Application of Ocean Color Remote Sensing for Managing the Bay of Bengal

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Abstract:

Ocean color remote sensing has brought a new era in ocean management. A reasonable number of satellites are dedicated at present for providing ocean color data to boost up ocean management. The major satellites include MODIS, OCM-2, VIRS, OLCI, etc. Major applications of those sensors are identifying potential fishing ground and harmful algal bloom, tracking cyclone, determining oil slick, monitoring mangrove ecosystem and trends. Ocean color remote sensing offers many advantages over conventional procedures for example synoptic coverage, repeated observations, and area averaging. The absence of nearshore, particularly the area below 200 m depth of the Bay of Bengal, data is a major limitation of those sensors. The necessity of regional and bio-optical algorithms, atmospheric corrections, in-situ data validations, artificial neural networks, and the accuracy of those sensors is still a challenge for oceanographers. This study aims to address the preferable ocean color remote sensors and their importance of oceanic management in the Bay of Bengal.

Keywords: Remote Sensing, Ocean Color Sensors, Trend Analysis, Coastal Zone, Bay of Bengal.

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1. Introduction:

Ocean color is a passive form of remote sensing. Sunlight passes through the atmosphere is absorbed and scattered by atmospheric particles, gases, and aerosols and enters the ocean and is absorbed and scattered by various constituents including pure water, phytoplankton, and dissolved and particulate matter. A proportion of the incoming light is eventually reflected towards the satellite. The signal ultimately received at the satellite contains major information about the in-water constituents and can be used following atmospheric correction (Sathyendranath 2000). In short, ocean color is the spectral composition of the visible light field that radiates from the ocean. It depends on the spectrum solar irradiance, atmospheric conditions, and the absorption and scattering properties of water and the substances (phytoplankton and suspended sediments) that are dissolved and suspended in the water column (Werdell and McClain 2019). The color of water causes the variability in seas and their constituents measured by remote sensing techniques serve as a significant technical part in ocean science. Space remote sensing supports human requirements by observing aquatic pools and warning against climatic hazards since the earliest starting time. The information on water constituents permits the expectation of fishing grounds and subsequently giving financial advantages from seas. The remote sensing technique provides an immediate pathway to overcome natural disasters and their consequences. (Jungblut, Liebich, and Bode 2018). Changes in land use and sedimentation along coastlines are also observed by satellite images (Aryastana, Ardantha, and Candrayana 2018). Phytoplankton tracking supports fisheries and subsequent economy. (Moreira and Pires 2016). To warn against the toxicity of the harmful algal blooms (HABs), governmental institutes use remote sensing techniques to identify and track phytoplankton (Schaeffer, Loftin, and Stumpf 2015).

Starting in the mid-20th century, remote sensing of the marine environment has grown to satellites dedicated to the task of delineating various aspects of the ocean (Fingas 2018). In Bangladesh, very few remote sensing related studies are available with a focus on the Bay of Bengal. Besides, researchers in the ocean color remote sensing field often face a major problem in identifying the actual depository of the data due to a lack of conciliated information hub. The present study will characterize the most used responsible satellite and their application for oceanic management in the Bay of Bengal as well as the advantages and limitations of individual satellites and their images. This paper will be an information hub for future ocean color remote sensing researchers and other scientific communities.

2. Ocean Color Satellite Data Products

Oceanographers use satellite data for an application ought to approach the selection of a suitable source with care. They consider the data provider, completeness, format, viewers, accuracy, interpretation, transparency, location, etc. (Robinson and Robinson 2010). Earth observations sensors with ocean color capability updated by the International Ocean Color Coordinating Group (IOCCG) are shown in Table 1.

Most of the ocean color sensors at present have a wide field of view, which translates to a wide sampling swath, and are mounted on sun-synchronous polar-orbiting satellites (e.g. Coastal Zone Color Scanner (CZCS), Sea-Viewing Wide Field-of-View Sensor (SeaWiFS), Ocean and Land Colour Instrument (OLCI), Moderate Resolution Imaging Spectroradiometer (MODIS)-Aqua and Terra. The satellites provide global coverage of the earth roughly every three days at the equator and more frequently at the poles. Data are frequently averaged over longer periods to deliver weekly, monthly, and seasonal composite images of the global ocean (Dierssen and Randolph 2013).

