Oceanographic characteristics of Lampung Bay and its relationship to the Indian Ocean Dipole (IOD) period 2013-2021

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Abstract. The Indian Ocean Dipole (IOD) may affect the distribution pattern of the sea surface temperature (SST) in the Indonesian seas. Understanding this impact is crucial for comprehending the dynamics of marine ecosystems, particularly in Lampung Bay. This study evaluates IOD effects on SST and associated upwelling/downwelling in Lampung Bay. 2014 fish catch data analysis reveals during negative IOD phases, SST increases (0.2°C to 2°C) with subsequent downwelling, coinciding with reduced catches (609.18 tons vs. 3,079 tons normal). Conversely, positive IOD phases show SST anomalies (-1°C to -2.5°C) with upwelling, correlating with increased catches to 3,349 tons in 2018. IOD-SST relationship primarily observed in Lampung Bay's open connection to Sunda Strait (r=0.64 to 0.69), while weak correlations in coastal waters (r < 0.2) suggesting the influence of other factors on SST in Lampung Bay.

1 Introduction

Lampung Bay constitutes a pivotal maritime domain that supports a majority of the activities originating from Sumatra Island [1]. The intensified activities within this bay can perturb the oceanographic equilibrium within its confines [2]. Furthermore, during the west season, water flows into Lampung Bay from the southwest and south of the Indian Ocean [3] and from the southern coast of Java during the east monsoon [4], implying a discernible influence of the Indian Ocean Dipole (IOD) in this region.

The IOD, being a complex global climatic variability phenomenon, exerts a considerable influence on oceanographic dynamics [5]. Okgareta et al. [6] showed that the IOD phenomenon affects the distribution pattern of SST in Lampung Bay. This study aimed to investigate the phenomena of upwelling and downwelling in the eastern Indian Ocean waters during the IOD phenomenon and to measure the influence of IOD on the SST distribution in Lampung Bay during each period of the IOD phenomenon. This will maximize mitigation efforts for climate change disasters caused by the global climate IOD in marine fish farming activities in Lampung Bay.

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2 Data and methods

2.1 Research site

The research site is the waters of Lampung Bay which are located at 105°9′0"-105°31′30" E and 05°24′0"-05°46′30" S. And the SST data were validated by CTD observation data in 12-13 November 2021 (**Fig. 1**).

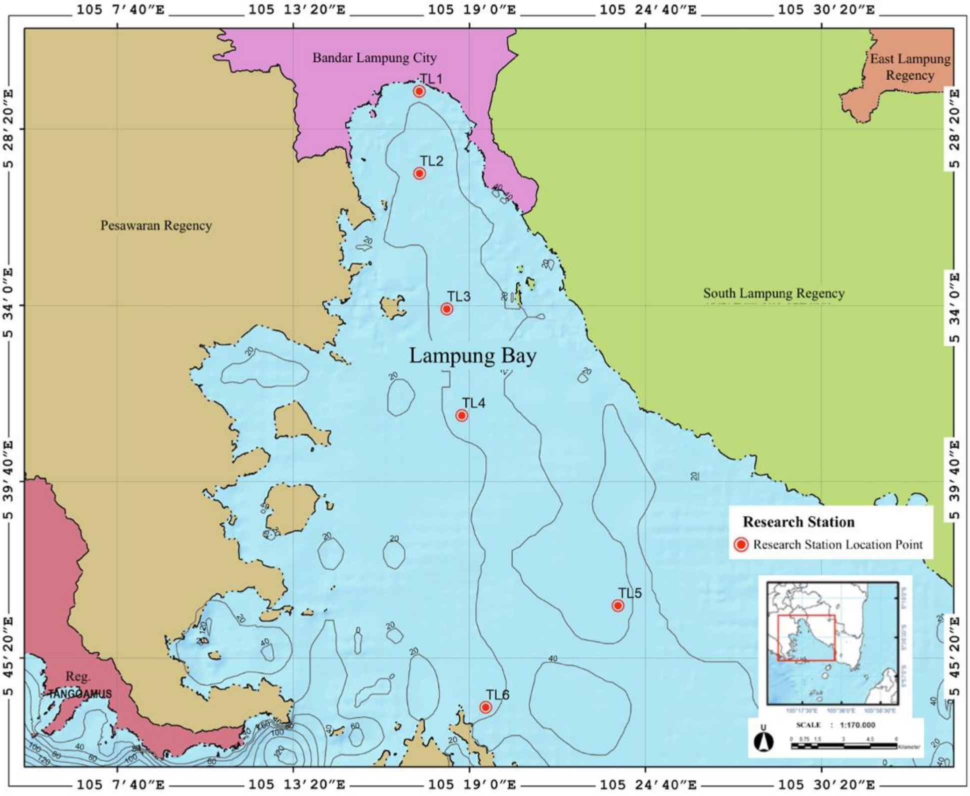

Fig. 1. Research area and CTD stations in the Lampung Bay at 12-13 November 20.21

