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Spatio-temporal distribution of chlorophyll-a concentration, sea surface temperature and wind speed using aqua-modis satellite imagery over the Savu Sea, Indonesia

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ABSTRACT

The climatological means and annual variation of chlorophyll-a (Chl-a) concentration, sea surface temperature (SST) and sea surface wind (SSW) from 2002 to 2016 in the Savu Sea (SS) within Indonesia were analysed. Chl-a variability and SST information was used as a reference in determining potential fishing grounds. The research aimed to investigate the variability of Chl-a and SST along with the influencing factor of the Australian-Indonesian Monsoon (AIM) winds. The study was conducted in SS waters, in East Nusa Tenggara (NTT), Indonesia, using 15 years of monthly Aqua MODIS Level 3 data. The retrieved data were corrected geometrically and radiometrically and then analysed to produce mean climatology data. The results indicated that the spatial and temporal AIM winds had a significant influence on the Chl-a concentration and the SST in SS waters. There was a two-month delay in the peak concentration of Chl-a/SST; moreover, the AIM wind speed, which peaks in June, was not followed by either the SST minima or the Chl-a maxima, which occur in August. The level of Chl-a in the SS waters showed seasonal patterns, with the highest concentration occurring during the east season (June–August), the peak concentration being 0.52 mg m^{-3}, alongside a wind speed of 5.42 m s^{-1} and an SST of 22.89 °C in August. Meanwhile, the lowest concentration of Chl-a 0.17 mg m^{-3} occurred in February during the west season (December–February), with a wind speed of 2.10 m s^{-1} and an SST of 29.57 °C. Three specific areas showed characteristics that differed from the general pattern of the monsoon winds' effects on Chl-a and SST in the SS. This study provides the latest description of Chl-a, SST and wind speed distribution at seasonal and spatial scales and their variability across the Savu Sea. The results of this study are essential for fishing catching activities and fisheries management in the region.

1. Introduction

The Savu Sea (hereafter SS) is a marginal sea situated in the southern Indonesian region, surrounded by the Lesser Sunda Islands of Indonesia. It has a complex bathymetry, covering a total surface area of 105,000 km^2; its deepest point is 3470 m, south of Pantar island (Atmadipoera and Suteja, 2018; Reed et al., 1987). The sea is connected to the Banda Sea (to the northeast), the Flores Sea through the Sumba Strait (northwest), the Timor Sea (southeast) and the Indian Ocean (southwest) (see Fig. 1). It is characterised by a volcanic inner island arc (Flores, Solor, Lomblen, Pantar and Alor) to the north and a non-volcanic outer arch (Sumba, Rote, Savu, and Timor) to the south.

The dynamics of the sea surface of the SS are strongly influenced by the Australian-Indonesian Monsoon (AIM) winds (comprising the southeast and northwest monsoons), which are southerly during the summer (southeast monsoon) and northerly (northwest monsoon) during the winter (Gordon, 2005; Setiawan and Habibi, 2010; Susanto et al., 2006; Wyrtki, 1961). Consequently, the chlorophyll-a (Chl-a) concentration and the sea surface temperature (SST) of the SS are strongly affected by the AIM winds (Ningsih et al., 2013) and deep-sea water exchanges through the Indonesia Throughflow (ITF) from the Pacific Ocean via the Banda Sea (Habibi et al., 2010; Potemra et al., 2003; Setiawan et al., 2019; Sprintall et al., 2019) and from the Indian Ocean via the Timor Sea (Wheeler and Mcbride, 2005). Furthermore, there are several factors that influence the SS, including the transport of saline surface water originating in the Flores Sea during the southeast

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monsoon, upwelling during the southeast monsoon, climate anomalies (i.e. El Niño-Southern Oscillation, ENSO) and the Indian Ocean Dipole (IOD) (Ningsih et al., 2013; Saji et al., 1999; Sprintall et al., 2010; Susanto et al., 2001).

The SS waters play a strategic role in the development of the regional government of East Nusa Tenggara province (NTT). Most cities in this province are highly dependent on the SS, which contributes up to more than 65% of its sustainable fisheries resources, boasting a fish potential of 156,000 tonnes year^{-1} (MMFRI-No.6–2014; Oktavia et al., 2018; Suman et al., 2016). In reality, the exploitation of marine fisheries resources in the SS has yet to reach the optimum level (Hidayat et al., 2019; Syamsuddin et al., 2008; Wijaya, 2013). It is therefore necessary to extend catch operations, improve catching equipment and search for and discover new fishing grounds by using echosounders and remote sensing (Nurdin et al., 2015; Selao et al., 2019; Zainuddin, 2011). As a result, the high potential of pelagic fish in the SS could be exploited optimally and managed sustainably.

