The Correlation of Upwelling Phenomena and Ocean Sunfish Occurrences in Nusa Penida, Bali

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Abstract. Sea surface Temperature (SST) is an important oceanographic variable that can figure the upwelling phenomena. This study aims to determine the variability of SST in relation to upwelling phenomena in the Indian Ocean Southern of Bali Island and the Ocean Sunfish occurrences in the southern of Nusa Penida. Data loggers and remote sensing approach that record temperature was used. An Onset HOBO U20 Water Level Logger U20-001-02 was deployed in Crystal Bay (08°42’S and 115°27’E) at 8 meters depth. The daily field SST data were available from June 2011 to December 2014 with 30 minutes time interval. The monthly satellite images obtained from MODIS on board the Aqua satellite. While the ocean sunfish occurrences were based on rate of encounter (ROE) of previous works by Putra (2015) on July to October 2014. It was found that field data and MODIS have a high correlation (r=0.89) with Root Mean Square Error (RMSE=1.64°C). The upwelling phenomena characterized by the evidence of the colder water mass (SST < 25°C) and a higher concentration of chlorophyll-a, reach its peak in August to September. This phenomena coincidence with the high occurrences of Ocean Sunfish in Crystal Bay on August to October.

1. Introduction

The sea surface temperature (SST) is one of the important physical properties of the marine ecosystem. It’s variability influence on various marine processes including physical, chemical, and biological process above [1]. SST gradients can be used to describe the dynamics of oceanographic condition associated with current systems, eddies, fronts, jets, and upwelling phenomena that can be linked to one process to another process [2]. Physically, the upwelling process is characterized by the colder water mass at the surface ocean and higher salinity than the surrounding area. The upwelling area supplies phytoplankton as the feed for the zooplankton, fish larvae, and adult pelagic fishes [3]. The higher phytoplankton abundance triggers the fishing activities at surrounding area [4-6].

In addition to fishing activities, these conditions also had a positive impact on the marine tourism activities. Diving is one of the activities are undertaken by tourists in the waters of Nusa Penida, one of the diving spots which became the main attraction is Crystal Bay. This dive site is known as a inhabiting of Ocean Sunfish, which can generally be seen between July and September [7, 8], mostly at peak season July to October [9] each year, while the SST of this area decreased [10].
Ocean Sunfish is distinguished by their role in the marine food web, its primarily consume gelatinous zooplankton [11-13], and also bizarre appearance and strange basking behavior. Recent studies suggested some hypotheses to explain this basking behaviour related to SST: thermal recharging [14-17] and parasite elimination [18]. Another tagging studies have revealed the ocean sunfish dive several hundred meters deep, possibly for forage [19]. Thus, it has been hypothesized that Ocean Sunfish might bask at the sea surface to re-warm the body after deep dives into cold water [20].

Generally, SST dataset can be obtained from 2 kinds of methods, field measurements and remote sensing approach [21]. SST can be measured with a wide synoptic coverage at fine spatial resolution and repeated time series by using remote sensing satellite [22]. Both infrared and microwave bands have highlighted the global SST map very well [23] but are not the case with coastal areas [24]. These sensors were not able to provide a good quality data for coastal and estuaries zone which were less than 2 km from the coastline [25]. The higher resolution (spatial and temporal) of SST data, especially from field measurements, has a great potential to monitor the oceanography dynamics in the estuarine and coastal areas. Unfortunately, there is a distinct gap in the space and time of SST data obtained from field measurement.

This study aims to determine the variability of SST from field measurements and satellite data associated with upwelling phenomena in the Indian Ocean Southern of Bali Island and the Ocean Sunfish occurrences in the southern of Nusa Penida. First, we will present the logger configurations and measurement method. Then, we discuss the diurnal, monthly and seasonally variability of SST from both field measurements and satellite data.