Table 1 Recent, existing, and near-future satellite sensor systems of relevance for ocean color (Groom et al. 2019)

Status	Platform	Sensor	Spatial Resolution	Bands	Revisit frequency	Water quality variables					Internet URL
						Chl	CYP	TSM	CDOM	Kd	
Current	Terra/Aqua	MODIS-A&T	1 km	36	daily	✓✓	✓ S	✓✓	✓✓	✓✓	https://oceancolor.gsfc.nasa.gov/
	Oceansat-2	OCM-2	300 m	8	2-3 days	✓✓	✓✓	✓✓	✓✓	✓✓	https://www.mosdac.gov.in/oceansat-2
	Suomi/ NOAA-20	VIRS	750 m	22	daily	✓✓	✓ S	✓✓	✓✓	✓✓	http://oceanwatch.pifsc.noaa.gov
	Sentinel 3 A/B	OLCI	300 m	21	Daily (with 2 satellites)	✓✓	✓✓	✓✓	✓✓	✓✓	https://sentinel.esa.int/web/sentinel/missions/sentinel-3/data-products/olci
Future	JPSS-2, JPSS-3	VIRS	750 m	7	daily	✓✓	✓ S	✓✓	✓✓	✓✓	https://www.jpss.noaa.gov/
	Sentinel 3 C/D	OLCI	300 m	21	Daily (with 2 satellites)	✓✓	✓✓	✓✓	✓✓	✓✓	https://sentinel.esa.int/web/sentinel/missions/sentinel-3/data-products/olci
	Oceansat-3	OCM-3	300 m	13	2-3 days	✓✓	✓✓	✓✓	✓✓	✓✓	space.skyrocket.de/doc_sdat/oceansat-3.htm
	Sabia-MAR	MUS	200/800m	13	1-2 days global	✓✓	✓✓	✓✓	✓✓	✓✓	space.skyrocket.de/doc_sdat/sabia-mar-1.htm
	PACE	OCI	1 km	5	daily	✓✓	✓✓	✓✓	✓✓	✓✓	https://pace.oceansciences.org/

✓✓: highly suitable, ✓: suitable, Chl: Chlorophyll; CYP: Cyanobacterial Pigments (S denotes surface blooms); TSM: Total Suspended Matter; CDOM, Colored Dissolved

Organic Matter; Kd: Diffuse Attenuation Coefficient (or attenuation coefficient of diffuse light).

3. Application of Ocean Color Remote Sensing in Marine Environment

Ocean color data is very important for a wide range of operational forecasting, oceanographic research, and associated applications. Few examples of the applications are mentioned below:

3.1 Fish School Detection: Identifying fishing grounds and then fish harvesting is very important but difficult. Timely and accurate advisory about the fishing grounds would come as a great help for the fishing community. Ocean color sensors are capable to identify the potential fishing grounds and that too, very accurately and timely. The underlying principle is the identification of phytoplankton colonies on which the fishes thrive**.** For identification of potential fishing ground in the Bay of Bengal**,** Sea Surface Temperature (SST) and Chlorophyll data retrieved regularly from NOAA-AVHRR (USA) and EUMETSAT (ESA) series satellites along with optical bands of Oceansat-II (India) and MODIS Aqua (USA) satellites (Karuppasamy et al. 2020).

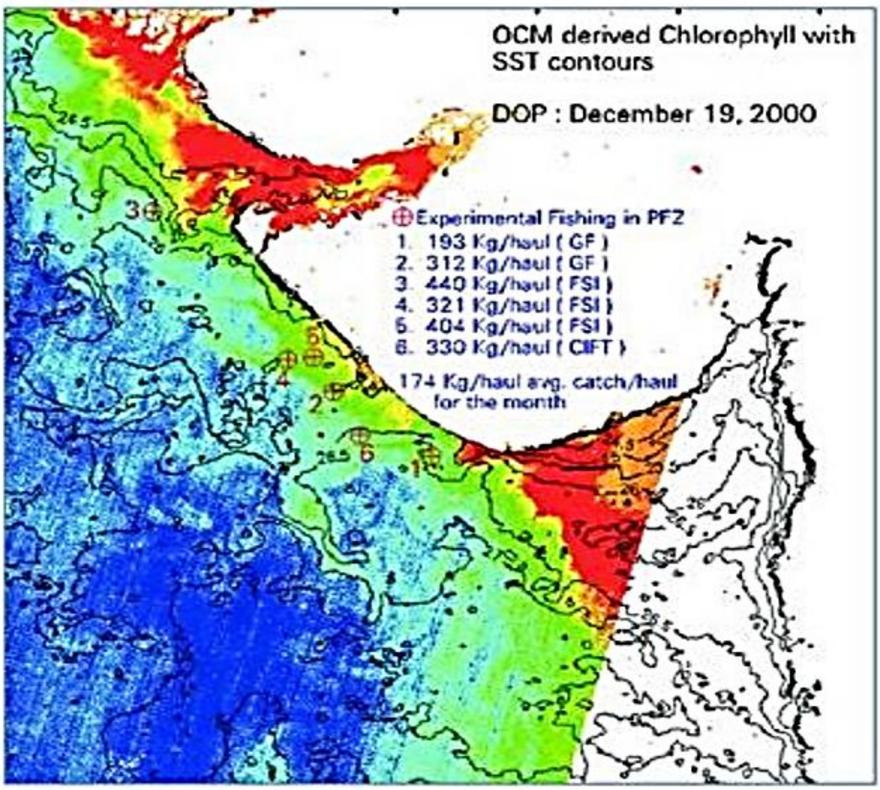

Figure1: Ocean Colour Monitor-derived Chl-a concentration with overlaid SST contours used to find fish school regions (Source: Groom et al. 2019)

