VARIABILITY OF CHLOROPHYLL-A DISTRIBUTION ASSOCIATED WITH INTERNAL SOLITARY WAVE PATTERNS USING DIFFERENT SENSOR OCEAN COLOR DATA IN THE LOMBOK STRAIT

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KEY WORDS: Chlorophyll-a distribution, internal solitary waves, Lombok Strait, Ocean color

ABSTRACT: Internal solitary wave (ISW) ocean color patterns in Lombok Strait are shown to be significantly similar to those in optical "sun-glint" imagery. ISW activity that can modify sea surface roughness will affect sea surface reflectance characteristics recorded by optical images. In this paper, multi-sensor ocean color images from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Visible and Infrared Imager/Radiometer Suite (VIIRS) are employed to understand the variability of chlorophyll concentration and remote sensing reflectance (Rrs), which detect the ISW patterns in the Lombok Strait. This study examines the relationship between the internal solitary wave patterns detected in the chlorophyll-a data and the Rrs bands using different sensor ocean color images. The comparison results of the correlation between ocean color multi-satellite images show that the cross-section profile on the detected patterns are characterized by a high correlation between chlorophyll-a and the green Rrs bands (531-670 nm), in two different sensors.

INTRODUCTION

Indonesian seas, the interocean part in the low-latitude from the Pacific to the Indian Ocean, has an essential role in the large-scale ocean circulation known as Indonesian throughflow (ITF). Lombok Strait is an ITF's outflow in the southern part of the Indonesian seas which is directly connected to the Indian Ocean and separates the islands of Bali and Lombok. Susanto et al. (2005) observed high-amplitude internal solitary waves (ISWs) that appear intensively in the Lombok Strait. ISWs have been observed in the Lombok Strait using in-situ measurement (Susanto et al., 2005; Syamsudin et al., 2019), have been simulated by numerical simulation (Ningsih, 2008), and observed with satellite measurements to determine the ISWs properties (Mitnik, 2008; Karang et al., 2011; Karang et al., 2012; Karang et al., 2019a; Karang et al., 2019b; Chonnaniyah, 2019). The availability of ocean color data based on different sensors, from Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Aqua satellite and the Visible and Infrared Imager/Radiometer Suite (VIIRS) on board the Suomi National Polar-orbiting Partnership (S-NPP) and Joint Polar Satellite System (JPSS-1) satellites provide a very good opportunity to support the analysis of the ISW dynamics. These satellite data are converted to reveal the chlorophyll-a distribution near the sea surface, which result from varying levels of phytoplankton concentrations. ISWs are physical processes that can strongly influence marine ecosystems and nutrient mixing in the euphotic zone.

The chlorophyll-a distribution below the sea surface can be affected by ISWs by lifting the nutrients into the euphotic zone (Yang et al., 2010; Sangra et al., 2001; Gaxiola-Castro et al., 2002). Da Silva et al. (2002) uses ocean color images from Sea-viewing Wide Field of view Sensor (SeaWiFS) to demonstrate that internal tidal waves can produce a color signature and proposes a simple model for estimating chlorophyll-a from remotely sensed data to validate the internal wave signals on the surface chlorophyll-a. Arvelyna et al. (2001) examined the chlorophyll-a distribution affected by the IWs in the Lombok Strait and adjacent areas. They concluded that the IWs probably affect the chlorophyll-a distribution and increase surface chlorophyll-a distribution near the coastal area. This study examines the relationship between the internal solitary wave patterns detected in the chlorophyll-a data and the remote sensing reflectance (Rrs) bands using different ocean color sensors.

DATA AND METHOD

Ocean color remote sensing is the most feasible approach to estimate phytoplankton biomass and the carbon cycle in the global ocean. The intensity and spectral distribution of the visible light reflected out of the water is an important principle of ocean color measurements in the biological and biogeochemical processes that affect the optical properties of the water column (Dierssen et al., 2013). This study investigates images from the MODIS and VIIRS ocean color sensor in the Lombok Strait when an ISW pattern was detected. MODIS sensor from Aqua satellite has 36 channels in the range of visible and infrared regions with the spatial resolution about 250 m and 1 km, the spectrum from 0.412µm to 14.235µm. The VIIRS has 22 channels, including 16 moderate-resolution bands (M-bands), five imaging resolution bands (I-bands), and one panchromatic DNB (Day/Night Band). The spatial resolution is from 375 m to 750 m which has a spectral range from 0.412 µm and 12.01 µm (Cao et al., 2017).

