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Study on water mass exchange at Ambon Bay using trajectory model: circulation of one tidal cycle

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Abstract. Ambon Bay is divided into two parts, Inner Ambon Bay (IAB) and Outer Ambon Bay (OAB) which separated by 10 m narrow canal called sill. It causes IAB and OAB has different water dynamics. Generally, circulation dynamics at Ambon Bay affected by upwelling process in the Banda Sea during southeast monsoon. During that period, tidal upwelling brought high-density water from thermocline layer in OAB to surface and enter the IAB. The mechanism of water mass exchange can be described using a three-dimensional trajectory model which evaluate the origin and movement of water particles. The particle movement during one tidal cycle based on model results are observed. Verification result shows that the model error is 2.32%. After one tidal cycle, particles predominantly move to OAB rather than enter IAB through the western side of the sill.

1. Introduction

Ambon Bay has unique geographical conditions where there is 10 m sill that divides the bay into two parts, Outer Ambon Bay (OAB) and Inner Ambon Bay (IAB) [1]. The sill causes both bays to have different water dynamics. Water circulation in IAB is relatively closed that causes the waste that goes into it would be trapped inside near the sill [2]. One of the factors that affect the circulation in Ambon Bay is upwelling process in the Banda Sea during southeast monsoon. During that period, water mass exchange in Ambon Bay is the most actively occurred [3, 4].

Study on water dynamics of Ambon Bay has been conducted by Wenno and Anderson (1984) [1]. The result stated that the current circulation in the bay predominantly driven by tides. In addition to tides, the current is also driven by density gradient based on the study of Corvianawatie (2014) using three-dimensional hydrodynamic model [5]. The vertical density profile shows that there was a denser water in OAB that moved to IAB during flood tide. When ebb tide, it moved back to OAB, but the small portion of it was left behind in IAB. However, the process of water mass exchange between OAB and IAB could not be explained only by the density profile. The path and source of water mass can be identified using the trajectory model that reviewed the origin and movement of water particles.

2. Methodology

2.1. Trajectory model principle

The principle of the trajectory model is based on the Lagrange approach. In this approach, the measured parameter is the particle displacement, because the position of a particle is a function of time [6]. Particle displacement is formulated as follows [6]:

$$x(t + dt) = x(t) + u \cdot dt$$
$$y(t + dt) = y(t) + v \cdot dt \qquad (1)$$
$$z(t + dt) = z(t) + w \cdot dt$$

Where x, y, and z denote the position of a particle in west-east, south-north, and vertical (depth) direction, u, v, and w symbol show particles velocity. The equation above stated that particles position at time $t+dt$ is obtained from the particle position at t plus the particle displacement during dt (time interval).

2.2. Model design and input

Three-dimensional trajectory model used in this study was adapted from Kampf (2010) [7]. It is a baroclinic model which built in Arakawa C grid system [5, 7]. Simulation of particle transport (trajectory) 3D was covered Ambon Bay area at 128.12°-128.24° E and 3.63°-3.68° S. The model area in x and y-direction has a length of 13.98 km and 6.66 km respectively. Model domain is divided into 63 and 30 grid in x and y-direction respectively and 222 m x 222 m of horizontal resolution [5]. The depth was divided into 20 layers with varying of grid size [5]. The simulation was performed using time interval of 60 seconds for 24 hours at neap (August 13, 2008) and spring tide (August 25, 2008).

At the initial condition, 4948 particles are placed in each grid of the model domain. Moreover, for the boundary condition, the closed boundary was applied. If particles reach the mainland, its velocity became zero. On the other hand, if particles move out of the model domain through the open boundary, then specific conditions are applied. If at time step n+1 particle position exceeds the model domain, the position of it will be returned to the position at n.

The input data for 3D (three-dimensional) trajectory model is current velocity i.e. u, v, and w which obtained from 3D hydrodynamics model conducted by Corvianawatie (2014) [5]. The driving forces of the hydrodynamics model were tides and seawater density gradient. Tides input was derived from TMD (Tide Model Driver) which consists of 8 tidal component, i.e. M2, S2, K1, O1, N2, P1, K2, and Q1. Momentum equation used in the model was consist of local and convective acceleration, pressure gradient force, and viscus force, while Coriolis acceleration and river discharge are neglected. In addition to that, the hydrodynamic model is also assimilated with density data from observation at two points every 24 hours [5]. Current velocity every 2 hours obtained from hydrodynamics model was used as input of trajectory model which it was linearly interpolated every simulation time step. The particle movements only drive by advection process, while the diffusion process was neglected.