3.2 Detection of Harmful Algal Bloom: Harmful algae sometimes increase inhabitants very rapidly, threatening fisheries, humans, and water qualities (Fingas 2018). Detection of these blooms from space have been accomplished by different methods. The use of sun-induced Chl-a fluorescence is one of the detection means which is provided by MODIS Aqua, MERIS, OLCI Sentinel-3 (Karuppasamy et al. 2020; Karki et al. 2018; Coronado-Franco, Selvaraj, and Pineda 2018; Lapucci et al. 2019).

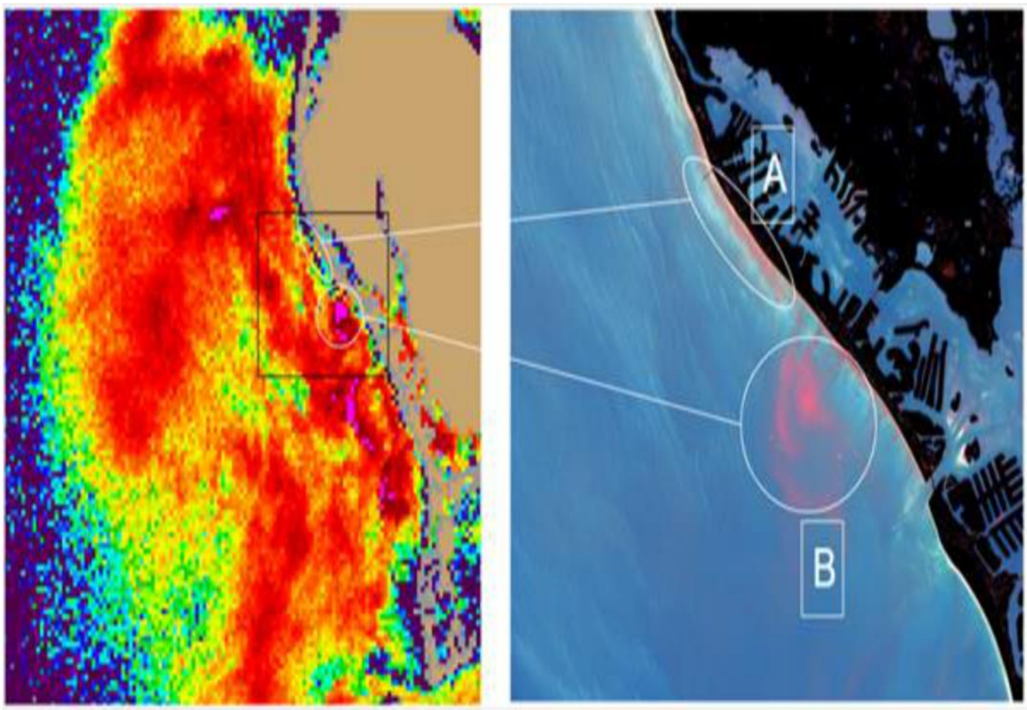

Figure 2: Satellite detection of HABs in littoral waters from Sentinal-3 (left) can detect offshore blooms (right, B) but not nearshore blooms (right, A) (Source: NOAA 2019)

3.3 Pre/post-Cyclonic Activity: On average 86 cyclones form in a year with around 47reaching the level of hurricanes or typhoons and 20 rises to category-3 in the world, which is the most severe (Siddiki, Islam, and Ansari 2012). To know the pre and post cyclonic activity such as the level of phytoplankton biomass, nutrients, sea surface temperature, etc. ocean color remote sensing is a must. Eight-day composite of Chl-a and SST temperature images need to be taken from the MODIS Aqua, MODIS Terra, Oceansat-2 satellite for satisfying any relevant objectives (Lotliker et al. 2014; Sarangi, Mishra, and Chauhan 2015; Baliarsingh et al. 2015).