2. Materials and Method

2.1. Study Area

Geographically, Nusa Penida waters are dealing directly with the Lombok Strait in the northern part and the Indian Ocean in the southern part. Lombok Strait is one of the major Indonesian Through Flow (ITF) pathway through to the Indian Ocean with the volume transport reach 2.6 Sv (1Sv = 106 m3 s-1). This ITF relatively brings the cool and fresh water from the Pacific Ocean to the Indian Ocean [26, 27]. In the other hand, the South Java Current (SJC) and upwelling process in the Indian Ocean have a significant role in maintaining the SST variability along the Java and Sumatera coastal area [28].

Figure 1. Nusa Penida waters and surrounding ( ★: Onset HOBO deploy location in Crystal Bay/CB, AB: horizontal line transect of SST and Chl-a MODIS; ITF: Indonesian Through Flow pathway; SJC: South Java Current)
2.2. **In situ SST Measurements**

SST measured used data loggers at a user defined time interval were used, with the date, time, and sampling interval set by software through a specific interface. An Onset HOBO U20 Water Level Logger U20-001-02 deployed in Crystal Bay (08°42'S and 115°27'E), attached to branching coral at approximately 8 meters below the surface (Figure 1). The loggers have autonomy of about one year, at a sampling interval of one record by 30 minutes, which has been selected for the whole period of study. This logger can record temperatures in range -200 to 500°C with the accuracy about ± 0.37° @ 20°C and ± 0.5° over -5° to 50°C. Each logger includes calibration certificate of accuracy in accordance with NIST-traceable standards at three pressure points distributed throughout the range. This logger can record 21,700 combined pressure and temperature measurements up to 30 meters water depth at sea level (Onset Computer Corporation, 2010). The data logger was generally replaced every 10 to 12 months and downloaded using the HOBOware Pro with an Onset Optic USB Base Station (BASE-U-4) and a coupler (COUPLER2-B). The daily SST data were available from June 2011 to December 2014 with 30 minutes time interval. Furthermore, the HOBO SST data were analyzed to look at the diurnal and monthly variation in Crystal Bay, Nusa Penida.

2.3. **Remote Sensing Data**

The monthly average of SST and Chl-a images obtained from MODIS (Moderate Resolution Imaging Spectroradiometer) on board the Aqua satellite was used in this study. The 3 level images with a 4-km spatial resolution from 2011 to 2014 were downloaded from Giovanni website (http://gdata1.sci.gsfc.nasa.gov/). A horizontal line transects of the monthly average of SST and Chl-a was used to know the spatial and temporal evolution of the upwelling process in the Indian Ocean Southern of Bali Island.

3. **Results and Discussion**

3.1. **Diurnal Sea Surface Temperature Cycle**

The complete data series of daily SST variability is presented in Figure 2. The low temperature was observed twice a day, it’s in the midnight (12 to 4 am) and mid-afternoon (11 am to 5 pm) (Figure 2a). Equally, with the low temperature recorded, the warm temperature was observed twice a day as well, it's in the morning (6 to 10 am) and (6 to 10 pm). The lowest temperatures were observed in the boreal winter (December – February), with the temperature variability was 0.39°C approximately. The moderate temperature variability observed in the transition period (March – May) and the boreal summer (June – August), it's 0.81°C and 0.72°C respectively. Meanwhile, the strongest temperature variability of daily temperatures (> 1.75°C) observed at the end of boreal summer (September – November), while the coolest temperature (± 24°C) also observed during this period.

The hovmoller diagrams figure out the temporary diurnal temperature variability for each monsoon period very clearly (Figure 2b). During the boreal winter period, the waters tend to be warmer with average 27.30 ± 0.10°C and 26.85 ± 0.23°C, respectively. During this period, the daily variation of SST was very small. The waters being colder (less than 26°C) at the boreal summer period and continued drop until September. The temperature tends to be cooler with average 25.84 ± 0.19°C and 25.11 ± 0.53°C, respectively. During this period, the daily variation of SST was bigger than ever. The low and warm temperatures were clearly observed twice a day in the peak of this time, especially in the mid-evening.
Figure 2. Diurnal cycles of temperature in Crystal Bay, Nusa Penida from HOBO (a) Daily SST average based on monsoon period; (b) Time – monthly average of SST hovmoller diagram.