2.2 Dataset sources

This study uses Landsat-8 data with a resolution of 100 m (Path/Row (123/64), (Website Landsat.usgs.gov/), which were processed via Google Earth Engine, Dipole Mode Index (DMI) downloaded from https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI/, and wind data from (https://cds.climate.copernicus.eu/), which was processed using Ocean Data View (ODV). The SST from Landsat-8 was validated using CTD observation data from the Research Team of the Teluk Lampung Kedaireka program [6].

To obtain the hydrodynamics of Lampung Bay, we derived the ocean current and wind pressure from the European Center for Medium-Range Weather Forecasts (ECMWF, https://www.ecmwf.int/en/forecasts/datasets). In addition, fish catch data from Lampung Province were obtained from the Balai Besar Pengembangan Budidaya Laut (BBPBL) (https://kkp.go.id/djpb/bbpbllampung).

2.3 Method study

The regression test of SST Landsat-8 and SST observation data was $R^2 = 0.6872$; therefore, it can be concluded that Landsat-8 data can be used to explain the actual SST in Lampung Bay [6].

The IOD phase is determined by the DMI, which is an aperiodic phenomenon or has an uncertain period of occurrence. IOD develops as a result of internal feedback mechanisms, external stimuli, and random influences such as weather variability [7]. The red boxes in **Fig. 2** show the years of positive IOC in August 2015 (0.68), October 2018 (0.84), and October 2019 (1.12). The black boxes show the normal phase and the blue boxes show the IOD-negative phase for May 2013 (-0.43) and July 2016 (-0.66) [6].

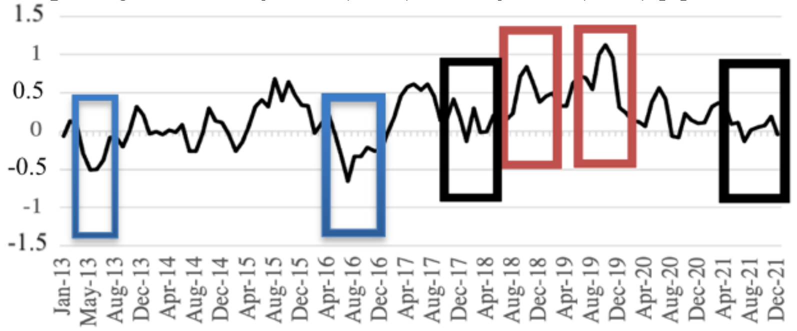

Fig. 2. Graph Phenomenon Indian Ocean Dipole in the Indian Ocean based on Dipole Mode Index (DMI) 2013-2021(IOD positive phase (red), IOD negative phase(blue), and normal phase (black). (source: Okgareta [6])

Temporal and spatial maps illustrating the distribution and anomalies of SST and wind. The research methodology encompasses spatial and temporal analyses, alongside a comparative descriptive analysis. Spatial analysis involves processing secondary data visualized through Google Engine, ODV, and MATLAB to generate spatial distributions. Subsequently, to obtain the desired data, calculations are performed within a script that can be directly used in Google Engine.

Ekman pumping and transport calculations can be performed by calculating the wind stress in the research area [8]. The wind component along the x-axis was assumed to be parallel to the coast (zonal), and the y-axis (wind component) was oriented perpendicular to the coast (meridional). Equations [9] [1,2] used in the calculation of Ekman transport (M_E) and Ekman pumping (W_E) are as follows:

$$M_E = (1/(\rho f) * \vec{\tau}) \times \hat{t} \tag{1}$$

$$W_E=(1/(\rho f) * \nabla) \times \hat{t} \tag{2}$$

When: $\vec{\tau}$ = Vector wind stress; $\hat{t}$ = Unit vector tangent to the coastline; ρ = Seawater density; f = Coriolis parameter.

