Spatial and Temporal Distribution of Chlorophyll-a in Relation to Environmental Factors in the Bay of Bengal: A Remote Sensing Approach

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Ocean Carbon From Space Workshop
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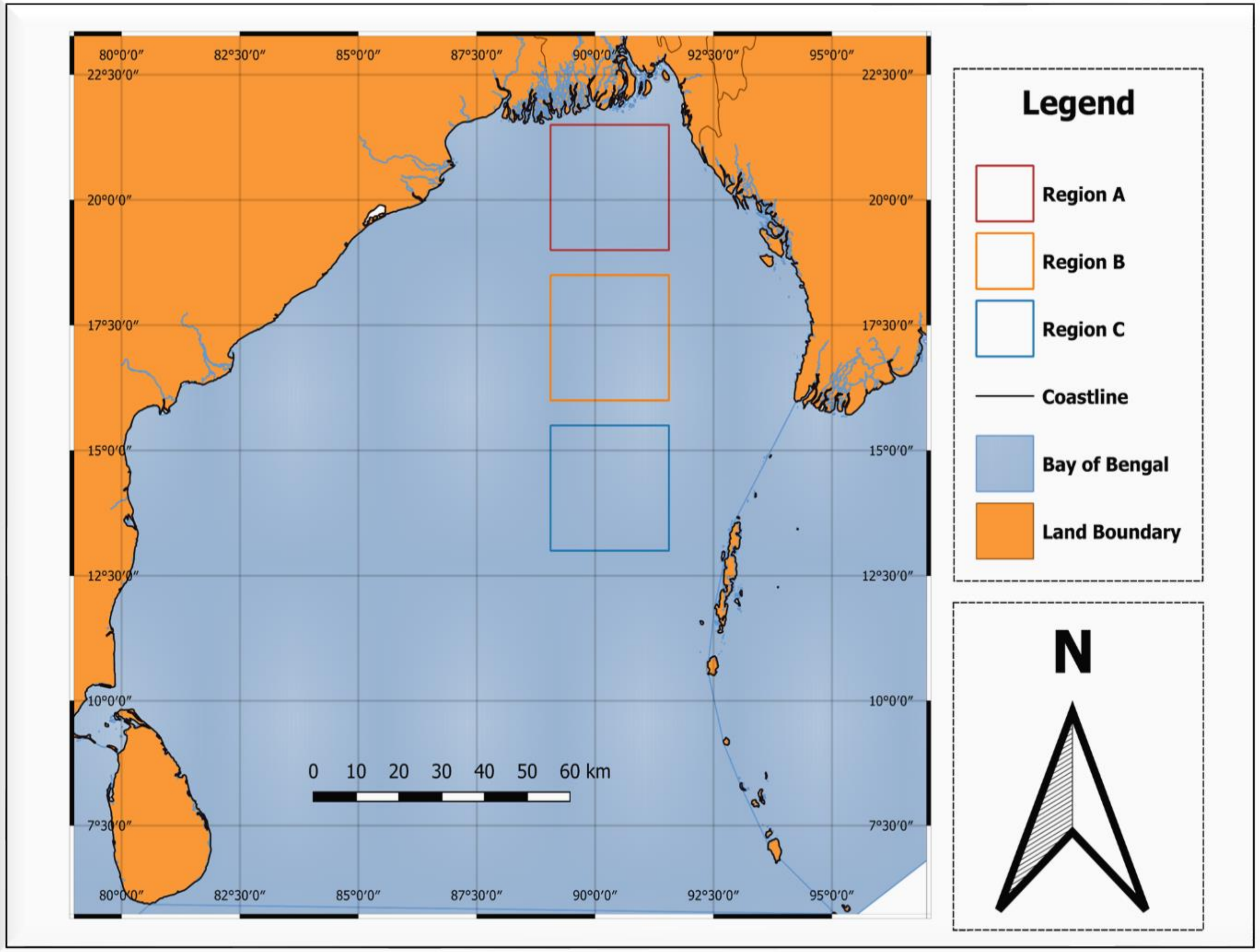
Introduction

- Phytoplankton is the foundation of marine food chain, converting solar energy into organic matter. Chl-a is a pigment found in all phytoplankton species **(Hubert et al., 2010)** and Chl-a distribution on a global scale is a direct indicator of phytoplankton biomass**(Cullen, 1982)**. The abundance of Chl-a has a significant impact on PP**(Lakshmi et al., 2014)**. Therefore, it is crucial to study for better understanding about marine ecosystem health, PFZ identification, global warming, and for the development of blue economy. Moreover, this study will help to achieve SDG goal 14(Life Below Water).
- The abundance of Chl-a is related with SST, WIND, Wind Direction, Nutrients, River Discharge, NPP, POC, SSHA, Current, Eddy etc.
- There had performed a piece of research on Chl-a distribution, and its relation to different parameters in the BoB **(Annapurna and Krishna, 2021; Baliarsingh et al., 2015; Gomes et al., 2000; Sarangi, 2016; Sarangi et al., 2008; Sarangi and Devi, 2017; Satyanarayana et al., 1994; Suwannathatsa et al., 2012; Yapa, 2012)**. Unfortunately, all of these works were done on Chl-a concerning single or multiple parameters for a very short time. Therefore, long-term studies of the spatial, and temporal distribution of Chl-a concerning a variety of environmental variables are lacking. This study founds this gap and conducted this study.

