



Evaluation of phytoplankton phenology in the northern Bay of Bengal using ocean color remote sensing

Md Leion Hassan^{a,b}, Md Enamul Hoque^a, Md Nahin Alam^a, Md Ibrahim^a, Sheikh AftabUddin^d,
Muhammed Forruq Rahman^b, Mamun Abdullah Al^{b,c,*}

^a Department of Oceanography, University of Chittagong, Chattogram, 4331, Bangladesh

^b Aquatic Microbial Ecology (AME-Research Group), Laboratory of Marine and Freshwater Research, Department of Fisheries and Marine Resources Technology (FMRT), Rangamati Science and Technology University (RMSTU), Rangamati, 4500, Bangladesh

^c Marine Synthetic Ecology Research Center (MSER), Southern Marine Science and Engineering Guangdong Laboratory (SML), School of Marine Sciences, Sun Yat-sen University, Zhuhai, 519082, China

^d Institute of Marine Sciences, University of Chittagong, Chattogram, 4331, Bangladesh

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ABSTRACT

Phytoplankton phenology is a crucial factor for understanding marine ecosystem health and chlorophyll-*a* is widely used as a proxy for this. This study investigates the phytoplankton seasonality in the northern Bay of Bengal (BoB) using 19 years (2004–2022) satellite-derived Chl-*a* concentration. Phenological characteristics, spatial and temporal variations across the five maritime zones were evaluated using relative threshold method. Over the study period, coastal, territorial, contiguous, offshore exclusive economic zone, and continental shelf limit exhibited 17, 18, 10, 2, and 6 bloom events, respectively. Bloom initiation and propagation showed consistent spatial patterns, originating near the coastal waters, then expanding through offshore waters. Eutrophic coastal and estuarine waters exhibited the highest Chl-*a* ($>5 \text{ mg m}^{-3}$) and most frequent blooms, while oligotrophic offshore regions showed lower concentrations ($<0.5 \text{ mg m}^{-3}$) but longer bloom durations, demonstrating a pronounced coastal-to-offshore productivity gradient. A highly productive phenoregion ($\sim 12,249 \text{ km}^2$) was identified in the $21\text{--}22^\circ\text{N}$ region, which encompasses coastal, territorial, and contiguous waters. Seasonally, blooms occurred throughout the year, with pronounced peak during the pre-monsoon, monsoon, and post-monsoon periods. Continuous Wavelet Transform (CWT) analysis revealed a strong and persistent annual periodicity, confirming the dominance of seasonal forcing in bloom dynamics. The CWT also showed a notable interannual variability in the 2–4-year band, with the most pronounced signals during 2004–2008 and after 2019. Thus, these results offer important implications for ecosystem-based fisheries management and marine spatial planning in the Bay of Bengal.

1. Introduction

Phytoplankton plays a crucial role as the main source of food and energy in oceanic ecosystems, accounting for almost half of the world's primary production (Cloern et al., 2014; Li et al., 2024). It plays a pivotal role in biological carbon fixation by generating organic carbon through photosynthesis and is responsible for nearly 50% of the global carbon fixation (Field et al., 1998). This carbon serves as a vital energy source for the marine food web and plays a crucial rule in the global carbon cycle (Jia et al., 2022; Naselli-Flores and Padisák, 2023). Phytoplankton also supports coral reef ecosystems and associated entities, including

zooplankton and benthic communities like sponges, bivalves, and pelagic larvae (Racault et al., 2015). The larvae of various marine species, such as fishes, crustaceans, molluscs, and echinoderms rely on phytoplankton during their earlier critical and vulnerable life stages. For instance, the persistence of gadoid fish larvae is notably influenced by the timing of local spring blooms (Platt et al., 2003; Krug et al., 2018). Consequently, changes in the growth and succession of phytoplankton can impact pelagic ecosystems and the stability of higher trophic levels due to variations in the timing of food availability (Platt et al., 2003; Gittings et al., 2018).

The growth and abundance of phytoplankton are mostly influenced

* Corresponding author. Aquatic Microbial Ecology (AME-Research Group), Laboratory of Marine and Freshwater Research, Department of Fisheries and Marine Resources Technology (FMRT), Rangamati Science and Technology University (RMSTU), Rangamati, 4500, Bangladesh.

E-mail address: mamun.fmrt@rmstu.ac.bd (M. Abdullah Al).

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consistently higher Chl-*a* concentrations and more frequent bloom events, while offshore regions experienced fewer but longer blooms. A highly productive nearshore phenoregion was identified downstream of major river systems and the Sundarbans, representing an ecologically important hotspot. Additionally, a pronounced seasonal cycle of phytoplankton blooms was observed, with peak productivity during the pre-monsoon and post-monsoon periods.