The total Ekman transport for both alongshore and cross-shore components is derived from wind stress, whereas Ekman pumping is determined by wind stress. Ekman pumping events are assessed through the vertical velocity at the base of the Ekman layer, correlating with the convergence or divergence of Ekman transport. A negative Ekman pumping value signifies Ekman transport convergence at the surface, driving water masses downward or causing downwelling. Conversely, Ekman transport and pumping indicate upwelling phenomena when there is Ekman transport divergence at the surface, driving water masses upward toward the sea surface.

Temporal analysis involves processing secondary data based on relevant timeframes, resulting in temporal distributions. Temporal vertical analysis was employed to identify SST anomalies during different phases of the Indian Ocean Dipole (IOD) (positive, negative, and neutral). In this study, a correlation analysis was conducted to determine the relationship between SST anomalies and DMI.

3 Results

3.1 Variability of wind and SST at the negative phase of IOD 2013

Fig. 3 shows the direction of the monsoon wind in the negative phase of the IOD from March to June 2013. Wind directions from the northwest to the southeast parallel to the Indian Ocean from January to February.

The average SST anomaly in Lampung Bay during negative IOD ranges from 0.2°C to 2°C. The negative phase of the IOD increases the SST anomaly in Lampung Bay [6]. According to the Irawan [10], Phytoplankton bloom have occurred because of increased nutrients, calm currents, salinity, and anomalies in Lampung Bay. The equatorial Indian Ocean undergoes distinct seasonal wind patterns in its west and east regions. The wind pressure started to intensify from March 2013 to June 2013 (Transition Season I).

This corresponds to an increase in SST in the southern Indian Ocean extending towards Lampung Bay, before gradually diminishing again by August 2013. The notable SST increase aligns with the occurrence of a negative IOD in 2013, reaching its peak in May 2013.