Objectives of the Study

- To determine the spatial, and temporal distribution of surface Chl-a in the BoB.
- To determine the monthly, seasonal, and annual distribution of Chl-a in the BoB.
- To observe the time series distribution of Chl-a in the BoB.
- To know the trend of Chl-a in the BoB.
- To identify the connection between Chl-a, and environmental factors (e.g., physical parameters-SST, Wind Speed, Wind Direction, SSHA, Current, Eddy; biochemical parameters-POC; biological parameters-NPP; nutrients, and hydrological parameter- river discharge) in the BoB.

Materials and Method



Study Area

- The BoB is one of the world's largest Bay, situated in the northeastern corner of Indian Ocean. This less studied region is crucial to study.
- Study Area comprised three regions (2.5° × 2.5° grid for each) in the BoB.
- "Region A" : lat 19°-21.50° N, and lon 89.06°-91.56°E.
- "Region B" : lat 16°-18.50° N, and lon 89.06°-91.56°E.
- "Region C" : lat 13°-15.50° N, and lon 89.06°-91.56°E.

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Materials and Method…

Data Sources

Platform/Sensors/ Organisation	Parameters	Weblink
MODIS/Aqua	Chl-a	http://apdrc.soest.hawaii.edu/las86/UI.vm; https://oceancolor.gsfc.nasa.gov/
MODIS/Aqua	SST	http://apdrc.soest.hawaii.edu/las86/UI.vm
Windsat/Coriolis	Wind Speed	http://apdrc.soest.hawaii.edu/las86/UI.vm
SSMIS/ DMSP F16	Wind Speed	http://apdrc.soest.hawaii.edu/las86/UI.vm
MODIS/Aqua	POC	https://oceancolor.gsfc.nasa.gov/
Merged products based on SeaWIFS, MERIS, MODIS-A, MODIS-T, VIIRS-SNPP & JPPS1, OLCI-S3A & S3B	NPP	CMEMS (copernicus.eu)
Sentinel-3A&B datasets are produced under EUMETSAT responsibility	SSHA	CMEMS (copernicus.eu)
WOD	Nutrients (Nitrate, Silicate, Phosphate) and Chl	https://www.ncei.noaa.gov/access/world-ocean-database/datawodgeo.html?fbclid=IwAR2wU8TM4fOPfeBxj-edD5bSFNx70-eh1rvJX91_PGmCcqYQZyJdPheGfp4; https://www.ncei.noaa.gov/access/world-ocean-database/bin/getwodyearlydata.pl
ERA5	Wind Vector component (u and v)	https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=overview
GODAS	Current (u and v)	http://apdrc.soest.hawaii.edu/las86/UI.vm
BWDB	River Discharge	http://www.hydrology.bwdb.gov.bd/

Data Properties

Parameters	Data Level	Data Format	Time	Period	Spatial Resolution	Unit
Chl-a	L3	NetCDF	2003-2020	Monthly	4 × 4 km	mg/m^3
SST	L3	NetCDF	2003-2020	Monthly	4 × 4 km	°C
Wind Speed (Windsat/Coriolis)	L3	NetCDF	2003-2019	Monthly	25 x 38 no rain, 39 x 71 in rain	ms^{-1}
Wind Speed (SSMIS/ DMSP F16)	L3	NetCDF	2020 Jan-2020 Dec	Monthly	61 x 66 cm	ms^{-1}
POC	L3	NetCDF	2003-2020	Monthly	4 × 4 km	mg/m^3
NPP	L4	NetCDF	2003-2020	Monthly	4 × 4 km	$(mgCm^{-2} day^{-1})$
SSHA	L4	NetCDF-4	2003-2020	Monthly	0.25° × 0.25°	m
Nutrients (Nitrate, Silicate, Phosphate) and Chl	In-situ	.gz	1997-2018; 1976,1995, 2007,2016	Annual Mean; Monthly (June-Sep)		µmol/kg, µg/l
Wind Vector	Single level	NetCDF	2020	Monthly		ms^{-1}
Current	reanalysis	NetCDF	2020	Monthly		ms^{-1}
River Discharge	In-situ	.xlsx	2019,2020	Monthly		m^3/s

Materials and Method…

Data Processing(A)

- Satellite Derived Data in NetCDF Format
- Data Imported to SeaDAS 7.5.3
- Imported Shapefiles(A,B,C) in SeaDAS
- Statistics for Each Shapefile (Mean, SD)
- Outliers Removed Using Quartile Functions
- Data tabulation in MS Excel 365

Data Processing(B)

- WOD and BWDB Derived Data
- Outliers Removed Using Quartile Functions
- Data tabulation in MS Excel 365

Data Analysis

- Multivariate Correlation, Regression, and Simple Linear Regression
- RMSE(Root Mean Square Error)

