Spatial and temporal variability of geostrophic currents in the Indo-Australian Basin using gridded ARGO Float data

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Abstract. Geostrophic current variability in the Indo-Australian Basin (IAB) of eastern Indian Ocean is analyzed by using monthly gridded salinity and temperature data sets (between 2004 and 2016), from CTD ARGO Float. Geostrophic current is derived from dynamic height calculation. We applied time-series EOF analysis by decomposing geostrophic zonal component into dominant variability in several major modes. The variability of geostrophic currents from CTD Argo data analysis had differences, both spatial and temporal variability. There were four major modes, accounting for of 50.47% of the sum explained variance. The anomaly that occurred near the southern coast of Java cannot be detected due to the limited spatial coverage of the ARGO Float distribution. The spatial pattern in the first mode was indicated by positive anomaly at 110°E-114°E and 7°S-13°S. Furthermore, negative anomaly showed in the southern part of the study area. Variability oscillated with annual, semi-annual and inter-annual periodicity. In the second mode, there was a negative anomaly at 10°S-16°S, the rest of area were shown as the positive anomaly. Variability oscillated with semi-annual, annual and inter-annual periodicity. In the third and fourth mode, they showed variability with the semiannual, annual and inter-annual periodicity.

1. Introduction

The estimation of geostrophic currents can be understood by calculating dynamic height from temperature and salinity profile. Dynamic height is a reference depth (surface level) which is below the actual sea level as a substitute for geometric depth. Usually, the dynamic height is denoted as dynamic meters (dyn m) [1]. The dynamic height can be determined by finding the reference level. However, the surface layer cannot be used as reference level due to uneven surface characteristics and non-constant surface pressure. Pressure evaluation of the hydrostatic equation involves density parameter. The geostrophic current is calculated from the difference of horizontal pressure gradients and Coriolis force [2].

The Indo-Australian Basin (IAB) has complex dynamics that affect current variability, climate change, water movements, and sea-level changes. The variability that occurred in the region can be happened in semiannual, annual and interannual periodicity. There are several research that had been done in the IAB region. [3] examined the intra-annual variability of Indonesian Throughflow from the 30-year Expendable Bathythermograph (XE) data in the Eastern Indian Ocean. The results showed that the flow in the region was influenced by Indian Ocean Dipole (IOD) and El-Nino Southern Oscillation (ENSO). The Indonesian Troughflow (ITF) flows through Makassar Strait as the main passage [4][5]. Furthermore, water mass circulation occurring in this region is the South Java Current (SJC), which flows in the tropical Indian Ocean along the West coast of Sumatra and South Java, moving through the...
Savu Sea to reach the Ombay Strait, one of Arlindo's main lines [6]. The SJC circulation is influenced by local wind pressure along the Sumatra and Java coast which propagates during the monsoon transition [7]. Another circulation in the southern area of Java is the South Equatorial Current (SEC). The water mass from the ITF exited major path from Makassar Strait and joined the SEC moving westward [7][8][9].

Many instruments have been widely used to investigate complex geophysical phenomena in the oceans, such as ocean circulation. Ocean circulation can be derived from sea level fluctuation and the difference of horizontal pressure gradient and coriolis force. Scientists have developed various platforms that provide marine environments data. We examined the variability of geostrophic currents in the IAB using ARGO Float data. ARGO Float is the floating instruments for collecting the characteristics of global oceans. It float from upper to intermediate ocean (up to +/-2000 dbar). The Argo program has been started since 2000 and currently has distributed more than 3000 instruments used simultaneously to measure salinity and temperature data [10]. The ARGO Float is floated every 10 days in one cycle. Every cycle is divided into 4 phase: descent to a target depth of 1000 m, drifts in that depth and descends again to a deeper point of 2000 m to start salinity and temperature profile [11].

The purpose of ARGO Float mission is to provide spatio-temporal salinity and temperature vertical-profile data. Based on that purpose, ARGO Float can be used for climate change assessments [12]. The present research, ARGO Float data can be used to understand the geostrophic currents [13]. With the ability to descent toward deep water, ARGO Float data can also be used to estimate the distribution of Tuna (*Thunnus.sp*) in the Indian Ocean off Java by analyzing temperature and salinity data [14]. The future research is to combine ARGO Float and altimeter data to reconstruct a better understanding of oceanographic phenomena in oceans [15]. The aims of this research was to compare the dynamic height of ARGO Float with sea level data from altimeter, then to analyzed the varibality of geostrophic current in the IAB using ARGO Float data.