Diurnal cycle and variation of SST mostly caused by solar radiation and the earth’s rotation. Near the equator, the seasonal variation generally weaker rather than in the higher latitude. Equator regions get a longer exposure more than other areas [29]. Evaporation process, wind and wave mixing also touted influence the SST variabilities. In weak winds condition and strong solar surface heating would trigger a warm water mass in the subsurface layer [21].

However, it is still unclear what main caused this diurnal cycle in Crystal Bay. The SST distribution in the Indonesia region is complex. It is difficult to understand the processes that control the SST variability [28]. Local monsoon, tidal mixing, and ITF probbaly become the most influence factor [28, 30]. During the boreal summer that associated with the rains season, the deep convective clouds will reduce the diurnal shortwave radiation forcing caused the diurnal SST variablity is weaker. While in the boreal winter, when the wind blows stronger, causing the vertical mixing bringing the cold water to the surface layer. This process is reinforced by the tidal mixing that caused stronger vertical mixing in this region. The role of ITF on the diurnal SST cycle in this area also still unclear.
3.2. Monthly Cycles of Sea Surface Temperature

The monthly cycle of SST observed from data loggers (HOBO) and remote sensing data (MODIS) showed Figure 3. The monthly average SST from HOBO varied between 24.56°C - 27.77°C with the mean is 26.24°C and the standard deviation is 1.0°C. The highest temperatures recorded in January and the lowest were in September. The monthly SST variability for each year (2011-2014) was less than 3.5°C. The highest monthly temperature cycle observed at 2011 with the variability reached 3.40°C. Meanwhile, for the next three years after (2012, 2013, 2014), the monthly temperatures variability were 3.20°C, 2.99°C, and 2.87°C, respectively (Figure 3a).

Comparing the monthly cycle of SST from HOBO and MODIS showed that the two datasets have high correlation (r=88.68 and RMSE=1.64°C). During boreal summer, SST was likely to be more uniform. The upwelling process causing the colder water lifted to surface layer from the bottom. This is evidenced by SST from both HOBO and MODIS. While in boreal winter, MODIS give higher SST than HOBO. The SST difference between this dataset reaches up to -0.84°C until 2.99°C. MODIS using infrared wavelength to measure the SST and only in the top surface layer (we call it’s ‘skin’ layer). The skin SST is the radiometric temperature of the sea surface and usually measured by the infrared wavelengths (3.7–12 μm) that are used by the satellite instruments. Whereas HOBO deployed at 8-meter depth which is often termed the 'bulk' SST. Bulk SST is defined to be the temperature within the upper few layer and convective processes. There will differ from the skin temperature by values as large as 1-3 K in the tropics [31].

Generally the spatial and temporal distribution of SST in the southern waters of Nusa Penida influenced by monsoon (Figure 3b). During boreal summer, SST decreased significantly compared to other months. Strong winds caused the Ekman transport, which causes the surface water mass moved away from the coastal area to offshore. This process leads "an empty space" on the coastal side and the pressure gradient. The water masses from the sub-surface layer was moving towards the coastal and follow the slope of the seafloor moving towards the surface and cause upwelling. The upwelling process in the Indian Ocean south of Java and Bali was characterized by the evidence of the cold water mass (SST < 28°C) and high concentration of chlorophyll_a (Chl-a) more than 0.5 m/m³ [2]. This upwelling reached its peak in August or September [32]. This cold-water mass pushed westward to the west coast of Sumatra [33-35]. This upwelling also affects on SST variability in Crystal Bay. The cold-water masses began to be seen since the beginning of boreal summer and persist until October.