Traditionally, fish-catching activities in the SS mainly rely on information from fishermen's experiences in making the best use of their senses to predict and find fishing grounds. The abundance of fish schooling in some waters often changes due to changes in environmental factors (Istnaeni and Zainuddin, 2019; Pranowo et al., 2014). Therefore, obtaining reliable data on oceanographic parameters is paramount. Chl-a and SST can help predict potential fishing grounds. Indeed, Chl-a can reflect plankton dynamics in the ocean and is generally used in studies of marine ecosystems (Asanuma et al., 2003; Hao et al., 2019; Yuan-Jian et al., 2012; Yulianto et al., 2018). SST is closely related to the suitability of physiological conditions and the morphological adaptations of fish. SST also serves as an indirect indicator of biological productivity and fish prey availability (Nababan et al., 2016; Nurdin et al., 2015; Planque et al., 2011). Chl-a is an essential indicator of oceanic upwelling and phytoplankton biomass (Manzer et al., 2019) and represents one of the most crucial drivers of marine ecosystem productivity (Gittings et al., 2018; Racault et al., 2017; Susanto and Marra, 2005). It is a direct indicator of fish prey and fish migration routes (Lalli and Parsons, 1997; Polovina et al., 2017; Sartimbul et al., 2010; Shen et al., 2018; Yu et al., 2019).

Several studies conducted in Indonesian waters (Mashita and Lumban-Gaol, 2019; Muskananfola et al., 2020; Nababan et al., 2016; Setiawan et al., 2019; Zainuddin et al., 2015) have indicated that oceanographic parameters such as temperature, salinity, Chl-a concentration, upwelling and eddies are correlated with the availability and abundance of fish and marine organisms. These findings clearly show that scientific information on oceanographic parameters and their dynamics are crucial to predicting fishing ground potential. Another study (Yu et al., 2017) has examined the impacts of climate variability and local biophysical environments on the interannual variability of the abundance of the western winter cohort of the neon flying squid *Ommastrephes bartramii* throughout 1995–2011. The investigation found that climatic and oceanographic factors affect the abundance of the winter-spring cohort of *O. bartramii* in the Northwest Pacific Ocean.

Geographic information system (GIS) technology and marine remote sensing can be applied to obtain the data on environmental conditions (such as oceanographic parameters) required to provide global information on sea surface layers' characteristics. Oceanographic satellite imagery can be used to monitor various oceanographic phenomena, such as eddies, fronts and sea surface height anomalies, which are positively related to fisheries' activities (Ahmad, 2019; Kunarso et al., 2008; Robinson, 2010; Zainuddin et al., 2004). One remote sensing satellite equipped with sensors to detect Chl-a and SST is the Aqua satellite, with its Moderate Resolution Imaging Spectroradiometer (MODIS) (Moradi and Kabiri, 2015; Qin et al., 2014). Sustainable pelagic fishing in the SS waters requires comprehensive research on the spatial and temporal variability of Chl-a and SST for predicting fishing grounds and managing fish resources in the region. Until recently, the SS lacked *in situ* measurements and studies on spatial and seasonal

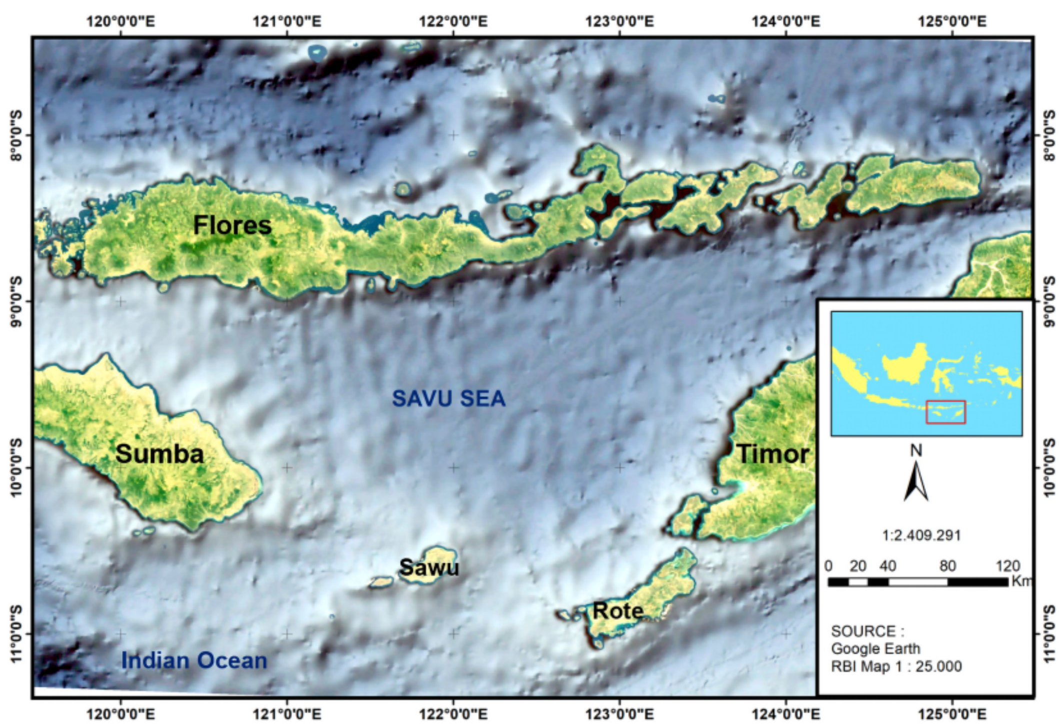

Fig. 1. Research location in the Savu Sea.

variations in Chl-a concentrations, SST and ocean winds. In response, this study aimed to investigate the spatio-temporal variability of Chl-a and SST and the driving factor of wind speed in the SS. This study elucidates Chl-a, SST seasonal variability and the effects of monsoonal winds on the monthly fluctuation of Chl-a to identify areas and months that might be productive fisheries in the Savu Sea.

