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Abstract

Chlorophyll-a is a pigment that is contained in phytoplankton. Through the photosynthesis process, chlorophyll-a plays an important role in the global carbon cycle. The purpose of this research is to investigate the effect of global warming on chlorophyll-a concentration in Indonesian waters. The data used includes the monthly data of sea surface temperatures from 1984-2013, CO_2 concentrations from 1980-2014, and chlorophyll-a concentrations from 2003-2014. The method used is linear regression. The results show that sea surface temperatures in Indonesian waters increased by about 0.51 °C from 1984-2013. The effects of global warming on chlorophyll-a concentrations varies between different areas of Indonesian waters. From the 12 research sites, 9 showed a decrease in concentration and 3 showed an increase.

Abstrak

Pengaruh Pemanasan Global terhadap Konsentrasi Klorofil-a di Perairan Indonesia. Klorofil-a adalah pigmen yang terkandung dalam fitoplankton. Klorofil-a mempunyai peranan penting dalam siklus karbon global melalui proses fotosintesis. Penelitian ini bertujuan untuk mengetahui pengaruh pemanasan global terhadap konsentrasi klorofil-a di perairan Indonesia. Data yang digunakan terdiri dari suhu permukaan laut bulanan dari tahun 1984-2013, konsentrasi CO_2 bulanan dari tahun 1980-2014 dan konsentrasi klorofil-a bulanan dari tahun 2003-2014. Metode yang digunakan dalam penelitian ini adalah regresi linier. Hasil penelitian menunjukkan bahwa dari tahun 1984-2013 telah terjadi peningkatan suhu permukaan laut wilayah perairan Indonesia sebesar 0,51 °C. Pengaruh pemanasan global terhadap konsentrasi klorofil-a bervariasi untuk setiap wilayah perairan Indonesia yang berbeda. Dari 12 lokasi penelitian, 9 lokasi menunjukkan tren penurunan dan 3 lokasi penelitian menunjukkan tren kenaikan suhu.

Keywords: chlorophyll-a, global warming, sea surface temperature, trend

Introduction

Chlorophyll-a concentration is an indicator of the presence of a certain amount of phytoplankton [1]. Phytoplankton are primary producers, with the ability to form organic matter from inorganic substances [2]. The oceans' phytoplankton constitutes about 50% of total global primary producers [3]; the distribution of their biomass is determined by the availability of sunlight and nutrients, both of which are influenced by the physical process of ocean circulation, mixed layer dynamics, atmospheric dust deposition, and the solar cycle [4].

Phytoplankton pigments play an important part in climate control, the oceans' carbon cycle, and the biogeochemical cycle [5-6], and influence the upper oceans' temperature and circulation [7]. Penetration of solar radiation in the mixed layer is affected by the existence of phytoplankton biomass and vertical distribution [8].

The earth's climate system is strongly influenced by the oceans, which are the main absorber of CO_2 concentration in the atmosphere. Every year, the oceans absorb almost one quarter of the global CO_2 concentration which has been emitted into the atmosphere [9]. Their ability to do so depends on inorganic carbon chemistry, alongside several other factors such as hydrography, circulation of water mass, wind stress, dynamics of the mixed layer, and the oceans' biological processes [10].

Global warming has a greater impact on the marine ecosystem than it does on the terrestrial ecosystem, due to temperature factors that influence the stability of the water column, enrichment of nutrients, and the biodiversity of phytoplankton and the reproductive cycle [11]. Changes in temperature, rainfall, and salinity, caused by global warming, directly affect the metabolic and developmental rates of many animals along with processes such as photo-synthesis, respiration, growth, and tissue composition in plants, as well as increasing the vertical stratification of the water column and the stability of the upper layer [12-14]. Changes to the physical, chemical, and dynamic properties of the oceans, caused by global warming, affect marine ecosystems through biological processes [15-16].

Given the important role of chlorophyll-a in air-sea interaction and the biogeochemical cycle, it is important to undertake research into changes in its concentration. The purpose of the current study is to investigate the effects of global warming on sea surface temperature and chlorophyll-a concentration in Indonesian waters.

