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Variability of Coastal Upwelling and Its Correlation with El Niño Southern Oscillation (ENSO) in the Maluku Sea

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Abstract: Upwelling has important value for marine ecosystems and fisheries businesses because it can increase marine primary productivity and capture fisheries productivity. The objective of this research was to analyze the spatial and temporal variability of coastal upwelling in the Maluku Sea and its relationship to the El Niño Southern Oscillation (ENSO) during 2010-2020 periods. The research location was in the Maluku Sea at coordinates 123º W - 128º E and 2.5º N to -2º S. Upwelling events were analyzed using the seasonal upwelling index, wind variability, sea surface temperature, and chlorophyll-a concentration. The influence of ENSO on upwelling events was analyzed spatially and temporally during the El Nino events (2015 – 2016) and La Nina events (2010 – 2011). The results of the analysis showed that coastal upwelling in the Maluku Sea occured once a year so it was categorized as a periodic upwelling type. Coastal upwelling in the Maluku Sea took place during the Australian monsoon (June, July and August or JJA). The highest upwelling intensity with >15 $m^3/s/100$ m coastline was observed in the Bacan - Obi - Sanana waters, Banggai - Taliabu waters, and Bitung waters. ENSO events modulated the intensity of coastal upwelling in the waters of the Maluku Sea; where La Nina decreased coastal upwelling intensity marked by an increase in sea surface temperature and a decreasing chlorophyll-a concentrations, whereas El Nino increased coastal upwelling intensity marked by a decrease in sea surface temperatures and increasing chlorophyll-a concentrations. .

Keywords: Coastal upwelling, ENSO, Wind, Chlorophyll-a, Sea surface temperature, Maluku Sea

INTRODUCTION

Upwelling is an event where water masses rise from the bottom layer to the surface of the waters (Nontji, 2007; Purba & Pranowo, 2015). The effects of wind and Ekman divergence are what cause the upwelling process. Wind that blows continuously at high speed for a long time parallel to the coastline and is influenced by the Coriolis force due to the rotation of the earth, which causes water masses to move away from the coast is called Ekman divergence. In the northern hemisphere the current will be bent to the right from the wind direction, while in the southern hemisphere the current will be bent to the left from the wind direction. Surface water that moves away from the coast will experience a vacuum at the surface so that it is filled by water from the lower layer which is cold. This cold water is rich in nutrients, making the waters of upwelling areas have high fertility (Stewart, 2002; Hendiarti et al., 2004; Painter et al., 2021).

Coastal upwelling is a type of upwelling that has a lot of influence on fisheries productivity around the world (Kämpf and Chapman, 2016; García-Seoane et al., 2023; Simons and Catlett., 2023). Upwelling areas are interesting to study because upwelling areas are fertile waters with high primary productivity so they have high fisheries productivity (Kunarso et al., 2005; Kunarso et al., 2021). Several studies state that upwelling areas have the highest total fish production compared to offshore waters and coastal waters without upwelling. Upwelling areas are only found around one percent (1%) of the world's sea surface area but support more than 20% of world fisheries productivity (Mann, 2000; Lohrenz et al., 2002; Malone et al., 2016; Thunell et al., 2007; Fennel & Wilkin 2009; Levin et al., 2015; Mazwane et al., 2022). Accurate predictions of upwelling areas can be used as indicators to determine potential fishing zones (Anggraeni et al., 2017). However, information about the existence of upwelling in Indonesia is still rarely used by fishermen in planning fishing operations. This is because information about the location and time of upwelling is still limited, and fishing businesses, especially traditional fishermen, do not yet understand that upwelling events are an important indicator in fishing zones (Simbolon, 2019).

Monsoon variability typically has an impact on upwelling in Indonesia. During the east monsoon, strong winds blowing from the east to the south are one of the factors generating upwelling in the waters of the Maluku Sea (Setiawan and Habibi 2011). The intensity of upwelling will increase when wind friction becomes stronger and lasts for a long time. Apart from inter-seasonal variability, annual variability (ENSO) also has a significant influence on upwelling variability in the waters of the Maluku Sea. Susanto and Marra (2005) stated that the strong and weak intensity of upwelling in various Indonesian waters is closely related to the El Niño Southern Oscillation (ENSO) phenomenon, which consists of El Nino and La Nina. El Nino occurs when masses of warm water move eastward away from the waters of northern Papua due to weakening trade winds, whereas during La Nina the opposite occurs.

ENSO is a global-scale ocean atmosphere interaction phenomenon that has a broad impact on the dynamics of Indonesian seas, including the Maluku Sea. One significant impact is the increase in trade wind speed during La Nina. This increase in trade wind speed has an impact on increasing sea surface temperatures, thickening the thermocline layer, and decreasing meridional wind speed in eastern Indonesia. If these conditions occur, it will affect upwelling variability in the waters of the Maluku Sea.

Several studies of coastal upwelling in Indonesian waters are Susanto et al., 2001; Susanto et al., 2006; Susanto and Marra, 2005; Iskandar et al., 2009; Wirasatriya et al., 2018; Silubun et al., 2015; Yoga et al., 2014; Wirasatriya et al., 2020 along the southern coast of Java, Setiawan and Kawamura, 2011; Main et al., 2017 in southern Sulawesi, Ningsih et al., 2013; Setiawan et al., 2020 in the western Lesser Sunda Islands, Kämpf 2015 in the Arafuru Sea, Moore et al., 2003; Gordon and Susanto, 2001; Susanto et al., 2006 in the Banda Sea, and Wirasatriya et al., 2017 analyzed the influence of ENSO on coastal upwelling in the Maluku Sea but the research focus was only during the east monsoon; Rintaka (2015) studied upwelling and its relationship with the abundance of chlorophyll-a in the waters of the Maluku Sea, but the research has not used a longer time series to obtain accurate results.

The Maluku Sea is part of the large eastern Indonesian marine ecosystem which has high fisheries potential and has a strategic role for Indonesian and global fisheries activities

(Triyulianti et al., 2018; Kahn and Fauzi, 2001; Amir et al., 2019; Haikal et al., 2012). However, the level of utilization of fishery resources in this area is not yet optimal due to several factors, one of which is the lack of identification of potential fishing grounds. Potential fishing grounds can be identified through identifying upwelling locations (Anggraeni et al., 2017).

This research aims to analyze the characteristics of coastal upwelling in the Maluku Sea and analyze its relationship with the El Niño Southern Oscillation (ENSO) over a period of 10 years, namely January 2009-December 2018. This study is important in contributing to the management of the marine and fisheries sectors in the North Maluku Province.

METHODOLOGY

Study Area and Data Collection

The research location covered the Maluku Sea at coordinates from 123^{0} to 128^{0}E longitude and 2.5^{0}N to 2^{0}S latitude. Temporal analysis was specifically carried out in three focus study areas, namely area one in Bitung waters with coordinates from 126^{0} to 127^{0}E longitude and 0.5^{0} to 1.5^{0}N latitude, area two in South Halmahera waters with coordinates 126.2^{0} to 127.2^{0}E longitude and 0.8^{0} to 1.8^{0}S latitude (Fig. 1) and area three in Banggai-Taliabu waters with coordinates 123.5^{0} to 124.5^{0}E longitude and 0.8^{0} to 1.8^{0}S latitude. These three areas were chosen because there were indications of coastal upwelling in those areas (Bitung waters studied by Setiawan and Habibi (2011) and South Halmahera waters studied by Wirasatriya et al. (2017); Banggai - Taliabu waters studied by Atmadipoera et al. (2018).