2. Materials and methods

2.1. Study area and data sources

The research site was located in SS waters in Nusa Tenggara Timur, NTT, which lies at 118° 54′ 54,44" –124° 23′ 17,089″ E and 8° 45′ 49,964" – 11° 9′ 43,919″ S (Fig. 1). The study used daily Chl-a and semi-daily SST products from Aqua MODIS Level 3, with a spatial resolution of 4.6 km (Esaias et al., 1998), for the period 2002–2016. The data were downloaded from https://oceancolor.gsfc.nasa.gov. The monthly wind data were obtained using QuickSCAT's Advanced Scatterometer (ASCAT) satellite, with a spatial resolution of 0.25 ° × 0.25 °, from https://manati.star.nesdis.noaa.gov. These data were geometrically and radiometrically corrected, enabling their direct use (Pickett et al., 2003). For nitrate (NO_3) and phosphate (PO4) concentrations, GLOBAL-REANALYSIS-BIO-001-029 with a grid interval of 0.25 ° × 0.25 ° were used in this study (Perruche, 2019). The data were then analysed using programming software (to produce climatological data) (Setiawan and Habibi, 2011) and ArcGIS software v 10.2.

2.2. Data analysis

In this study, all data were composed into monthly climatology, monthly Chl-a, monthly SST and monthly wind speed to summarise the spatial and temporal distribution over the period 2002–2016. All parameters were sorted into monthly means, then used to obtain monthly climatology by applying the following equation (Wirasatriya et al., 2017):

$$\overline{X}(x, y) = \frac{1}{n}\sum_{i=1}^{n} x_i\,(x, y, t) \tag{1}$$

Where: $\overline{X}(x, y)$ is the monthly mean value or monthly climatology value at position (x,y); x_i (x, y, t) is the *i*th value of the data at (*x*,*y*) position and time *t*, *n* is the number of data in one month and the number of monthly data in one period of climatology (i.e., from 2002 to 2016 = 15 data) for monthly mean calculation and monthly climatology calculation, respectively. If x_i is an empty pixel, that pixel is not included in the estimate. Among the ocean colour sensors available, MODIS is currently the most used for investigating ocean biology. The data were tested and validated using *in situ* measurements to ensure their accuracy (El Hourany et al., 2017; Ghanea et al., 2016; Kuo et al., 2018; Moore et al., 2009; Young and Donelan, 2018).

3. Results

3.1. Spatio-temporal distribution and monthly climatology of wind speed

The results are described seasonally starting from the east season, transition season I, west season and transition season II. Spatio-temporal wind speed distribution and monthly climatology average wind speed data in the SS are shown in Fig. 2a, b and 3a. It can be seen that during the west season (December–February), the wind speed fluctuated from 2.50 to 3.39 m s^{-1}, the highest speed occurring in January. During transition season I (March–May) the wind speed increased significantly, from 1.36 m s^{-1} in March to 4.52 m s^{-1} in May. For the east season (June–August), the wind speed was higher than during the other seasons, with values ranging from 5.06 m s^{-1} in August to 6.16 m s^{-1} in June. For transition season II (September–November), the wind speed gradually decreased from 3.69 m s^{-1} in September to 1.91 m s^{-1} in November. Based on this 15-year monthly climatology of mean wind speed in the SS, the highest wind speed was 6.16 m s^{-1} (in June), while the lowest wind speed was 1.36 m s^{-1} (in March) (Fig. 3).

3.2. Spatio-temporal distribution and monthly climatology of SST

The results regarding the SST distribution and the monthly climatology average of SST in the SS are shown in Fig. 2a and 3a. During the west season (December–February) the SST ranged from 28.79 to 29.69 °C and seemed to be evenly distributed across all regions of the SS, except for near Timor, where it was as high as 30.17 °C at the coordinates 123°40′00–125°00′00 E and –10°00′00–12°00′00 S. During transition season I (March–May) the SST showed a similar pattern to during the west season, especially in March and April, when the SST ranged from 28.41 to 29.40 °C. In May, however, the SST tended to decrease. During the east season (June–August) the SST began to decline in June, reaching its lowest level in August. A lower SST occurred in all coastal regions, with noticeable colder areas at the western part of the SS at the coordinates 119°00′0–122°0′ E and –8°50′0–11°0′0 S. The SST ranged from 22.89 to 27.52 °C. During transition season II (September–November) the SST showed similar patterns to earlier seasons, with a tendency to increase from 27.07 °C in September to 29.27 °C in November. The highest SST (29.57 °C) occurred in March, while the lowest SST (22.89 °C) was seen in August.

3.3. Spatio-temporal distribution and monthly climatology of Chl-a

The results of the Chl-a spatial and temporal distribution and the monthly climatology means of Chl-a are presented in Fig. 2a, b and 3a. Chl-a concentration during the west season (December–February) ranged from 0.16 to 0.17 mg m^{-3} at coastal water regions. Transition season I (March–May) also showed a slight increase and a similar trend pattern to the west season, with a Chl-a concentration of 0.18–2.9 mg m^{-3}. During this season, Chl-a concentrations were significant at the regions of the Sumba Strait and south of Lembata and Alor. During the east season (June–August) the Chl-a concentration was considerable, ranging from 0.42 to 0.52 mg m^{-3}, with a significant increase and peak concentration in August. The Chl-a concentration ranged widely across the SS waters. During transition season II (September–November) the Chl-a concentration remained high in September, before gradually decreasing, reaching its lowest value in November. At the end of this season, the Chl-a concentration was observed in the western part of the SS (south of West Manggarai district) and the eastern part of the SS (south of Alor district). The highest Chl-a occurred in August (0.52 mg m^{-3}), while the lowest occurred in February (0.17 mg m^{-3}).

