Climatological oceanic-driven upwelling in the Western North Sumatera Waters using INDESO (2008-2014)

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Abstract. It is widely known that during upwelling feature, two different water-masses exchange simultaneously, on the one side surface warm-water mass sink downward and on the other side, deep cold-water-mass rise toward the surface which also bring demanded nutrients upward that may further locate areas of rich in marine productivity. Western North Sumatera Waters (WNSW) is considered as potential upwelling zones in Western and Northern Provinces of Sumatera. However, studies on upwelling as well as its physical mechanisms associated with ocean-atmosphere interaction that might govern the upwelling system in the region is yet to perform. A three-dimensional numerical model outputs are utilized in the present research to address the emergence of upwelling feature throughout the WNSW. The purpose of the research are to identify the thermal front associated with cyclonic and anti-cyclonic eddies.

1. Introduction
Circulation and characteristics of water mass movement both spatially (horizontal and vertical) and temporally leading to upwelling dynamics in the Western North Sumatera Waters (WNSW) up to now is yet to be well-documented and keep a continuous argued-hypothesis. The only reports of possible upwelling occurrences at WNSW which extend up to the Andaman Sea were traced by old manuscripts described by Wyrtki [1] and Nontji [2] which still under assumptions. Seasonal ocean modelling study on general circulation covering the WNSW has been performed however due to coarse model resolution, surface current pattern indicating the potential upwelling zone leading to fishing ground is not well-identified yet [3, 4]. Many studies found that seasonal surface wind circulation play a major role in driving the upwelling evolution in many sea regions [5, 6, 7].

A low-cost way to observe the front movement is by performing a model. Model offer an overview of the study site that mimic to the situation in the field. Model provide an early information by means of simulating and forecasting of the oceanic states. It is also believed that the model provide a valuable contribution to the development of marine and fisheries research in addition to field measurement. Model used in the present research is a three-dimensional numerical model of Infrastructure Development for Space Oceanography (INDESO). The model has been successfully applied in the Indonesian Seas with various marine and fisheries cases [8, 9, 10]. The core of the model originate from Nucleus for European Modelling of the Ocean (NEMO) which is also constantly developed to fix bugs found in the model by testing the stability of the model in many different open domain cases. By using
the model outputs, seasonal baroclinic circulation that incorporate ocean and atmosphere forcings will be thoroughly investigated. Initial value and boundary condition of the model (e.g., bathymetry, tidal forcing, meteorological variables as well as the combination of data assimilation retrieved from satellite) are available to run the model with various scenarios. Sensitivity experiments by setting appropriate parameterization have been examined to obtain the model stability. Model results are compared with other studies obtained by either modelling or field measurement by scientific research cruise. It is expected that upper layer circulation in WNSW could be well understood. Hence, the present research is important to conduct. In addition, the research proposed a long term characteristics of upwelling dynamics that is yet to introduce over WNSW. Previous research is carried out over particular season, year, and region in the northern part. It is, however, still less sufficient to achieve a better insight of the upwelling phenomena in the entire WNSW [11, 12]. The expected outcome is to strengthen the hypotheses by a better understanding of the water mass movement in the surface layer, i.e., general circulation, hence the upwelling dynamics in this waters can be easily understood. The main question of the research is how the upwelling dynamics could be detected by employing a three-dimensional model output. The examined-hypotheses are as follows: baroclinic current circulation model per depths (in the present research, we stress in the surface current) is capable to determine the movement of the water mass spatially under different season climatologically. Baroclinic model is able to identify upwelling areas and fronts. The research aims to identify upwelling characterized by thermal front associated with cyclonic and anti-cyclonic eddies.

2. Materials and Methods
The model outputs employed in the present study is derived from INDESO which is based on hydrostatic approximation driven by explicit and implicit parameterization of tides, high resolution of three-hourly wind-forcing as well as atmospheric-forcing associated with air pressure, moisture, and heat fluxes and the combined assimilation data retrieved from satellite in the open boundary. The model is governed by the equation of motion in the ocean also known as the primitive equation. The governing equations is written as follows:

\[
\frac{du}{dt} - f v = - \frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( A_h \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( A_h \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left( A_v \frac{\partial u}{\partial z} \right) \tag{1}
\]

\[
\frac{dv}{dt} + f u = - \frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( A_h \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left( A_h \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left( A_v \frac{\partial v}{\partial z} \right) \tag{2}
\]

Hydrostatic equation is written:

\[
\frac{1}{\rho} \frac{\partial p}{\partial z} = -g \tag{3}
\]

Continuity equation is written:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{4}
\]

The variables are described in table 1.
Table 1. Variables of the equations of motion.

| Variables | Descriptions          |
|-----------|-----------------------|
| $u$, $v$, $w$ | Current components  |
| $x$, $y$ | Horizontal direction |
| $z$ | Vertical direction |
| $f(x, y)$ | Coriolis parameter |
| $p$ | Pressure |
| $A_H$ | Horizontal turbulent exchange coefficient |
| $A_V$ | Coefficient of vertical eddy |

The model covers a horizontal resolution of about 9.25 km (1/12°) with 50 vertical levels where at near surface the resolution is the highest (1 m), as bathymetry is decreasing the resolution is coarser. A comprehensive explanation revealing the validation and the usage as well as model configuration is found in Tranchant et al [13]. The 2007-2014 daily averages of zonal and meridional components of currents and sea-surface temperature (SST) are used in the study. The identification of the upwelling and downwelling is depicted by anti-cyclonic and cyclonic eddies of surface baroclinic circulation.