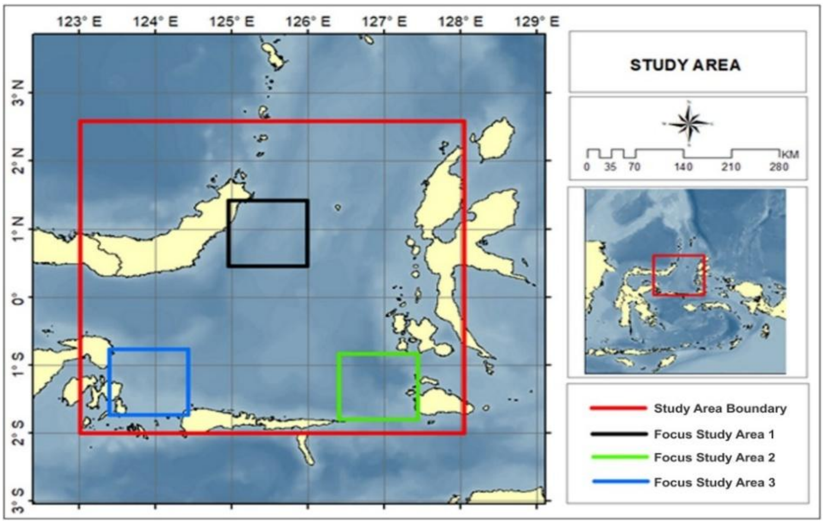


Figure 1: Map of study area in Maluku Sea

The variables data used in the coastal upwelling analysis were wind direction and speed, sea surface temperature, chlorophyll-a concentration, salinity, and ENSO index in the period of January 2010 to December 2020. The data was obtained in NetCDF format from several sources. Wind data was obtained from http://www.ecmwf.int/ with a resolution of 12.5 km, salinity data from http://www.ecmwf.int/ with a resolution of 12.5 km, sea surface temperature and chlorophyll-a data from http://oceancolor.gsfc.nasa.gov/ with a resolution of 4 km, and Nino Index data from http://www.esrl.noaa.gov. The data was then processed using Grads software to produce spatial and temporal data. The ENSO index was obtained from NOAA (National Oceanic and Atmospheric Administration).

Data Analysis

Evident of Coastal Upwelling based on Upwelling Index

The intensity of coastal upwelling was analyzed using the Upwelling Index (UI) with a formula given by Kutsuwada (1998):

$$\tau_x = \rho\ C_D\ W\ u$$

$$\tau_y = \rho\ C_D\ W\ v$$

where, τ_x (kg s^{-2} m^{-1}) is wind friction component parallel to the coastline; τ_y (kg s^{-2} m^{-1}) is wind friction component perpendicular to the coastline; C_D is drag coefficient (1.4 x 10^{-3}); ρ is air density (1.3 kg m^{-3}); W (m s^{-1}) is wind speed; u (m s^{-1}) is wind speed component on the x-axis; and v (m s^{-1}) is wind speed component on the y-axis. The coastal upwelling index was calculated using a formula developed from Ekman's theory (1905), where Ekman transport was analyzed using the Pond and Pickard (1983) equation:

$$M_x = \frac{\tau_y}{f}$$

where, Mx (kg s^{-2} m^{-1}) is Ekman offshore transport mass; τ_y (kg s^{-2} m^{-1}) is wind friction component perpendicular to the coastline; f (rad s^{-1}) is coriolis parameter (2 Ω sin θ); Ω is speed of the earth rotation (7.29 x 10^{-5} rad s^{-1}); and θ is latitude.

The formula for calculating the coastal upwelling index (UI) was based on the Bakun (1975) equation:

$$\mathrm{UI} = M_x \frac{100\ m\ coastline}{1025\,\frac{kg}{m^3}} \left(\frac{\frac{m^3}{s}}{100}\,m\ coastline\right)$$

where, UI (m^3/s/100 m coastline) is coastal upwelling index and Mx (kg s^{-2} m^{-1}) is Ekman offshore transport mass.

The assumption used was that if the Ekman transport value was negative (Ekman's transport offshore) then upwelling was occurring. Conversely, if the Ekman transport value was positive (Ekman's transport onshore), downwelling was occurring.

Evident Coastal Upwelling based on the Variability of Surface Wind, Sea Surface Temperature, Chlorophyll-a Concentration, and Salinity

Several research results explain that coastal upwelling events can be analyzed based on the distribution of sea surface temperature, salinity, and chlorophyll-a concentration (Yunwei et al., 2015; Susanto et al. 2001; Susanto and Marra, 2005). Analysis of coastal upwelling events using composite data in the period 2010-2020 followed Nur'utami and Hidayat (2015) method. Surface wind, sea surface temperature, salinity and chlorophyll-a data were analyzed compositely for each month and then grouped into four seasons, namely West Season or Asian monsoon (December - January - February or DJF), Transition Season I (March

- April - May or MAM), East Season or Australian monsoon (June – July - August or JJA), and Transition Season II (September - October - November or SON).

Analysis of the Influence of ENSO on Upwelling Intensity

The intensity of ENSO events during the period 2010 – 2020 was analyzed temporally based on the Nino 3.4 index. Positive values indicated the occurrence of the El-Nino episodes, while negative values indicated the occurrence of the La-Nina episodes. Then a spatial analysis was carried out for water conditions during the El-Nino and the La Nina event. The results were compared to normal conditions by calculating anomaly values during strong El Nino and La Nina events. This anomaly value showed the influence of ENSO on coastal upwelling intensity in the Maluku Sea.

Analysis of the relationship between ENSO and oceanographic parameters used a spatial-temporal analysis approach and correlation analysis. The spatial-temporal analysis focused on the three study areas. Temporal analysis would display fluctuation patterns between ENSO and oceanographic parameters and the intensity of coastal upwelling. Correlation analysis was used to display the relationship between the dependent variable (ENSO) and the independent variables (Upwelling Index and oceanographic parameters including wind, sea surface temperature, salinity and chlorophyll-a). Correlation analysis used the following equation:

$$r = \frac{n\sqrt{XY} - (\sum X)(\sum Y)}{\sqrt{\{n\sum x^2 - (\sum x)^2\}\{n\sum Y^2 - (\sum Y)^2\}}}$$

where, n is amount of data; *X* is independent variable; and *Y* is a dependent variable. The degree of relationship were divided into five categories based on Irianto (2006), they were: the correlation value of 0.00 to 0.20 indicated no correlation, 0.21 to 0.40 indicated weak correlation, 0.41 to 0.60 indicated medium correlation, 0.61 to 0.80 indicated strong correlation, and 0.81 to 1.00 indicated perfect correlation.

RESULTS AND DISCUSSION

Coastal Upwelling Evidence based on the Upwelling Index

The results of data analysis showed that the wind friction value did not deflect the direction of Ekman transport since its direction tended to be the same as the wind direction. Therefore, the wind components perpendicular to the coastline used were ignored in the calculations. This is in accordance with Atmadipoera et al. (2018) and Utama et al. (2017), who stated that the Coriolis Effect can be ignored in locations close to the equator. Thus, the main driving factor for coastal upwelling in this study was the intensity of surface wind friction. Figure 2 shows the distribution of coastal upwelling intensity in the Maluku Sea in four seasons during 2010 - 2020. The results of Upwelling Index analysis showed that coastal upwelling in the Maluku Sea occurred during the December-January-February (DJF), June-July-August (JJA) and September-October-November (SON) with different intensities and locations of events. During the DJF period, coastal upwelling with an index value of 8 $m^3/s/100$ m coastline occurred in the western waters of Ternate Island, while during the SON period coastal upwelling with an index value of 5 $m^3/s/100$ m coastline occurred in the

Banggai-Taliabu waters. Coastal upwelling with the highest intensity (≥ 10 m3/s/100 m coastlines) occurred during the JJA period over a fairly large area, namely Bacan - Obi - Sanana waters, Banggai - Taliabu waters and Bitung waters. The results of analysis of annual composite data between the period 2010-2020 showed that an upwelling index with an intensity of ≥ 10 m3/s/100 m coastline was found in the DJF periods of 2010, 2015 and 2016, 2010-2020 JJA (except 2010, where the La Nina episod occurred), and SON season of 2015. These conditions indicated that upwelling with strong intensity occurred during the JJA period in the Bacan - Obi - Sanana waters, Banggai - Taliabu waters, and Bitung waters. In the DJF and SON periods, coastal upwelling only appeared when the El Nino episod occurred. Meanwhile, during the MAM period, there was no indication of upwelling, either during El Nino or under normal conditions. The highest upwelling index value in the Maluku Sea was observed during the JJA season, similar to the research results of Setiawan and Habibi (2011) which stated that during the JJA period, winds from the south moved quite intensively which caused coastal upwelling in the Maluku Sea.