4. Discussion

4.1. Spatial and temporal distribution patterns of Chl-a, SST and monsoon wind

The results of this study indicated that one of the factors influencing the distribution and the concentration of Chl-a and SST in SS waters was monsoon wind (Fig. 2a, b and 3a). This finding is in line with the results of previous studies that have noted that the variability of Chl-a and SST is influenced by several factors, such as monsoon wind speed, ENSO, IOD, tides, waves, heat flux and river runoff (Hao et al., 2019; Nababan et al., 2016; Nurdin et al., 2015; Susanto and Marra, 2005; Wheeler and Mcbride, 2005; Wirasatriya et al., 2017; Wirasatriya et al., 2019a,b; Wirasatriya et al., 2020). Seasonally, the Chl-a concentration was highest during the east season (June–August), with an average value of 0.48 mg m^{-3}, whereas the lowest value was seen during the west season (December–February), with an average value of 0.17 mg m^{-3}. This finding is in agreement with previous studies (e.g. Habibi et al., 2010; Ningsih et al., 2013; Setiawan et al., 2019; Wirasatriya et al., 2020) that

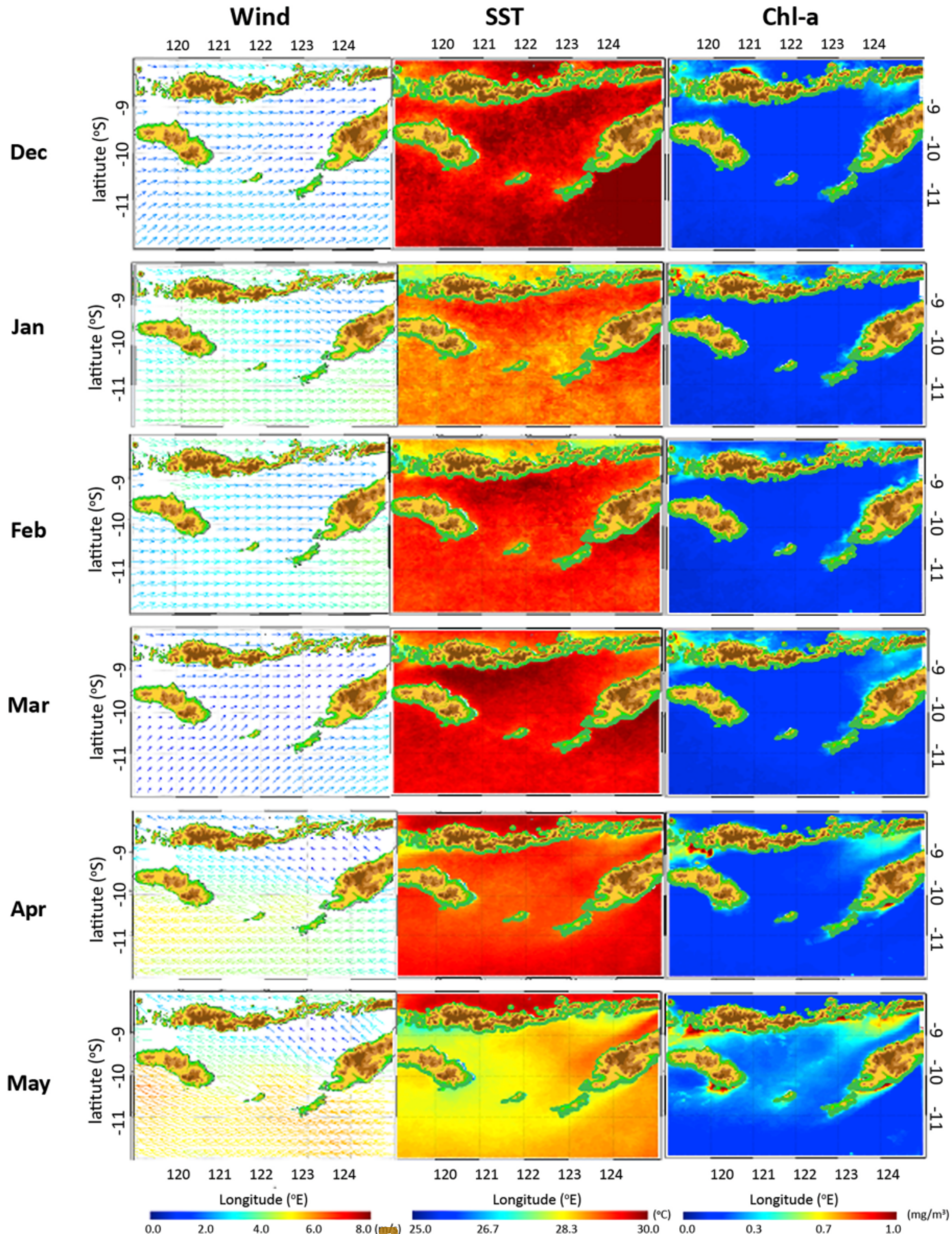

Fig. 2a. Spatial and seasonal distribution of Chl-a, SST and wind speed in the Savu Sea during the west season and transition season I.