As a first step, to ensure the existence of a detected ISW pattern in the optical image, the high spatial resolution of MODIS-Aqua (250 m) and VIIRS (375 m) Level-1 images in the Lombok Strait areas were collected from the Level-1 and Atmosphere Archive & Distribution System Distributed Active Archive Center (LAADS DAAC) website (https://ladsweb.modaps.eosdis.nasa.gov/). Four Level-1 data files without cloud cover contamination on April 30, 2016, and May 31, 2018, were processed with a free software SeaDAS version 7.5.3 based on the BEAM toolbox, for remote sensing re-projection raster files.

Second, to study variability of the chlorophyll-a distribution associated with ISW patterns using different sensor ocean color images in Lombok Strait, the Level-2 ocean color data were collected from Ocean Color Web (https://oceancolor.gsfc.nasa.gov/). Four Level-2 data files on April 30, 2016, and May 31, 2018, were processed with a free software SeaDAS for remote sensing re-projection raster files and cross-profile plot pixels along with the ISW pattern in the chlorophyll-a concentration and Rrs bands. Chlorophyll-a concentrations in the ocean color data using the standardized estimation of chlorophyll require an empirical relationship developed from field measurements collected over the global ocean (O'Reilly et al., 1998). The OC3M algorithm developed for MODIS using the 4th order polynomial derived from field measurements of chlorophyll-a and Rrs. Band ratio between the higher value of Rrs in the blue channels (443 or 488 nm) with the green channel (551 nm) is used in this algorithm. The OC3V algorithm developed for VIIRS with the same polynomial as OC3M, using the band ratio between the higher value of Rrs in the blue channels (443 or 486 nm) with the green channel (550 nm).

RESULTS

The high spatial resolution of MODIS-Aqua (250 m) has been used to observe ISW patterns under the presence of sun glint (Jackson, 2007). The ISWs detected in the sun's glint images as bright and dark bands result from sea surface roughness variation, similarly to those revealed in Synthetic Aperture Radar (SAR) images (Alpers, 1985). The convergent and divergent zones generate the sea surface roughness due to the ISW currents activity that moves on the surface in phase with wave's subsurface crests and troughs (Munk et al., 2000). Figure 1 shows two packets of IWs propagating northward into the Flores Sea and southward into the Indian Ocean. This image was acquired in the optical channels at band 645 nm of MODIS-Aqua image with 250 m spatial resolution and taken on May 31, 2018, at 05:45 WITA (local time) during the south-east monsoon.

Figure 1. MODIS-Aqua image of the Lombok Strait was recorded on May 31, 2018, at 05:45 WITA (local time). This image is optical imagery at band 645 nm with 250 m of spatial resolution.

Susanto et al. (2005) have shown that the high-amplitude of ISW is primarily generated from the Lombok Strait. Large vertical displacements of water masses also have been shown caused by ISW with the wave amplitude (crest to trough) exceeding 100 m. Chlorophyll-a concentration images from MODIS-Aqua and VIIRS/S-NPP (Figure 2) show an ISW-like pattern in the strait's northern part. This ISW-like pattern has a similar shape as in the visible band image of Figure 1.