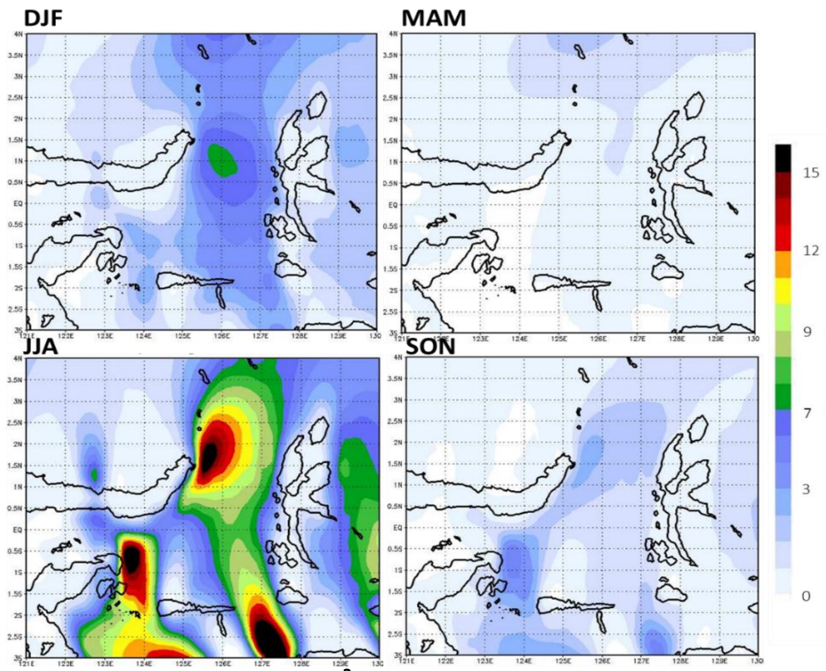


Figure 2: Seasonal Upwelling Index ($m^3/s/100$ m coastline) in the Maluku Sea during the periode 2010-2020

Coastal Upwelling Evidence Based on the Variability of Surface Wind, Sea Surface Temperature, Salinity and Chlorophyll-a

Surface Wind Variability

The dynamics of the sea surface waters of the Maluku Sea are influenced by monsoons which blows from the South during the Australian monsoon (JJA) and from the North during the Asian monsoon (DJF). The main influence of this monsoon is the weakening of trade winds along the equator, which hence influences the strength of seasonal wind gusts in the region (Harsono, 2014). Wind blowing over the sea surface can induce other physical parameters in the form of heat and momentum transfer between the ocean and the atmosphere. This condition is the main driving factor for circulation at the sea surface layers, including upwelling occurrences (Ndah et al., 2017). Figure 3 is the result of a composite analysis of seasoan surface wind direction and speed in the waters of the Maluku Sea. During the DJF period, the wind generally came from the North with a maximum speed of 4.0 m/s. The maximum wind speed was found in the waters west of Ternate and Obi waters. During the MAM and SON periods, wind speeds were generally weak throughout almost the entire Maluku Sea area.

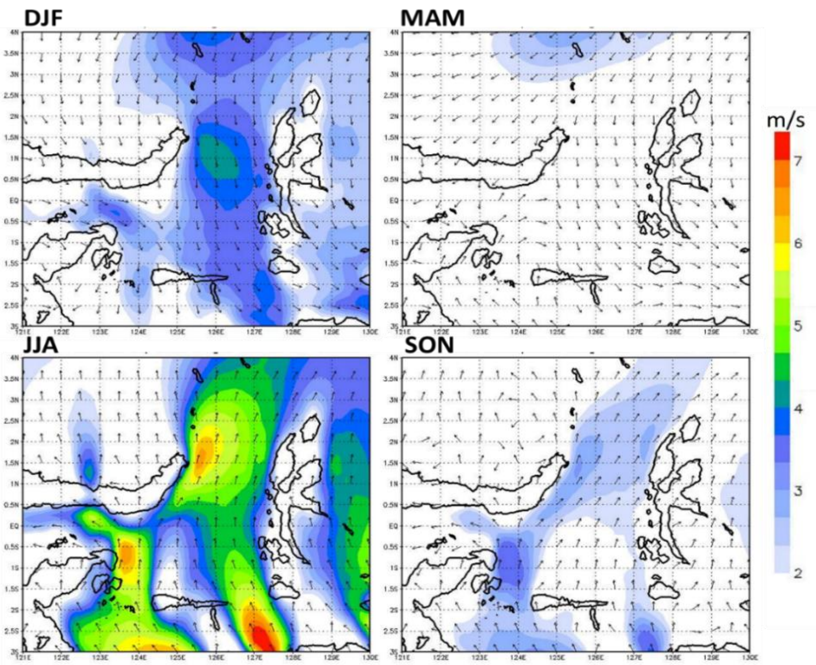


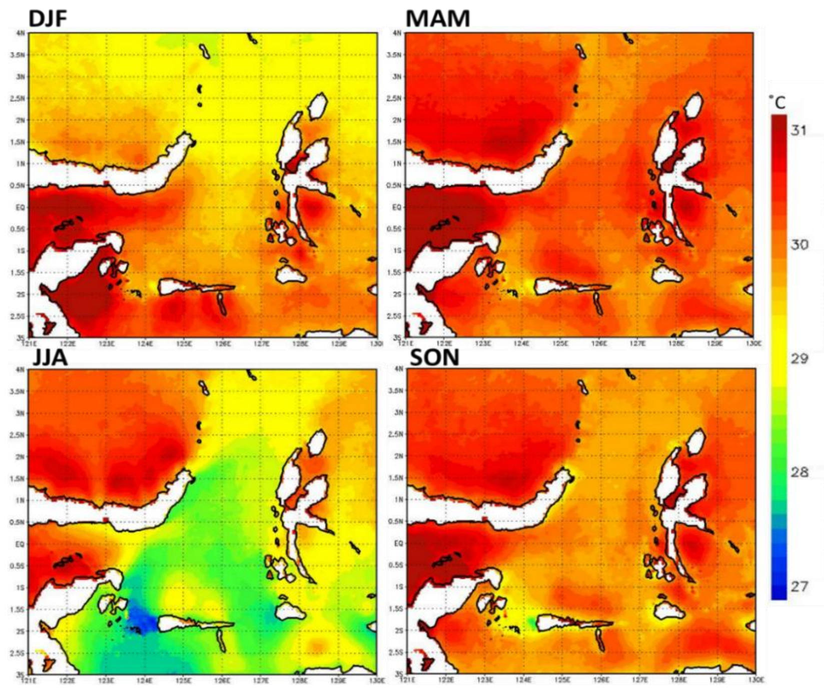
Figure 3: Seasonal surface wind direction and speed (m/s) in the Maluku Sea during 2010-2020

During the JJA period, winds generally blew from the South with a maximum speed of more than 7 m/s. The increase in wind speed occurred in most of the Maluku Sea waters, namely in Bacan - Obi - Sanana waters, Banggai - Taliabu waters, and Bitung waters. Based on analysis of annual composite data, wind speeds were ≥ 5 m/s in the JJA period except in 2010, at which time there was a La Nina episod. Meanwhile, a significant increase in wind speed occurred during the 2015 JJA period caused by the El Nino event.

High wind speeds during the JJA period triggered coastal upwelling in the Maluku Sea. This is in accordance with the opinions of Anom (2017) and Ashok et al. (2007) stating that wind power applied to the surface layer of water can generate surface currents which have a speed of around 2% of the wind speed itself. Another opinion that is in line with the results of this research is Atmadipoera et al. (2018) explain that upwelling events in the Maluku Sea are influenced by strong and persistent wind pressure that occurs from June to October during the Australian monsoon. Sihotang et al. (2018) also explain that the upwelling events in the Halmahera Sea occur during the East Season, namely from June to August, with an average wind speed reaching 4.994 m/s.

Sea Surface Temperature (SST) Variability

SST is an important parameter used to detect coastal upwelling. The location of upwelling can be detected through the spatial distribution of SST with the criteria that the SST is cooler than the surrounding area with a gradient of >2^{0}C (LAPAN, 2003; Qu et al., 2005). This low sea surface temperature is the result of the lifting of water masses from deep layers to the surface (Kämpf and Chapman, 2016).



<u>Figure 4</u>: Seasonal sea surface temperature (°C) in the Maluku Sea during the periode 2010-2020

The composite results of the SST distribution during the four seasons are shown in Figure 4. The highest SST distribution was found in the MAM and SON periods with an average value of > 29.5 ^{0}C. The results of analysis of annual composite data during the 2009-2018 period showed that SST values in the MAM period tended to be stable, while in the SON period it experienced a decline where SST values ranged between 27 - 29.5^{0}C due to the strong El Nino phenomenon in 2010 and 2015. This showed that there was no indication of upwelling during the MAM period, whereas during the SON period, upwelling occured when there were other driving factors, in this case El Nino.