CRedit authorship contribution statement

Md Leion Hassan: Writing – review & editing, Writing – original draft, Software, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Md Enamul Hoque:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Md Nahin Alam:** Visualization, Software, Methodology, Formal analysis, Data curation. **Md Ibrahim:** Visualization, Software, Methodology. **Sheikh AftabUddin:** Writing – review & editing, Supervision, Investigation. **Muhammed Forruq Rahman:** Writing – review & editing, Supervision, Investigation. **Mamun Abdullah Al:** Writing – review & editing, Validation, Supervision, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

- Abdullah Al, M., Akhtar, A., Hassan, M.L., Rahman, M.F., Warren, A., 2019. An approach to analyzing environmental drivers of phytoplankton community patterns in coastal waters in the northern Bay of Bengal, Bangladesh. *Reg. Stud. Mar. Sci.* 29, 100642. <https://doi.org/10.1016/j.rsma.2019.100642>.
- Albanai, J., 2024. Determining seasonal spatial and temporal distribution of chlorophyll-*a*, and its concentration in Kuwait and the arabian gulf using satellite and In-situ data. *Trans. Marit. Sci.* 13 (2). <https://doi.org/10.7225/toms.v13.n02.016>.
- Amol, P., Vinayachandran, P.N., Shankar, D., Thushara, V., Vijith, V., Chatterjee, A., Kankonkar, A., 2020. Effect of freshwater advection and winds on the vertical structure of chlorophyll in the northern Bay of Bengal. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 179, 104622. <https://doi.org/10.1016/j.dsr2.2019.07.010>.
- Andreo, V.C., Dogliotti, A.L., Tauro, C.B., 2016. Remote sensing of phytoplankton blooms in the Continental shelf and shelf-break of Argentina: spatio-temporal changes and phenology. *IEEE J. Sel. Top. Appl. Earth Obs. Rem. Sens.* 9 (12), 5315–5324. <https://doi.org/10.1109/JSTARS.2016.2585142>.
- Baliarsingh, S.K., Lotlikar, A.A., Sahu, K.C., Kumar, T.S., 2015. Spatio-temporal distribution of chlorophyll-*a* in relation to physico-chemical parameters in coastal waters of the northwestern Bay of Bengal. *Environ. Monit. Assess.* 187 (7), 481. <https://doi.org/10.1007/s10661-015-4660-x>.
- Behrenfeld, M.J., Boss, E.S., 2014. Resurrecting the ecological underpinnings of ocean plankton blooms. *Ann. Rev. Mar. Sci.* 6, 167–194. <https://doi.org/10.1146/annurev-marine-052913-021325>.
- Benshila, R., Durand, F., Masson, S., Bourdallé-Badie, R., de Boyer Montégut, C., Papa, F., Madec, G., 2014. The upper Bay of Bengal salinity structure in a high-resolution model. *Ocean Model.* 74, 36–52. <https://doi.org/10.1016/j.ocemod.2013.12.001>.
- Boyce, D.G., Petrie, B., Frank, K.T., Worm, B., Leggett, W.C., 2017. Environmental structuring of marine plankton phenology. *Nat. Ecol. Evol.* 1 (10), 1484–1494. <https://doi.org/10.1038/s41559-017-0287-3>.
- Cabré, A., Shields, D., Marinov, L., Kostadinov, T.S., 2016. Phenology of size-partitioned phytoplankton carbon-biomass from ocean color remote sensing and CMIP5 models. *Front. Mar. Sci.* 3, 39. <https://doi.org/10.3389/fmars.2016.00039>.
- Chaturvedi, N., 2005. Variability of chlorophyll concentration in the Arabian Sea and Bay of Bengal as observed from SeaWiFS data from 1997–2000 and its interrelationship with sea surface temperature (SST) derived from NOAA AVHRR. *Int. J. Rem. Sens.* 26 (17), 3695–3706. <https://doi.org/10.1080/01431160500159818>.
- Chen, S., Meng, Y., 2022. Phytoplankton blooms expanding further than previously thought in the ross sea: a remote sensing perspective. *Remote Sens.* 14 (14). <https://doi.org/10.3390/rs14143263>, 3263–3263.