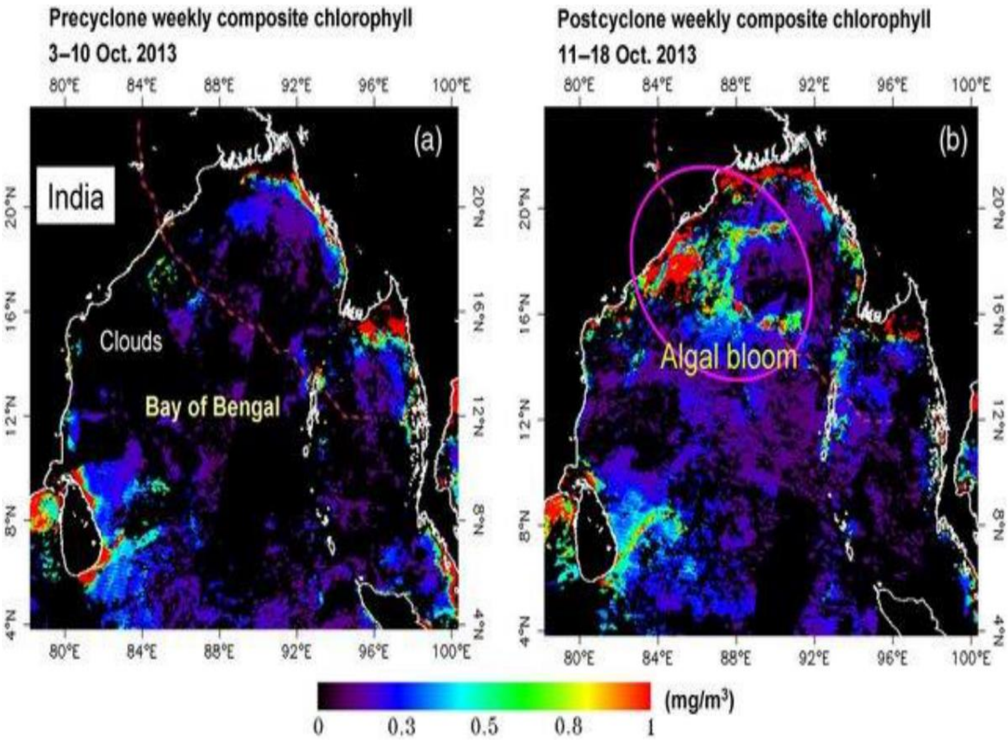

Figure3: MODIS-Terra 8-day composite Chl-a concentration images of Bay of Bengal during (a) pre- and (b) post-cyclone stages (Source: Sarangi, Mishra, and Chauhan 2015)

3.4 Determination of Euphotic Depth: Ocean color remote sensing assumes a significant part in deciding the euphotic zone on a global scale. The upper 150–200 m layer of the ocean ('sunlit' or the 'euphotic' zone) is controlled by the depth at which the Photosynthetically Active Radiation (PAR) diminishes to 1% of its surface value (Jungblut, Liebich, and Bode 2018). To know the euphotic depth variability in different oceans, diffusion attenuation coefficient; *Kd* $(PAR)_{490}$ data required from MODIS/ MERIS satellite sensor (Shang, Lee, and Wei 2011; Majozi et al. 2014).

3.5 Phytoplankton Size Class, Structure Distribution: Productivity, biomass, and size of phytoplankton are critical in shaping the lower food web of the marine ecosystem. Phytoplankton size, class structure majorly depends on nutrients and light availability. MODIS-Chl-a data can be used to identify the phytoplankton size, class (Pico, Nano, and Micro fractions) distribution in the Bay of Bengal (Sahay et al. 2017).

3.6 Identification of Thermal Fronts: Thermal fronts are one of the important oceanographic phenomena which can affect the physical, chemical, and biological features of the sea. Studies show that the presence of the thermal fronts influences the biological production of the sea. Identification of thermal fronts in different seas can be carried out by using MODIS-SST (Puthezhath 2014).