The annual sea surface temperature composite results for the period 2010-2020 showed that during the DJF period, the sea surface temperature distribution ranged between 29 – 30 ^{0}C. The lowest sea surface temperature with a value of 29 ^{0}C was found in the northern waters of the Maluku Sea, while the sea surface temperature with a value of 30 ^{0}C was found in the central and southern parts of the Maluku Sea. Variability in sea surface temperature during the DJF period tends to fluctuate. The highest increase sea surface temperature occurred in the DJF period in 2011, where during this period sea surface temperatures with values ≥30 ^{0}C were spread throughout almost all waters of the Maluku Sea. Similar to SON period, sea surface temperature in the DJF period also decreased to 27.5 – 29.5 ^{0}C when El Nino occurred in 2010 and 2016, especially in the northern waters of the Maluku Sea. This indicated that during the DJF period, upwelling had potential to occur, especially during El Nino event. Upwelling areas observed in the DJF period during El Nino event were Morotai and Loloda waters.

The lowest value of sea surface temperature distribution was found in the JJA period (27 – 28 ^{0}C) which was evenly distributed in almost all Maluku Sea, especially in Bacan - Obi - Sanana waters, Banggai - Taliabu waters, and Bitung waters. Based on annual composite data, sea surface temperature during the JJA period increased during La Nina 2010 and decreased significantly during El Nino 2015. The low sea surface temperature during the JJA period was a strong indication of coastal upwelling during that period. This was in accordance with Wirasatriya et al. (2017) reporting that during the southeast monsoon period the sea surface temperature in the Maluku Sea experiences cooling which was an indication of upwelling. Kemili and Putri (2012) stated that upwelling in the Maluku Sea occured in East Season with a duration of 2-3 months and was characterized by a decrease in temperature ranging from 0.5 - 1.8 ^{0}C below the annual average.

Salinity Variability

Salinity is an indicator for identifying upwelling-downwelling phenomena in waters by looking at the increase or decrease in salinity in the surrounding area (Wardani et al., 2013). The seasonal distribution of salinity in the Maluku Sea is presented in Figure 5. In the DJF period, the distribution of salinity in the Maluku Sea during the 2009-2018 period ranged between 33.5 – 33.9 ‰, this range was evenly distributed almost throughout the Maluku Sea. During the MAM period, salinity generally decreased, especially in the Bacan - Obi - Sanana waters and the Banggai - Taliabu waters. The lowest salinity value in the Maluku Sea was found in the MAM period, namely ranging from 33.3 – 33.6 ‰. During the JJA period, the salinity of the Maluku Sea waters ranged between 33.5 – 34 ‰. The highest salinity was found in the SON period, namely 34 – 34.2 ‰. The distribution of high salinity with a value of ≥ 34 ‰ was obtained during the JJA period which was spread evenly throughout almost all waters of the Maluku Sea.

Based on analysis of annual composite data for the period 2010-2020, it was found that salinity in the MAM period tended to be stable at a low value, namely ≤ 33.6 ‰. During the MAM period, there was quite a bit of rainfall, which led to this condition. The pattern of the rainy season in the Maluku Sea is included in the equatorial type, namely that during one year there are two peak rainy seasons with the highest rainfall in the MAM period (BMKG, 2011). This condition was in accordance with (Patty, 2013; Tongkukut, 2011) findings that one of the determining factors of salinity in North Sulawesi waters were rainfall and wind. High rainfall causes salinity in North Sulawesi waters to be low. In contrast to the MAM period, salinity in the DJF, JJA and SON periods during the 2010-2020 tended to fluctuate, increasing during El Nino (2015 - 2016) and decreasing when La Nina (2011). The spatial distribution of salinity with high values ≥ 34.2 ‰ was obtained during the JJA and SON periods which were concentrated in coastal waters, this was an indication of the occurrence of a coastal upwelling phenomenon. This condition was in accordance with Schneider et al. (2017), reporting that surface salinity in Chilean coastal waters during the upwelling season (occurring in summer) tended to be high, ranging between 34.0 – 34.5‰, while surface salinity tended to be low ≤ (33.6 ‰) during the rainy season.

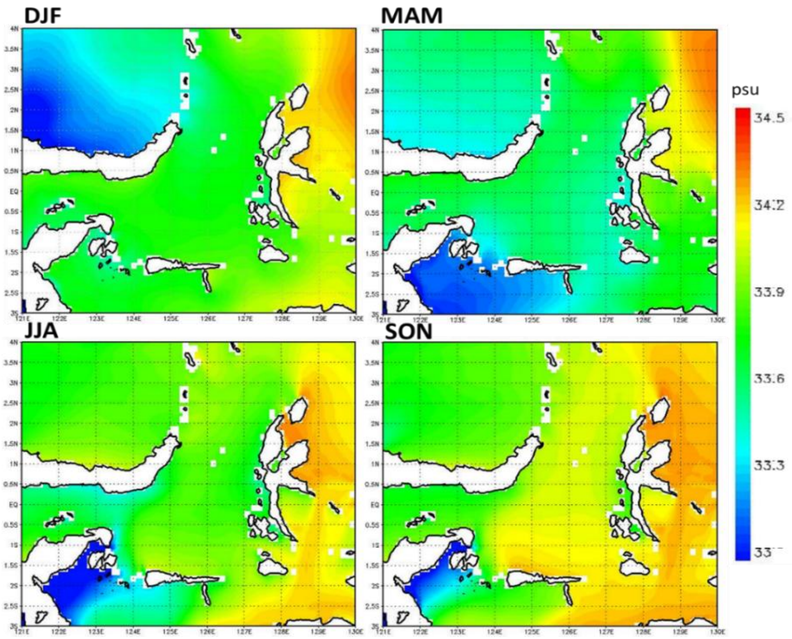


Figure 5: Seasonal surface salinity (‰) in the Maluku Sea during the periode 2010-2020

Chlorophyll-a Variability

One of the criteria used to estimate the upwelling phenomenon is the chlorophyll content in a body of water which is higher than the surrounding area (Simbolon, 2019). Figure 6 is a composite image of chlorophyll-a concentration distribution for four seasons in the Maluku Sea. The lowest chlorophyll-a concentration (≤ 0.4 mg/m^3) was found in the transition period of MAM and SON. Meanwhile, the highest chlorophyll-a concentration was found in the JJA season. Chlorophyll-a concentrations with a value of ≥ 0.5 mg/m^3 in the JJA season were spread throughout almost all the Maluku Sea area, especially Bacan - Obi - Sanana waters, Banggai - Taliabu waters, and Bitung waters. High chlorophyll-a concentration during the JJA period was concentrated near coastal waters and extended to the open ocean, this condition was not found in other periods (DJF, MMA or SON). This was a strong indication that during the JJA period, coastal upwelling occurred, characterized by increasing concentrations of chlorophyll-a in the coastal waters and moving it to offshore waters. This analysis was in accordance with Simbolon (2019) that found concentration of chlorophyll-a in coastal waters tended to be higher due to the supply of nutrients originating from run off of organic material, while the high content of chlorophyll-a in waters far from land (offshore areas) was the result of the dynamic process of water masses, namely upwelling (Alimina & Simbolon, 2007).

The results of analysis of annual composite data for the period 2010-2020 showed that chlorophyll-a concentrations with values ≥ 0.5 mg/m^3 were found in the DJF period of 2010 and 2016, the JJA period throughout 2009 – 2018, and the SON period of 2015. Those conditions indicated that coastal upwelling occurred during the JJA period in the Bacan - Obi - Sanana waters, Banggai - Taliabu waters, and Bitung waters. During the DJF period (especially in the Loloda - Morotai waters) and SON (especially in the Banggai - Taliabu waters), indications of coastal upwelling appeared in the El Nino episode. Meanwhile, during the MAM period, there was no indication of upwelling, either during El Nino or under normal conditions. The high chlorophyll-a concentration during the JJA period in the Maluku Sea was a strong indication of coastal upwelling. This condition was in accordance with (Setiawan & Habibi, 2011; Wirasatriya et al., 2017; Atmadipoera et al., 2018) that found high concentrations of chlorophyll-a in the Maluku Sea (≥ 0.5 mg/m^3) occured during the Eastern Monsoon seasons caused by coastal upwelling.

