Blooming Mechanism off Lombok Strait

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Abstracts

A series of ocean color sensors, OCTS on ADEOS and SeaWiFS on OrbView-2, provided images of chlorophyll-a distribution along the Sunda Islands. A limited number of sea surface wind observation by NSCAT on ADEOS showed the important contribution of the sea surface wind to the distribution of chlorophyll-a. The sea surface topography observation by SAR on J-ERS-1 also supported the surface flow from the Lombok strait and contribution of flows to the phytoplankton distribution. From satellite observation, it is confirmed that the irregular wind, which is different from the major monsoon wind, determines the distribution of phytoplankton. The southeast wind in February 1997 regulated the runoff from the Lombok Strait. The phytoplankton bloom was started when the southeast wind has stopped. From in-situ observation in March 1998, the spatial distribution of the phytoplankton bloom was made clear. The surface layer up to 30 m with a lower density around 21.5 kg m^{-3} and slightly higher nitrate around 0.5 uM L^{-1} maintains the phytoplankton bloom along the coast.

1. Introduction

The Indonesian through flow runs from the Pacific to the Indian Ocean through Indonesian Islands. The North Equatorial Current in the Pacific is the major source of the Indonesian through flow, which enters the Indonesian sea through the Mindanao strait, passing the Celebes Sea, Jawa Sea, the Banda Sea, the Arafura Sea, the Timor Sea and runs into the Indian Ocean. Also the South Equatorial Current in the Pacific is another source of the Indonesian through flow, which is running into the Salam Sea and the Maluka Sea. Figure 1 shows the major route of the Indonesian through flow and related flows on the Java Sea including the minor flows through straits. Although the major part of the Indonesian through flow runs into the Indian Ocean through the Timor Sea, the small portion of the Indonesian through flow runs into the Indian Ocean through the Lombok strait and other minor straits. The intensities of these flows or currents are dependent on the southeast or western monsoon. During the southeast monsoon, from May to September, the Indonesian through flow from the Timor Sea and the South Equatorial Current run along the Sunda Islands toward the West. On the contrary, the northwest monsoon from October to April, the South Equatorial Current runs southern off of the Sunda Islands, while the eastward coastal current, called the Java coastal current, runs along the Sunda Islands. Many scientists discussed these changes with observation and numerical models. [*Gordon et al.*, 1994, *Gordon*, 1995, *Fieux et al.* 1994].

We selected the southern off of the Lombok strait for the research region, where the runoff from the Lombok Strait may have a contribution to the distribution of phytoplankton with related to the seasonal variation of currents in the Indian Ocean. We repeated the expeditions as a joint research between Japan and Indonesia in this region to study the mechanism of the primary production related to the Indonesian through flow using research vessels of the Indonesian government. In these expeditions, we had series of observation by the satellite born color sensors and other sensors, although it was difficult to synchronize between the in-situ measurement and the satellite observation.

2. Remote Sensors

2-1. Ocean Color Thermal Scanner

In August of 1996, the National Space Development Agency of Japan (NASDA) launched the ADEOS. Unfortunately, ADEOS stopped its mission in June of 1997 because of the trouble on the solar panel. During its mission life, OCTS had provided images of chlorophyll-a and sea surface temperature distribution over the globe. The OCTS covers 1400 km in the swath range from the altitude of 800 km. The swath range varies with the tilting function of the scanning mirror, which is designed to avoid a solar glitter from the surface. The OCTS has a spatial resolution of 700 m at a nadir. Figure 2-a shows a chlorophyll-a distribution observed and Figure 2-b shows a sea surface temperature distribution observed by OCTS. These images show a beginning of the chlorophyll-a bloom off the Lombok strait.

2-2. Sea Wide Field of View Sensor

Shortly after the ADEOS mission, the NASA and the OrbImage cooperation launched the OrbView-2 polar orbiting satellite with the SeaWiFS. The SeaWiFS provides images of chlorophyll-a distribution as much as the OCTS. The SeaWiFS covers 2000 km in swath from the altitude of 800 km. The SeaWiFS has a spatial resolution of 1.4 km at a nadir, although it varies with a tilting angle. Figure 3-a shows a chlorophyll-a distribution observed by SeaWiFS and Figure 3-b shows a sea surface temperature distribution observed by AVHRR. These images show a plume of chlorophyll-a from the Lombok strait.