3. Results and analysis

3.1. Model verification

Model verification was done using a mathematical method. Drifting distance of three particles during 24 hours based on model results are compared with the manual calculation from current velocity. The model error is obtained by calculating the RMSE (Root Mean Square Error) and divided by the total drifting distance of model results as shown in Table 1.

**Table 1.** Model error based on mathematical verification.

Particle	Initial location	Error (%)
1	128.143° E and 3.676° S	1.44
2	128.183° E and 3.676° S	2.54
3	128.193° E and 3.660° S	2.99

On the other hand, verification results of particle 2 indicate that drifting distance obtained from the model is smaller than calculation. In contrast with particle 2, the drifting distance of particle 3 from

the model is larger than manual calculation. Error model of particle 2 is 2.54%, while particle 3 is 2.99%. Based on verification results, it can be concluded that model calculation tends to overestimate the drifting distance with an average error of 2.32%.

3.2. Tides in Ambon Bay

Tide is the dominant driving force of current in Ambon Bay [8]. Based on previous studies, tidal type in Ambon Bay is mixed predominantly semidiurnal with a dominant component of M2. According to Stewart (2008), the period of semidiurnal tidal component M2 is around 12 hours 25.24 minutes [9]. Based on the period, it takes about 24 hours 50.47 minutes to produce 1 semidiurnal tidal cycles (2 times of high water and 2 times of low water) as shown in Figure 1. The graph in Figure 1 shows that in spring condition, it takes around 25 hours to produce one complete tidal cycle. On the contrary, at neap tide, the tidal cycle tend to be diurnal (1 time of high and 1 time of low water) as shown in Figure 1.
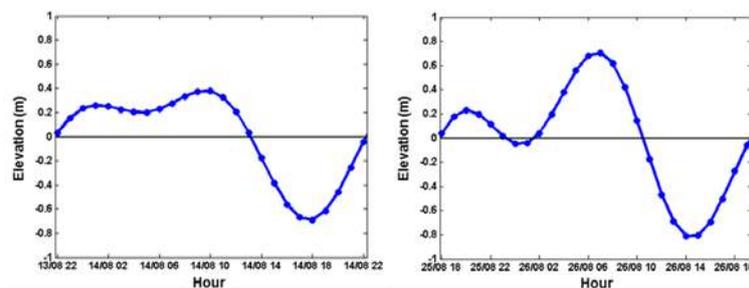
Figure 1. Tides elevation at neap (left) and spring (right) condition obtained from hydrodynamics model.

3.3. Particle trajectory on one tidal cycle

Effect of daily tidal pattern to water mass transport in Ambon Bay can be described by the particle movement during one tidal cycle of neap and spring tide. Simulation result for one neap tidal cycle in August 2008 shows that particles in OAB spread to west and east. The particle from eastern OAB (red) spread to west and east side, while particle from western OAB (orange) dominantly moved to the southwest side. On the contrary, particle in eastern IAB tends to remain in its original position (Figure 2).
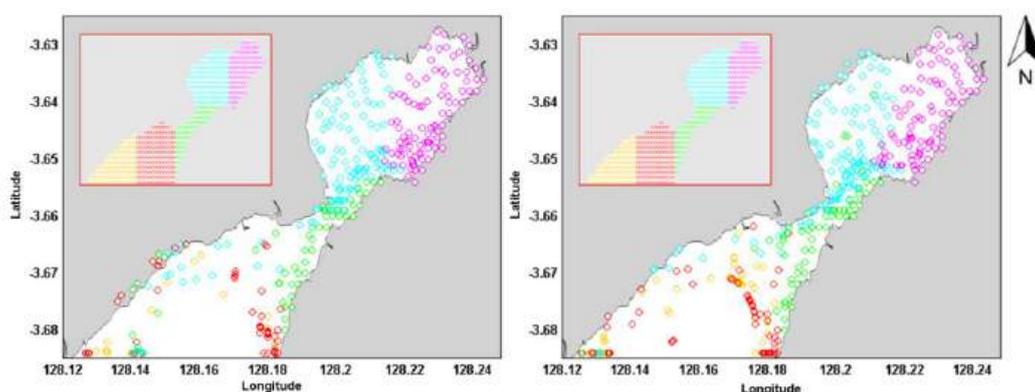

Figure 2. Surface particles distribution after one tidal cycle simulation when neap (left) and spring (right) condition. Initial position of particles shown in red box.