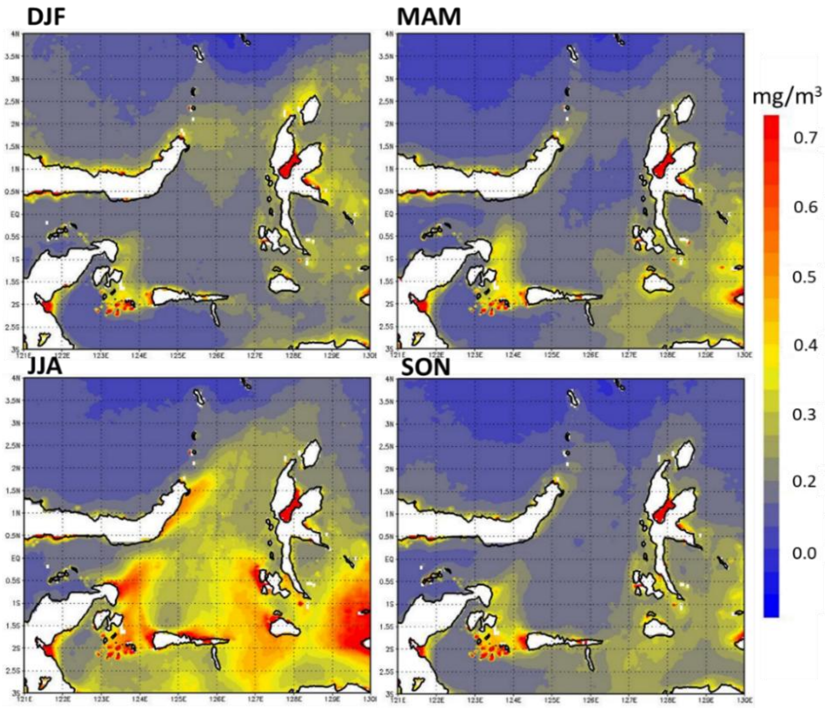


Figure 6: Seasonal chlorophyll-a (mg/m^3) in the Maluku Sea during the periode 2010-2020

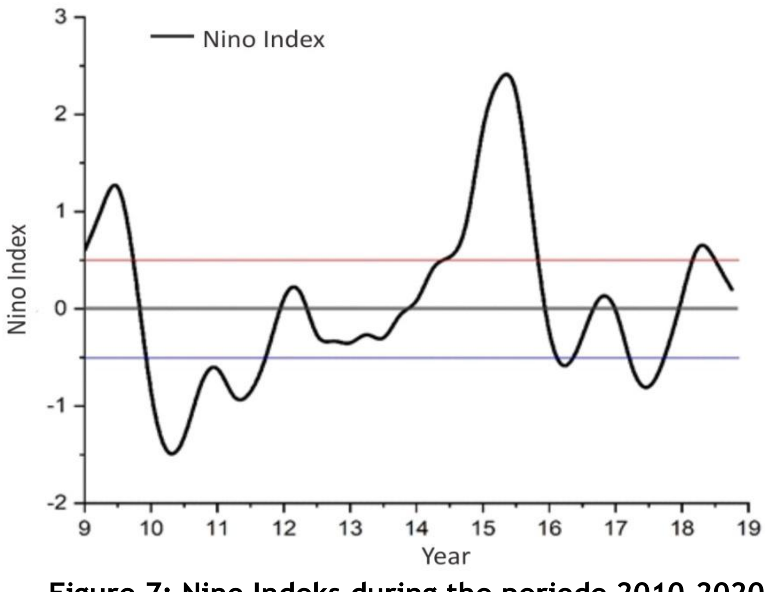
Based on the research data, the MAM and SON seasons showed the lowest wind speed, high sea surface temperature, and low chlorophyll-a concentration. During the DJF and JJA seasons, wind speed increased especially during the JJA period. The increased wind speed in the JJA season was followed by a decreased sea surface temperature and an increased chlorophyll-a concentrations in all focus study areas, Bacan - Obi - Sanana, Banggai – Taliabu, and Bitung areas. This condition indicated that the strong Australian monsoon winds had an effect on increasing the intensity of coastal upwelling, which was characterized by low sea surface temperature and high chlorophyll-a concentrations. The results of this study were in accordance with Setiawan and Habibi (2011), that the monsoon influenced the variability of chlorophyll-a concentrations and sea surface temperatures in the Maluku Sea. During the Australian monsoon period, Southern winds lowered the sea surface temperature that enabling mechanical mixing and in turn increasing chlorophyll-a concentrations in surface layers. The low sea surface temperatures, high surface wind speeds, and increasing chlorophyll-a concentrations were indications of coastal upwelling (Ratnawati et al., 2016). Thus, it can be said that the main driving factor for coastal upwelling in the Maluku Sea is a strong Australian monsoon, which shifts the sea surface layers northward, parallel to the wind direction. This condition occurs because the Maluku Sea is close to the equator, so the Coriolis effect can be ignored (Atmadipoera et al., 2018). The coastal upwelling that occurs in the Maluku Sea is a periodic type of upwelling, namely occurs only in a certain season of the year.

In theory, the upwelling process can result when there is a decreasing sea surface temperature and an increasing in chlorophyll-a and salinity in the waters (Li et al., 2020). However, salinity variability during the four seasonal periods in the Maluku Sea did not appear to have the same response when compared with other oceanographic parameters observed in this study (wind, sea surface temperature and chlorophyll-a). In this study, salinity has a longer response to the upwelling process compared to the response of sea surface temperature and chlorophyll-a parameters. When coastal upwelling occurred during the JJA season, sea surface temperature decreased and chlorophyll-a increased significantly; while in the following season (SON), salinity had a significant increase due to a delay in response to changes in salinity brought about by the coastal upwelling process.

Effect of ENSO on Coastal Upwelling Intensity

Spatial Analysis of Coastal Upwelling Indicator Variables during Normal, El Nino and La Nina Conditions

El Nino and La Nina events in Indonesia can be observed from the Nino 3.4 index as the average sea surface temperature anomaly in the Nino 3.4 region (Susanto and Marra, 2005). Positive values indicate El Nino episodes while negative values indicate La Nina episodes. NOAA (National Oceanic and Atmospheric Administration) groups the intensity of El Nino or La Nina events based on the Nino index value. El Nino with a weak intensity is at a value of 0.5 – 1, El Nino with a medium intensity is at a value of 1 – 1.5 and El Nino with a strong intensity is when the Nino index is above 1.5.



<u>Figure 7:</u> Nino Indeks during the periode 2010-2020

Meanwhile, La Nina with a weak intensity is at -0.5 – (1), La Nina with a medium intensity is at a value of -1 – (-1.5) and La Nina with a strong intensity is when the Nino index above is below -1.5. Figure 7 shows the Nino index during the period 2010-2020. During this period there were several El Nino and La Nina episodes with varying intensities. The lowest value occurred during 2010 – 2011 with a Nino index value of -1.6 which indicates the occurrence of La Nina with strong intensity. Meanwhile, the highest value occurred during the 2015 - 2016 period with a value of 2.5, which indicates the occurrence of an El Nino with strong intensity.

During the El Nino in 2015-2016, wind speed increased quite significantly with the dominant gust direction blowing from the north and from the south. This condition is caused by an increase in pressure gradients in the northern Maluku Sea (Wirasatriya et al., 2017) and a weakening of zonal winds during El Nino conditions (Atmadipoera et al., 2018; Martono, 2017).

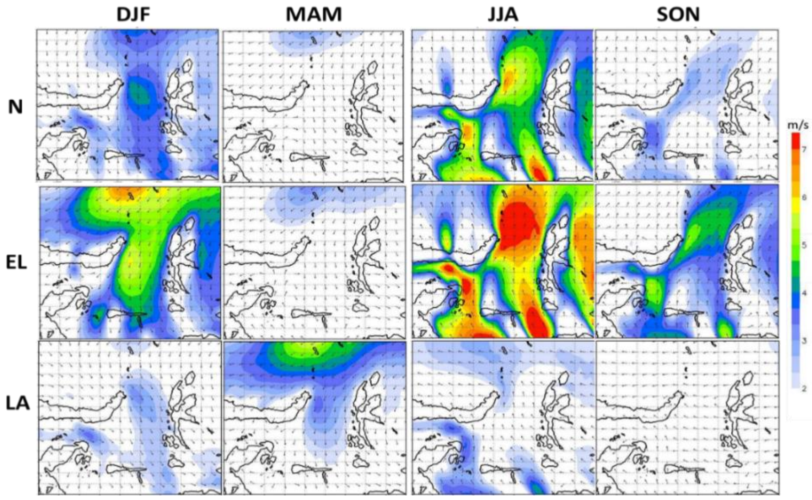


Figure 8: Spatial analysis of surface wind direction and speed under normal (N) condition, El Nino (EL) 2015-2016 and La Nina (LA) 2010 – 2011