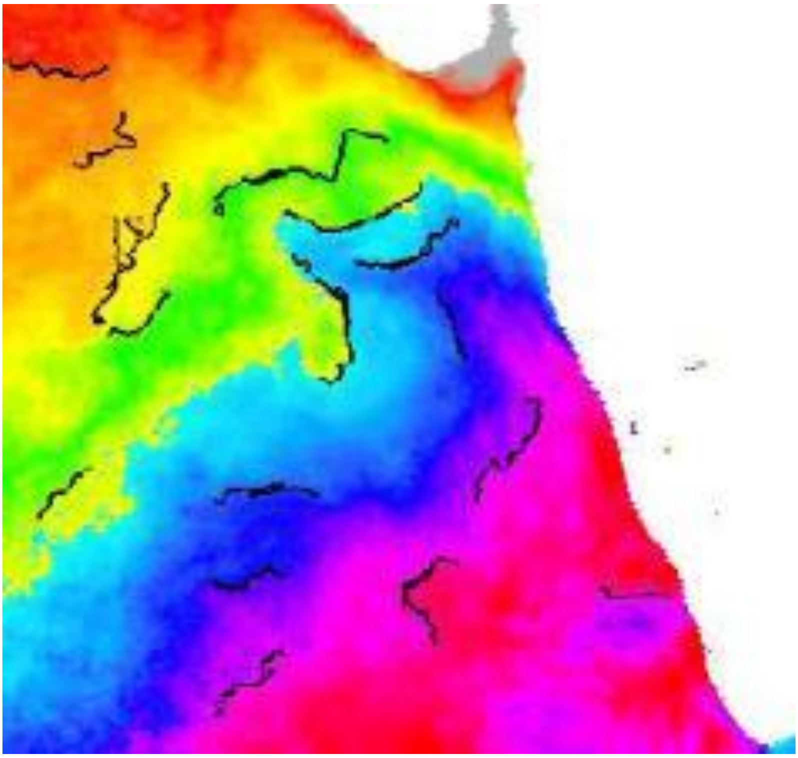

Figure 3. Overlapped thermal fronts image on SST image in January 2010 (Source: Puthezhath 2014)

3.7 Mangrove Ecosystem Mapping: Mangrove ecosystems dominate the coastal wetlands of tropical and subtropical regions throughout the world. They give various ecological and economical ecosystem services contributing to coastal erosion protection, water filtration, the arrangement of regions for fish and shrimp rearing (Kuenzer et al. 2011). Figure4. shows the majestic Sundarbans mangroves captured by satellite. Also, being the largest delta system, the water at the delta appears to be highly turbid due to the heavy discharge from all the river systems (Chauhan and Raman 2017).

Figure 4: Highly turbid mangrove delta captured by OCM-2 (Source: Chauhan et al. 2018)

3.8 Oil Slick Determination: Oil slick destructively affects the marine ecosystem severely. Oil spills appear in different signatures from the normal seawater depending on the spectral and spatial characteristics of remote sensing images. Satellite ocean color remote sensing can be a useful tool for the detection and tracking of oil spills (Lacava et al. 2017; Lei et al. 2019).

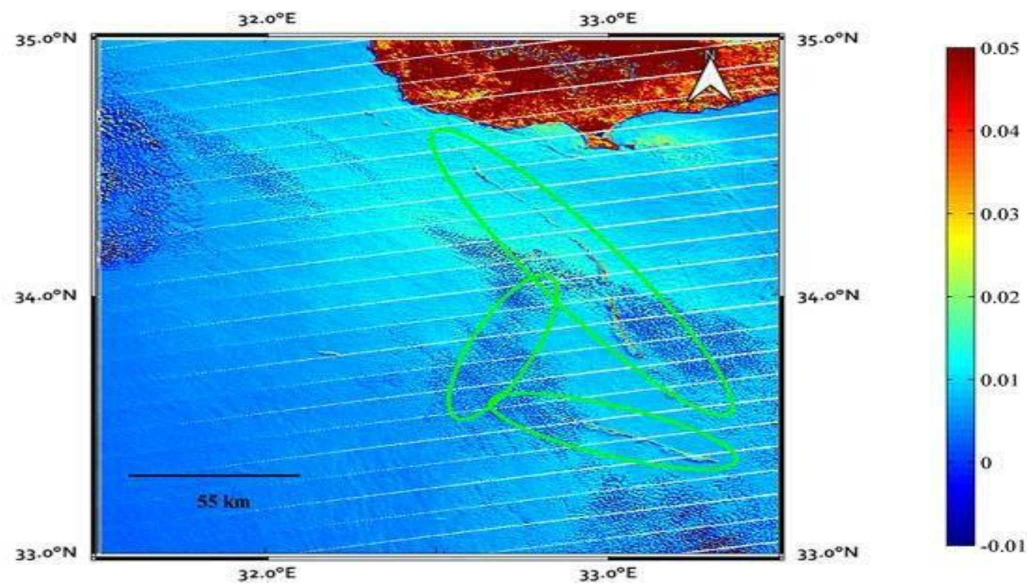

Figure 5. Detection of the oil slick in the ocean (Source: Lacava et al. 2017)

3.9 Trend Analysis: Several spatial and temporal patterns that a satellite ocean color the instrument can reveal, specifically evaluation of (1) seasonal patterns on global scales; (2) interannual variability on basin-sized scales; and (3) regional patterns on short time scales. Spatial, temporal, and annual variability of Chl-a (Antu 2019; Pramanik et al. 2020; Sari et al. 2018), sea surface temperature (Poornima et al. 2019), particulate organic carbon (Fan et al. 2018; Golder 2020; Shen, Zhiliang; Yang, Heming & Liu 2020), particulate inorganic carbon (Wang, Yu, and Fan 2020) and so many things can be calculated using ocean color remote sensing data.