In spring condition, it appears that the particles from eastern OAB (red) spread to west and east side (Figure 2). Similar to them, particles from western OAB (orange) also spread to the west and east side of the bay. Moreover, particles from the sill (green) tend to congregate on the east side which small portion of it entered IAB. Different from OAB, particles from IAB tend to remain inside the bay.

There are some of the particles from western IAB (light blue) which move out to OAB, whereas particles from the eastern side (purple) remain in IAB. These conditions show that circulation in IAB tend to be isolated so that the particles are difficult to pass through the sill.

In order to investigate the circulation pattern in Ambon Bay, the path-lines of five particles were observed. Two particles were released at IAB, two at OAB, and one particle at narrow canal (sill). After one neap tidal cycle, particles at IAB (purple and light blue) move to southwest with average current magnitude of 0.02 m/s and 0.045 m/s respectively. Particles at eastern OAB (red) also move to southwest with an average current magnitude of 0.13 m/s. On the other hand, the particle at sill (green) move to the southwest and then turned back into IAB with average current magnitude of 0.024 m/s (Figure 3).
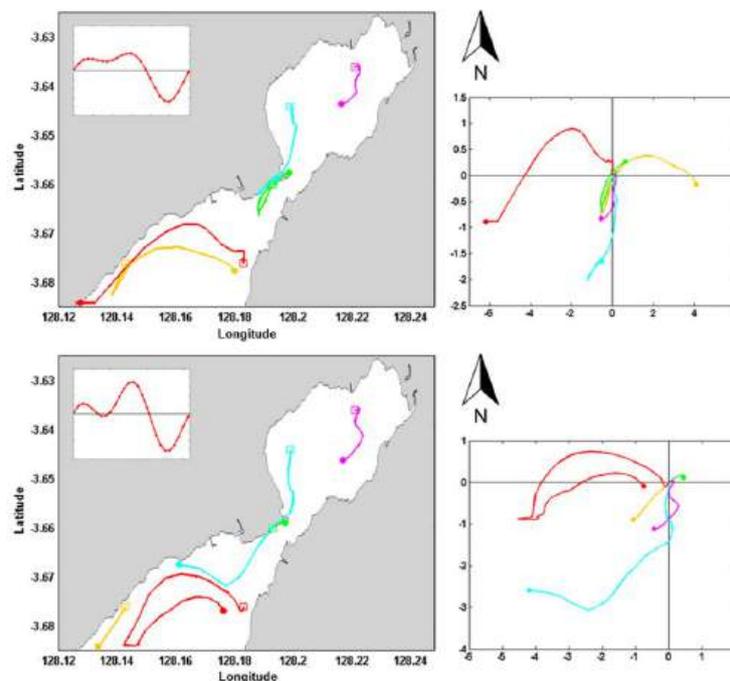
Figure 3. Surface particle path-lines (left) and tracking graph (right) after one tidal cycle simulation when neap (above) and spring (below) condition. Square and dot symbols show initial and final position; *x* and *y*-axis show west-east and south-north direction in kilometers.

Different path-lines pattern were found in spring condition. Almost all of five particles move to the southwest on one spring tidal cycle as shown in Figure 3. Based on the graph, four of the particles movement did not create the closed path. The near-closed path was found in particle from eastern OAB (red) which move to the west and then turned back to its starting point. Based on the path-lines pattern, it appears that the entrance and exit way of particles from IAB in through the western side of narrow canal or sill.

Tidal type when the neap condition tends to be diurnal where there is one time of high and low water. Theoretically, these tidal type will produce a tidal stream leading to the bay when flood and coming out the bay when ebb tide [8]. It will cause the particles to move into the bay when flood and out the bay when ebb, so that create a closed path-line. However, this pattern could not be seen from particles path-lines either in neap and spring tide in August 2008. It could be caused by diurnal inequality of tides. The diurnal inequality means that the duration of flood and ebb tides are different. Furthermore, it can be seen that flood and ebb tide duration in spring condition relatively equal

compared to the neap condition because the near-closed path-line was found in the spring tide. The drifting distance of particles when spring tide also further than neap condition, because current velocity is faster in spring than neap.

In addition to tides, the morphology of the bay also affected the particle movement, particularly at OAB. When flood tide, particles from OAB are difficult to enter the IAB because the narrow canal or sill obstruct their movement. The particles will be deflected back to OAB as shown in path-line of particle orange and red.

4. Conclusion
Verification results show that an average model error is 2.32%. Either on one neap and spring tidal cycle, surface particles dominantly move from inner bay to outer bay through the western side of the sill. It also can be seen from the surface particles path-lines that the drifting distance when spring is further than the neap tide.

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