Materials and Methods

Twelve research sites were identified: west of northern Sumatra, west of southern Sumatera, south of Java, south of Bali-Sumbawa, the Java Sea, the Flores Sea, the Banda Sea, the Arafura Sea, the Karimata Strait, the Makassar Strait, the Sulawesi Sea, and the Halmahera Sea (north of Papua).

The data used consists of monthly sea surface temperatures from 1984-2013, monthly chlorophyll-a concentrations from 2003-2014, and monthly CO_2 concentrations from 1980-2014. Sea surface temperature data was obtained from Jet Propulsion Laboratory NASA, chlorophyll-a concentration data was obtained from Pacific Islands Fisheries Science Center NOAA, and CO_2 concentration data was obtained from Earth System Research Laboratory NOAA.

All the collected data was analyzed using statistical methods. Monthly sea surface temperature data was processed into annual averages over a time range of 30 years, to obtain a climatological element. This helped to determine any anomalies in the data. Based on these anomalies, we analysed the impact of global warming on Indonesian waters. Trends of interannual variability of sea surface temperature, CO_2 concentration, and chlorophyll-a concentration were analysed using linear regression.

Results and Discussion

Figure 1 shows the high interannual variability of sea surface temperature anomalies in the waters west of Sumatra, south of Java, and south of Bali-Sumbawa. The lowest anomalies occurred in 1994 and 1997 by about -1.12 °C and -0.95 °C respectively, in the waters west of northern Sumatra. The highest anomalies occurred in 1998 and 2010 by about 1.10 °C and 1.0 °C respectively, in the waters south of Bali-Sumbawa, as well as by about 1.0 °C and 0.82 °C in the waters south of Java. There was an increase in the trend of interannual variability of sea surface temperature anomalies in all of these waters, as shown in Table 1.

Figure 2 shows the low interannual variability of sea surface temperature anomalies in the Arafura Sea, the Banda Sea, the Flores Sea, and the Java Sea. The lowest anomalies occurred in 1997 by about -0.52 °C and -0.55 °C in the Arafura Sea and the Java Sea, respectively. The highest anomaly occurred in 1998 by about 0.65 °C in the Arafura Sea, as well as by about 0.64 °C, 0.63 °C and 0.62 °C in 2010 in the Flores Sea, Banda Sea, and Java Sea, respectively. There was an increase in the trend of interannual variability of sea surface temperature anomalies in all of these waters, as shown in Table 1.

Figure 3 shows the low interannual variability of sea surface temperature anomalies in the Celebes Sea, the Halmahera Sea north of Papua, the Karimata Strait, and the Makassar Strait. The lowest and highest anomalies occurred in the Makassar Strait; the lowest was in 1994 by about -0.53 °C, and the highest was in 1998 by about 0.66 °C. There was an increase in the trend of interannual variability of sea surface temperature anomalies in all of these waters, as shown in Table 1.