3. Mechanism of chlorophyll bloom

It was possible to classify the water layers into four layers in the offshore water and three layers in the coastal water judging from the vertical distribution of chlorophyll-a. Figure 4-a shows a vertical cross section of chlorophyll-a along 116 degree-East between 9 degree-South to 12 degree-South. Figure 4-b is a vertical cross section of nitrate (NO3). Figure 4-c is a vertical cross section of Density. Figure 4-d is a vertical cross section of current vectors observed by ADCP.

The offshore water is classified into four different water layers. The top layer is the surface mixed layer with showing a lower density and with a depleted nitrate. In this top layer, the chlorophyll-a concentration is around 0.1 mg m^{-3}, which is lower than the surface water near the Islands. The nitrate is supplied by the runoff from the Lombok strait, but the nitrate cannot be supplied to the offshore through the surface layer, where the nitrate is consumed by the phytoplankton immediately. The second layer is the pycnocline with a depleted nitrate. The pycnocline is the stable water layer under the mixed layer and over the nitracline with preventing a penetration or a mixing of waters between both sides. In this second layer, the chlorophyll-a concentration is very low, less than 0.1 mg m^{-3}, because of low nitrate. The third layer is the nitracline, where the higher density water and the chlorophyll maximum are observed. The chlorophyll maximum shows the chlorophyll-a concentration around 0.4 mg m^{-3}, which is lower concentration than the chlorophyll maximum near the coast. The forth layer is the high density and the high nitrate water mass under the chlorophyll maximum. The second and deeper layers showed the stable flows.

The coastal water is classified into three different water layers. The top layer is the surface mixed layer with the lower density and with the slightly higher concentration of the nitrate. In this top layer, the chlorophyll-a concentration is around 0.2 mg m^{-3}. This top layer is supposed to be the water mass from straits along the Sunda Islands. The second layer is the stable water mass with the pycnocline and the nitracline. In this second layer, the chlorophyll maximum is observed with the chlorophyll-a concentration around 1.0 mg m^{-3}. The third layer is the high density and the high nitrate water mass under the chlorophyll maximum. The second and deeper layer is the westward Indonesian through flow along the Islands, because of the steady westward current. This also suggests that the structures of the water mass in the second and deeper layer are that of the Indonesian through flow along the Sunda Islands.

In this section, we classified the water masses into the offshore and the coastal type. From this classification, it is possible to address that the surface mixed layer is observed in all sections. The surface mixed layer near the coast is slightly deeper than that of the offshore. The observation depth of the satellite ocean color sensor is in the order of the inverse of K, the attenuation coefficient of the water. Except the coastal turbid waters, the observation depth of the water in this area is corresponding to the surface-mixing layer. This means that the chlorophyll-a distribution observed by the ocean color sensor only explains the water characteristics only in the surface-mixing layer.

The chlorophyll-a blooming in this region, especially observed by the satellite sensor, is the phenomenon in the surface-mixing layer, which is influenced by the flows from the straits along the Sunda Islands, the tidal currents, and the sea surface winds. The major westward stream of the Indonesian through flow along the Sunda Islands did not make a significant contribution to the surface-mixing layer with running under the surface-mixing layer.

4. Conclusion

In the previous studies, there were two hypotheses on the bloom of phytoplankton in the Indian Ocean on two different seasons. *Nontiji* [1977] proposed the hypothesis that the nutrient rich water originated from the westward SEC during the southeast monsoon produced the bloom. *Setiapermana* [1992] proposed the hypothesis that the divergence between the eastward Java coastal current and the westward SEC during the northwest monsoon produced the bloom. These two hypotheses explain the blooms for two seasons, the southeast monsoon and the northwest monsoon.

In this study, the continuous observation by satellite, especially using the ocean color sensors, revealed the mechanism of primary production along the Sunda Islands. Those data described that the runoff from the straits along the Sunda Islands are continuously running into the Indian Ocean except the period while the strong southeast wind suppress the flow into the Indian Ocean.

The OCTS provided the data set to understand the mechanism of the primary production. The NSCAT supported the understanding of the current field with the wind data. Although the satellite observation in March 1997 was in the western monsoon period, the strong southeast wind prevented the flows from the Lombok strait to the Indian Ocean. It is suggested that the southeast wind on the both side of the Sunda Islands regulated the flows, especially the southeast wind along the northern side of the Sunda Islands regulated the outgoing flow into the Indian Ocean. Following to the southeast wind period, the west wind was dominant as in the western monsoon period. During this west wind period, the flows from the Lombok strait were continuously observed.

