Seasonally volume, heat, salt and freshwater transports within Balikpapan Bay to Makassar Strait

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Abstract. Study about water mass transport within Balikpapan Bay (BB) is crucial since many watersheds discharge from this bay which directly flows into Makassar Strait. To understand transport of water mass within BB, INDESO data was made monthly in 2015. The annual volume, heat, salt and freshwater transport are estimated to be 18.02 mSv, 2.14 PW, 0.64 x 10⁹ kgs⁻¹, and 1.05 mSv, respectively. Compared to the annual mean volume transport of Makassar Strait (6.4 Sv), the annual transport of water mass from BB is likely contribute less amount of volume and heat transport with the weighted-transport temperature at 30.37 °C. They are somewhat smaller than the difference between each season. This difference may be attributed by the external force, i.e. current circulation and tidal wave, as well as the precipitation along BB.

1. Introduction
Balikpapan Bay (BB) waters is semi-enclosed bay which directly flows into Makassar Strait and located between Balikpapan city and Penajam Paser Utara municipal, Eastern Kalimantan Indonesia. This bay connects many cities around Kalimantan as trade-route or passages as well. About 54 watersheds, with the area within 211,456 Ha [44], flow out through the bay mouth [3][19]. Freshwater mass coming from river discharge and saline water are two main parameters which control the estuarine environment and its ecosystem [14]. Tidal force will affect seawater with different frequency rely on its affair [5]. In flood time, saline water reaches into the bay head shortly at certain distance. Hence, the bay waters will flow into the off-sea during ebb time [18][42]. Runoff river, which characterized by low saline water, may accumulate nutrient into the bay mouth and distribute it in the broader ocean system. Freshwater and seawater interaction can be described properly by understanding the behavior of low saline water (LSW), studied previously by [22][24][36].

Freshwater transport is necessary for large-scale seawater processes since it provides LSW which causes modification at density water [39]. Modest processes for instance meso-scale swirl, heat and salt diffusion may affect the large-scale of oceanographic circulation as well, for instance global eddies [20], internal mixing [35], and exchange flow [26][27]. In some cases, this prevailing transport can explain the dawning and shifting water masses, i.e. the Barents Sea [28], the Yellow and East China Seas [29], and the Black Sea [37].

Recently, research about transport of freshwater has been conducted secondly by [48] in Pelabuhan Ratu Bay using freshwater fraction estimation, and [13] in Delta Mahakam East Kalimantan utilizing box model analysis. More specific in BB site, several researches have been studied, for example related
to the heat expansion activities [31], and water mass dynamics [25]. However, [25] is limited to high and low tides dynamics only. Hence, longer temporal study is required to find out its affect accordingly.

So far, the observation-based on volume transport estimation in BB has not been conducted yet. Since this bay connects directly into Makassar Strait, it is crucial to figure out water mass transport which contribute into the strait. It will be described in this paper which its objective is to understand the seasonal variability of water mass by analyzing the volume transport of heat, salt and freshwater as well as its contribution to the Makassar Strait.

2. Observation

This research was made in 2015 utilized Infrastructure Development of Space Oceanography (INDESO) data model handled by the Indonesian Ministry of Maritime Affairs and Fisheries. This model provided meteorological, biogeochemical, and physical ocean data which can be download openly in the INDESO website (http://www.indeso.web.id) [15]. Figure 1(a) shows the bottom topography and river discharge within BB [3][6]. Hence, study site with broader domain with 116.5-117.5 E to 1.0-2.0 LS is desired to describe the seasonal water mass transport within BB, see Fig. 1(b). Three stations data which aim to analyze volume, heat, salt and freshwater transport are located within the bay mouth. The two stations data consist of INDESO and CTD (Conductivity Temperature Depth) are obtained to validate the data model. The distance between field data to model data is about 42.48 km.

Figure 1. Study site and bathymetry of Balikpapan Bay (a), INDESO model domain (b).