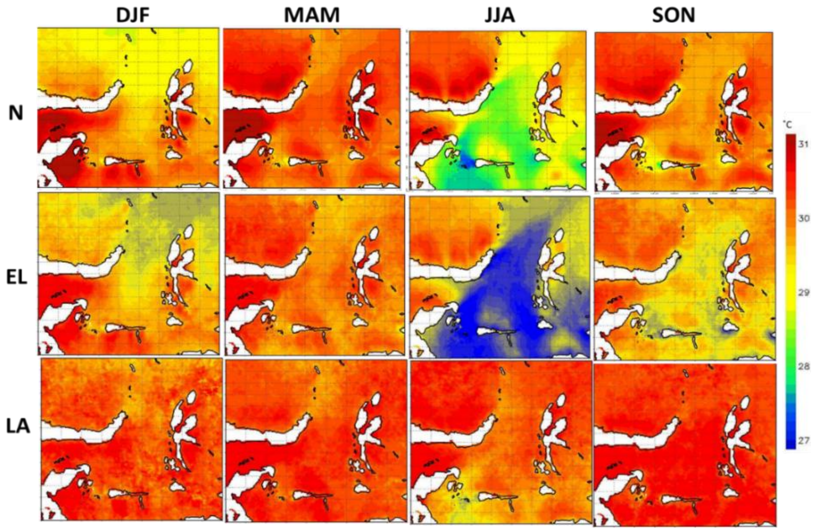


Figure 9: Spatial analysis of sea surface temperature under normal (N) condition, El Nino (EL) 2015-2016 and La Nina (LA) 2010 – 2011

An increase in wind speed in the waters of the Maluku Sea during El Nino is accompanied by a decrease in SST and an increase in chlorophyll-a concentration. The intensity of the decrease in sea surface temperature and increase in chlorophyll-a during El

Nino appears significant in the JJA period. The distribution of sea surface temperature with a value of ≤ 27 ^{0}C and a chlorophyll-a concentration of ≥ 0.5 mg/m^3 appears to be widespread in almost all waters of the Maluku Sea in the JJA period during El Nino. This condition occurs because during the JJA period the wind blows from the south, so that the surface currents that appear result in wind friction that moves towards wider northern waters that are not blocked by islands. This was in line with Wirasatriya et al., 2017, that during El Nino, the distribution of sea surface temperature with values lower than 27.5 ^{0}C and chlorophyll –a with values greater than 0.5 mg/m^3 experienced regional expansion. This also indicates that during El Nino, high wind speeds were the main driving factor for coastal upwelling in the Maluku Sea, which was characterized by a decrease in sea surface temperature and an increase in chlorophyll-a compared to normal conditions.

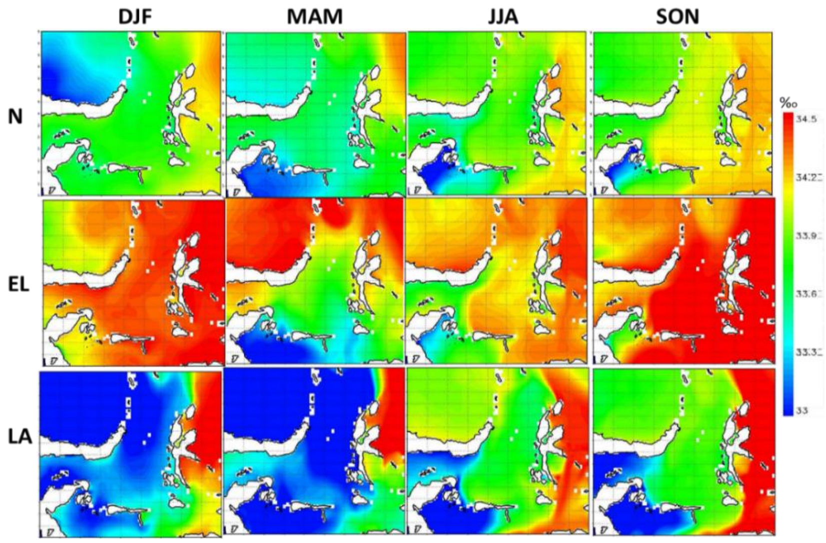


Figure 10: Spatial analysis of surface salinity under normal (N) condition, El Nino (EL) 2015-2016 and La Nina (LA) 2010 – 2011

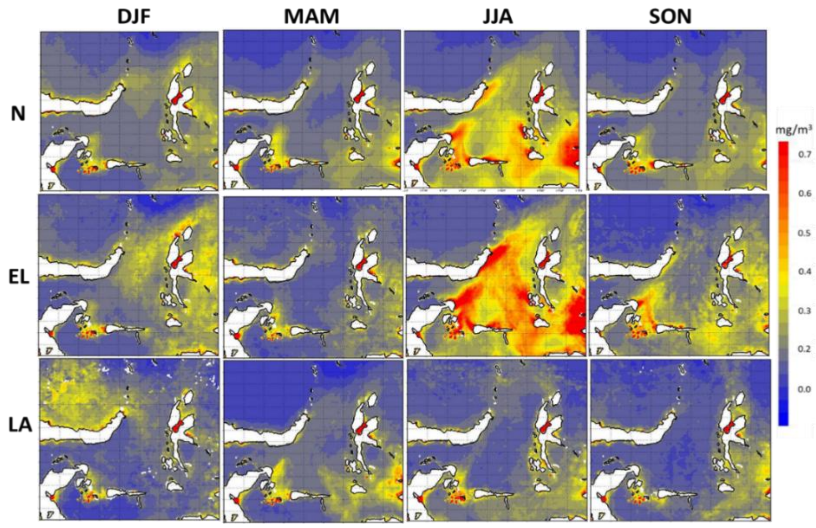


Figure 11: Spatial analysis of chlorophyll under normal (N) condition, El Nino (EL) 2015-2016 and La Nina (LA) 2010 – 2011

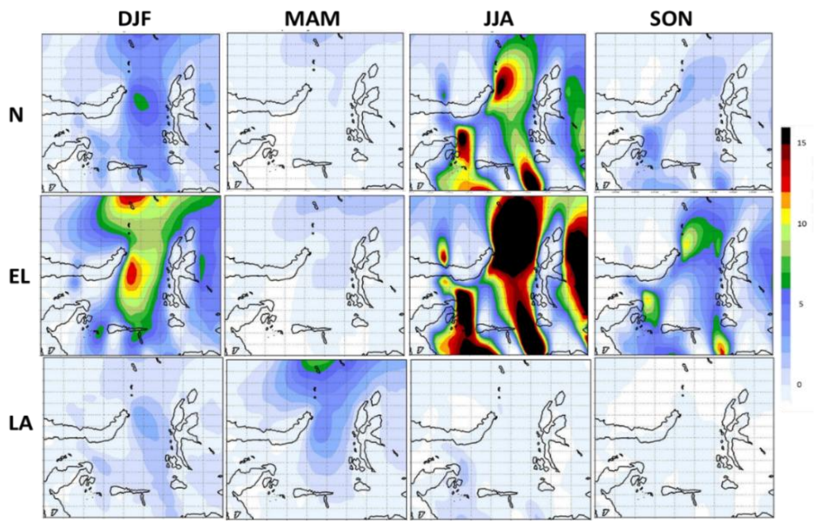


Figure 12: Spatial analysis of upwelling index under normal (N) condition, El Nino (EL) 2015-2016 and La Nina (LA) 2010 – 2011

During the La Nina period of 2010-2011, wind speeds tended to decrease below normal conditions in varying directions. During the DJF and JJA periods, the dominant wind direction blows from the north and from the south, while during the MAM and SON periods the dominant wind direction blows from the west and from the east. This happens because during La Nina conditions, zonal wind speed increases (Atmadipoera et al., 2018). During La Nina, surface wind speed weakens, followed by increasing SST and decreasing chlorophyll-a concentrations. An increase in SST and a decrease in chlorophyll-a during La Nina were also observed in the JJA period, which indicates coastal upwelling occurred during that period. SST distribution with values ≤ 27 ^{0}C and chlorophyll-a concentrations ≥ 0.5 mg/m^3 was not seen in the waters of the Maluku Sea during the JJA period during La Nina. This was in line with Wirasatriya et al., 2017, that during El Nino, the distribution of sea surface temperature with values lower than 27.5 ^{0}C and chlorophyll-a with values greater than 0.5 mg/m^3 occures in a smaller area. This condition indicates that during the 2010-2011 La Nina conditions, the coastal upwelling phenomenon in the waters of the Maluku Sea experienced a decrease in intensity, marked by an increase in sea surface temperature and a decrease in chlorophyll-a compared to normal conditions. Apart from low wind speed which is the main driving factor, deeper thermocline layers during La Nina have the impact of decreasing chlorophyll-a content in the surface layer (Aldrian, 2008).