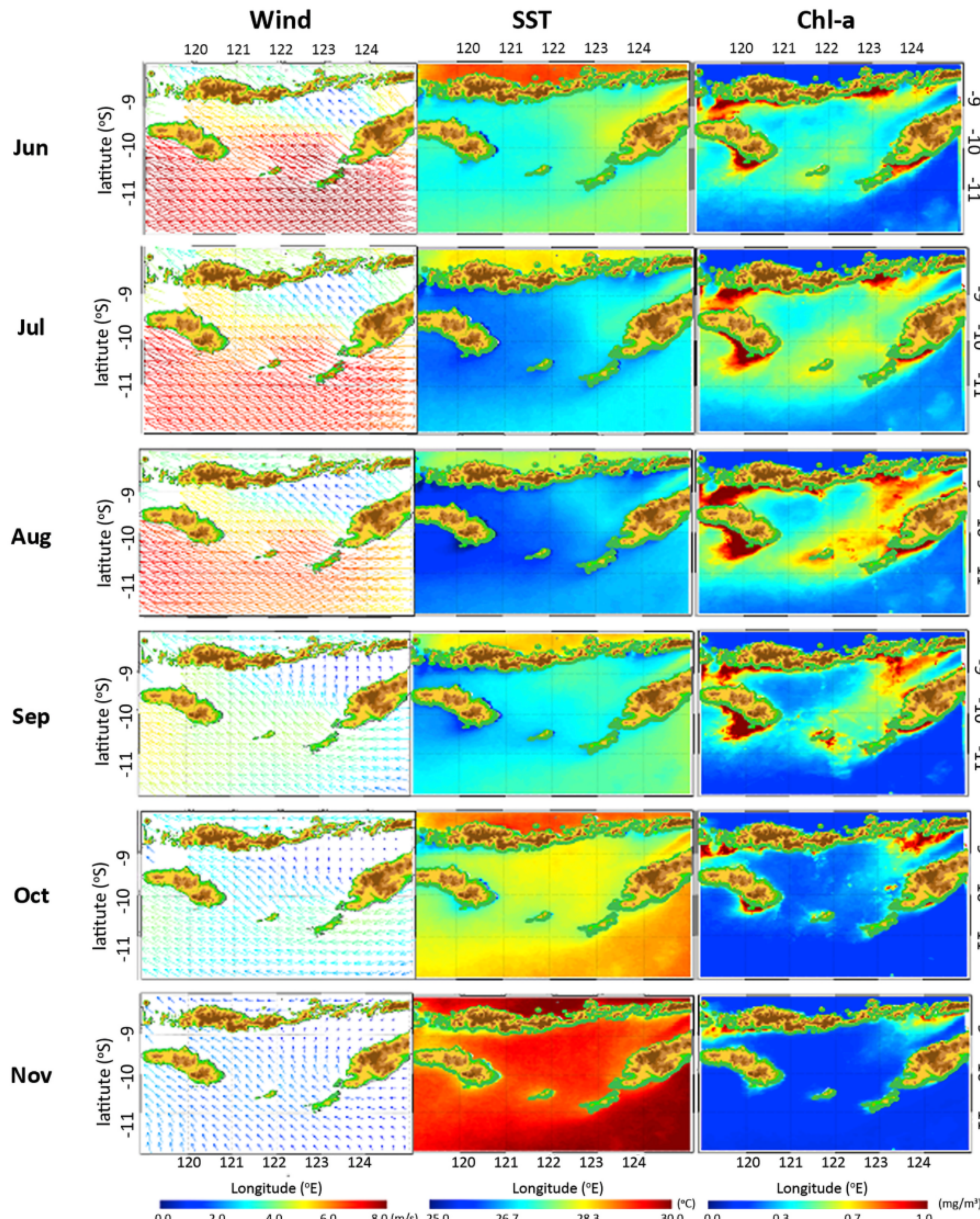

Fig. 2b. Spatial and seasonal distribution of Chl-a, SST and wind speed in the Savu, Sea during the east season and transition season II.

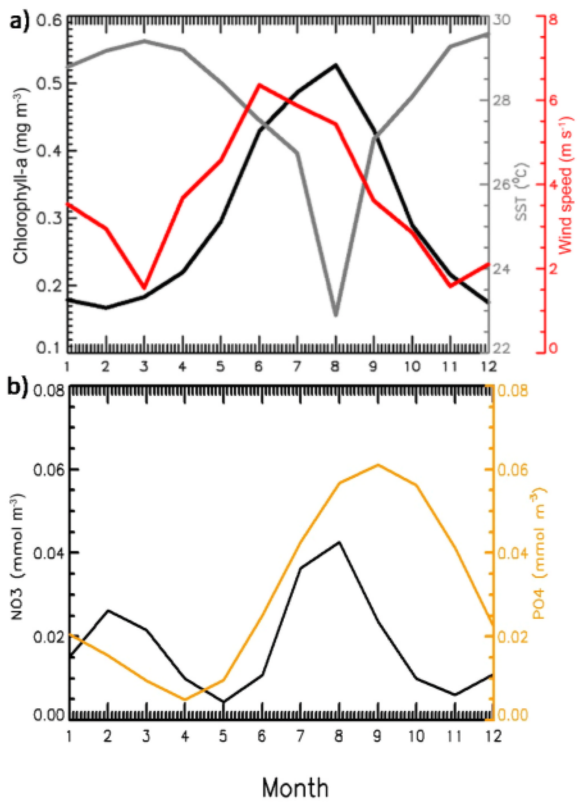

Fig. 3. Multitemporal of a) Chl-a (black), SST (grey) and wind speed (red); b) NO_3 (black) and PO_4 (yellow) in the climatological monthly means (2002–2016) in the Savu Sea. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