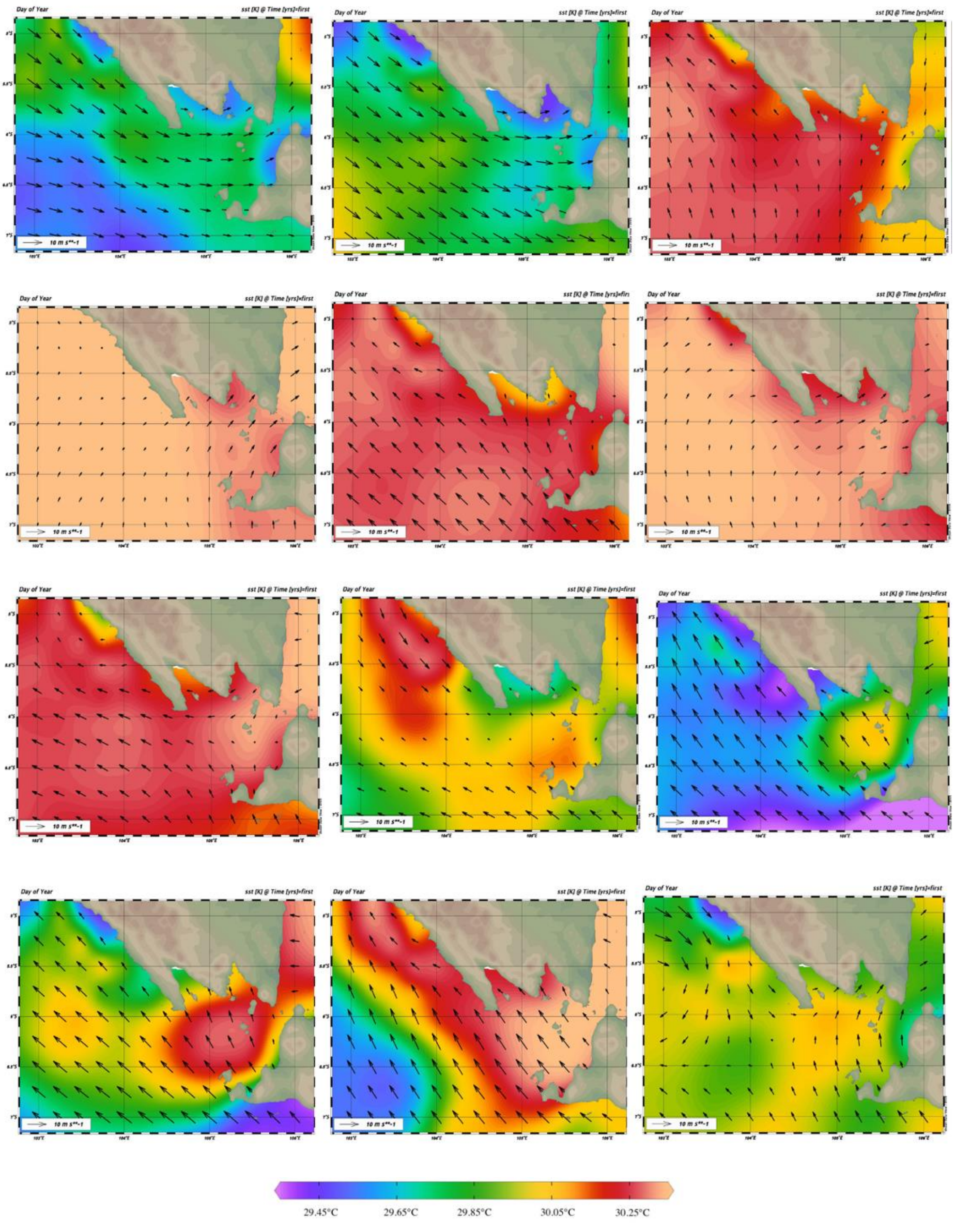

Fig. 3. Wind vectors movement chart during the negative phase of IOD in the Southern Indian Ocean (heading towards Lampung Bay) in 2013.

3.2 Ekman transport and the downwelling region during the peak negative phase of IOD in May 2013

The wind direction (black arrow) from March to June 2013 moved from the northwest of the Indian Ocean to the southeast of the Indian Ocean, tending to be parallel to the coastline of the western island of Sumatra and turning into the bay (**Fig. 4**).

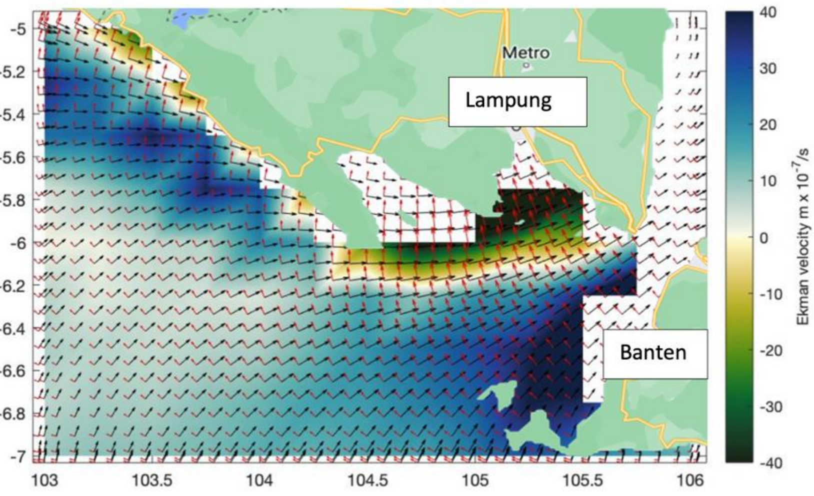

Fig. 4. Directions Ekman Velocity transport in March to June 2013 in the Lampung Bay and Ekman Velocity. (The black arrow is wind, the red arrow is Ekman Transport, and the shaded colour represents Ekman Velocity).

The red arrow is the calculation of the direction of Ekman velocity transport. **Fig. 4** shows that the wind tends to enter Lampung Bay, indicating the direction of water mass input from the western Indian Ocean (Sumatra) during the negative IOD. This brings water masses that ultimately force the downwelling phenomenon in the eastern (western) Indian Ocean. Indonesia and Lampung Bay, which push nutrient sources to the bottom of the ocean, result in a decrease in fishing [11]. The year 2013 was the negative phase of IOD that occurred. To investigate whether there were signs of downwelling in the eastern Indian Ocean during the negative phase of the IOD and whether its effects reached Lampung Bay, **Fig. 5** illustrates the vertical temperature distribution in the eastern Indian Ocean and Lampung Bay in May 2013 (peak of the negative IOD) and December 2013 (when the negative IOD effects diminished). The SST tends to be warmer near the surface and decreases with depth. Based on data from the Central Statistics Agency (BPS) of Bandar Lampung City, there was a decrease in the number of captured fish in 2013 and 2016 compared to that in 2014. A significant decrease occurred in the IOD-negative phase, with the number of captured fish being only 609.18 tons compared with 30,794 tons in 2014.

