamation. The presence of GSW reclamation is presented at Tg. Priok harbor expansion which causes the current enters inside (August 16th and November 16th) and outside (February 16th and May 16th) the bay. Current intensification seems weaker than scenario 2, which is expected as the result of a little channel that parallel towards the coastline. Current zonal component also appears weaker compared to scenario 1 and 2.

Vertical structure of sea current in Jakarta Bay was made for describing current pattern based on its depth whether Jakarta Bay current has robust stratification or not. Typically, Jakarta Bay is dominated by zonal components in the surface, then the flow is shown by the components of the zonal flow (u) in transect A-B that extends vertically. In general, the flow at the surface has a powerful magnitude. This is shown in figure 6, 7 and 8 where the magnitude of the flow is way more than zero (positive or negative). Afterwards, the current pattern is getting into the bottom and facing an attenuation. Vertical structure of current on scenario 1 follows the surface current pattern on which the direction reversal occurred twice (in West and East Monsoon) based on Monsoonal pattern. Reversal of flow is indicated by a positive or negative value on the u component. Based on four pictures in different Monsoons (figure 6), sea current magnitude in the bottom has a value close to zero. However, in May 16, August 16, and November 16, the magnitude represents a strong current at the bottom. This is due to the vertical transect that intersects with islands.

Scenario 2 shows the difference of the vertical structure of current from scenario 1 where the intensification of current magnitude occurred. The Monsoonal pattern of vertical flow on scenario 2 also adheres to its surface. The intensification of currents in the bottom prevails at the channel of reclamation land. Vertical transect on zonal current component reveals a similar pattern on scenario 2. However, sea current near Jakarta coastline shows a negative value throughout the year. Blank area at figure 7 and 8 arises due to the vertical transect through reclamation land.
Figure 3. Current pattern in Jakarta Bay on scenario 1 at 10 m depth overlapped with flow magnitude (color) (ms⁻¹), presented in four representative Monsoons.

Figure 4. Current pattern in Jakarta Bay on scenario 2 at 10 m depth overlapped with flow magnitude (color) (ms⁻¹), presented in four representative Monsoons.
Figure 5. Current pattern in Jakarta Bay on scenario 3 at 10 m depth overlapped with flow magnitude (color) (ms$^{-1}$), presented in four representative Monsoons.

Figure 6. Structure and pattern of vertical current in Jakarta Bay on scenario 1, indicated by zonal component (u) (ms$^{-1}$) at transect A-B in four representative Monsoons.
Figure 7. Structure and pattern of vertical current in Jakarta Bay on scenario 2, indicated by zonal component (u) (ms⁻¹) at transect A-B in four representative Monsoons.

Figure 8. Structure and pattern of vertical current in Jakarta Bay on scenario 3, indicated by zonal component (u) (ms⁻¹) at transect A-B in four representative Monsoons.
3.3. Freshwater dispersal from Ciliwung River discharge

Components of the river were included in the model to see the distribution of water output from the river mouth into the bay. The river source was determined in the middle of Jakarta mainland configuration (the mouth of Ciliwung River) and river discharge value was made as constant along the year.

Scenario 1 shows that the waters movement of the river in West Monsoon head eastward along the flow. River discharge that comes out relatively high and dispersed uniformly along the coast. In Transitional I Monsoon, river discharge were carried away to the west side. However, the dispersion is higher and tends to gather in the coastal region (west of Jakarta). River discharge still appears smaller which is marked by thin blue color on the east coast of Jakarta. Then in East Monsoon, the river discharge output seems reduced to centralize the distribution closed to the river source in Transitional II Monsoon.

The process of river flow intrusion into the Jakarta Bay water system on scenario 2 has similar pattern with scenario 1. However, relatively low river discharge occurs and tends to disperse more widely than scenario 1. This happens due to the intensification of currents on the channels paralleled to the coastline so that the river discharge is carried out faster and causes an increase on the dispersion. The presence of GSW reclamation modification causes a quicker and wider movement of river input, which fills the channel of the reclamation land. Based on the model on figure 10, the movement of the input river occurs due to the intensification of current, while dispersion after the reclamation is caused by the formation of channels in the reclamation area.

Scenario 1 shows that the passive tracer from the river input in coastal area encounters a change of direction in Monsoonal period. The presence of modified GSW reclamation on scenario 2 (figure 10) causes a current discharge is carried away by the river input faster than scenario 1, hence it is assumed that the pollutants are disposed faster from Jakarta Bay. Model result of GSW reclamation on scenario 3 (figure 11) illustrates a high level of dispersion in the channel but isolated. This causes a closed current circulation so that the output streams are difficult to escape from the bay system. The distribution of output river discharge on scenario 3 has two river sources. The position of source point located on the west side (Cisadane River) and on the central (Ciliwung River) of Jakarta Bay. Transitional I and Transitional II Monsoons have a contribution to accumulate the river discharge in the western side of GSW reclamation Jakarta Bay.

Figure 9. Passive tracer movement pattern of the river (the river source point is set on the mouth of Ciliwung River) assuming constant all the year with the river discharge in the Jakarta Bay on scenario 1 (normal condition) overlapped with the vector of current in four representative Monsoons.
Figure 10. Passive tracer movement pattern of the river (the river source point is set on the mouth of Ciliwung River) assuming constant all the year with the river discharge in the Jakarta Bay on scenario 2 (modified reclamation condition) overlapped with the vector of current in four representative Monsoons.

Figure 11. Passive tracer movement pattern of the river (the river source point is set on the mouth of Ciliwung River) assuming constant all the year with the river discharge in the Jakarta Bay on scenario 3 (reclamation with GSW blueprint) overlapped with the vector of current in four representative Monsoons.

4. Conclusion
Current circulation pattern in Jakarta Bay varies Monsoonly. Zonal component dominates the current movement of the scheme. Current circulation pattern simulation in scenario 1 (normal condition) shows that the water flows freely through the side of western or eastern of the cape. However, scenario 2 (GSW
reclamation modified) shows that the water flow enters through the side of the cape and is divided and flowed through the channels. On each channel, there are slits where current intensification occurs and develops an eddy.

The highest magnitude of currents occurs in the West Monsoon where the water flows eastward for scenario 1 and scenario 2. The pattern of currents in scenario 3 (in accordance with GSW reclamation) appears complex, isolated, and weaker than scenario 1 and 2 (almost no intensification of currents).

The presence of the reclamation (scenario 2) also leads to the formation of eddy due to current intensification. Moreover, eddy formation is caused by the current intensification and reclamation configuration forms a shape of ‘Garuda bird’. On the results of passive tracer in the river input, the discharge is influenced by current circulation pattern and in scenario 2, it moves relatively faster than scenario 1 and scenario 3.

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