have found that the Chl-a concentration from the South Java Sea to the SS increases from June to August (east season) and decreases in the west season. The results also showed that the concentration of Chl-a in the SS tended to be high in shallow coastal regions, which may have been due to Ekman transport mechanisms supplying nutrient-rich water from the deepwater to the euphotic zone. Other possible causes include vertical mixing processes (Hao et al., 2019; Mashita and Lumban-Gaol, 2019; Susanto et al., 2001) which lead to high Chl-a concentrations at the surface of coastal waters and in estuaries.

In the present study, the evidence of the elevated nutrient concentration during the increasing Chl-a concentration in the SS is shown in Fig. 3b. As a main limiting nutrient for phytoplankton growth (e.g. Howarth, 1988; Howarth and Marino, 2006), NO_3 variation demonstrates a good agreement with the variation of Chl-a. The peak of Chl-a concentration in August is in accordance with the peak of NO_3 concentration. Furthermore, this condition is also supported by the increasing PO_4 concentration. Although the concentration of PO_4 peaks a month later than NO_3, the high PO_4 concentration during August may support the phytoplankton growth along with the peak of NO_3 concentration. The fluctuation of NO_3 is closely related to the fluctuation of wind speed (Fig. 3). The wind blows above the SS may generate coastal upwelling due to offshore Ekman transport mechanism or mechanical mixing that lifts nutrient-rich bottom water mass. However, the lag by 1 month (2 months) of the first (second) peak of NO_3 concentration relative to the peak of wind speed indicates that the elevated bottom nutrient is slowly moving to the surface. The fluctuation of PO_4 concentration is also influenced by wind speed. However, the inconsistency of the relation between wind speed and PO_4 concentration is shown during the east season. The peak of PO_4 concentration occurs in September when the wind speed has dropped to 3 m s^{-1}. This indicates that there are other factors that keep the increasing PO_4 concentration under the weak wind speed condition. The input from terrestrial nutrient brought by the river runoff (e.g. Maslukah et al., 2019) may become one possibility and therefore need to be investigated further for the future study.

The distribution of SST in the SS was found to be even (uneven) when the wind speed was weak (high), with high SST occurring in some areas. The seasonal patterns of SST in the SS revealed that the highest average was 29.10 °C, occurring during the west season, while the lowest average was 25.09 °C, occurring during the east season. The monthly patterns of SST showed that it was highest early in the west season (December), reaching 29.56 °C. This high SST pattern continued through March–April (transition season I). This trend is similar to the results of other studies (e.g. Ningsih et al., 2013; Potemra et al., 2003) finding that SST in the SS increases from December to April, with the highest SST occurring during the west season (December–February) and the lowest occurring during the east season (July–August). This is because during the west season, the sun's position in the Southern Hemisphere results in high solar radiation flux and thus high SST. During the west season, the Northern Hemisphere experiences its cold season, while the Southern Hemisphere experiences its hot season. SST and Chl-a have a spatially and temporally robust negative relationship, as the highest Chl-a concentration occurs at the same time as the lowest SST in the SS. This Chl-a maxima is driven by the mechanisms of coastal upwelling, transporting nutrient sources to activate phytoplankton blooms at the surface (Nababan et al., 2016; Setiawan et al., 2019; Sprintall et al., 2019). Upwelled, cool deepwater together with surface wind stress contribute to the cooling of SST.

The Chl-a distribution follows the AIM wind pattern. When the AIM wind speed increases/decreases, Chl-a also increases/decreases (Asanuma et al., 2003; Hidayat et al., 2019; Shen et al., 2018). The concentration of Chl-a is higher along the coast and lower towards the open sea, possibly due to coastal upwelling, nutrient supply brought by coastal processes and river discharge (Muskananfola et al., 2020; Setiawan and Habibi, 2011; Setiawan et al., 2019). Furthermore Yulianto et al. (2018) have stated that high Chl-a content can be found at the surface layer near the land, decreasing towards the sea.

The AIM wind pattern in SS waters causes Chl-a and SST to change with time and season. The AIM winds and the SST have been identified as the essential determinants affecting the distribution and the variability of Chl-a (Asanuma et al., 2003; Nababan et al., 2016; Yu et al., 2019). Fig. 3 above shows that the concentration of Chl-a increases during the east monsoon (June–August), while the SST decreases. During the southeast monsoon, the wind blows from Australia to the SS, causing the SST to decrease in this area, while the Chl-a concentration tends to rise due to upwelling (Habibi et al., 2010; Wheeler and Mcbride, 2005). Susanto et al. (2006) have stated that an increase in the southeast monsoon's wind speed causes an increase in upwelling, thereby uplifting nutrient-rich cold water masses from the deepwater to the surface. Greater upwelling intensity from June to August increases the cold water masses transported from the deepwater to the sea surface, causing a cooling down in SST from June to August.