2. Methods

2.1. Research area and data

The research area was located in Indo-Australian Basin between Java and Australia, at 100°E-120°E and 5°S-20°S (Figure 1). There were four points to compare ARGO Float and altimetry data. We used Global gridded NetCDF or Matlab dataset produced by the Barnes Method (BOA-Argo). The data is open access, it can be download on http://www.argo.ucsd.edu/ Gridded_fields.html. While sea level anomaly data (SLA) was Delayed Time (DT) Mean Sea Surface Anomaly (MLSA), it can be downloaded on Copernicus Marine Environment Monitoring Service website (http://marine.copernicus.eu/).

The geostrophic current was calculated in two-components: zonal and meridional. They were computed in Ferret v.7.0 software using the *dynamic_height.jnl* function. The first step in calculating geostrophic current components was to define salinity, temperature and pressure parameter to the software environment. Then we calculated the density, specific volume and specific volume anomaly until we obtained the dynamic height. The Coriolis force was also been computed. The last step was calculating the geostrophic current component. The flowchart was showed in Figure 2.

2.2. Geostrophic currents components

Geostrophic currents component calculations were calculated from differences in horizontal pressure gradient and Coriolis force. [16] wrote the dynamic height equation as:

\[
D(p, T, S, p) = \int_{p_0}^{p_r} \delta(T, S, p) dp
\]

The geostrophic component equations can be written as:

\[
\begin{align*}
  u &= -\frac{\partial p}{\partial y} \\
  v &= \frac{\partial p}{\partial x}
\end{align*}
\]
We used zonal components (u) in this research. This condition based on [17] that said the most circulation in the IAB is bi-directional west-east direction.

The standard deviation was applied both in dynamic height and u component to depict data distribution. The Root Mean Square Difference (RMSD) value was calculated to see how much the difference in the dynamic height value of ARGO Float and sea level from the altimetry data. Correlation coefficient calculation was done to see the relationship between the sea level of altimetry and the dynamic height of ARGO Float.

2.3. The dynamic height and the sla comparison
The dynamic height data in surface layers are compared with the SLA from altimetry data. They were compared in four locations representing offshore and nearshore area. The four locations were represented as A, B, C, and D. The distance between the altimeter and the ARGO Float data extraction points was 9.51 nautical miles. Comparison of dynamic height and SLA have already conducted by [18] who compared dynamic height and sea level in the Equatorial Pacific Ocean.

2.4. Empirical orthogonal function (EOF)
Analysis of variability requires data with large spatial and temporal resolutions because variability is a repetitive fluctuation, we want to campaign those repetitive fluctuation for further analysis. So it requires long time series data with a large spatial resolution. The data must be compressed into smaller values that contain independent information. The technique was done by decomposing the data into main components with the Empirical Orthogonal Function (EOF) [19]. EOF analysis produces spatial and temporal decomposition which is divided into several modes. The order of each mode represents the significance of variability that can be explained in that mode based on the explained variance percentage value. Each mode also contains spatial pattern information with eigenvector values, which describe the spatial structure of the mode as standing oscillation, and temporal variations that illustrate how data oscillations change with time in Principal Components (PC) [20].

The principle of EOF analysis explained in [21] is to obtain spatial decomposition (s) and temporal (t) denoted as:

$$X(t,s) = \sum_{k=1}^{N} c_k(t) u_k(s)$$  \hspace{2cm} (3)
where $M$ is the number of modes resulting from the decomposition of spatial signals $u_k(s)$ and expansion coefficients or temporal principal components $c_k(t)$.

![Figure 2. The flowchart of geostrophic currents calculation from ARGO Float.](image)

3. Results and discussions

Geostrophic flow estimation was done by utilizing salinity and temperature profile data by calculating dynamic height. Differences in horizontal pressure gradients and Coriolis forces that occur are dominant factors in the process of geostrophic flow. Geostrophic component calculations have been carried out using Ferret v.7.0 software using `function dynamic_height.jnl`.