Temporal Analysis of Coastal Upwelling Indicator Variables and its Relationship with ENSO

The results of the temporal analysis of zonal wind speed and Nino Index are shown in Figure 13. In general, study area 1 showed the same pattern between meridional wind speed and ENSO. This pattern was seen more clearly when there was a strong La Nina in 2010 - 2011 and a strong El Nino in 2015 - 2016. The correlation value between zonal wind speed and the Nino index in study area 1 was 0.38 with a significance value of 0.1, indicating the influence of ENSO on zonal wind speed in study area 1 although the influence was weak. Meanwhile, wind speed in study areas 2 and 3 did not appear to have a significant relationship with ENSO. This was caused by geographical position of study areas 2 and 3 in the western region of Halmahera Island so that the tradewinds blowing from the Pacific Ocean were blocked by Halmahera Island. In contrast to study area 1, which was located in the north bordering directly with the West Pacific Ocean, so the trade winds influenced the zonal wind speed in that study area.

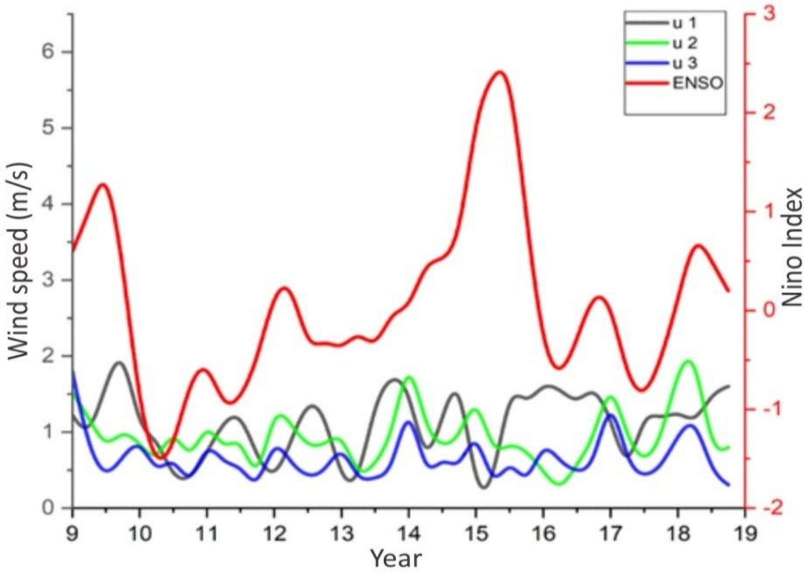


Figure 13: Correlation of zonal wind speed and Nino Index during the period 2010 – 2020 (u1 is zonal wind speed in study area 1, u2 is zonal wind speed in study area 2 and u3 is zonal wind speed in study area 3)

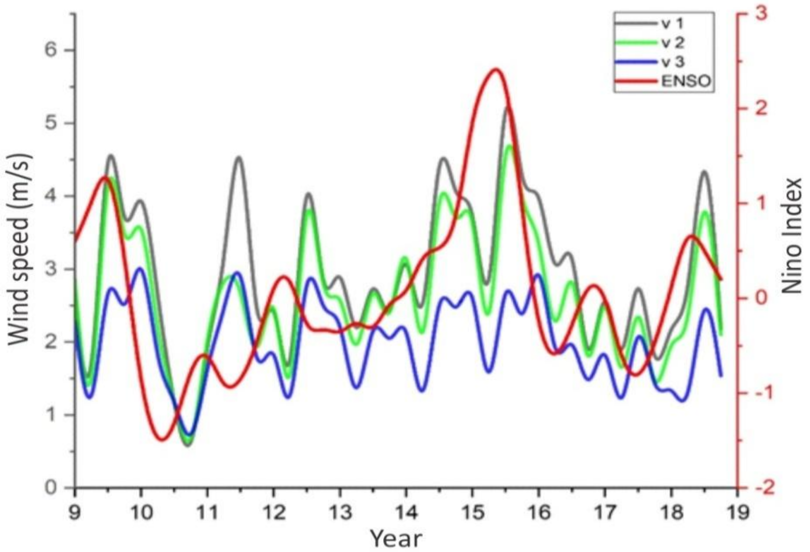


Figure 14: Correlation of meridional wind speed and Nino Index during the period 2010 - 2020 (v1 is meridional wind speed in study area 1, v2 is meridional wind speed in study area 2 and v3 is meridional wind speed in study area 3)

The temporal relationship between meridional wind speed and the Nino Index is presented in Figure 14. Study areas 1 and 2 have almost the same pattern as the Nino Index, while study area three forms a different pattern, especially during the 2010 - 2011 and 2017 - 2018 La Nina events. Correlation analysis shows that study areas 1 and 2 have correlation values of 0.5 and 0.46 respectively with significance values of 0.001 and 0.003 respectively indicating that there is a relationship with a moderate level of correlation with ENSO.

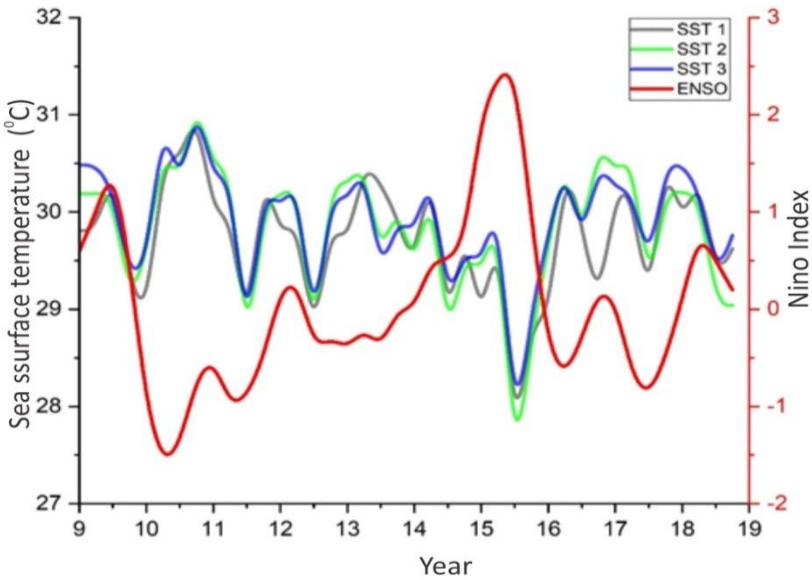
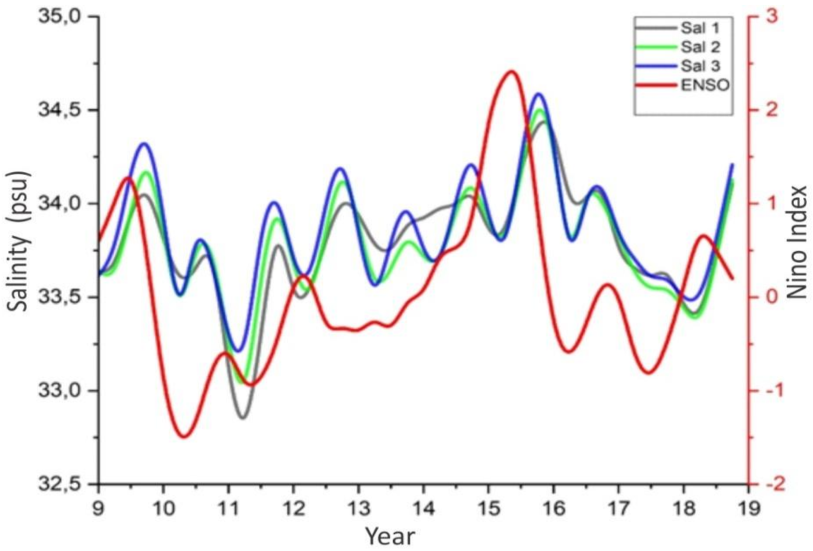


Figure 15: Correlation of sea surface temperature and Nino Index during the period 2010 – 2020 (SST1 is sea surface temperature in study area 1, SST2 is sea surface temperature in study area 2 and SST3 is sea surface temperature in study area 3)

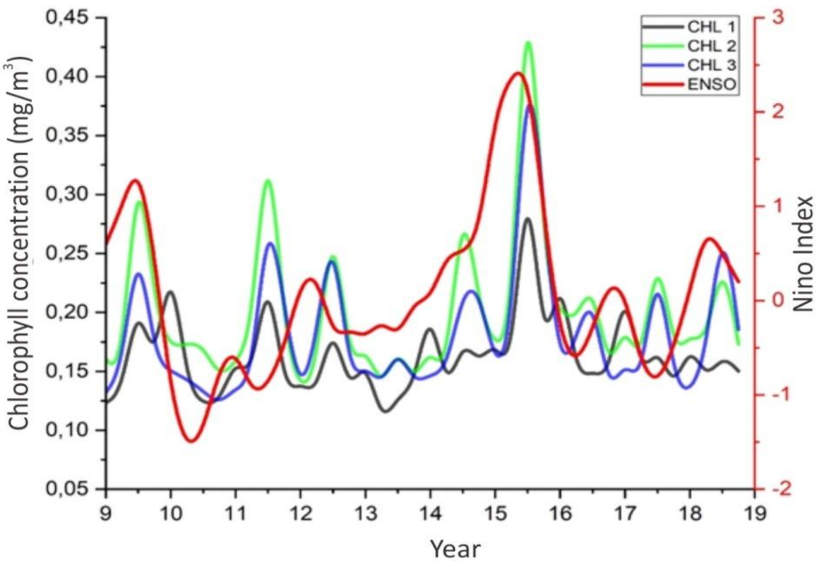
Meanwhile, study area 3 has a correlation value of 0.39 with a significance value of 0.009 indicating a weak relationship with ENSO. This is because geographically study area 3 is located in the north of the Sula Islands where the wind blowing from the south will decrease in speed because it is blocked by islands or land.