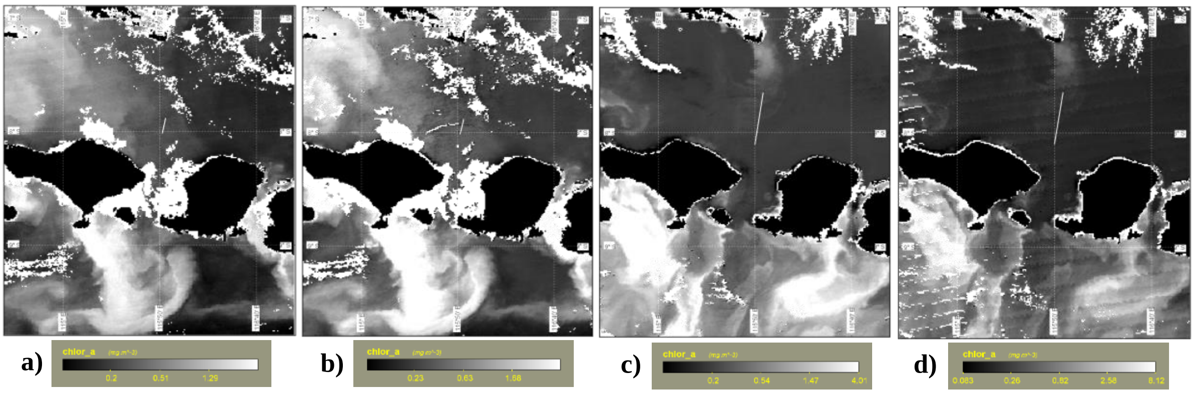


Figure 2. Chlorophyll-a concentration images contained in the ocean color data acquired on April 30, 2016, from (a) MODIS-Aqua at 05:50 WITA (local time), (b) VIIRS/ S-NPP at 05:48 WITA (local time), and May 31, 2018, from (c) MODIS-Aqua at 05:45 WITA (local time) and

(d) VIIRS/JPSS-1 at 05:30 WITA (local time). The white line is the cross-line for the profile plot.

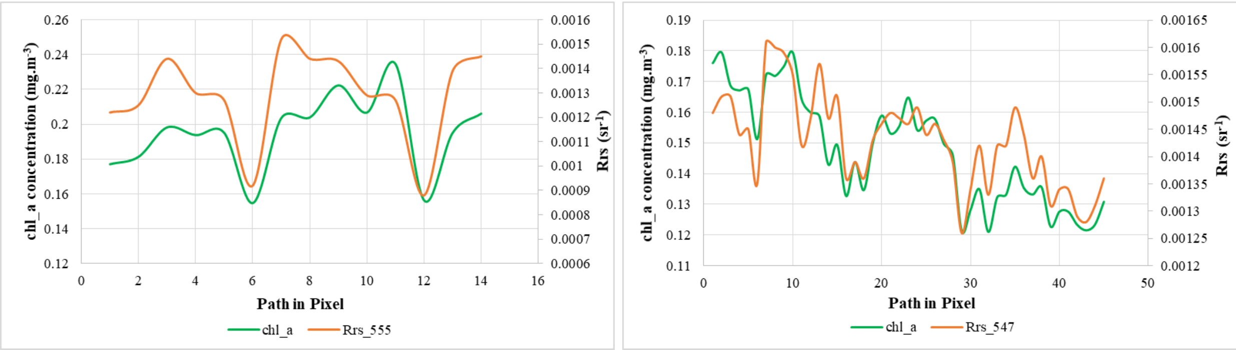
To better understand which Rrs band has the most similar profile to surface chlorophyll-a derived from ocean color data, all Rrs bands from different sensor satellite and the chlorophyll-a were analyzed. MODIS and VIIRS chlorophyll-a employ the standard OC3 (O'Reilly et al., 1998) band ratio algorithm merged with the color index (CI) of Hu et al. (2012). Table 1 shows the correlation coefficient between Rrs bands and chlorophyll-a concentration from MODIS and VIIRS sensors. This study investigated the ISW-like pattern at two different times to determine the variability of chlorophyll-a distribution associated with ISW.

Table 1. The correlation coefficient between Rrs bands with chlorophyll-a concentration from MODIS and VIIRS sensors.

