Wind driven circulation in Makassar Strait during monsoon 2017

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Abstract. The Makassar Strait (MS) connects the Pacific Ocean and Indonesia Waters via the Indonesia throughflow system. The flow varies because MS is also influenced by the monsoon. To determine the monsoon effect, we applied the two-dimensional numerical model with 6 hourly wind data. It was used to predict the MS current circulation during February, April, August, and October. According to recent studies, the results showed a good verification. The currents in the MS were dominated from the north of MS. The currents moved to the south of MS but sometimes deflected to the north. The currents were stronger during August and weaker during February. In August, the current from the north of MS moved to the south of MS, and it was partly deflected toward the north around Sulawesi Island. There was also the current from the south of MS directed toward the north. While in February, the current around Kalimantan Island was always to the south of MS. Based on the results, the MS currents were dominated by the currents from the north of MS or the Pacific Ocean.

1. Introduction
The Makassar Strait (MS) separates Kalimantan Island and Sulawesi Island. The strait is also included in the Indonesian throughflow (ITF) system that connects the Pacific Ocean and the Indian Ocean [1]. This strait is highly influenced by turbulent mixing as a confluence region of different water masses, such as salty Pacific water and fresh Java Sea water [2]. The pattern of currents in the Makassar Strait is dominated by the mass of water from the Pacific Ocean but drastically changes to the much fresher water in the south of the Makassar Strait [3, 4].

MS is influenced by monsoon especially south of the Makassar Strait. It is directed towards Asia in the boreal summer from July to September and towards Australia in the boreal winter from January to March [5, 6]. The monsoon which is very carefully related to wind has a significant influence on current circulation formation [7], although the effect of bottom friction is having a significant impact [8]. Southeast monsoon (SEM) in Makassar Strait has a substantial effect so that several marine physical formations such as upwelling [9]. Northwest monsoon also influences wave heights and flow
patterns, while the transition period is not influenced by monsoon but is influenced by the Kelvin wave propagation phenomenon from Lombok Strait [10].

The 2D hydrodynamic model has been widely used in previous studies. Areas with extreme current speed could use this model because it was more affordable analysis method at the continental shelf region [11]. As another motivation, monsoon data and flows were useful information for development and research [12]. This study adopted a Navier-Stoke model that was modified by the addition of the effect of wind friction [13, 14, 15]. Based on that motivations, this study aimed to explain physical events that were affected by wind in 2017.

2. Materials and Methods
The research domain is located in the Makassar Strait at coordinates 116° - 120° E and -3° - 1° N. Bathymetry of the research domain can be seen in Figure 1. Wind data obtained from the National Centers of Environmental Prediction NCEP throughout 2017 and bathymetry obtained from the data Shuttle Radar Topography Mission with 30 minutes resolution SRTM30 [8].

![Figure 1. Batimetri of Makassar strait](image)

This study used the Navier-Stoke equation to obtain a numerical solution for horizontal velocity u and v. This equation has previously been used successfully in current simulations of Aceh Waters [16, 17], Sabang Waters [18,19], ocean currents in the Malacca Strait, South China Sea, and Gulf of Thailand which were affected by wind [8, 14]. The system used differential equation as followed [13]:

\[
\frac{\partial u}{\partial t} + \text{Adv}_h(u) - fu = -g \frac{\partial \eta}{\partial x} + \frac{\tau^\text{wind}}{\rho \eta h} + \text{Diff}_h(u) \tag{1}
\]

\[
\frac{\partial v}{\partial t} + \text{Adv}_h(v) + fu = -g \frac{\partial \eta}{\partial y} + \frac{\tau^\text{wind}}{\rho \eta h} + \text{Diff}_h(v) \tag{2}
\]

\[
\frac{\partial \eta}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0 \tag{3}
\]

where \(u\) and \(v\) are currents velocity in zonal and meridional term, \(\rho\) is sea water density, \(\eta\) is sea level elevation, and \(h\) is total depth added to sea elevation. The parameters used are \(f\) as the Coriolis parameter and \(\tau\) as a friction effect. Seafloor friction \(\tau^\text{bot}\) changed based on location and wind friction \(\tau^\text{wind}\) changed every six hours.
3. Results and Discussion

The average wind circulation on February 2017 in the Makassar strait was shown in Figure 2 (a). The wind was dominated from north to south with an average wind speed of 2 m/s. The wind from Kalimantan urged the wind coming from the north, and both of them moved to the southeast of the Makassar Strait.