The thermocline layer divides two water masses into a body of water, which is the boundary between the water on the surface and the water below it. This layer is characterized by contrasting temperature fluctuations compared to other water layers, whereas the halocline layer is a vertical layer of deep-sea water that can be identified by the salt content or salinity, which changes drastically with depth. Fluctuations in salinity within this stratum are induced by variations in water density, rendering it a pivotal interface for segregating freshwater and saline water within an aquatic environment [12]. From the image of Lampung Bay in May 2013, thermocline and halocline layers can be observed at a depth of 80 m. At the surface, the average temperature was 29.75°C. However, when going further, the value drops to 27.29°C at a depth of 80 m.

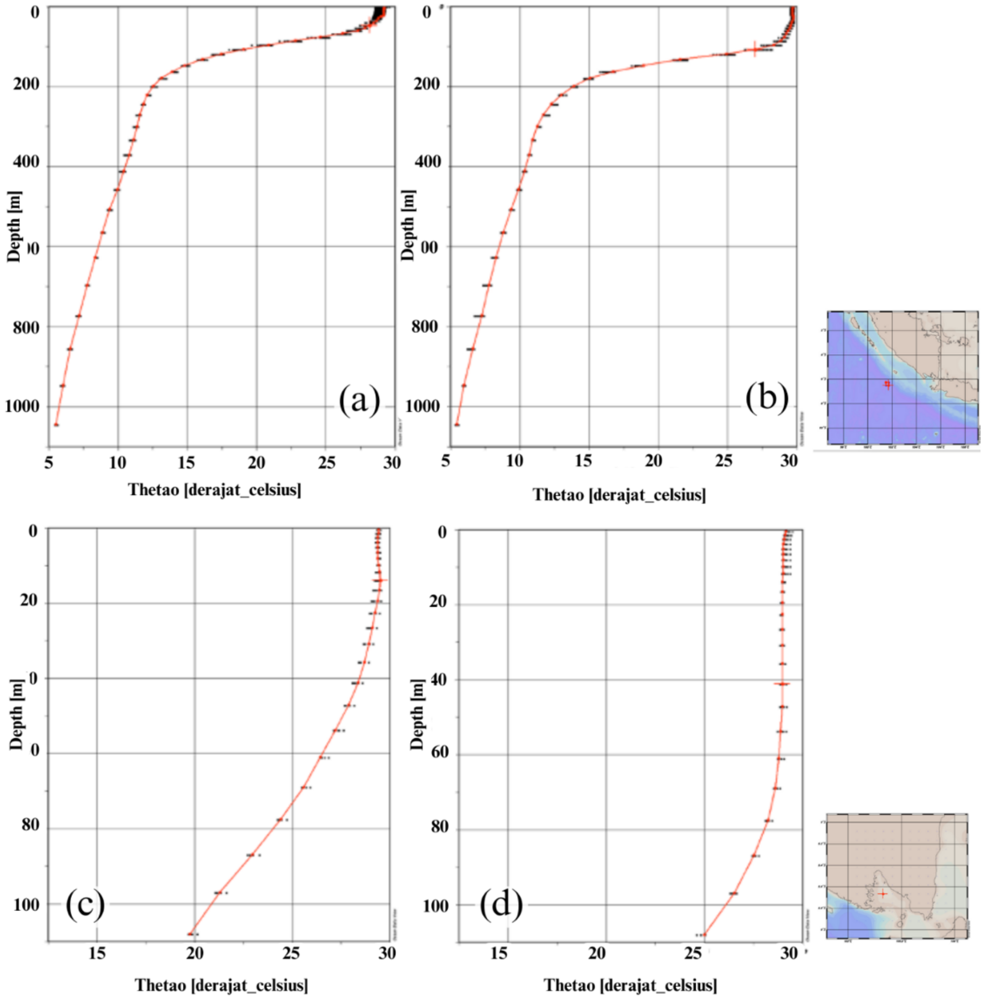

Fig. 5. Temperature profiles in the Indian Ocean in May 2013 (a), December 2013 (b), in Lampung Bay in May 2013 (c), and December 2013 (d).