MODIS			**VIIRS**		
Product	April 30, 2016	May 31, 2018	**Product**	April 30, 2016	May 31, 2018
Rrs_412 nm	0.50	-0.52	Rrs_410 nm	-0.13	-0.19
Rrs_443 nm	0.45	-0.64	Rrs_443 nm	-0.22	-0.49
Rrs_469 nm	0.43	-0.43	Rrs_486 nm	-0.24	-0.27
Rrs_488 nm	0.39	-0.01	Rrs_551 nm	0.47	0.86
Rrs_531 nm	0.70	0.79	Rrs_671 nm	0.59	0.54
Rrs_547 nm	0.75	0.84			
Rrs_555 nm	0.76	0.73			
Rrs_645 nm	0.24	0.62			
Rrs_667 nm	0.46	0.74			
Rrs_678 nm	0.40	0.77			

Based on Table 1, the correlation coefficients for all data used in this study show the highest correlation values for the green Rrs bands (531-670 nm). There is a difference in the correlation coefficient in the blue band (412-488 nm) on the MODIS sensor. On April 30, 2016, the image showed a positive correlation value in the blue bands, while the image on May 31, 2018 shows a negative correlation value. These response differences could be caused by the differences in chlorophyll-a concentrations on both images. The image on April 30, 2016 has a chlorophyll-a concentration range of 0.15-0.22 $mg.m^{-3}$ with a difference in the chlorophyll-a concentration in the crest and troughs pattern of 0.040 $mg.m^{-3}$, while the image on May 31 2018 has a chlorophyll-a concentration range of 0.12-0.18 $mg.m^{-3}$ with a difference in chlorophyll-a concentration in the crest and troughs pattern 0.028 $mg.m^{-3}$ (Figure 3).

The VIIRS sensor shows a similar correlation coefficient in the two different images, a positive correlation on the green Rrs band and a negative correlation on the blue Rrs band. There is a difference in the value of the highest correlation coefficient in the two images. On April 30, 2016 the highest correlation was in the Rrs band (671 nm) and the image on May 31, 2018 the highest correlation was in the green Rrs band (551 nm). The high correlation in the Rrs band 671 nm could be due to the fluorescence effect. Fluorescence is generated from re-emission of the solar radiation in the red portion absorbed in the visible wavelengths by the phytoplankton chlorophyll-a (Martin, 2014).



(a) **(b)**

Figure 3. The cross-profile plot between chlorophyll-a concentration and the Rrs band with the highest correlation coefficient for MODIS-Aqua acquired on (a) April 30, 2016 (Figure 2a) and (b) May 31, 2018 (Figure 2c).

CONCLUSION

This study has shown ISWs modification of the chlorophyll-a concentration in the water column which can be detected by ocean color data sensors. The chlorophyll-a distribution that follows the ISWs pattern can be used as a proxy in measuring ISWs itself or vice versa to determine the role of ISWs in nutrient distribution in the Lombok Strait. This is very important considering the abundance of ocean color data in the global database. The combination of ocean color data, field measurement data and ocean modeling data are needed to study the relationship mechanism of ISWs and subsurface nutrients required for the ISWs research development in the future.

ACKNOWLEDGEMENT

Thanks to NASA Ocean Biology and Biogeochemistry for providing ocean color data both from MODIS and VIIRS sensors to support this effort.

REFERENCES

Alpers, W., 1985. Theory of Radar Imaging of Internal Waves. Nature, 314, pp. 245–247.

Arvelyna, Y., Oshima, M., 2005. Preliminary Study of Internal Wave Effects to Chlorophyll Distribution in the Lombok Strait and Adjacent Areas. In: Proc. of SPIE (5656) Active and Passive Remote Sensing of the Oceans, edited by Frouin, R.J., Kawamura, H., Pan D., pp. 139-146.

Cao, C., Xiong, X., Wolfe, R., et al., 2017. Visible Infrared Imaging Radiometer Suite (VIIRS) Sensor Data Record (SDR) User's Guide (Version 1.3). NOAA Technical Report NESDIS 142, Washington, D.C.

Chonnaniyah, Osawa, T., Karang, I. W. G. A., 2019. Study of Internal Solitary Waves Feature Extraction Based on Stationary Wavelet Transform by Sentinel- 1A Image in Lombok Strait. Ecotrophic, 13(1), pp. 29-40.