3.1. The standard deviation of the dynamic height and geostrophic current from ARGO Float

Figure 3 showed the spatial display of the deviation values for dynamic height and geostrophic zonal component. The standard deviation of the spatial pattern (Figure 3a) showed the highest value, located in the south coast of Java and in the offshore area around 10°S-16°S. Other areas showed a low standard deviation. The results of the calculation of the standard deviation of geostrophic zonal component (Figure 3b) showed high value near the south Java coast and declined toward offshore areas. There were several areas that experienced empty data, such as in the south coast of Java, Christmas Island, and around northwestern of Australia. It possibly because the distribution of ARGO Float was not distributed in those areas.

![Figure 3. The distribution of ARGO Float data, (a) standard deviation of dynamic height, (b) standard deviation of the geostrophic current component.](image)
3.2. The comparison of the dynamic height and sla

The results of the comparison of SLA of altimetry and the dynamic height of ARGO Float were shown in Table 1. The highest RMSD value is 11.25 cm at B. The lowest RMSD value was at A at 5.83 cm, while the highest correlation coefficient is at C at 0.70. The other points (A, B and D) showed moderate correlation. [22] said that moderate correlation is in range 0.40 – 0.599 and high correlation is in range 0.60 – 0.70.

| Station | Coordinate Points | RMSD (cm) | Corr. Coeff (r) |
|---------|-------------------|-----------|-----------------|
| A       | 8°30’S ; 101°30’E | 8°35’60”S ; 101°22’48”E | 5.83 | 0.56 |
| B       | 10°30’S ; 113°30’E | 10°35’60”S ; 113°22’48”E | 11.25 | 0.40 |
| C       | 13°30’S ; 106°30’E | 13°35’60”S ; 106°22’48”E | 8.30 | 0.70 |
| D       | 16°30’S ; 116°30’E | 16°35’60”S ; 116°22’48”E | 6.12 | 0.58 |

Based on the calculation of RMSD and correlation coefficient, the results showed that the point with a low RMSD value and a high correlation coefficient was in the offshore area, at station C, while the station with a higher RMSD and lower correlation coefficient was at station B, which was near the south coast of Java and station D which was near the shallow waters of northwestern Australia. It can be understood that the ARGO Float data cannot reach shallow water, therefore it is possible that the quality of the resulting data can be influenced by these shallow waters since the ARGO Float data is in gridding form. While the value of RMSD and correlation coefficient on offshore data from ARGO Float and altimetry has moderate identic.

3.3. The variability of geostrophic current

The salinity and temperature data from ARGO Float were analyzed by calculating the dynamic height to obtain zonal and meridional components. Geostrophic current variability was analyzed by EOF. There were areas that are not covered by the EOF analysis due to lack of ARGO Float data. This can be understood given the limited ARGO Float distributions near the coasts. The areas that not covered were along the South Coast of Java, the area around Christmas Island around 105°E and 10°S, and the the northwestern part of Australia.

EOF analysis was displayed in the first mode, accounted for 26.48% of explained variance (Figure 4). The spatial pattern of the first mode showed positive anomaly around 100°E-114°E and 7°S-13°S, with the highest positive anomaly was seen around 104°E-110°E and 9°S-10°S. The negative anomaly was seen around 100°E-120°E and 13°S-20°S (Figure 4a). The temporal variations of PCs showed the highest value in 2014 and the lowest in 2015, with annual (1 year), semi-annual (0.50 years) and inter-annual (1.77 years) periodicity (Figures 4b, 4c).

The variability of the geostrophic zonal component from ARGO Float data has differences both spatially and temporally. The results of the first mode accounted for 26.48% of explained variance. The spatial pattern shows a positive anomaly in the area near the South coast of Java. There was also a negative anomaly in the offshore area. Temporal variations in the first mode showed peaks amplitude that happened in December, February, March or April for each year. Negative amplitude peaks occur in August or September for each year. In June to October, the Southeast Monsoon moves from Australia to Asia [20, 21]. The opposite condition happened during the Northwest Monsoon. In the first mode, when the Southeast Monsoon a positive anomaly occurred around 13°S-17°S, and a negative anomaly were occurred around 7°E-13°E.