The volume transport within BB can be evaluated using prescription of [7], where $dA$ is the area of one section (m$^2$) and $u$ is average current (ms$^{-1}$), see eq. (1).
The total transport of heat and salt, \( F_H \) and \( F_S \) respectively, can be calculated from equation (2) and (3) \([7]\). Since INDESO data does not provide the water density data, \( \rho \) (kg m\(^{-3}\)), then it will be calculated using \([10]\) which expressed in terms of pressure \( p \) (in bars), temperature \( T \) (in °C), and practical salinity \( S \). The specific heat, \( C_p \) (J m\(^{-3}\)K\(^{-1}\)), is calculated in two stages by \([10]\) as well. The reference temperature, \( T_0 \), is 3.72 °C adopted by \([33]\).

\[
F_H = \rho C_p \int_A (T - T_0) udA \tag{2}
\]

\[
F_S = \rho \int_A S udA \tag{3}
\]

The relationship between mean transport along the section and temperature profiles can be occupied by the weighted-transport temperature \([40]\). Using equation (1) and (2), a weighted-transport temperature, \( T_T \), can be calculated in equation (4) \([7]\).

\[
T_T = F_H (\rho C_p F_V)^{-1} + T_0
\]

Freshwater analysis used were salinity anomaly \( S'(x,z) \), freshwater fraction \( F_r \), and volume transport of freshwater \( F_W \) \([2][9][24][48]\).

\[
F(x,z) = \frac{S_{ref}(z) - S(x,z)}{S_{ref}(z)} \tag{4}
\]

\[
F_r = \frac{1}{h} \int_0^h \frac{S_{ref} - S}{S_{ref}} dz \tag{5}
\]

\[
F_W = \int_A F_r u dA \tag{6}
\]

\( F(x,z) \) is freshwater fraction, \( S_{ref}(z) \) is reference salinity at the depth \( z \) (PSU), \( S(x,z) \) is salinity value at station \( x \) depth \( z \) (PSU). \( F_r \) defined as average value of freshwater fraction along the section, whilst the \( h \) defined as depth of the water column. Reference salinity obtained by adding 0.1 PSU to the highest salinity value observed at station \([30]\). The amount of reference salinity by this research is 34.38 PSU. Freshwater region defined by anomaly salinity which has value less than zero \([48]\). The area of freshwater in this section is about 1.71 x 105 m\(^2\) with 27.75 km length and 18.49 m depth.

In order to validate the data model, root mean square error (RMSE) is applied \([34]\). Figure 2 shows vertically section salinity obtained by model and observation near bay mouth. The number of RMSE result in 2.53 PSU which denoted the average residual number of both. This residual number belongs to extensive since INDESO model singly inputs river discharge which impactful on the physical and biogeochemical through Indonesian waters \([12][41]\). Hence, Balikpapan waters is strongly influenced by watersheds along East Kalimantan land \([16]\). The distance between both stations which range sufficiently may overcome hefty residual value as well. Yet model data is reasonably since the residual number is less than monthly range salinity, depicted at 4.50 PSU.
3. Result and discussion

3.1. Properties of LSW and sea surface current pattern

In order to investigate water mass transport, the properties of LSW and current pattern along BB waters are needed. LSW can be delineated by sea surface temperature occupied in the study area. Based on the anomaly salinity defined by [2][7][9][24], LSW in BB has salinity value less than 34.25 PSU. This value assumed that seawater does not induce by freshwater which its value is nearly to the Makassar Straits salinity waters ranged at 34.48-34.70 PSU [38]. Figure 3 shows the monthly-average surface salinity overlay with surface current at 0-5 m depth. The region of LSW is variable every season which lying about 29 to 157 km. This number is estimated by the length of 34.25-PSU-salinity or less, souring from the bay mouth. Balikpapan waters generally experience two-main-different seasons, for instance northeast monsoon and southwest monsoon. Both monsoons invade from December to February (DJF) and June to August (JJA) respectively [1].

The vastest number was observed in the northeast monsoon showed by DJF. LSW occupied at around 157 km with salinity variance 31.00- 32.75 PSU. These features are distantly away originating from watersheds along east Balikpapan land and Mahakam Delta which run over Makassar Straits. The average precipitation in DJF depicted 143 mm/month (Fig. 6). As the result of heavy rain-producing, this prevailing leads to LSW lengthy in this season. In northern hemisphere winter (DJF), monsoon wind blows from Siberia region toward Australian continent [17], this convective activity remains the current pattern tend to flow from northeast direction toward southeast with average current 13.50 cms⁻¹.

LSW flowed out from BB is considered less-extend during southwest monsoon. During this period, the surface salinity dominant to saline compared to the northeast monsoon attempted just around 31.00-34.25 PSU. Saline water sways from Makassar Straits relatively higher throughout JJA which ranged at 34.66-34.68 PSU [38]. Strong current averages at about 16.45 cms⁻¹ that flow from southwest toward northwest overcome the Makassar Straits waters induces the bay area accordingly.