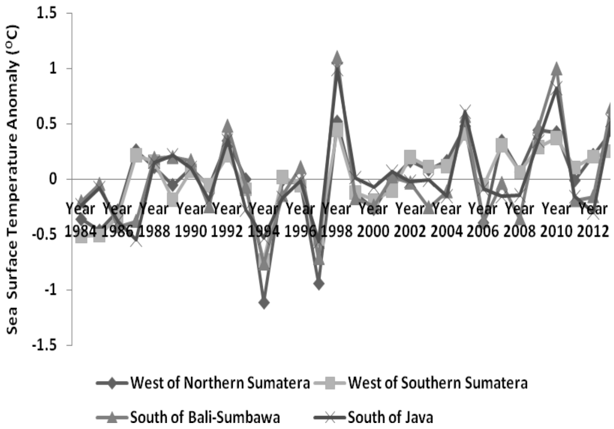

Figure 1. Interannual Variability of Sea Surface Temperature Anomalies

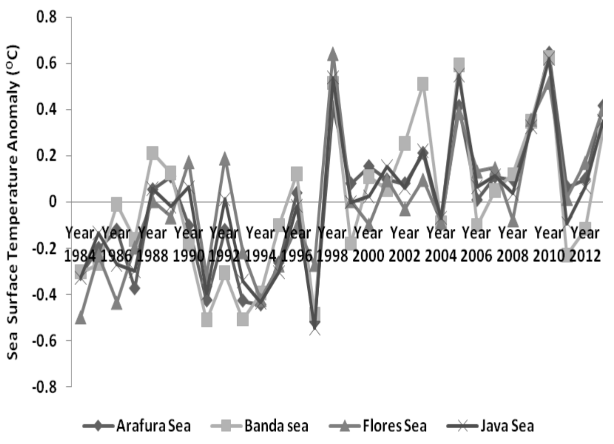

Figure 2. Interannual Variability of Sea Surface Temperature Anomalies

Figure 4 shows the monthly variability of chlorophyll-a concentration in the waters west of Sumatra, south of Java, and south of Bali-Sumbawa. The concentration in the waters west of Sumatra remained relatively low throughout the year. It varied between 0.166 mg/m^3 and 0.262 mg/m^3 in the waters west of northern Sumatra, and from 0.217 mg/m^3 to 0.342 mg/m^3 in the waters west of southern Sumatra.

The chlorophyll-a concentration in the waters south of Bali-Sumbawa and south of Java shows a monsoonal pattern, with one peak and one trough (?).

The peak occurred in August in the waters south of Bali-Sumbawa and in September in the waters south of Java, while the trough occurred in January in the waters south of Bali-Sumbawa and in March in the waters south of Java. The chlorophyll-a concentration in these waters increased between June and October, reaching 0.683 mg/m^3.

Figure 5 shows the monthly variability in chlorophyll-a concentration in the Arafura Sea, the Banda Sea, the Flores Sea, and the Java Sea. Throughout the year, the concentration in the Arafura and Java Seas remained relatively high, with a value range between 0.527 mg/m^3 and 0.845 mg/m^3 in the Arafura Sea, and from 0.386 mg/m^3 to 0.914 mg/m^3 in the Java Sea. It rose in the Arafura Sea from January up to July, but declined between August and December. In the Java Sea, it started to drop in February; this continued until October, when it started to rise before falling again in February.

Chlorophyll-a concentration in the Banda Sea shows a monsoonal pattern, with the peak occurring in August and the trough in April. From June to September, concentrations increased up to a relatively high 0.472 mg/m^3.

The monthly variability of concentrations in the Flores Sea shows an equatorial pattern, with peaks occurring in January and August and troughs in May and November. The concentration in the Flores Sea remained relatively low, with a value range between 0.169 mg/m^3 and 0.290 mg/m^3.

Figure 6 shows the monthly variability in chlorophyll-a concentration in the Celebes Sea, the Halmahera Sea north of Papua, the Karimata Strait, and the Makassar

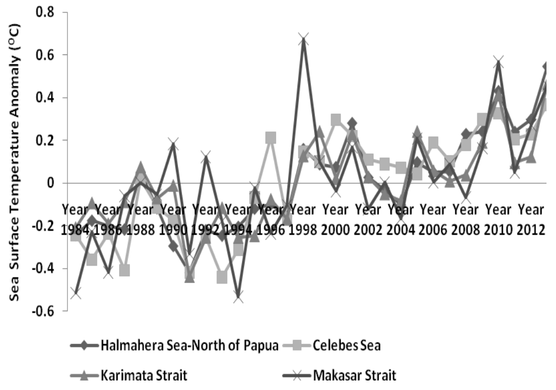

Figure 3. Interannual Variability of Sea Surface Temperature Anomalies

Table 1. Trend of Sea Surface Temperature Anomalies

Area	Increasing (°C/year)
West of Northern Sumatra	0.017
West of Southern Sumatra	0.018
South of Bali-Sumbawa	0.012
South of Java	0.013
Arafura Sea	0.020
Banda Sea	0.016
Flores Sea	0.019
Java Sea	0.019
Celebes Sea	0.022
Halmahera Sea-North of Papua	0.020
Makassar Strait	0.018
Karimata Strait	0.015