Da Silva, J. C. B., New, A. L., Srokosz, M. A., et al., 2002. On the observability of internal tidal waves in remotely-sensed ocean colour data. Geophysical Research Letters, 29(12), pp. 1569-1573.

Dierssen, H. M., Randolph, K., 2013. Remote Sensing of Ocean Color. In: Earth System Monitoring: Selected Entries from the Encyclopedia of Sustainability Science and Technology, edited by Orcutt, J., Springer Science + Business Media, New York.

Gaxiola-Castro G, Alvarez-Borrego S, Najera-Martinez S et al., 2002. Internal waves effect on the Gulf of California phytoplankton. Cienc. Mar., 28, pp. 297-309.
Hu, C., Lee, Z., & Franz, B., 2012. Chlorophyll a algorithms for oligotrophic oceans: A novel approach based on three-band reflectance difference. Journal of Geophysical Research, 117(C1).
Jackson, C., 2007. Internal Wave Detection Using the Moderate Resolution Imaging Spectroradiometer (MODIS). Journal of Geophysical Research, 112(C11), pp. C11012.
Karang, I. W. G. A., Chonnaniyah, Osawa, T., 2019a. Lombok Strait internal wave occurrence frequency derived from Sentinel-1A SAR images. In: Proc. SPIE 11372, Sixth International Symposium on LAPAN-IPB Satellite, LIS100 (113721O).
Karang, I. W. G. A., Chonnaniyah, Osawa, T., 2019b. Landsat 8 Observation of the Internal Solitary Waves in the Lombok Strait. Indonesian Journal of Geography. 51(3), pp. 251-260.
Karang, I. W. G. A., Nishio, F., Mitnik, L., & Osawa, T., 2012. Spatial-Temporal Distribution and Characteristics of Internal Waves in the Lombok Strait Area Studied by ALOS-PALSAR Images. Earth Science Research, 1(2), pp. 11–22.
Karang, I. W. G. A., & Nishio, F., 2011. Internal waves in the Lombok Strait revealed by ALOS PALSAR images. In: Proc. IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Vancouver, Canada. pp. 253-256.
Martin, S., 2014. An Intorduction to Ocean Remote Sensing. Cambridge University Press, New York, pp. 173-174.
Mitnik, L. M., 2008. Advanced land observing satellite PALSAR observations of the oceanic dynamic phenomena in the coastal zone. In: International Geoscience and Remote Sensing Symposium (IGARSS), 2(1), pp. 351–354.
Munk, W., Armi, L., Fiscer, K., Zachariasen, F., 2000. Spirals on the Sea. In: Proc. R. Soc., 456, pp. 1217-1280.
Ningsih, N. S., Rahmayani, R., Hadi, S., & Brojonegoro, I. S., 2008. Internal Waves Dynamics in the Lombok Strait Studied by a Numerical Model. International Journal of Remote Sensing and Earth Sciences, 5, pp. 17–33.
O'Reilly, J.E., Maritorena, S.,Mitchell, B. G., Siegel, D. A., Carder, K. L., Garver, S. A., Kahru, M., & McClain, C. R., 1998. Ocean color chlorophyll algorithms for SeaWiFS. Journal of Geophysical Research, 103, pp. 24937-24953.
Sangra P, Basterretxea G, Pelegri J L et al. 2001. Chlorophyll increase due to internal waves on the shelf break of Gran Canaria (Canary Islands). Sci. Mar., 65, pp. 89-97.
Susanto, R. D., Mitnik, L. & Zheng, Q., 2005. Ocean Internal Waves Observed in The Lombok Strait. Oceanography, 18(4), pp. 125-132.
Syamsudin, F., Taniguchi, N., Zhang, C., Hanifa, A. D., Li, G., Chen, M., et al., 2019. Observing internal solitary waves in the Lombok Strait by coastal acoustic tomography. Geophysical Research Letters. 46, pp. 10475-10483.
Yang, D., Haibin, Y.E., Wang, G., 2010. Impacts of internal waves on chlorophyll a distribution in the northern portion of the South China Sea. Chinese Journal of Oceanology and Limnology, 28(5), pp. 1095-1101.