The synchronized observations between the satellites and the research vessel were realized in March of 1998. In this period, the flow from the Lombok strait was continuously observed. The water sampling from the water column revealed the structure of the water mass along the Sunda Islands. The water layers are classified into four layers in the offshore water and into three layers in the coastal water.

In the offshore, the top layer is a surface mixed layer with a low density and a low nitrate concentration, where a chlorophyll-a concentration was less than 0.1 mg m^{-3}. The second layer is a pycnocline with a low chlorophyll-a concentration and a low nitrate concentration. The third layer is a nitracline with higher density water and a chlorophyll-a maximum around 0.4 mg m^{-3}. The fourth layer is high density and nitrate rich water under a chlorophyll-a maximum.

Along the coast, the top layer is a surface mixed layer with a low density and a slightly higher nirate, where a chlorophyll-a concentration was around 0.2 mg m^{-3}. This top layer is water mass from the Lombok strait and observed by satellite sensors. The second layer is a stable water mass with a pycnocline and nitracline, where a chlorophyll-a maximum was observed in the order of 1.0 mg m^{-3}. The third layer is high density and nitrate rich water under a chlorophyll-a maximum.

The surface mixed layer in the offshore and the coastal area showed a different nitrate concentration. The nitrate is supplied by the runoff from the Lombok strait, but the nitrate cannot be supplied to the offshore through the surface layer, as the nitrate is consumed by the phytoplankton immediately.

This mechanism is also observed by the SAR image as the distribution of the surface roughness. The surface roughness indicated the runoff of the coastal water from the Lombok strait and the water mass scattered to the offshore.

For these distribution of the water mass and the distribution of chlorophyll-a bloom in the surface, this study made clear the influence of the southeast wind to regulate the flow of the water from the straits along the Sunda Islands and the less influence of the west wind. The southeast wind along the Sunda Island will regulate the water mass in the both side of the Sunda Island, the Java Sea and the Indian Ocean, with reducing the outgoing flows into the Indian Ocean. On the contrary, the west wind along the Sunda Island may push the water mass in the Java Sea into the Indian Ocean through the straits along the Sunda Islands.

5. References

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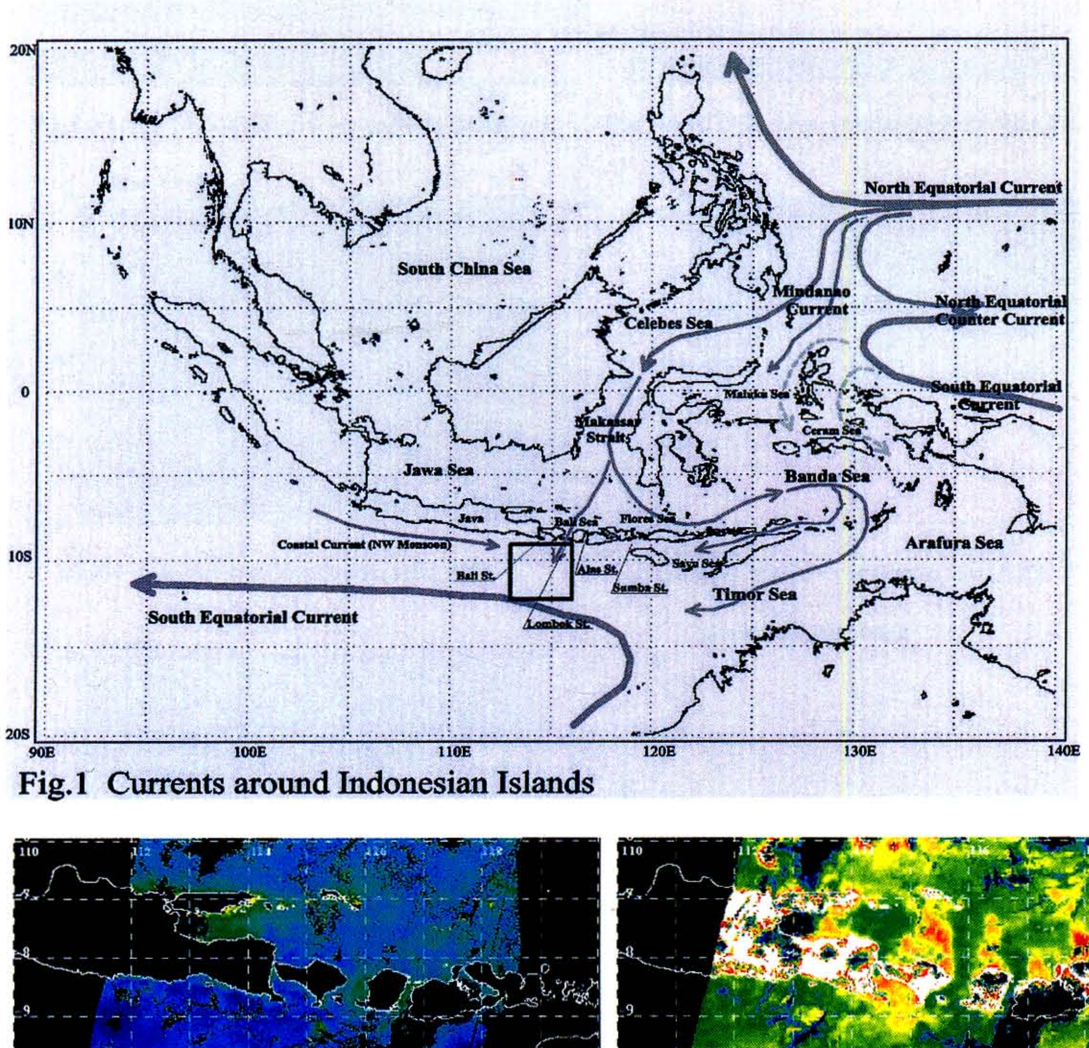