Data Visualization Tools

- Python → Numpy, Pandas, Matplotlib, Seaborn package
- SeaDAS 7.5.3
- QGIS 3.14
- ODV 5.3.0

Materials and Method…

Equations

$CI = R_{rs}(555) - [R_{rs}(443) + (555-443)/(670-443) * (R_{rs}(670) - R_{rs}(443))]$

which was equivalent to, $CI \approx R_{rs}(555) - 0.5(R_{rs}(443) + R_{rs}(670))$

OCI (Ocean Color Index) algorithm by (Hu et al., 2012)

1st Quartile (Q1) = $(N+1) \times \frac{1}{4}$

3rd Quartile (Q3) = $(N+1) \times \frac{3}{4}$

Inter-Quartile Range (IQR) = Q3-Q1

Lower Limit = Q1 – 1.5 × IQR

Upper Limit = Q3 + 1.5 × IQR

Outlier Remove

$y = \beta0 + \beta1.x1 + \beta2.x2 + \ldots + \beta n.xn$ **(Multivariate Regression)**

$Y = a + bX$ **(Linear Regression)**

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(SST)_{Satellite} - (SST)_{in-situ}{}^{2}}$$ **(Validation)**

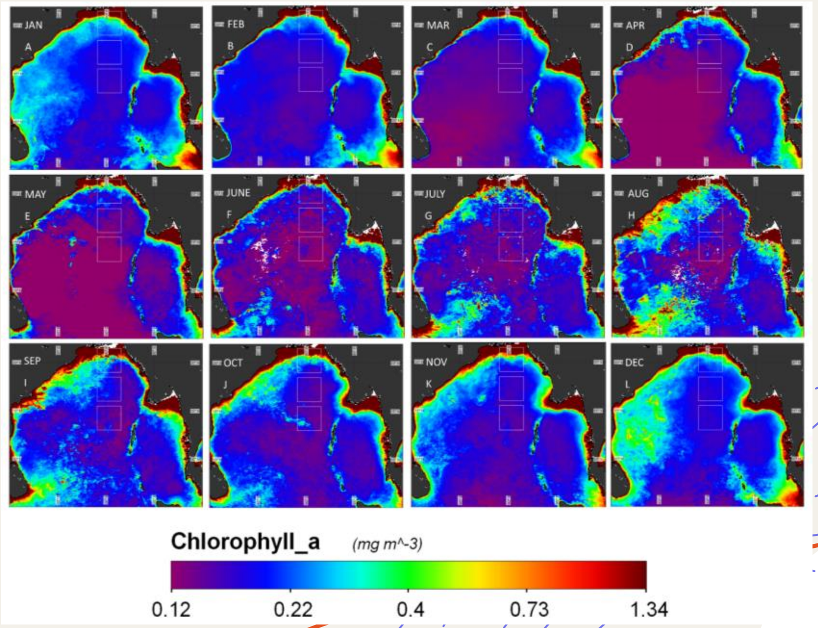
Results

Monthly Variability of Chl-a

- Chl-a (mg/m^3) was varied from 1.34 ± 2.23 mg/m^3 to 0.12 ± 0.02 mg/m^3 in three regions.
- Highest Chl-a (1.34 ± 2.23 mg/m^3) founds in Region A.
- Lowest Chl-a (0.12 ± 0.02 mg/m^3) founds in Region C.
- Coastal area was more productive than the offshore.

Chl-a(mg/m^3)	Region A	Region B	Region C
Maximum	September (1.34±2.23)	Jan & Nov (0.17 ± 0.02)	Sep & Dec (0.15 ± 0.02)
Minimum	June(0.53 ± 1.12)	August (0.123 ± 0.03)	May & Aug (0.12 ± 0.02)

- Chl-a concentration was >1.00 mg/m^3 from September to November.