The LSW decreases at an average 32 km gradually from June to October. This pattern followed by rain-intensity which decline considerably every month as well (Fig. 6). There exists a distinct-LSW which none of precipitation found in September though the LSW denoted at 66 km in distance. Hence, October’s event shows contradictory. Ocean current and tidal strain may affect these existence [4][23]. The average current on September and October depicted 19.72 cms⁻¹ and 10.61 cms⁻¹ respectively (Table 2). Tidal type in BB categorized as mix-tide prevailing semi-diurnal tide which has 4-6 hours phase period [25].
3.2. Salinity variance

The two-distinct-stations are obtained from the bay mouth and off-sea denoted by S02 and S-Ref, respectively. Each station estimates monthly surface salinity at 0-5 m depth. These two-difference station aim to describe LSW effect to the area which located near (S02) and far (S-Ref) off the bay, about 157 km away. Figure 5 shows sea surface salinity variance between S02 and S-Ref derived from INDESO data model. Generally, the salinity near the bay mouth has lower than off-sea about 1.23 PSU which fluctuates each month, i.e. lowest in May and striking incline into October. This occasion retained by plunging rainfall about 68.16 mm/month (Table 2). Precipitation can enhance the coastal region such BB by contributing freshwater at the coast through runoff [32].

On the contrast, salinity at the area miles away from the bay looks like more stable during the year. The variance is just about 1.82 PSU with changing rate average salinity denoted at 0.33 PSU/month. [47] cited that major constraint affect salinity in the ocean are river runoff, precipitation, evaporation, and geographical structure of the region. Hence, precipitation and river runoff are dominant in Balikpapan waters due to many watersheds leak out from this bay, for instance Semoi R., Riko R., Wain R., Sepaku R., and many more. These rivers cover 15.994 Ha (1 Ha = 10,000 m²) associated with 54 watersheds [6]. As following recital, S-Ref located far away from the bay, so that the LSW is just a bit induce this region compared to S02. Therefore, Makassar Strait waters influences S-Ref the most.
3.3. The total volume of heat and salt shipment within the bay mouth

In this study, volume, heat, salt and freshwater transport of water mass was estimated by using method [7]. Table 1 depicts annual volume, heat, salt and freshwater transport during year 2015. In general, the annual volume transport of water mass which flows out from the BB is 18.02 mSv (1 mSv = 10^3 m^3 s^-1). This prevailing number is much smaller compared to annual mean depth-integrated transport of Makassar Strait which observed about 6.4 Sv (1 Sv = 10^6 m^3 s^-1) [45]. Therefore, heat and salt transport were 2.14 PW and 0.64 x 10^9 kg s^-1 respectively with the weighted-transport temperature 30.37 °C.

Then, monthly analysis was also defined to understanding its seasonal feature. Heat and salt transport within the bay mouth are broadly following the pattern of current velocity as well as its volume transport. Figure 5 shows volume, heat, and salt transport of water mass monthly within the bay mouth. During the northeast monsoon, the highest water mass transport is found in either heat or salt transport. The average transport of heat and salt depicts at around 0.23 PW and 0.06 x 10^9 kg s^-1 respectively. Following the volume transport pattern, both are similar. In this season, current velocity is likely affect the water mass transport at average 22.37 cms^-1.

Conversely, a decreasing transport of heat and salt may occur on the southwest monsoon to the second transitional season. Its monthly declining average is -0.04 PW and -0.014 x 10^9 kg s^-1 for heat and salt export respectively. The mean velocity denotes at average 15.10 cms^-1. At the outside of the bay, the southwest current pattern flows stronger compare to the northeast monsoon ones, see Fig. 3. This is likely affect the transport of salt and heat from the bay as well.

By considering previous study [13] in Delta Makaham which located near to BB, the monthly salt budget is about 7.53 x 10^9 PSU day^-1. The salt transport in BB is expected to twentyfold of Mahakam River. The semi-enclosed bay is one of the reasons this bay has extensive salt transport compare to Mahakam Delta. The hydrodynamic regime of semi-enclosed estuaries, i.e. BB, is as a result of various components for instance the tides, wind stress, as well as the freshwater and seawater interaction [46]. In addition, the area of box model utilized by [13] may cover the southern part of the delta only.