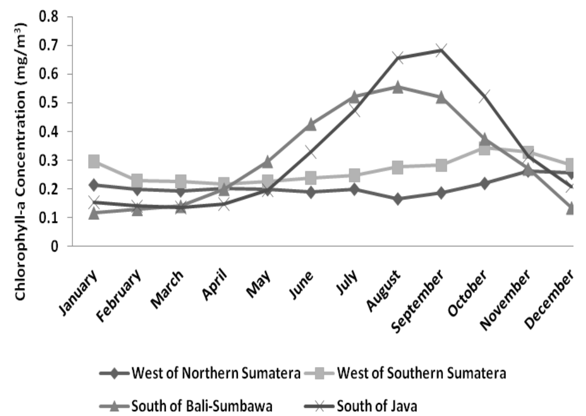

Figure 4. Monthly Variability of Chlorophyll-a Concentration

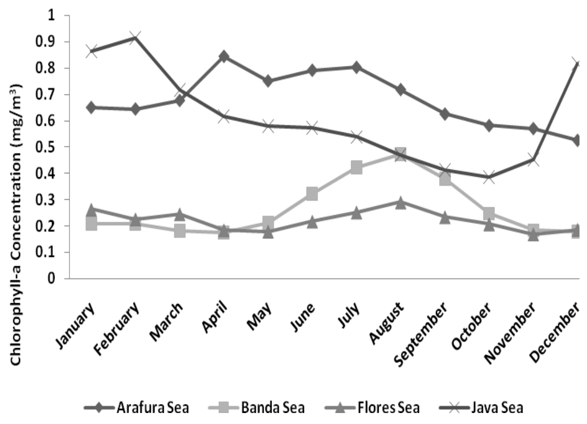

Figure 5. Monthly Variability of Chlorophyll-a Concentration

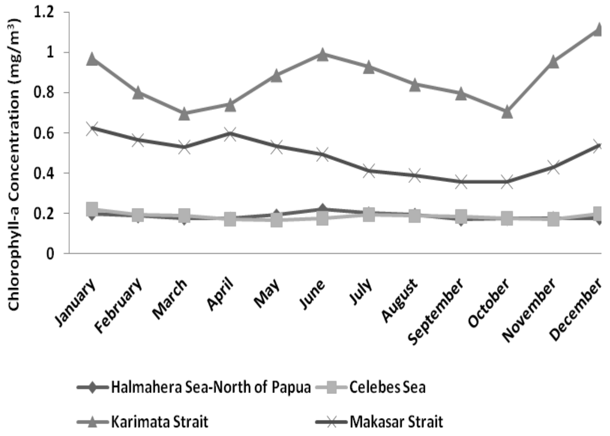

Figure 6. Monthly Variability in Chlorophyll-a Concentration

Strait. Throughout the year, the concentration in the Halmahera Sea north of Papua and the Celebes Sea remained relatively low, with a value range between 0.171 mg/m^3 and 0.219 mg/m^3, and from 0.167 mg/m^3 to 0.222 mg/m^3, respectively. Higher concentrations occurred in the Karimata Strait and the Makassar Strait, with a value range between 0.695 mg/m^3 and 1.116 mg/m^3, and from 0.358 mg/m^3 to 0.622 mg/m^3, respectively. The monthly variability in the Karimata Strait shows an equatorial pattern, with peaks in June and December and troughs in March and October. In the Makassar Strait, variability was opposite to that of the waters south of Java; chlorophyll-a concentration during east season (June-August) and second transition season (September-November) are lower than during west season (December-February) and first transition season (March-May).

Figure 7 shows the interannual variability in chlorophyll-a concentration in the waters west of Sumatra, south of Java, and south of Bali-Sumbawa. In 2006, the concentration in the waters south of Java and Bali-Sumbawa significantly increased; this was also seen in the waters west of southern Sumatra in 2006 and 2013. Fluctuations in the concentration in the waters west of northern Sumatra remained relatively low. Generally, there was a decrease in the trend of interannual variability of the chlorophyll-a concentration in all of these waters, as shown in Table 2.

Figure 8 shows the interannual variability in chlorophyll-a concentration in the Arafura Sea, the Banda Sea, the Flores Sea, and the Java Sea. The annual average in the Arafura and Java Seas was higher than in the Banda and Flores Seas. Fluctuations in the Flores and Banda Seas were relatively low, whereas in the Arafura and Java Seas, they significantly decreased in 2010. The overall trend showed a decrease in the interannual variability of chlorophyll-a concentration in all of these waters, as seen in Table 2.