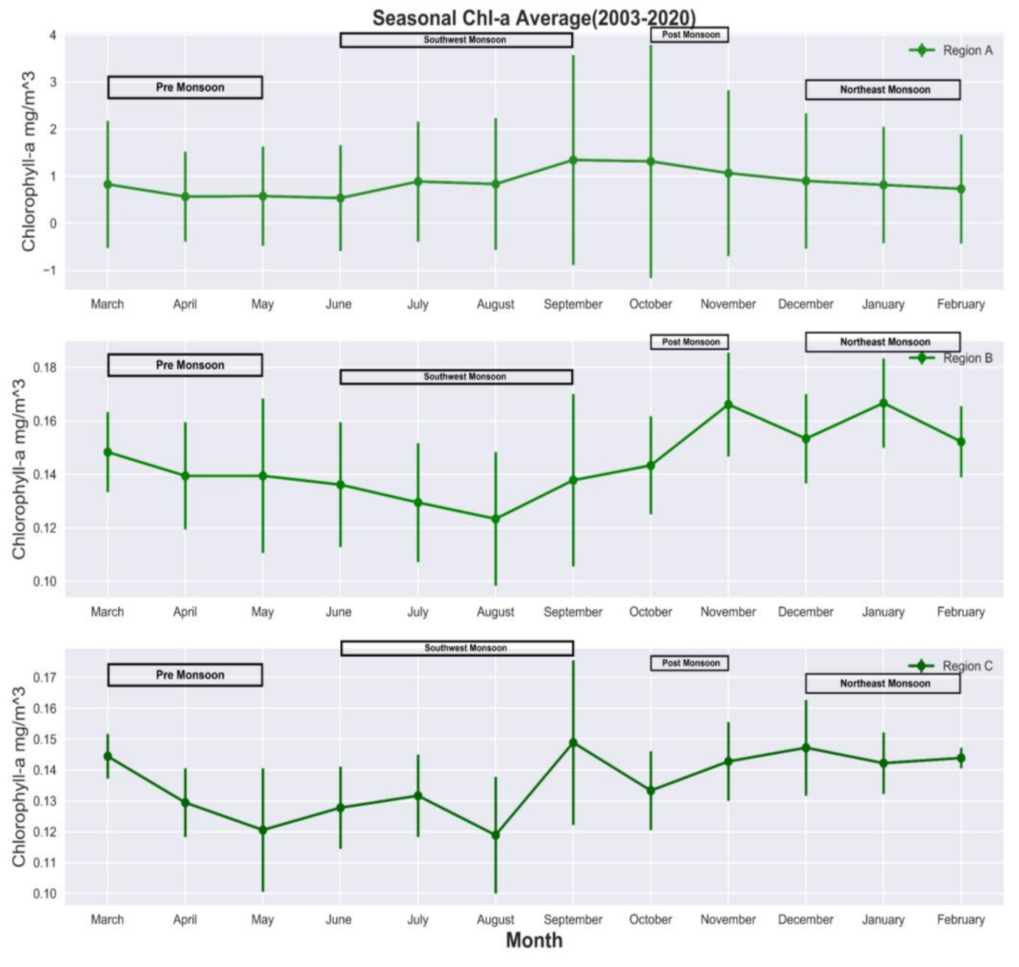
Results…

Seasonal Variability of Chl-a

- Seasonal Chl-a was observed 1.34 ± 2.23 mg/m^3 to 0.12 ± 0.02 mg/m^3 in three regions.

- The post-monsoon period showed the highest concentrations (1.19 ± 2.12 mg/m^3) of Chl-a while the pre-monsoon period showed the lowest concentrations (0.66 ± 1.12 mg/m^3) of that in the coastal area.

- The coastal area shows highest productivity in every seasons where the offshore shows the opposite.