3.3 Wind and SST variations at the peak positive phase of IOD in 2018

Fig. 6 shows the direction of the monsoon winds during the positive IOD phenomenon in 2018, which tended to move towards the western Indian Ocean.

Longshore wind movements around the Sunda Strait, including Lampung Bay, indicate mass transport away from the coast, resulting in a vacuum of water mass on the surface of Lampung Bay and upwelling. This process occurs during August-November every year with a negative IOD phenomenon, and is marked in **Fig. 6** by a decrease in SST in Lampung Bay. According to Kunarso [13], the positive IOD phenomenon and the addition of La Niña cause upwelling in Lampung Bay, which causes the SST of Lampung Bay to decrease compared with normal years, coupled with an increase in monsoon winds [4] from June to October, causing high chlorophyll-a and low SST in Lampung Bay.

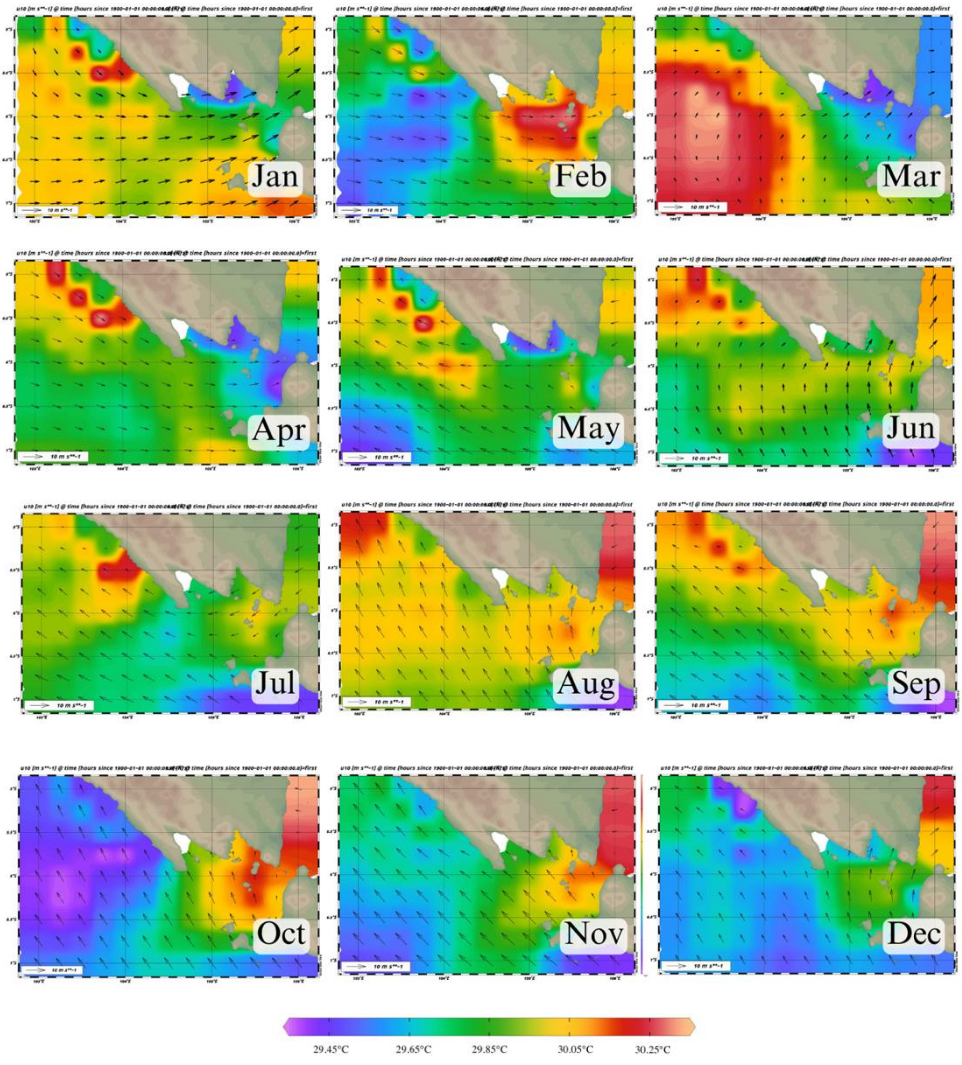

Fig. 6. Temperature profiles in the Indian Ocean in May 2013 (a), December 2013 (b), in Lampung Bay in May 2013 (c), and December 2013 (d)