Temporal analysis of sea surface temperature and Nino Index during the period 2009 – 2018 is shown in Figure 15. The graph shows relationship between sea surface temperature in the three study areas and ENSO index. In general, sea surface temperature increases when La Nina occurs and decreases when El Nino occurs. The results of this research were in accordance with Setyadji and Amri (2017), that ENSO events have relationships with temperature of Indonesian seas, where it was colder during El Nino events and warmer during La Niña events. This happened because during El Nino the air pressure in the East Pacific was low, hence the wind and warm water column from the West Pacific flows into the East Pacific. This incident had an impact on lowering temperatures and sea levels in the West Pacific (Putra et al., 2017). The correlation value in each study area was -0.49 in study area 1, -0.51 in study area 2, and -0.47 in study area 3. All study areas showed an inverse relationship to ENSO index with a moderate level of correlation.

Figure16 shows the relationship between the distribution of salinity in the three study areas and the Nino Index during the period 2010-2020. The graph shows the same pattern between the Nino Index and salinity in the three study areas. Even though it has the same pattern, it appears that there was a time lag in the salinity response to ENSO which lasts around 2 to 3 months after the increase and decrease in the Nino Index. The correlation value in each study area was 0.63 in study area 1, 0.59 in study area 2 and 0.60 in study area 3. Study areas 2 and 3 have a moderate level of correlation, while study area 1 has a strong level of correlation. The high correlation value in study area 1 is because it is located very close to the West Pacific Ocean so that its response to salinity increasing or decreasing occurs more quickly.

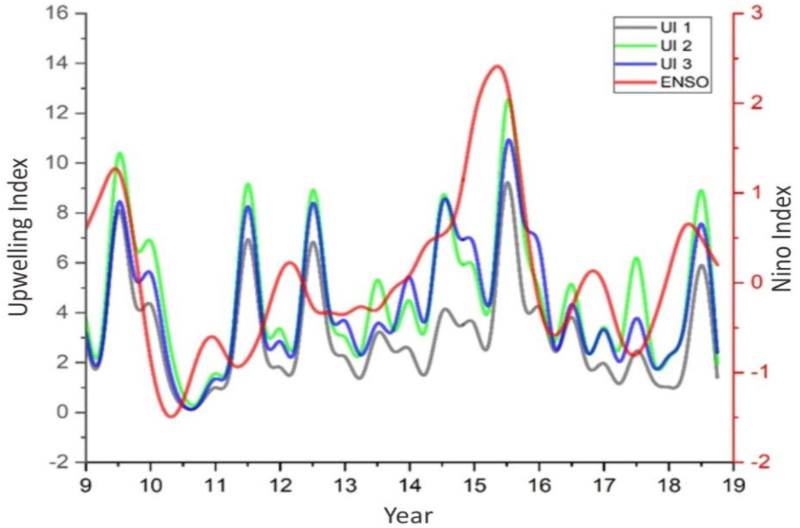


<u>Figure 16</u>: Correlation of surface salinity and Nino Index during 2010 – 2020 periods (Sal1 is surface salinity in study area 1, Sal2 is surface salinity in study area 2 and Sal3 is surface salinity in study area 3)



<u>Figure 17</u>: Correlation of chlorophyll-a and Nino Index during the period 2010 – 2020 (CHL1 is chlorophyll-a concentration in study area 1, CHL2 in study area 2, and CHL3 in study area 3)

The graph of the relationship between the temporal distribution of chlorophyll-a concentrations in the three study areas and the Nino Index during 2010-2020 is shown in Figure17. In general, there were similarities between the pattern of chlorophyll-a concentrations and the Nino Index. An increase in chlorophyll-a concentration in all study areas occurred during the El Nino period and a decrease in chlorophyll-a concentration occurred during the La Nina period.



<u>Figure 18</u>: Correlation of Upwelling Index and Nino Index during the period 2010 – 2020 (UI1 is Upwelling Index in study area 1, UI2 in study area 2, and UI3 in study area 3)

The concentration of chlorophyll-a in study area 2 experienced the highest increase in concentration, especially when the El Nino phenomenon occurred, while study area 1 gave the weakest response. An increase in chlorophyll-a concentration generally occurs when entering the JJA period when the wind blows from the south. In general, all study areas have a moderate level of relationship to ENSO. The correlation value in study area 1 is 0.49, study area 2 is 0.47 and study area 3 is 0.44. The existence of a relationship between chlorophyll-a concentration and the Nino Index indicates that during El Nino found increase the intensity of coastal upwelling and during La Nina found decrease the intensity of coastal upwelling.

Figure 18. shows that there was the same pattern between increasing and decreasing coastal upwelling intensity in the three study areas. The results of the correlation analysis in study area 1 obtained a correlation value of 0.46, in study area 2 it was 0.42 and in study area 3 it was 0.45. These results show that there was a relationship between the intensity of coastal upwelling in the three study areas and ENSO with a moderate correlation category. The highest increase in coastal upwelling intensity occurred during the 2015 - 2016 El Nino phenomenon, while the highest decrease occurred during the 2010 - 2011 La Nina phenomenon. Study area 2 is the region that has the highest intensity of coastal upwelling, while study area 1 has the lowest intensity of coastal upwelling both during the El Nino or La Nina phenomena.

The results of temporal analysis and correlation of oceanographic parameters which were indicators of coastal upwelling events show that there was a relationship between ENSO and coastal upwelling in the waters of the Maluku Sea. Wind speed increases during El Nino, followed by low SST and increased salinity and chlorophyll-a concentrations. When La Nina occurs, wind speed decreases and SST increases and salinity and chlorophyll-a concentration decrease. This condition reinforces the findings of other research that the intensity of coastal upwelling increases during El Nino and weakens during La Nina. The highest increase in upwelling intensity during El Nino was in study area 2. The decrease in upwelling intensity during La Nina occurred evenly throughout the research area. According to Wirasatriya et al. (2017), increased wind friction as a result of the increased pressure gradient during El Nino was what caused the increase in upwelling intensity in the Maluku Sea. Apart from the wind factor, the thermocline layer was shallower than normal so that water masses from the deeper layers rose more easily when upwelling occurs (Aldrian, 2008).

CONCLUSION

Coastal upwelling in the Maluku Sea occur during the Australian monsoon (June, July and August or JJA) in the Bacan - Obi - Sanana, Banggai - Taliabu, and Bitung waters. Upwelling indications can be detected in increasing surface wind speeds, decreasing sea surface temperatures, and high concentrations of chlorophyll-a. Coastal upwelling in the Maluku Sea occurs once a year so it is categorized as periodic upwelling. During the 2010 – 2020 period, ENSO (El Nino Southern Oscillation) was proven to modulate coastal upwelling in the waters of the Maluku Sea. During La Nina, the coastal upwelling in the Maluku Sea experiences a decreasing intensity marked by an increased sea surface temperature and a decreased chlorophyll-a concentration, while during El Nino, coastal upwelling in the Maluku Sea experiences an increasing intensity marked by an increased sea surface temperature and a decreased chlorophyll-a concentration. The recommendation from this study results is that further research on vertical section analysis is needed to determine the dynamics of multy-layers upwelling in the Maluku Sea. All three focus study areas have high fishing potentials, especially during the months of June, July and August, when coastal upwelling occurs. Fisheries potentials in the region are higher during El Nino and lowers in La Nina.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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