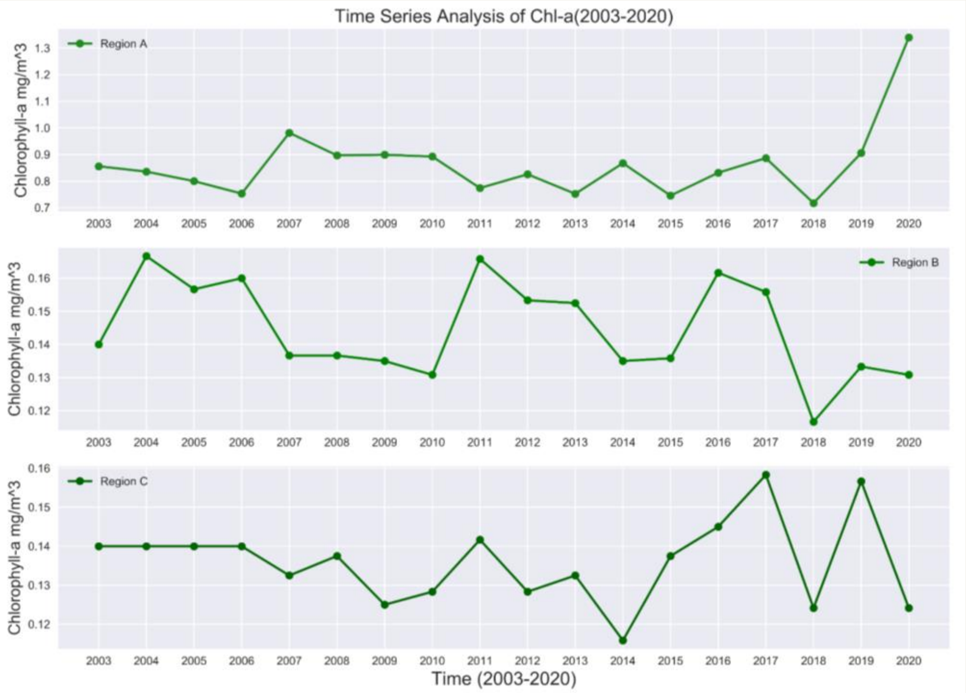


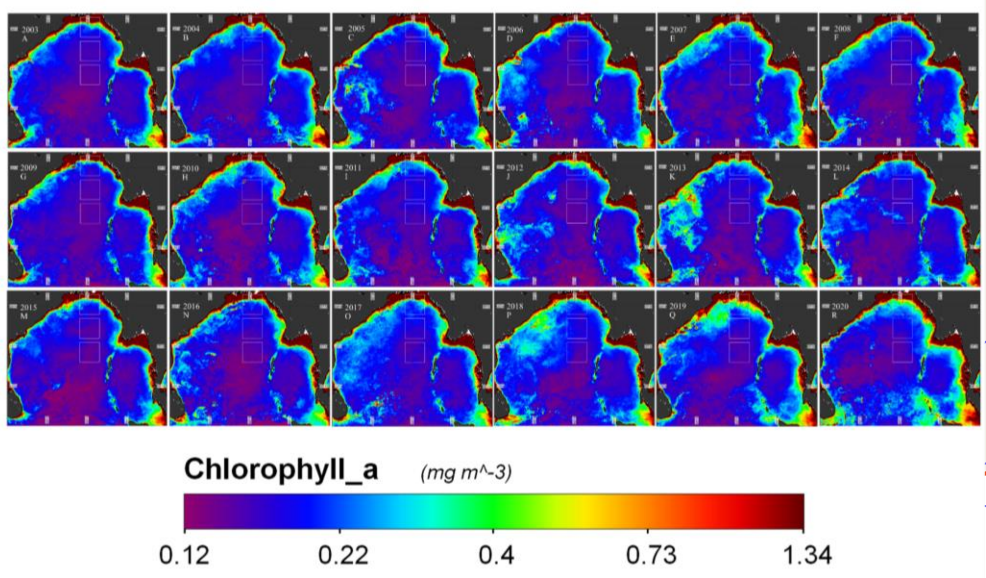
Results…

Annual Variability of Chl-a

- Coastal area showed the highest Chl-a concentrations than the offshore during the 18 years.

- The greatest Chl-a concentrations (1.34 mg/m^3) were discovered in 2020 in the coastal area, while the lowest Chl-a concentrations (0.12 mg/m^3) were found in 2014, 2018,2020 in offshore.

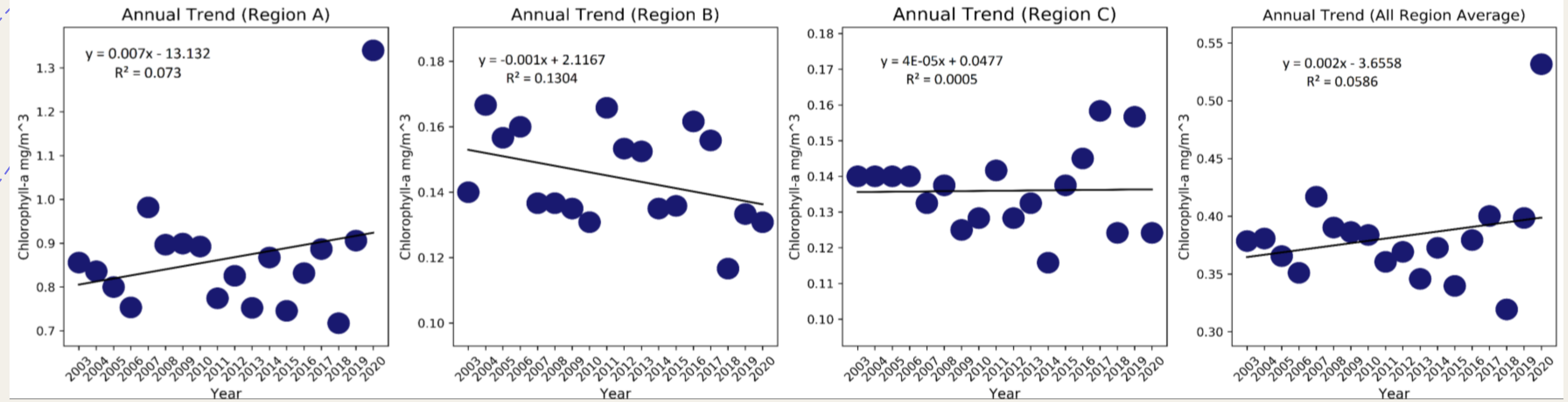




Results…

Trend of Chl-a

❖ Bay of Bengal showed a rising trend of Chl-a at a rate of 0.02 mg/m^3 per decade.