Fig.1 Currents around Indonesian Islands

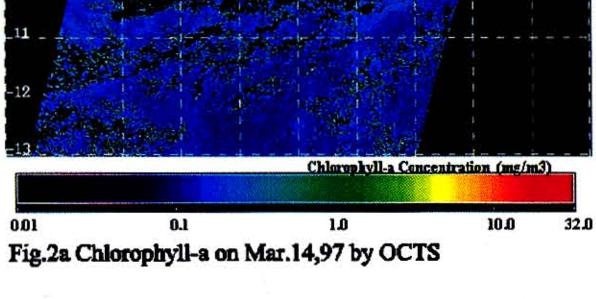

Fig.2a Chlorophyll-a on Mar.14,97 by OCTS

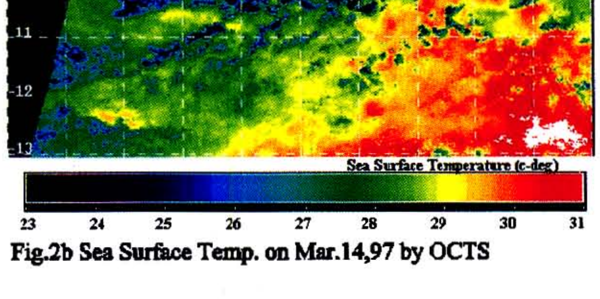

Fig.2b Sea Surface Temp. on Mar.14,97 by OCTS

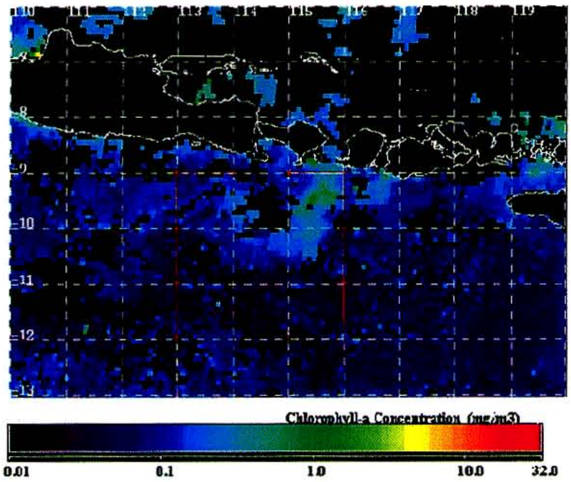

Fig.3-a Chl-a 14-Mar-98 to 21-Mar-98 by SeaWiFS

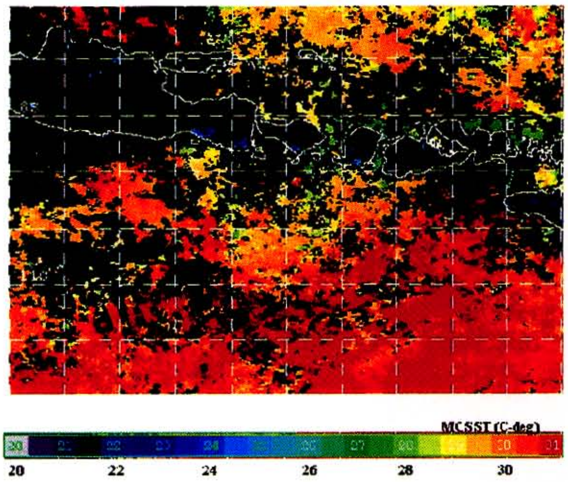

Fig.3-b MCSST from 14-Mar-98 to 21-Mar-98 by AVHRR