4.2. The three sites with distinctive characteristics of Chl-a, SST and monsoon wind speed

The distribution patterns of Chl-a, SST and AIM winds in the SS are presented in Fig. 2. This figure shows that during the east monsoon (June–August), the speed of AIM winds blowing from the east and the southeast (Australia) towards the SS caused a decrease in SST and an increase in Chl-a. Wind speed during the east monsoon ranged from 5.42 to 6.36 m s^{-1}, showing that the AIM winds affect the Chl-a concentration. This finding is supported by Setiawan and Habibi (2011, 2010), who state that the southeast monsoon wind causes a high level of Chl-a and the cooling down of the SST. The monthly average climatological results for wind speed, SST and Chl-a shown in Fig. 3 indicate that the increase in Chl-a concentration and the cooling down of the SST were most significant in August. The peak of AIM wind speed, however, occurred in June. This study therefore reveals that a two-month delay occurred in Chl-a increase and SST cooling at the same time as the peak wind speed during the east monsoon. The peak monsoon wind speed (6.36 m s^{-1}) occurred in June, while the peak Chl-a concentration (0.52 mg m^{-3}) occurred in August, when SST cooling reached 22.89 °C. These two-month time lag patterns may have been due to the variability of physical oceanographic processes, the complex topography of the islands surrounding the SS and the bathymetry of the seabed (Atmadipoera and Suteja, 2018; Reed et al., 1987; Susanto et al., 2001, 2006). Such time lag phenomena need to be investigated in future studies.

This study also revealed that during the east monsoon period (June–August), three specific sites were identified in the SS (see Figs. 4 and 5) showing different oceanographic characteristics from previous general patterns that AIM wind speed affects Chl-a and SST variability (Ningsih et al., 2013; Setiawan et al., 2019; Susanto et al., 2001) in the region. These three sites have unique oceanographic characteristics. The first site (Area A) is located in the northeast SS, at the coastal region of East Flores and Lembata Regency. During the east monsoon, it showed the highest concentration of Chl-a occurs in June with the average content of 0.92 mg m^{-3} and warm SST 27.42 °C, and a slow wind speed of 1.74 m s^{-1}. The high Chl-a concentration in Area A can be attributed to the southerly monsoon wind and Ekman mass transport mechanisms, which enhance nutrients and Chl-a (Setiawan and Habibi, 2010; Sprintall et al., 2010; Susanto et al., 2001). The low wind speed recorded in this area may have been due to the topographical characteristics of the surrounding islands of East Flores and Lembata, which slowed down the monsoon wind speed before it developed fully on the regional sea surface. The second site (Area B) is located in the northwest SS, at the offshore waters of Ende and Ngada. This area showed a high monsoon wind speed, low SST and low Chl-a concentration. The depths of Areas A and B are relatively of the same range, between 3000 and 4000 m. A high monsoon wind speed of 5.78 m s^{-1} occurred in June, alongside an SST of 27.42 °C. The high wind speed in this area did not affect the Chl-a concentration (0.39 mg m^{-3}), which was even lower during the east monsoon. As the location is at a deep sea, there is a lack of upwelling process to transfer nutrients from the bottom to surface waters (Potemra et al., 2003). In addition, Gittings et al. (2018) have stated that in tropical marine ecosystems, enhanced thermal stratification during warmer conditions leads to less vertical mixing and reduced nutrient

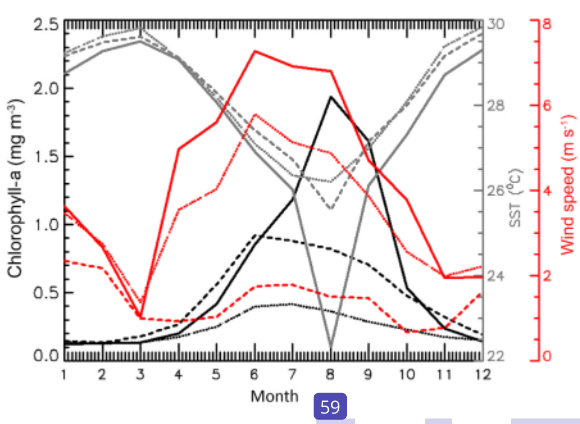

Fig. 4. Climatological monthly means of Chl-a (black), SST (grey) and wind speed (red) in the three Savu Sea study areas (Areas A, B and C). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

supply to the euphotic zone. This may have contributed to the reduced Chl-a concentration at Area B. Lastly, the third site (Area C) is located at the western part of the SS, in the southern coastal waters of East Sumba, with a water depth ranging from 400 to 600 m. The wind had a greater effect on the Chl-a concentration and the SST. Indeed, the Chl-a concentration reached 1.32 mg m^{-3}, with an average wind speed of 7 m s^{-1} and an SST of 25 °C. Area C had a higher content of Chl-a than the other two regions, which may have been due to Ekman mass transport mechanisms. Moreover, southeasterly wind stress has been found to play a vital role in determining the Chl-a maxima in this region (Setiawan et al., 2019; Sprintall et al., 2010). During the southeast monsoon the southeasterly wind generates cyclonic eddies, whereby nutrients are transported to the sea surface, leading to phytoplankton blooms (Asanuma et al., 2003), causing the high Chl-a concentration. All these mechanisms can be assumed as the driving forces of the Chl-a maxima in the SS.