Environmental Factors Associated with Chl-a(mg/m^3) in the BoB

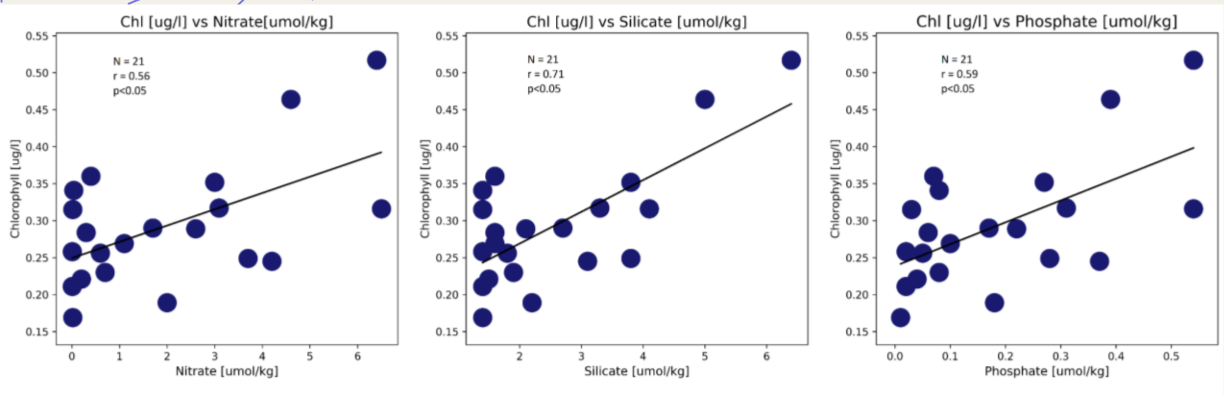
❖ Chl-a and SST showed a significantly ($p<0.05$) negative relation, and for each additional SST, Chl-a showed a declination of 0.035 mg/m^3 in the BoB.

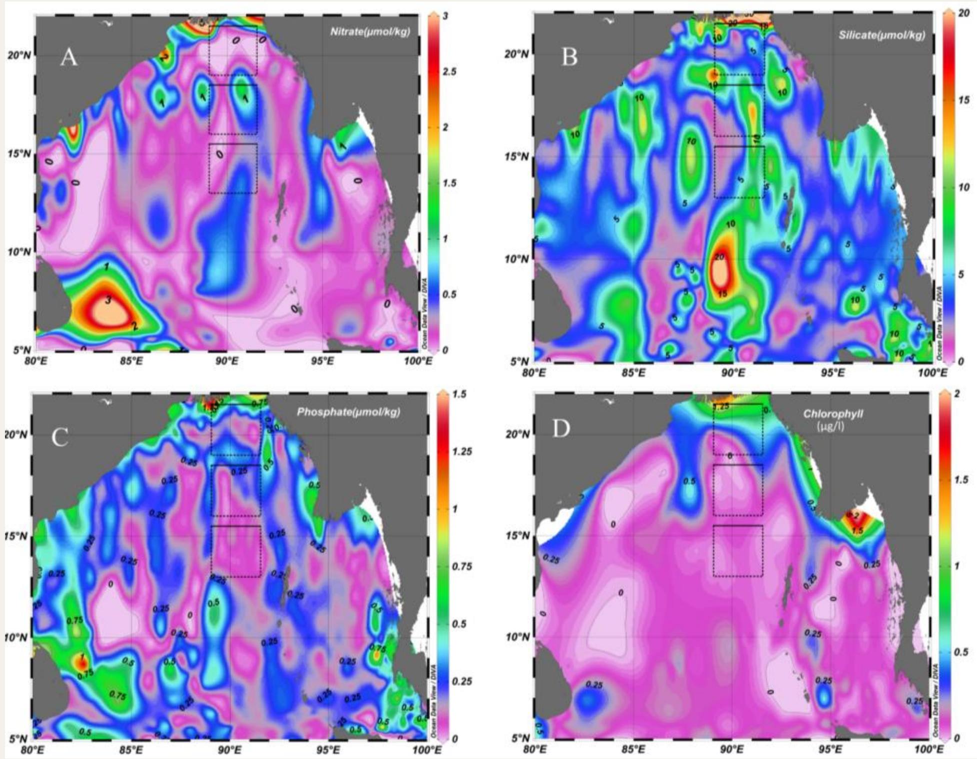
❖ Chl-a showed a positive relationship with POC, NPP, SSHA, River Discharge and Nutrients (silicate, nitrate, phosphate) in the BoB where wind speed showed no significant relationship with Chl-a in the study area.

❖ Regression analysis showed that for each additional POC, NPP, SSHA, Nitrate, Silicate, Phosphate, River Discharge, Chl-a increased by 0.006 mg/m^3, 0.001 mg/m^3, 0.531 mg/m^3, 0.140 µg/l, 0.078 µg/l, 1.448 µg/l, 0.00001 mg/m^3 respectively in the BoB. Moreover, Nitrate had a great influence (45.65%) on Chl-a (µg/l) than Phosphate (37.57%) and Silicate (16.78%) in the BoB.