Positive IOD anomalies of SPL ranging from -1°C to -2.5°C [6] illustrate the decrease in SPL in Lampung Bay during the positive IOD phenomenon, followed by upwelling in the western region of Sumatra, including Lampung Bay [6]. Temperature directly affects enzymatic reactions during phytoplankton photosynthesis, while indirectly altering the hydrological structure of the water column, subsequently affecting phytoplankton distribution.

Nutrients enter the mixed surface layer and euphotic zone (the sunlit layer) through upwelling currents. The productivity of the upwelling area, which promotes phytoplankton photosynthesis and forms the core of the marine food chain, is often measured. According to Kunarso [5], the average chlorophyll-a concentration in Lampung Bay reached its highest point in the last 10 years (2007-2017) in 2015, with a chlorophyll-a value of 0.720 mg/m3. Upwelling areas comprise less than one percent of the world's ocean area yet contribute to over 20 percent of global fish catches [14].

3.4 Ekman Transport and upwelling areas during positive IOD events in 2018

Longshore wind movements around the Sunda Strait, including Lampung Bay, indicate mass transport away from the coast, resulting in a vacuum of water mass on the surface of Lampung Bay and replaced by subsurface water from the Indian Ocean. This process occurs during August-November every year with a negative IOD phenomenon and is marked in Figure 7 by a decrease in SST in Lampung Bay.

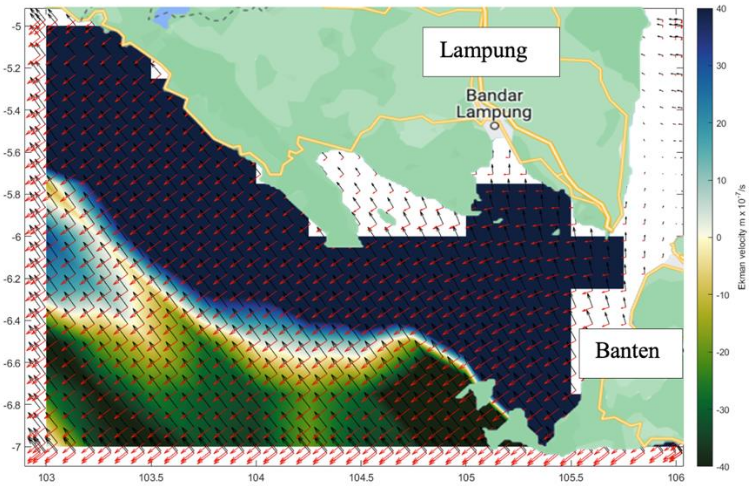

Fig. 7. Directions Ekman velocity transport in October 2018 in the Lampung Bay and Ekman Velocity. (The black arrow is wind, the red arrow is Ekman Transport, and the shaded color represents Ekman Velocity).

BBPBL data from Bandar Lampung City show an increase in the number of fish catches in 2018 and 2019, namely 3,349 tons and 3,403 tons per year, respectively, which is higher than in 2017 (447 tons) and 2021 (3,232 tons per year). According to Sato [15], the metabolic rate of fish in the body of water is highly dependent on temperature and physiological tolerance to the significant impact of the distribution of other biotic factors, where the distribution of fish is consistently found offshore in upwelling areas. Therefore, during the positive IOD period, the waters of Lampung Bay have strategic potential to become a location for marine fisheries cultivation. The community can also maximize fishing catches during positive IOD periods. **Fig. 8** shows the vertical temperature distribution in the eastern Indian Ocean and Lampung Bay in October 2018, which represents the peak of the positive IOD occurrence in 2018, and in January, when the IOD influence was absent in 2018.