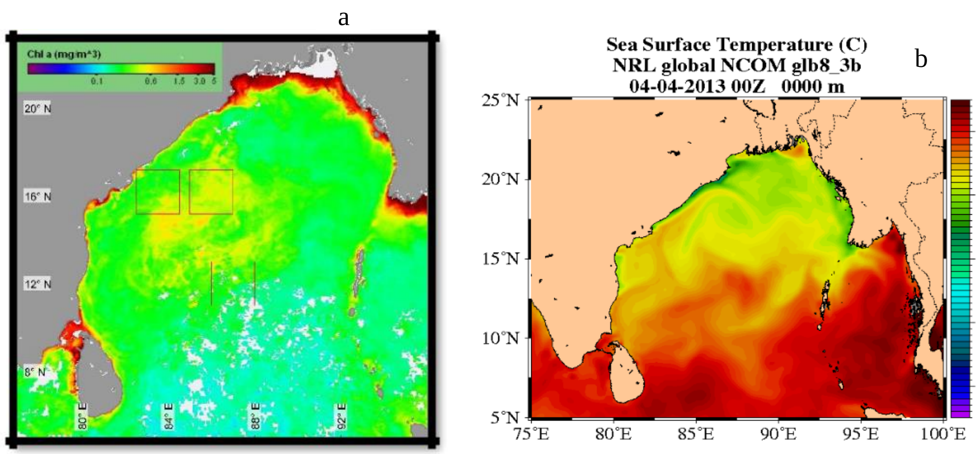

Figure 6. Chl-a (a) and SST (b) in the Bay of Bengal (Source: Antu 2019)

4. Advantages and Disadvantages of Ocean Color Remote Sensing:

There are several advantages of ocean color remote sensing that are mentioned below

1. It allows repetitive coverage which comes in handy when collecting data on dynamic themes such as ocean and coastal water;
2. Estimation of global primary production on seasonal and decadal scales;
3. mproved understanding of the interaction between coastal and oceanic waters;
4. The understanding flow of material through the marine food webs, implications for marine resources;
5. Providing data for assessing impact and adaptation of marine ecosystem to climate change;
6. Data processing and analysis are easy and fast.
7. Remote sensing data is analyzed at the laboratory which minimizes the fieldwork.
8. Easy to locate floods, track the cyclone and other natural hazards to plan a rescue mission easily and quickly.
9. A relatively cheap and constructive for reconstructing a base map

There are also a few disadvantages which need to consider for applying the ocean color remote sensing and possible solutions are mentioned below

1. The absence of nearshore, particularly the area below 200 m depth of the Bay of Bengal, data is a major limitation of the sensors. Due to the low depth and lot of river discharge submission, the water is very turbid. So, the ocean color sensors cannot detect the real scenario of this area. The bottom reference is one of the main reasons for missing the real value in the low depth region.
2. Ocean color obtained by satellite-borne sensors is essentially just possible for a clear (cloud-free) atmosphere, but the cloud-free image is not available all the months. Specific cloud masking algorithms must then be developed
3. Ocean color sensors require atmospheric correction (due to absorption by gasses and aerosols and scattering by air molecules and aerosols). Images available on the website are on a global scale. They are not regionally corrected. A regional algorithm needs to apply to overcome the problem.
4. Ocean and the atmosphere cannot be decoupled in turbid waters. Artificial neural networks (NN) or optimization technique is used to couple the two systems and to inverse them together.
5. The development of innovative bio-optical algorithms is badly required for precisely identifying the occurrence of specific phytoplankton species which is still a challenge for oceanographers.
6. Ocean color sensors need to be validated with the in-situ data.
7. Satellite data are not as accurate as in situ measurements and are restricted to the surface layer.

5. Conclusion

This study highlights the major representative ocean color remote sensing satellites with their applications, advantages, and disadvantages for ocean management. Nowadays, ocean color remote sensing has brought a revolution in oceanographic management. So, this must be applied in ocean studies on a broad scale to understand the feature and associated parameters easily. Our study concentrated to explain that ocean color remote sensing has made a vital application in the detection fish school; harmful algal bloom, cyclonic activity, oil slick; determination of euphotic depth variability, trend analysis with the dedicated ocean color sensors and their advantages and limitation in the era of oceanography. Along with advancing the science and technology of remote sensing, strong international collaboration and government support are needed in oceanographic research in the Bay of Bengal. Capacity building and training will be conducted to fully utilize satellite observation and integrated observing systems.

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7. References

Antu, Al-Hasan. 2019. "Temporal and Spatial Variablity of Chlorophyll-a Concentration in the Bay of Bengal of Bangladesh Using MODIS Aqua Data." MS thesis, Fisheries and Marine Resource Technology, Khulna University, Khulna-9208.

Aryastana, Putu, I Made Ardantha, and Kadek Windy Candrayana. 2018. "Coastline Change Analysis and Erosion Prediction Using Satellite Images." In *MATEC Web of Conferences*, 197:13003. EDP Sciences.