Results…

Environmental Factors Associated with Chl-a(mg/m^3) in the BoB



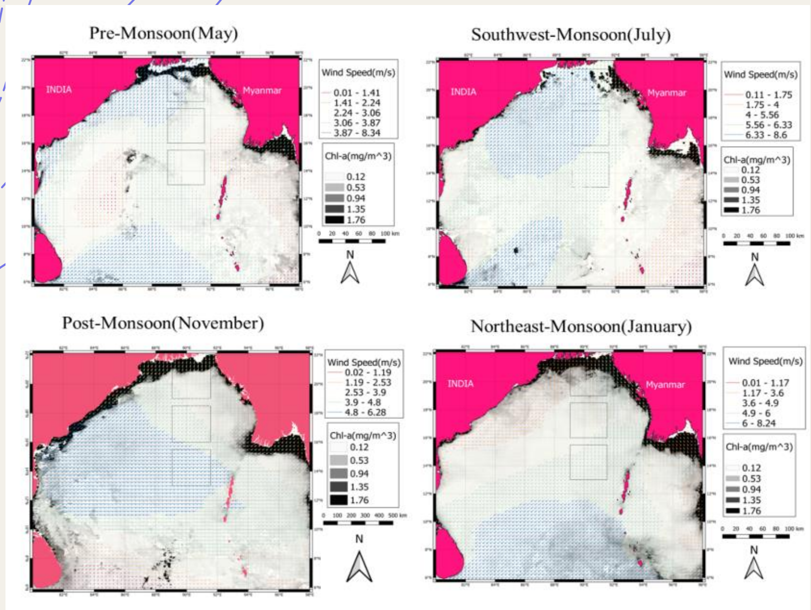


- The concentrations of Chl-a and Nutrients was always higher in the coastal area than that of offshore.
- The Chl-a, Nitrate, Silicate and Phosphate were found within the range of 0.17-0.52 µg/l, 0.01-6.5µmol/kg, 1.4-6.4 µmol/kg, 0.01-0.54 µmol/kg respectively in the BoB.
- Influence of nutrients on Chl-a in the BoB was Nitrate> Phosphate> Silicate.
- The lower amount of nutrients caused lower concentrations of Chl in the BoB.

Results…

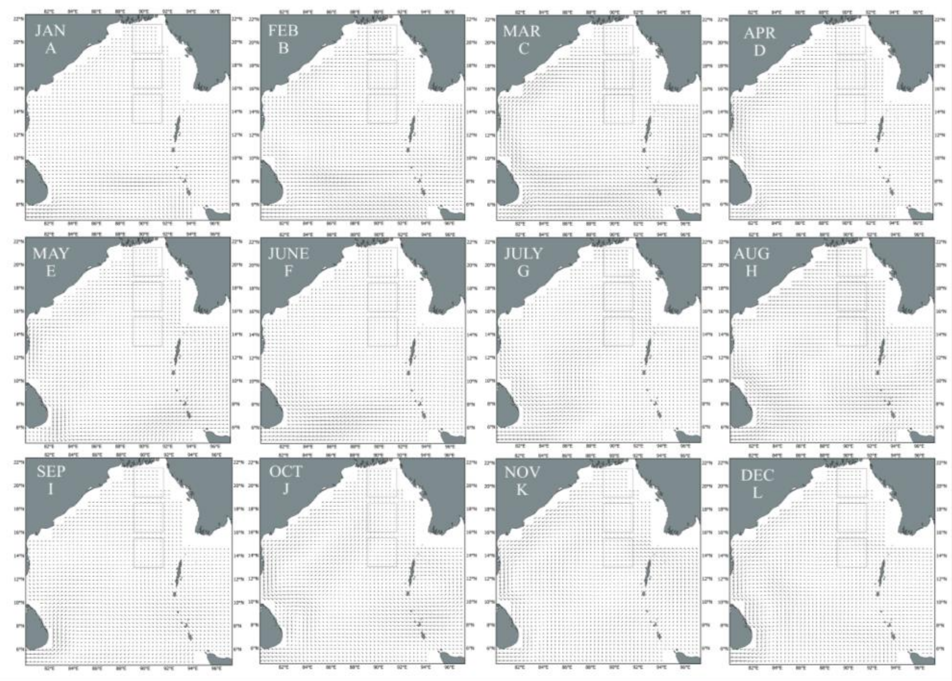
Environmental Factors Associated with Chl-a(mg/m^3) in the BoB

Wind Vector



- ❖ Southwesterly wind during southwest and pre-monsoon period and northeasterly wind during post and northeast monsoon period were observed.
- ❖ During southwest and pre-monsoon the wind speed showed high.
- ❖ Southwesterly and northeasterly wind showed an effect on Chl-a concentrations.