In the second mode, accounted for 11.09% of explained variance (Figure 5) showed a spatial pattern with negative anomaly around 10°S-16°S, with the lowest negative values at 10°30’S-13°S and 100°E-112°E. There was positive anomaly in the two areas between negative anomaly at 4°S-9°S, then at coordinates 15°S-20°S (Figure 5a). The temporal variation of PC showed the peak amplitude in April-May and October-November almost every year, with dominant periodicity was semi-annual (0.50 years), annual (1 year) and inter-seasonal (0.20 years) (Figure 5b, 5c).
Figure 4. EOF analysis from geostrophic zonal component in the first mode (a) spatial pattern (b) temporal variation (c) PSD analysis with 95% of confidence interval.

The second EOF mode result accounted for 11.09% of the explained variance. The spatial pattern was shown in Figure 4a. The positive anomaly was seen near the South coast of Java. The anomalous negative was seen along the 10°S-15°S area. The areas below 15°S had a positive anomaly. The PC graph showed peaks in May and November in each year with a semi-annual periodicity. The geostrophic zonal component variability coincides with the occurrence of semi-annual Kelvin Waves generated by Westerly Wind Bursts at the equator the Indian Ocean. During the Kelvin Wave, it was suspected that the geostrophic zonal component experienced a positive anomaly in waters near the south coast of Java, around 6°S-8°S. The third and fourth modes have a small percentage explained variance so it does not explain dominant variability.

Figure 5. EOF analysis from geostrophic zonal component in the second mode (a) spatial pattern (b) temporal variation (c) PSD analysis with 95% of confidence interval.

The results of the third mode, accounted for 6.99% of explained variance (Figure 6), showed a spatial pattern with a positive anomaly around 13°S-20°S and 5°S-9°S. Then there was negative anomaly found in three areas at 9°30’S-13°S and 100°E-108°E, 11°S-14°S and 111°E-120°E, and 17°S-20°S and 105°E-111°E (Figure a). The spatial pattern varies with the PCs with a positive peak in 2008 and 2013. The dominant periodicity was inter-annual (1.64 years and 5.50 years) and annual (1 year) (Figures 6b, 6c).
Figure 6. EOF analysis from geostrophic zonal component in the third mode (a) spatial pattern (b) temporal variation (c) PSD analysis with 95% of confidence interval.

In the fourth mode accounted for 5.91% of explained variance (Figure 7), a positive anomaly was seen with the highest value at 8°S-13°S and 100°E-105°E, the high positive anomaly was also seen around 13°S-15°S and 107°E-111°E. The negative anomaly was seen around 15°S-16°S and 100°E-105°E with the lowest negative anomaly at 9°S-11°S and 108°E-111°E (Figure 7a). Spatial patterns vary with time series of PC with dominant semi-annual (0.50 years), annual (1 year) and inter-seasonal (0.20 years) periodicity (Figures 7b, 7c).

The third and fourth modes do not explain the dominant variability, regarding the little number of the explained variance percentage of 6.99% and 5.91% respectively. Therefore, the variability explained in these two modes was not too significant. In the third mode, we found the small variability of spatial pattern with a positive anomaly (Figure 6a). Furthermore, the variability of geostrophic currents in this mode captured inter-annual periodicity (5.50 years) (Figure 6c).

The spatial pattern of geostrophic currents in the fourth mode also shows spatial patterns that are not too varied. There was a positive anomaly that occurred from the west part of the Indian Ocean and moved to the east part (Figure 7a). We captured the difference of temporal periodicity from the first to the third mode, which was inter-seasonal periodicity (0.20 years) (Figure 7c).

Figure 7. EOF analysis from geostrophic zonal component in the fourth mode (a) spatial pattern (b) temporal variation (c) PSD analysis with 95% of confidence interval.
4. Conclusion
The ARGO Float data has moderate value compared with Altimeter data. The variability of geostrophic currents showed different spatial patterns, especially between the south coast of Java and offshore area. The geostrophic currents variability oscillated with semi-annual, annual and inter-annual periodicity.

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