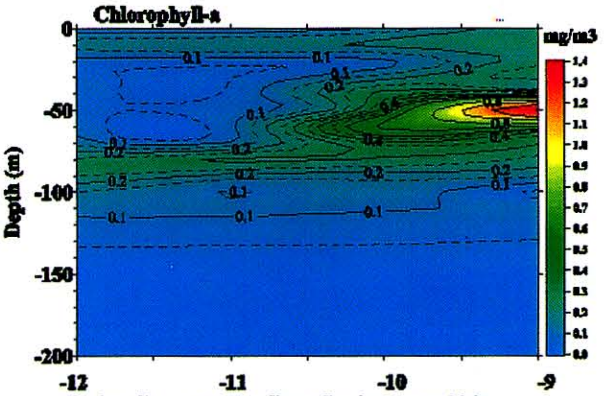

Fig.4-a Chlorophyll-a Cross Section along 116E

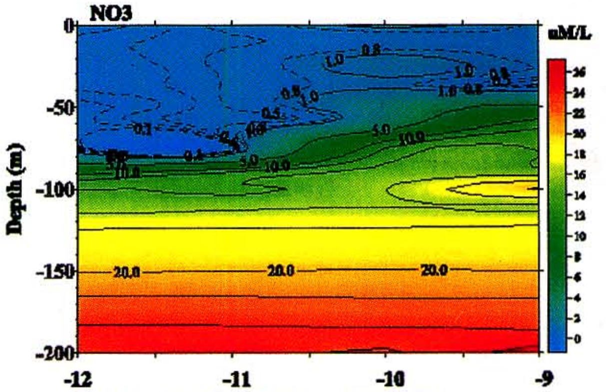

Fig.4-b Nitrate Cross Section along 116E

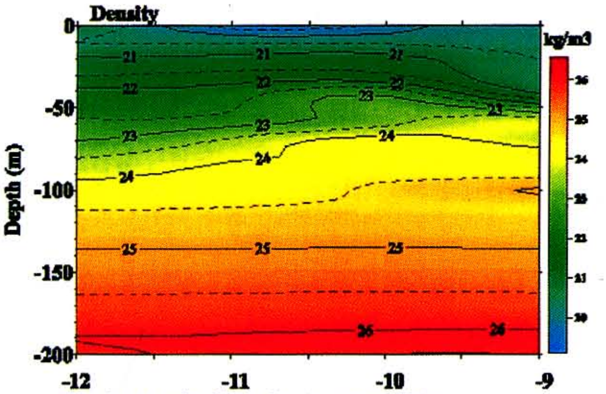

Fig.4-c Density Cross Section along 116E

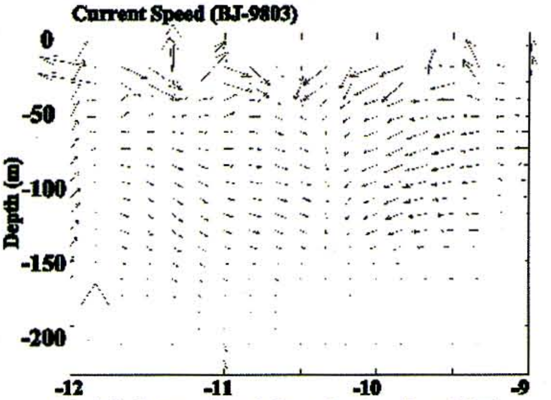

Fig.4-d Current Speed Cross Section along 116E
(Left bottom arrow=2kt)