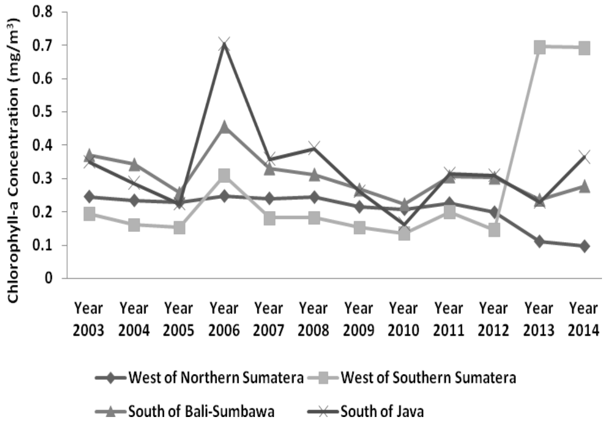

Figure 7. Interannual Variability in Chlorophyll-a Concentration

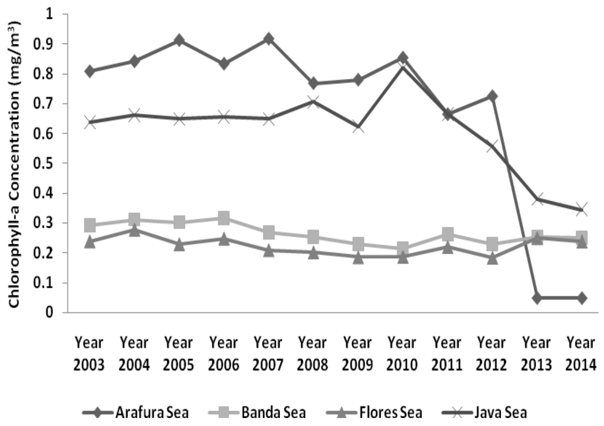

Figure 8. Interannual Variability in Chlorophyll-a Concentration

Table 2. Trends of Chlorophyll-a Concentration

Area	Increasing (mg/m^3 per year)	Decreasing (mg/m^3 per year)
West of Northern Sumatra		-0.011
West of Southern Sumatra		-0.004
South of Bali-Sumbawa		-0.009
South of Java		-0.008
Arafura Sea		-0.062
Banda Sea		-0.006
Flores Sea		-0.002
Java Sea		-0.02
Celebes Sea	0.003	
Halmahera Sea-North of Papua	0.013	
Makasar Strait	0.007	
Karimata Strait		-0.018

Figure 9 shows the interannual variability in chlorophyll-a concentration in the Celebes Sea, the Halmahera Sea north of Papua, the Karimata Strait, and the Makassar Strait. The annual average in the Makassar and Karimata Straits was higher than in the Halmahera Sea north of Papua and the Celebes Sea. The overall trend showed an increase in the Celebes Sea, the Halmahera Sea north of Papua, and the Makassar Strait, and a decrease in the Karimata Strait, as seen in Table 2.

Interannual variability of sea surface temperature in Indonesian waters is influenced by the phenomena of the Indian Ocean Dipole (IOD) and the El Niño-Southern Oscillation (ENSO). Temperatures decreased during positive phases of these phenomena, while they increased during negative phases. The positive phases enhance the intensity of the upwelling process in the waters south of Java and south of Bali-Sumbawa, and in the Banda Sea, causing the sea surface temperature to cool; the opposite effect is caused by the negative phase. Based on analysis of sea surface temperature anomalies between 1984-2013, it is known that the surfaces of Indonesian waters have warmed by about 0.017 °C/year. Such warming is strongly related to ongoing increases in the CO_2 concentration, both globally and locally.

Figure 10 shows the results of the CO_2 concentration measurement conducted by the Global Atmospheric Watch BMKG at Kototabang Bukittinggi, West Sumatra, from 2004-2014. These results tell us that the CO_2 concentration has increased in the Indonesian region, as well as globally from 1980-2014, as shown in Figure 11.