Table 1. The amount of annual volume, heat, salt, and freshwater transports during 2015^a:

| Volume Transport (mSv) | Heat Transport (PW) | Salt Transport (kg s^-1) | Freshwater Transport (mSv) | Weighted-Transport Temperature (°C) |
|------------------------|---------------------|--------------------------|---------------------------|-----------------------------------|
| Estimate               | 18.02               | 2.14                     | 0.64 x 10^9               | 1.05                              | 30.37                             |

^a the reference temperature of 3.72 °C and salinity of 34.38 is applied, respectively. The data were calculated from INDESO data on S01-S03.
3.4. Volume transport of freshwater

The volume transport of freshwater (VTF) through Balikpapan waters, $F_W$, can be approximated using the formula by [2, 9, 48]. Freshwater fraction (FF) is desired to express the relative impact of fresh and salt-water source. Thus the value of FF is the fraction of fresh (zero salinity) water that would need to be mixed with the sea water source in order to produce the observed salinity [30]. According to equation (4) to (6), it can be seen the mean VTF, FF as well as current velocity as Table 2. On average, the FF in this bay adheres to the rainfall pattern (Figure 6), i.e. June to October event relatively drop off with 1.50 %/month, whilst the rainfall declining as well. This incident is vigorously delimited by freshwater input from river discharge and rainfall in the bay waters [11].

During northeast monsoon to the first transition season, DJF-MAM, the average velocity is less swiftly compared to the southwest monsoon to the second transition ones. Its mean-deviation detailed just about 4.84 cms$^{-1}$ under the others. On the contrarily, the precipitation is slightly dominant during this period with a half times higher than JJA-SON. This prevailing due to BB has equatorial type of rain-producing [43], which consequence short-term of dry-season around JJA-SON as well as extensive wet-season. Hence, both current velocity and precipitation will affect the amount of VTF. For instance, VTF during wet-season (DJF-MAM) depicts at average 121.66 m$^3$s$^{-1}$ which greater than the dry-season ones just about 53.75 m$^3$s$^{-1}$. It can be seen that rainfall alter largely this bay with 150.38 mm/month. Since the velocity variance is insufficient, it may be effect to the VTF limitedly during this period. This strongly witnessed by [8] which revealed that VTF in the bay mouth is heavily influenced by precipitation and current velocity.

By looking more detail from the previous section, the VTF, FF, current velocity as well as rainfall play an important role to the LSW distribution within the bay seasonally. There exists shorty LSW followed by lower VTF, FF, and rainfall, i.e. during dry season. In this season, the LSW distribution
just averages at around 139.48 km with mean VTF, FF, and RF describes 53.75 m$^3$s$^{-1}$, 2.98 %, 106.85 mm/month respectively. Thus following number is below than the wet-season ones. Similar occasion will be found in the wet season which disclose the lengthy LSW consistent with vast VTF, FF, and rainfall as well.

Table 2. Monthly current velocity, freshwater fraction, and volume transport of freshwater within Balikpapan Bay$^b$.

| Month   | Average current velocity (cms$^{-1}$) | Freshwater fraction (%) | Volume transport of freshwater (m$^3$s$^{-1}$) |
|---------|--------------------------------------|-------------------------|-----------------------------------------------|
| January | 11.30                                | 5.68                    | 71.87                                         |
| February| 27.32                                | 6.26                    | 185.18                                        |
| March   | 28.52                                | 5.58                    | 187.44                                        |
| April   | 16.21                                | 5.71                    | 113.09                                        |
| May     | 16.40                                | 7.22                    | 135.52                                        |
| June    | 18.90                                | 6.54                    | 136.48                                        |
| July    | 20.22                                | 4.65                    | 98.08                                         |
| August  | 18.96                                | 2.55                    | 51.46                                         |
| September| 19.72                          | 1.37                    | 26.34                                         |
| October | 10.61                                | 0.52                    | 4.03                                          |
| November| 2.23                                 | 2.22                    | 6.12                                          |
| December| 8.62                                 | 3.63                    | 36.84                                         |

$^b$ the current velocity, freshwater fraction, and volume transport of freshwater were estimated from INDESO data on S01-S03.

Figure 6. Volume transport of freshwater ($F_W$), rainfall (RF) and mean-current velocity within Balikpapan Bay waters visualized from Table 2. RF data were made from meteorological dataset [21] at Sepinggan Station, Balikpapan.
4. Conclusion
In an analysis of water mass transport within Balikpapan Bay, the yearly-average transport of volume, heat, salt and freshwater estimate to be 18.02 mSv, 2.14 PW, 0.64 x 10^9 kg s\(^{-1}\), and 1.05 mSv respectively. The seasonal amount of Balikpapan waters transport is somewhat smaller compare to the other season. Nevertheless, they mostly reflect to the current pattern along the year. This particular is likely ascribed by the external force, such as current circulation and tidal wave, as well as rainfall within the bay.

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