3. Results and Discussion

The climatological characteristics of SST and baroclinic circulation in WNSW showed that the thermal front associated with cold pool and cyclonic eddy leading upwelling formation are detected in the Andaman Sea, in the east coast of Aceh and in the Indian Ocean. The onset start in the early northeast monsoon and cover a massive area as mentioned earlier. As it evolves in the following months, the coverage areas is declining and at the end of wet season on February, it is only detected in the northern Aceh Waters (Figure 1).

Figure 1. Climatological features (2008-2014) of monthly SST in °C (shading) and currents in m/s (vector) during northeast monsoon in WNSW. Black circles indicate potential upwelling zones.
Figure 2. Climatological features (2008-2014) of monthly SST in °C (shading) and currents in m/s (vector) during transition season (a, b, and c) and southwest monsoon (d, e, and f) in WNSW. Black circles indicate potential upwelling zones.
During northeast monsoon, the baroclinic circulation move northwestward as observed in the Malacca Strait where currents move out towards open seas of the Andaman and north Indian Ocean. At the entrance of the Malacca Strait in the north, it is observed that the magnitudes of currents reach its maximum as a result of the convergence of water mass coming from western Aceh. As the front occurred, the cyclonic as well as anti-cyclonic eddies that may lead to upwelling and downwelling emerge in the east coast of Aceh and off northern coast of the Aceh Waters. In the Andaman Sea, relatively calm circulation as well as cool SST are found. In the onset of the northeast monsoon, warmer SST reaching 29-31°C is found in the Malacca Strait and off west coast of Aceh to eastern Indian Ocean (Figure 1). In addition, the anti-cyclonic and cyclonic rotation appear as a result of thermal front. As cold water is surrounded by warm water, the upwelling is forming. On the contrary, the warm pool might reflect the downwelling condition. It is shown in Figure 1 that cold pool is identified off northern coast of the Aceh Waters extending to the Andaman Sea.

In the transition season during March-May, the upwelling is located off northern coast of Aceh to Andaman Sea and eastern Indian Ocean. The front due to warm pool followed by anti-cyclonic rotation occurred in the north Aceh Waters. During transition period, warm SST spanning from 30-31°C are found throughout WNSW. During southwest monsoon from June to August, the currents originating from the Indian Ocean flow eastward down to the Malacca Strait and south Indian Ocean. As temperature increase gradually when entering the shallow waters, the thermal front occurred in the northwestern Aceh Waters. The evolving cold pool covering massive areas off northwestern of Aceh is observed throughout season which might imply abundance of fisheries resources over the region. Since it is located near Aceh Mainland in the north, the utilization of fisheries resources could be optimized. Well-managed not only fisheries but a whole ocean productivity might boost the provincial economic growth which further bring wealth to the Acehnese people.

**Figure 3.** Characteristics of monthly rainfall (mm) and ENSO signal (°C) in Banda Aceh during 2013-2017.
In the second transition season during September-November, cool SST is observed in the Andaman Sea on September and October. In the Malacca Strait as well as off western coast of Aceh warm SST is detected. It is interesting to note that massive warm pool is climatologically detected in the western Sumatera Waters throughout season which influence the climate system over the region [14]. Relatively calm currents in the entire WNSW are found throughout season. The upwelling and downwelling features with weak intensity are found in the northwestern Aceh Waters. At the end of the transition season on November, SST increase as the rainfall onset arrive over Sumatera region.

By understanding physical characteristics leading to upwelling identification over WNSW, the present research contribute to well-mapped of potential fisheries resources that might improve the sustainable fishing ground policy and management. As policy has been arranged, it is expected that fisheries productivity would boost through fuel efficiency in enhancing fish catches. In addition, the results of this study can provide an advanced understanding on science and technology particularly on the importances of oceanographic research, particularly in the field of physical oceanography which have some relevancies on efficiency of survey research using ocean modelling and knowledge transfer and dissemination through community services in particular traditional fishermen.

4. Conclusion
The detection of potential fisheries resources by identifying the climatological characteristics of the upwelling dynamics are well-described in northeast and southwest monsoon. The attention is given during southwest monsoon where high potential fisheries is believed to hold in this season which is supported by location the fishing areas that are close to the Aceh Mainland. Mechanisms of upwelling as a result of the interaction of atmospheric and oceanic processes derived from INDESO outputs in the WNSW are well-understood where anti-cyclonic and cyclonic eddies as a result of the thermal front are well-mapped in the WNSW.

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