Ongoing increases in CO_2 concentrations will, over time, disrupt the equilibrium of the Earth's climate system [17]. Longwave radiation that are reflected by the Earth's surface cannot penetrate the layers of the atmosphere, due to the greenhouse effect. The more CO_2 is emitted into the atmosphere, the greater the amount of long-wave radiation that is trapped in the atmosphere. These conditions leads to increased temperatures on the Earth's surface, in the air and in the oceans.

In some areas of Indonesia's waters, a different patern of the monthly variability of chlorophyll-a concentration

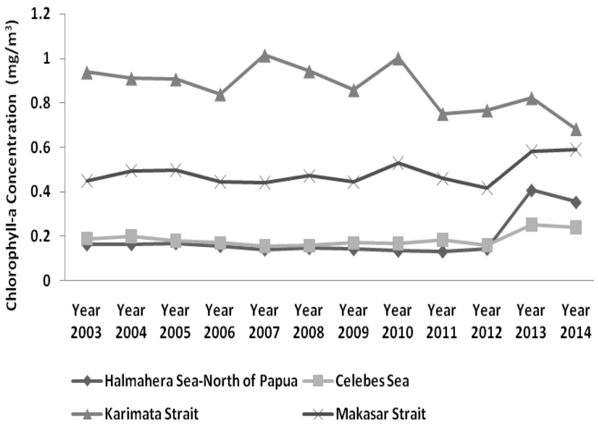

Figure 9. Interannual Variability in Chlorophyll-a Concentration

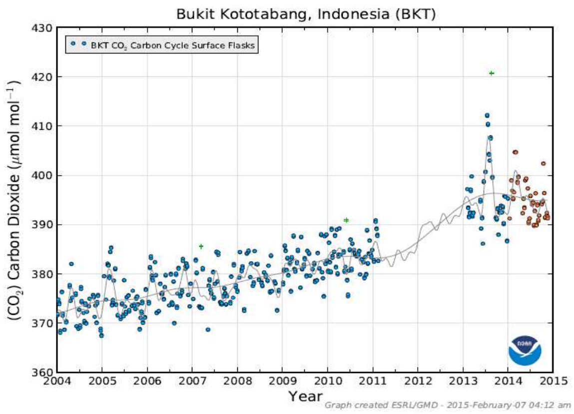

Figure 10. Trends of CO_2 Concentration at Kototabang, Indonesia (sumber:www.esrl.noaa.gov/gmd/dv/iadv)

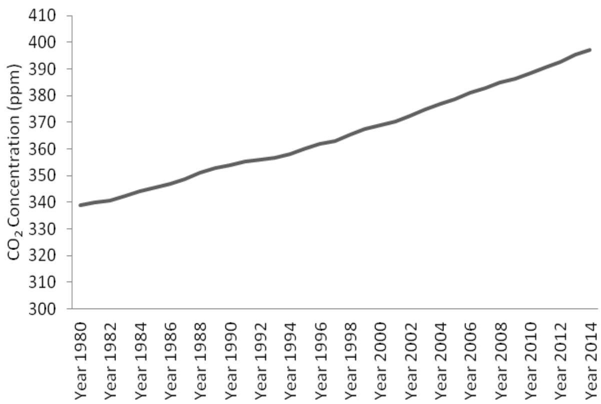

Figure 11. Trends of Global CO_2 Concentration

was observed. This variance is influenced by several factors, most notably atmospheric dynamics and geographical position. The effect of atmospheric dynamics, which occurs in the waters south of Java, south of Bali-Sumbawa, and in the Banda Sea, is closely related to the interaction between the atmosphere and the oceans. The transfer of momentum from surface wind stress to the oceans affects the oceans' dynamics, especially in the surface layer. The effect of geographical position is related to the supply of nutrients from the mainland; this effect occurs in the waters west of Sumatra, the Arafura Sea, the Java Sea, the Flores Sea, the Celebes Sea, the Halmahera Sea - north of Papua, the Karimata Strait, and the Makassar Strait.