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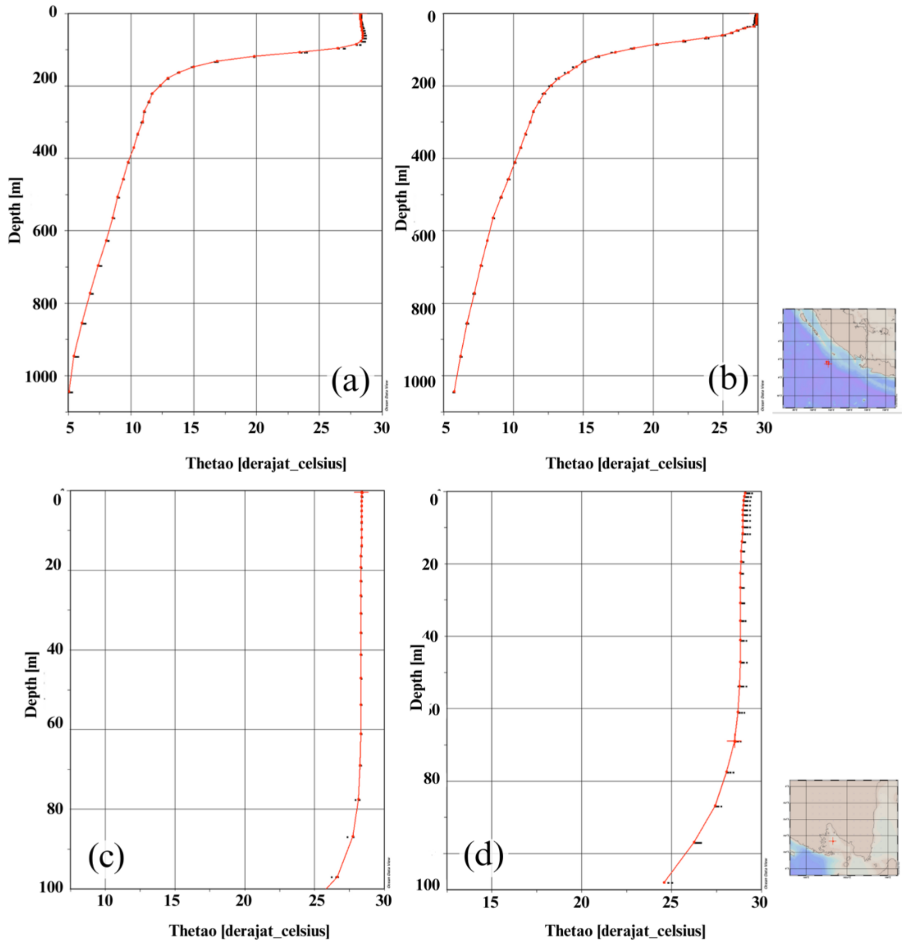

Fig. 8. Temperature profiles in the Indian Ocean January 2018 (a), October 2018 (b), in Lampung Bay January 2018 (c), and October 2018 (d).

3.5 The relation of IOD and SST anomalies in Lampung Bay

As described above, there is a relationship between IOD (indicated by DMI) and SST in Lampung Bay. We then statistically examined its relationship using the correlation coefficient (r). During the years of positive IOD (negative), the r is 0.64 (0.69) at the most open connection station to the Sunda Strait. The r value was not too large, which may indicate that the SST in Lampung Bay is also influenced by other factors, such as the semi-closed topography of the bay. This condition influences the direction of the currents and movement of the water masses. The current tends to alternate and receives water masses from the Sunda Strait (water masses from the Indian Ocean and Java Sea) only at high tide [16]..

A weak r (r<0.2) was found in waters near land (sta.TL1 and TL6). Station TL1 is near the Lampung Bay Harbor, and TL6 is adjacent to Legundi Island near the mainland. This is due to external factors from land that influence the SST conditions in every bay [19]. The influence of IOD on the SST anomaly in Lampung Bay also affects other parameters, such as chlorophyll-a [19].

4 Conclusion

Lampung Bay experiences warmer SST during Transition Season I and the East Monsoon than during other seasons. Spatially, the average SST values in Lampung Bay decreased during the positive phase of the IOD, and vice versa during the negative phase. This finding indicates that the SST in Lampung Bay is influenced by the IOD phenomenon.

The impact of the IOD is also seen in the upwelling (downwelling) phenomena in the western part of the West Sumatra coast. During the negative phase of the IOD, downwelling occurred on the western coast of Sumatra, extending to Lampung Bay, and vice versa during the positive phase of the IOD. The relationship between IOD and SST is observed in the offshore part of Lampung Bay ($r>0.7$), while coastal water indicates that there are other factors influencing SST. ($r<0.2$).

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