Baliarsingh, S. K., Chandanlal Parida, Aneesh A. Lotliker, Suchismita Srichandan, K. C. Sahu, and T. Srinivasa Kumar. 2015. "Biological Implications of Cyclone Hudhud in the Coastal Waters of Northwestern Bay of Bengal." *Current Science* 109 (7): 1243–45. https://doi.org/10.18520/cs/v109/i7/1243-1245.

Chauhan, Prakash, A K Mishra, Rimjhim Bhatnagar Singh, Arvind Sahay, Nivedita Sanwlani, and Mini Raman. 2018. "Ocean's Colour From Space Images from Oceansat OCM Sensor." *Indian Institute of Remote Sensing (IIRS)*. Dehra Dun 248001, India.

Chauhan, Prakash, and Mini Raman. 2017. "Satellite Remote Sensing for Ocean Biology: An Indian Perspective." *Proceedings of the National Academy of Sciences, India Section A: Physical Sciences* 87 (4): 629–40.

Coronado-Franco, Karold Viviana, John Josephraj Selvaraj, and José Ernesto Mancera Pineda. 2018. "Algal Blooms Detection in Colombian Caribbean Sea Using MODIS Imagery." *Marine Pollution Bulletin* 133: 791–98.

Fan, Hang, Xiujun Wang, Haibo Zhang, and Zhitong Yu. 2018. "Spatial and Temporal Variations of Particulate Organic Carbon in the Yellow-Bohai Sea over 2002-2016." *Scientific Reports*. Nature Publishing Group. https://doi.org/10.1038/s41598-018-26373-w.

Fingas, Merv. 2018. "Remote Sensing for Marine Management." In *World Seas: An Environmental Evaluation*, 103–19. Elsevier. https://doi.org/10.1016/b978-0-12-805052-1.00005-x.

Golder, Md Rony. 2020. "Seasonal Variability of Particulate Organic Carbon in the Bay of Bengal Using Satellite Imagery." MS thesis, Fisheries and Marine Resource Technology, Khulna University, Khulna-9208.

Groom, Steve B., Shubha Sathyendranath, Yai Ban, Stewart Bernard, Bob Brewin, Vanda Brotas, Carsten Brockmann, et al. 2019. "Satellite Ocean Colour: Current Status and Future Perspective." *Frontiers in Marine Science* 6 (JUL).

https://doi.org/10.3389/fmars.2019.00485.

Jungblut, Simon, Viola Liebich, and Maya Bode. 2018. *YOUMARES 8–Oceans Across Boundaries: Learning from Each Other: Proceedings of the 2017 Conference for YOUng MARine RESearchers in Kiel, Germany*. Springer Nature.

Karki, Sita, Mohamed Sultan, Racha Elkadiri, and Tamer Elbayoumi. 2018. "Mapping and Forecasting Onsets of Harmful Algal Blooms Using MODIS Data over Coastal Waters Surrounding Charlotte County, Florida." *Remote Sensing* 10 (10): 1656.

Karuppasamy, S, T P Ashitha, R Padmanaban, M Shamsudeen, and J M N Silva. 2020. "A Remote Sensing Approach to Monitor Potential Fishing Zone Associated with Sea Surface Temperature and Chlorophyll Concentration." *Indian Journal of Geo-Marine Sciences* 49 (6): 1025–30.

Kuenzer, Claudia, Andrea Bluemel, Steffen Gebhardt, Tuan Vo, and Stefan Dech. 2011. "Remote Sensing of Mangrove Ecosystems: A Review." *Remote Sensing* 3 (December): 878–928. https://doi.org/10.3390/rs3050878.

Lacava, Teodosio, Emanuele Ciancia, Irina Coviello, Carmine Di Polito, Caterina S L Grimaldi, Nicola Pergola, Valeria Satriano, Marouane Temimi, Jun Zhao, and Valerio Tramutoli. 2017. "A MODIS-Based Robust Satellite Technique (RST) for Timely Detection of Oil Spilled Areas." *Remote Sensing* 9 (2): 128.

Lapucci, C, S Taddei, B Doronzo, M Fattorini, S Melani, G Betti, F Maselli, A Ortolani, B Gozzini, and C Brandini. 2019. "Earth Observation as an Aid to Coastal Water Monitoring: Potential Application to Harmful Algal Bloom Detection." *Earth Observation Advancements in a Changing World*, 171.

Lei, Fuqiang, Wenliang Wang, Wei Zhang, Kaisheng Li, and Zhihua Xu. 2019. "Oil Spills Tracking Through Texture Analysis from MODIS Imagery." In *IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium*, 9768–71. IEEE.