The chlorophyll-a concentration of the waters west of Sumatra, the Celebes Sea, and the Halmahera Sea north of Papua is found to be low for almost the whole year on the areas close to the vast ocean. This low concentration is caused by the depth of the waters, the nutrient supplies in the sea bed, required to grow phytoplankton is very limited. This is due to the poor ability of the water mass to bring nutrients to the surface layer. Conversely, there is a high concentration in the waters featuring large islands such as the Arafura Sea, the Java Sea, the Makassar Strait, and the Karimata Strait for almost the whole year, especially during the rainy season. This is due to the abundant supply of nutrients from the mainland, carried by the river stream.

In the Flores Sea, high chlorophyll-a concentrations occur at the time of the west season, which is associated with rainy season, and at the time of the east season, which is associated with upwelling processes in the Banda Sea. Upwelling is the process whereby water mass rises from the bottom layer to the surface layer. This water mass has a cold temperature, high salinity, and high nutrient content, including phosphates, nitrates, and silicates. These nutrients are needed for phytoplankton growth; therefore, in the area where upwelling process occurs, an increase in chlorophyll-a production is always observed. The upwelling process is caused by strong interaction between the atmosphere and the ocean, particulary the exchange of momentum.

During the rainy season, the volume of river flow from the mainland increases, leading to a higher influx of nutrients delivered by river run-off into coastal waters. In the east season, the upwelling process occurs in the Banda Sea, causing an increase in the chlorophyll-a concentration in the surface layer. At the same time, the water mass of the Banda Sea moves westward past the Flores Sea, due to the monsoon, causing the Flores Sea to receive a surplus amount of chlorophyll-a from the Banda Sea.

The monthly variability in chlorophyll-a concentration in the waters south of Java, south of Bali-Sumbawa, and in the Banda Sea shares the same pattern; that is, monsoonal, with one peak and one trough. This is because during the east season and the second transition season, the upwelling process occurs in these waters. At the time of the east season and the second transitional season (September to November), the concentration is high, while it is low at the time of the west season and the first transition season (March to May). The peak during the east season and the second transition season is closely related to the upwelling process.

Each of the Indonesian waters area shows different trends in the interannual variability of chlorophyll-a concentration; of the 12 research sites, 9 show decreases and 3 show increases. The annual global ocean primary production has decreased more than 6% since the early 1980 and nearly 70% occured in the high latitudes [18] and a global rate of 1% decrease of the global median per year was estimated [19]. The experiment model showed a decrease in globally averaged chlorophyll-a concentrations, both in the 20th century (12.1%) and future projections to the year of 2100 (51.0%) [20], slight reduction in chlorophyll-a concentrations during the twentieth century, but a 50% decrease between 2000 and 2200 was projected [21] also a decrease in global mean PP and EP between 2 and 20% by 2100 related to the preindustrial conditions [22]. Global ocean chlorophyll increased 4.13% from 1998 to 2003 and the highest increase took place in coastal regions [23].

The warming of the oceans, due to increases in CO_2 concentrations, affects the conditions of the marine environment and the atmospheric environment. Changes to the marine environment affect the marine ecosystem, which, in turn, has an impact on biogeochemical cycles. Ocean warming also increases the vertical stratification of the water column and the stability of the upper layer, limiting the supply of nutrient substances. Changes in the atmospheric environment also affect marine ecosystems through ocean-atmosphere interactions in the boundary layer. Based on the above study and observations, further investigation is needed regarding the mechanisms causing decreases or increases in the chlorophyll-a concentration in the Indonesian waters. Such research should encompass physics, biology, marine chemistry, and its interaction with the atmosphere (?)

Conclusions

Based on analysis of the results, it can be concluded that continuous increases in CO_2 concentration in the atmosphere, both globally and in Indonesia, lead to warming of the oceans, especially in the upper layer. From 1984-2013, the surface temperature of Indonesian waters increased by about 0.51 °C. The monthly variability of chlorophyll-a concentration has different patterns in each of the Indonesian waters, due to the monsoon system. Surface temperature warming, in turn, affects the abundance and distribution of chlorophyll-a concentration. Each of the water areas showed a different pattern in terms of the effects of surface warming on chlorophyll-a concentration; from the 12 research sites, 9 showed a decrease and 3 showed an increase.

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