4.3. Fisheries activities and management implications

This study showed that in the SS the highest concentration of Chl-a occurred during the southeast monsoon, indicating high fertility and high primary productivity for fishing grounds and fisheries capture activities, as the high Chl-a content could be used as seawater primary productivity indicators (Lalli and Parsons, 1997). Furthermore, Istnaeni and Zainuddin (2019), Nurdin et al. (2015) and Planque et al. (2011) have stated that successful fishing capture activities depend on accurately determining potential fishing grounds through knowledge and the use of key indicators, i.e. Chl-a and SST, which influence fish availability. Therefore, a comprehensive understanding of upwelling and Chl-a data in the SS is essential for fisheries.

Chl-a is an essential biological parameter because it is closely related to productivity, which is a crucial variable in marine resources management, particularly in the fisheries sector (Hao et al., 2019; Kunarso and Supangat., 2008). Changes in Chl-a determine ocean primary productivity and consequently fisheries production (Manzer et al., 2019; Racault et al., 2017; Sartimbul et al., 2010). Furthermore, Robinson (2010) and Selao et al. (2019) have stated that waters with a high Chl-a concentration can be used to predict potential fishing grounds. The high abundance of Chl-a attracts small fish, in turn attracting big fish such as tuna and cakalang (skipjack).

The total pelagic fishing catch for cakalang during the year 2015 in the SS was 65,000 tonnes out of the sustainable potential of 156,000 (Suman et al., 2016). These data indicate that the potential of pelagic fish, including Cakalang in the SS, needs to be utilised optimally by operating capture tools most effectively and efficiently. Moreover, the catches quoted above mainly come from the southeastern part of the SS, because most fishing vessels are based in the city of Kupang (the capital city of NTT province). By contrast, two of the three areas (A and C) which this study has found to have high concentrations of Chl-a are located in the north and west of the SS. These areas still have low numbers of fishing vessels and their fisheries resources are less exploited. Therefore, the results of this study could be used as vital information to explore new potential fishing grounds for fishing activities in other parts of the SS and for marine resources management in the region.

5. Conclusion

Through this analysis of the spatial and temporal distribution of Chl-a concentration, SST and monsoon wind speed using 15-year time series Aqua MODIS satellite imagery in the SS, the AIM wind speed was found to have substantial effects on the variation of Chl-a and SST in SS waters. A two-month time lag was identified between the peak wind speed in June and the peaks of both the Chl-a concentration and the SST in August. The concentration of Chl-a and SST was found to change following a seasonal pattern, whereby the highest concentration occurred during the east monsoon (June–August), peaking in August

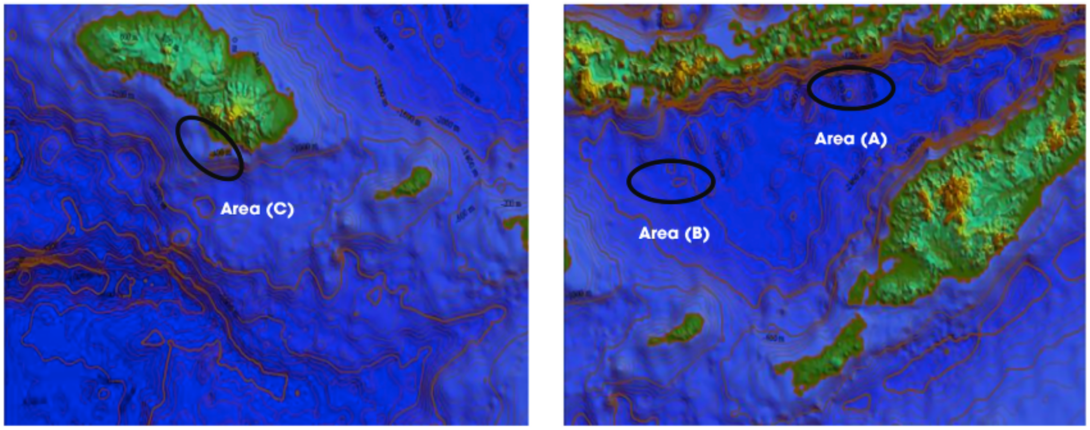

Fig. 5. The three study areas (A, B and C) in the Savu Sea.

with a concentration of 0.52 mg m^{-3}, a wind speed of 5.42 m s^{-1} and an SST of 22.89 °C. The lowest concentration of Chl-a (0.17 mg m^{-3}) was found to occur during the west monsoon (December–February), especially in February, alongside a wind speed of 2.10 m s^{-1} and an SST of 29.57 °C. The fluctuation of Chl-a concentration is in accordance with the fluctuation of nutrients especially NO_3 which indicates the role of wind speed to elevate the bottom nutrient-rich water to the surface through vertical mixing or coastal upwelling mechanisms. Three specific areas located in the northern and western parts of the SS were identified as having oceanographic characteristics that differ from the general patterns found in the SS. Further studies are needed to investigate the drivers that may be responsible for the specific patterns identified, in terms of Chl-a, SST and wind speed variabilities in the three areas. The results of this study should help support the development of fishing capture activities and marine resources management in the SS.

CRediT authorship contribution statement

Max Rudolf Muskananfola: Conceptualization, Methodology, Investigation, Visualization, Writing – review & editing, Supervision. **Jumsar:** Investigation, Data curation, Writing – original draft. **Anindya Wirasatriya:** Conceptualization, Software, Formal analysis, Supervision, Writing – review & editing.

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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