Lotliker, Aneesh A., T. Srinivasa Kumar, Venkat Shesu Reddem, and Shailesh Nayak. 2014. "Cyclone Phailin Enhanced the Productivity Following Its Passage: Evidence from

Satellite Data." *Current Science* 106 (3): 360–61.

https://doi.org/10.18520/cs/v106/i3/360-361.

sMajozi, Nobuhle P, Mhd Suhyb Salama, Stewart Bernard, David M Harper, and Mussie Ghirmai Habte. 2014. "Remote Sensing of Euphotic Depth in Shallow Tropical Inland Waters of Lake Naivasha Using MERIS Data." *Remote Sensing of Environment* 148: 178– 89.

Moreira, Diana, and José C M Pires. 2016. "Atmospheric CO2 Capture by Algae: Negative

Carbon Dioxide Emission Path." *Bioresource Technology* 215: 371–79.

NOAA. 2019. “Rapid Detection of Harmful Algal Blooms (HABs) in Waters Nearshore Using SUAS.” 2019. https://uas.noaa.gov/News/Articles/ArtMID/6699/ArticleID/830/Rapid-Detection-of-Harmful-Algal-Blooms-HABs-in-Waters-Nearshore-Using-sUAS.

Poornima, D, R Shanthi, L Senthilnathan, T Thangaradjou, A Saravanakumar, and R K Sarangi. 2019. “Decadal Pattern of Spatial and Temporal Variability of Nitrate Along the Southwest Bay of Bengal Using Remote Sensing Techniques.” *Journal of the Indian Society of Remote Sensing* 47 (3): 487–95.

Pramanik, Saikat, Sourav Sil, Avijit Gangopadhyay, M K Singh, and N Behera. 2020. “Interannual Variability of the Chlorophyll-a Concentration over Sri Lankan Dome in the Bay of Bengal.” *International Journal of Remote Sensing*, 1–18.

Puthezhath, ARJUN S. 2014. “Identification of Thermal Fronts in the Arabian Sea Using

MODIS-SST Data.” *Kerala University Of Fisheries And Ocean Studies. Panangad*.

Robinson, Ian S., and Ian S. Robinson. 2010. “The Methods of Satellite Oceanography.” In *Discovering the Ocean from Space*, 7–67. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-68322-3_2.

Sahay, Arvind, Syed Moosa, Anurag Gupta, and Joaquim I Goes. 2017. “Remote Sensing of Environment Ocean Color Satellite Determinations of Phytoplankton Size Class in the Arabian Sea during the Winter Monsoon.” *Remote Sensing of Environment* 198: 286–96. https://doi.org/10.1016/j.rse.2017.06.017.

Sarangi, Ranjit Kumar, Manoj Kumar Mishra, and Prakash Chauhan. 2015. “Remote Sensing Observations on Impact of Phailin Cyclone on Phytoplankton Distribution in Northern Bay of Bengal.” *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 8 (2): 539–49. https://doi.org/10.1109/JSTARS.2014.2347036.

Sari, Q W, P A Utari, D Setiabudidaya, I Yustian, E Siswanto, and I Iskandar. 2018. “Variability of Surface Chlorophyll-a Distributions in the Northwestern Coast of Sumatra Revealed by MODIS.” In *Journal of Physics: Conference Series*, 1080:12045.

Sathyendranath, Shubha. 2000. “Reports of the International Ocean-Colour Coordinating Group.” *IOCCG, Dartmouth, Canada* 3: 140.

Schaeffer, B A, K A Loftin, and R P Stumpf. 2015. “Agencies Collaborate, Develop a Cyanobacteria Assessment Network. EOS.” *Earth Space Sci News* 96.

Shang, Shaoling, Zhongping Lee, and Guomei Wei. 2011. “Characterization of MODIS-Derived Euphotic Zone Depth: Results for the China Sea.” *Remote Sensing of Environment* 115 (1): 180–86.

Shen, Zhiliang; Yang, Heming & Liu, Qun. 2020. *Particulate Organic Carbon and Its Composition in Jiaozhou Bay*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-58169-8_18.

Siddiki, Ubaydur Rahaman, Nurul Islam, and Mohammad Nayeem Aziz Ansari. 2012. "Cyclonic Track Analysis Using GIS over the Bay of Bengal." *International Journal of Applied Science and Engineering Research* 1 (5): 689–701.

Wang, Xiujun, Jun Yu, and Hang Fan. 2020. "Spatial and Seasonal Variability of Surface Particulate Inorganic Carbon and Relationship with Particulate Organic Carbon in the Yellow-Bohai Sea." *Journal of Oceanography*, 1–13.

Werdell, P.Jeremy, and Charles R. McClain. 2019. *Satellite Remote Sensing: Ocean Color*. *Encyclopedia of Ocean Sciences*. 3rd ed. Elsevier Inc. https://doi.org/10.1016/B978-0-12-409548-9.10817-6.