MODIS showing the spatial distribution of SST in the southern part of Nusa Penida tends to be cooler than the east side (Lombok Strait) and western side (Badung Straits). The warm water is visible on both the straits are a mass of water that tends to ITF pathway. In the early boreal summer of 2013 and 2014, there was warm water masses appearance in the southern waters of Nusa Penida. This condition does not occur in the previous 2 years. This water masses lead the intensity of upwelling weaker which is characterized by a narrow size of the area and of short duration. The size of the area and duration of upwelling in the southern part of Nusa Penida can be used as a benchmark upwelling strength. Based on MODIS data in 2012, showing the intensity upwelling tend to be stronger than other years (Figure 3b). SST measured colder, spread in a wider area (115.325 - 115.575°E) with a longer duration. Spatial and temporal distribution of primary production seen very clearly. The Chl-a concentration reaches up to 2.5 mg m⁻³ with an area spreading from 115.425 - 115.575°E. Likewise, in the western part of Nusa Penida (Badung Straits).
Figure 3. Monthly SST variability in Crystal Bay, Nusa Penida, (a) HOBO and MODIS, monthly climatology 2011 – 2014; Longitude – monthly average hovmoller diagram of SST (b) and Chl-a (c) from MODIS. The red and white box represents the Crystal Bay site.
3.3. Relation of Upwelling and Ocean Sunfish Occurrences

Nusa Penida comprises a group of islands in the southeast of Bali. Based on ecological surveys since 2002 – 2009, in Nusa Penida can found 1419 hectares of coral reef, 230 hectares of mangrove with 13 species and 108 hectares of seagrass bed with 8 species. Furthermore a marine rapid ecological assessment (REA) in Nusa Penida’s water found 296 species of coral reef [36]. There is also tremendous fish biodiversity; the REA found 576 species of fish, five of which are new species in Nusa Penida [37]. This island contains a high level of marine biodiversity and has significant tourism potential, visited by more than 200,000 tourists each year. One of unique and charismatic fish that occur predictably annually in Nusa Penida’s waters is Ocean Sunfish. This marine megafauna became one of main attraction that undertaken by tourists through diving activities [7]. The Ocean Sunfish season is between July-September each year [6, 7].

Some research works already initiated by few scientists as a preliminary study to documented Indonesian Ocean Sunfish. On going works were initiates by Marianne Nyegaard, PhD research at Murdoch University (Perth, Western Australia) from 2011 and now on. She spent three consecutive sunfish seasons diving with the Ocean Sunfish in Nusa Penida waters. During the 2014 she undertook field research, specifically to look at the movement of the Ocean Sunfish, and the potential for them to be resident in the Bali area. Recent studies by Putra [8], under Marianne Nyegaard’s supervision, documented the sighting of Ocean Sunfish in the waters of Nusa Penida. From this work, approximately 70 sighting of Ocean Sunfish from about 400 diving activity recorded in Nusa Penida waters during August to October 2014. The analysis shows that, the most frequently sighting and the highest rate of encounters (ROE) of the Ocean Sunfish were in Crystal Bay (Figure 4) [8].

![Graph showing rate of encounters (ROE) of the Ocean Sunfish in Nusa Penida waters during August to October 2014.](image)

Figure 4. Rate of encounters (ROE) of the Ocean Sunfish in Nusa Penida waters during August to October 2014 [8].

This higher occurrence of the Ocean Sunfish in Nusa Penida waters coincided with the lower SST recorded from data loggers (HOBO) and remote sensing data (MODIS) at the early of boreal summer (September-November) (Figure 3a and b). In this period, the distribution of Chl-a concentration reaches up to 2.5 mg m\(^{-3}\) in surrounding Nusa Penida waters (Figure 3c). This lower SST and higher abundance of Chl-a characterized that there are upwelling process at surrounding area [3-6]. Possibly, this area supplies phytoplankton as the feed for the gelatinous zooplankton that triggers the Ocean Sunfish activities at surrounding area. Previous works found that the Ocean Sunfish is distinguished by their role in the marine food web, its primarily consume gelatinous zooplankton [11-13].
4. Conclusion
The variability of SST in the southern waters of Nusa Penida influenced by monsoon and upwelling phenomena that lifted cold-water mass and also high concentration of Chl-a. In boreal summer 2014, the higher occurrences of the Ocean Sunfish in Nusa Penida waters coincided with the lower temperatures and the higher Chl-a concentration.

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