![Figure 2. The results for February 2017, (a) Monthly wind circulation at 10 m height (m/s) (b) Monthly sea level (m) and current circulation (m/s)](image)

Ocean flow circulation in February was shown in Figure 2 (b). The current in the Makassar strait waters moved from north to south, and the speed of the currents in the south was influenced by the Indonesian flow system. Flow along the coastline of the island of Borneo tend to be parallel to the coastline except in the southern part of the domain. In this part, it was deflected south towards the Java Sea.

![Figure 3. The results for April 2017, (a) Monthly wind circulation at 10 m height (m/s) (b) Monthly sea level (m) and current circulation (m/s)](image)

The average wind circulation on April 2017 in the Makassar strait waters was shown in Figure 3(a). The wind was dominated from the north which was deflected to the southeast toward the island of Sulawesi with an average speed of 2 m/s. Figure 3 (b) showed ocean currents moving fast from north to south of the domain. Flow along the coastline of the island of Borneo tend to be parallel to the
coastline except in the southern part of the domain. In this section, the current was deflected to the south.

![Figure 4](image1.png)

**Figure 4.** The results for August 2017, (a) Monthly wind circulation at 10 m height (m/s) (b) Monthly sea level (m) and current circulation (m/s)

The average wind circulation on August 2017 in the Makassar strait waters was shown in Figure 4 (a). Winds in the southern part of the Makassar Strait were generally southeast. The wind turn to the south wind when it reached the middle and north parts of the Makassar Strait. Wind speed in the south was faster compared to the north. Current circulation was shown in Figure 4 (b). The current moved fast from north to south. Some of the currents were deflected north around the island of Sulawesi. Others were continued to the south. The north and south currents meet in the middle so that they bend each other.

![Figure 5](image2.png)

**Figure 5.** The results for October 2017, (a) Monthly wind circulation at 10 m height (m/s) (b) Monthly sea level (m) and current circulation (m/s)

The average wind circulation on October 2017 in the Makassar strait waters was shown in Figure 5(a). The wind was dominated from the southwest which moved towards the north of the Makassar Strait. Wind speed in the south was faster compared to the north. Current circulation was shown in
Figure 5(b). The current moved from north to south, and some of the currents were deflected north around the island of Sulawesi. Others were continued to the south. The north and south currents meet in the middle so that they bend each other.

The simulation was carried out by taking four months and comparing it with previous research. Based on wind direction and magnitude at four simulation times, the circulation of currents in the MS was in accordance with previous studies [3] and become a benchmark for verification. Current circulation was strongly influenced by wind, February and April wind directed currents from north to south, and August and October wind carried fresh water circulation from the Java Sea into the MS. Sea level data also showed that sea level was relatively high in April, August and October. This height was caused by the mass of water entering the MS from the Pacific Ocean on April and the Java Sea on August and October.

4. Conclusions
The results of circulating Makassar Strait (MS) during February, April, August, and October were consistent with previous studies [3]. Directions and magnitudes showed good verification, but this study offered a more accurate resolution. Currents in MS predominantly from the north MS then moved to south but was sometimes deflected north. Stronger currents during August and weaker during February. On August, the currents from north MS moved to the south of MS and partially veered north around the west coast of Sulawesi Island. There was also a current from south MS which was directed north. While on February, the currents around the east coast of Kalimantan Island always head south to MS.

Based on the results, MS flows were dominated by currents from north MS or the Pacific Ocean. Wind could only slow or strengthen the flow of the Pacific Ocean towards the Java Sea.

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