Current

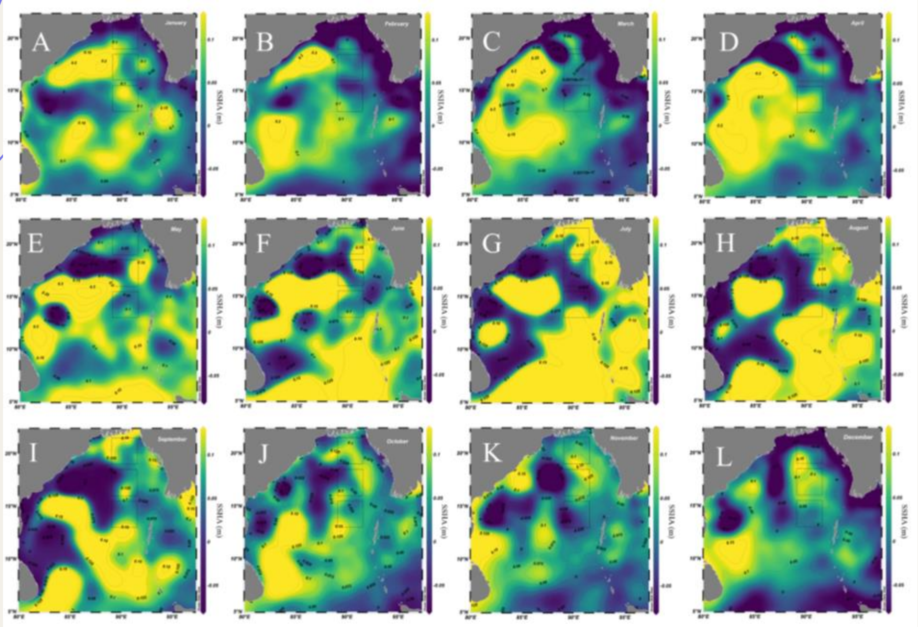


- ❖ Arabian Sea (AS) water entered into the BoB during the southwest monsoon season through activating the West India Coastal Current (WICC).
- ❖ During post-monsoon season in October, AS waters flowed into the BoB, then reversed in November during this study.

Results…

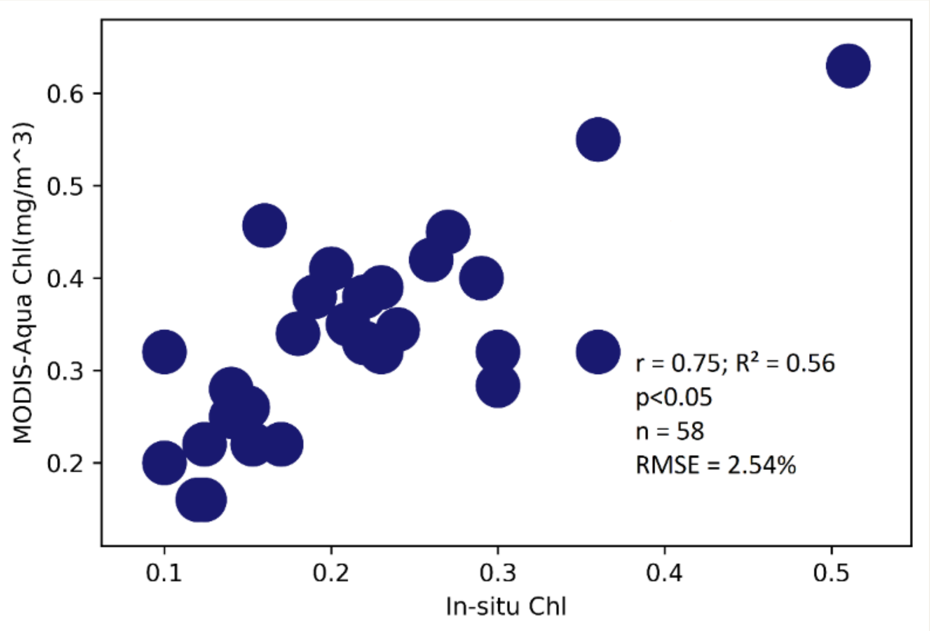
Environmental Factors Associated with Chl-a(mg/m^3) in the BoB

Eddy



- Northern BoB is mostly comprised of a warm-core eddy that founds in the eastern, and western boundary mostly.
- Eddy had a great influence on Chl-a.
- The presence of more Chl-a in eddies along the shore was due to advection from the coastal zone rather than production within the eddy itself.

Validation



- MODIS-Aqua data validated with the in-situ Chl derived from WOD.
- A significant ($p<0.05$) correlation between MODIS-Aqua derived Chl and WOD derived Chl were found.
- r = 0.75 (strong correlation), where n=58, R^2 = 0.56 and RMSE = 2.54%.

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Conclusion

- Chl-a found 1.34 ± 2.23 mg/m^3 to 0.12 ± 0.02 mg/m^3 whereas the coastal area comprised higher Chl-a irrespective of the month, season, and year.

- BoB showed a rising trend of Chl-a at a rate of 0.02 mg/m^3 per decade.

- Chl-a and SST showed a significantly ($p<0.05$) negative relation whereas Chl-a showed a positive relationship with POC, NPP, and SSHA, River Discharge and Nutrients (silicate, nitrate, phosphate) in the BoB. Wind speed showed no significant relationship with Chl-a in the study area; however, southwesterly and northeasterly wind showed an effect on Chl-a concentrations.

- POC, NPP, SSHA, Nitrate, Silicate, Phosphate, River Discharge, Chl-a increased by 0.006 mg/m^3, 0.001 mg/m^3, 0.531 mg/m^3, 0.140 µg/l, 0.078 µg/l, 1.448 µg/l, 0.00001 mg/m^3 respectively in the BoB. Nitrate had a great influence (45.65%) on Chl-a (µg/l) than Phosphate (37.57%) and Silicate (16.78%) in the BoB.

- Reversing pattern of ocean current observed.

- Northern BoB is mostly comprised of a warm-core eddy and it had inlfucence on Chl-a.

- Satellite and in-situ data showed strong correlation($r=0.75$) where $n=58$, $R^2 = 0.56$ and RMSE = 2.54%.


Thank You!