- Cloern, J.E., Foster, S.Q., Kleckner, A.E., 2014. Phytoplankton primary production in the world's estuarine-coastal ecosystems. *Biogeosciences* 11 (9), 2477–2501. <https://doi.org/10.5194/bg-11-2477-2014>.
- Cloern, J.E., Abreu, P.C., Carstensen, J., Chauvaud, L., Grall, J., Greening, H., Johansson, R.J.O., Kahru, M., Sherwood, E.T., Xu, J.I.E., Yin, K., 2016. Human activities and climate variability drive fast-paced change across the world's estuarine-coastal eco systems. *Glob. Change Biol.* 22 (2), 513–529. <https://doi.org/10.1111/gcb.13059>.
- D'Silva, M.S., Anil, A.C., Naik, R.K., D'Costa, P.M., 2012. Algal blooms: a perspective from the coasts of India. *Nat. Hazards* 63, 1225–1253. <https://doi.org/10.1007/s11069-012-0190-9>.
- Dasgupta, S., Singh, R.P., Kafatos, M., 2009. Comparison of global chlorophyll concentrations using MODIS data. *Adv. Space Res.* 43 (7), 1090–1100. <https://doi.org/10.1016/j.asr.2008.11.009>.
- Diaz, B.P., Knowles, B., Johns, C.T., Laber, C.P., Bondoc, K.G.V., Haramaty, L., et al., 2021. Seasonal mixed layer depth shapes phytoplankton physiology, viral production, and accumulation in the north Atlantic. *Nat. Commun.* 12 (1), 6634. <https://doi.org/10.1038/s41467-021-26836-1>.
- Field, C.B., Behrenfeld, M.J., Randerson, J.T., Falkowski, P., 1998. Primary production of the biosphere: integrating terrestrial and Oceanic components. *Science* 281, 237–240. <https://doi.org/10.1126/science.281.5374.237>.
- Friedland, K.D., Mouw, C.B., Asch, R.G., Ferreira, A.S.A., Henson, S., Hyde, K.J., et al., 2018. Phenology and time series trends of the dominant seasonal phytoplankton bloom across global scales. *Global Ecol. Biogeogr.* 27 (5), 551–569. <https://doi.org/10.1111/geb.12717>.
- Gittings, J.A., Raitos, D.E., Krokos, G., et al., 2018. Impacts of warming on phytoplankton abundance and phenology in a typical tropical marine ecosystem. *Sci. Rep.* 8, 2240. <https://doi.org/10.1038/s41598-018-20560-5>.
- Henson, S.A., Cole, H.S., Hopkins, J., Martin, A.P., Yool, A., 2018. Detection of climate change-driven trends in phytoplankton phenology. *Glob. Change Biol.* 24 (1), e101–e111. <https://doi.org/10.1111/gcb.13886>.
- Henson, S.A., Dunne, J.P., Sarmiento, J.L., 2009. Decadal variability in North Atlantic phytoplankton Oceans, 114. <https://doi.org/10.1029/2008JC005139>. C4.
- Hovmöller, E., 1949. The trough-and-ridge diagram. *Tellus* 1 (2), 62–66.
- Hu, Q., Chen, X., He, X., Bai, Y., Jiang, T., Huan, Y., Liang, Z., 2025. Impacts of IOD and ENSO on the phytoplankton's vertical variability in the northern Indian Ocean. *Front. Mar. Sci.* 12, 1523434. <https://doi.org/10.3389/fmars.2025.1523434>.
- Huang, H., Bai, L., Shen, H., Ding, X., Wang, R., Lü, H., 2023. A phytoplankton bloom caused by the super cyclonic storm amphan in the central Bay of Bengal. *Nat. Hazards Earth Syst. Sci.* 23 (12), 2807–2819. <https://doi.org/10.5194/nhess-23-2807-2023>.
- Iqbal, M.M., Billah, M.M., Haider, N.M., Islam, M.S., Rajib, P.H., Bhuiyan, M.K.A., Dawood, M.A.O., 2017. Seasonal distribution of phytoplankton community in a subtropical Estuary of the south-eastern coast of Bangladesh. *Zoology Ecol.* 27 (3–4), 304–310. <https://doi.org/10.1080/21658005.2017.1387728>.
- Jagadeesan, L., Vivek, R., Mayuri, C., Ghosh, V.R.D., Swarnaprava, B., Balachandran, K. K., 2023. Roles of upwelling and riverine influx on the summer phytoplankton bloom in the Western Bay of Bengal. *Reg. Stud. Mar. Sci.* 62, 102921. <https://doi.org/10.1016/j.rsma.2023.102921>.
- Jia, J., Gao, Y., Sun, K., Lu, Y., Wang, J., Shi, K., 2022. Phytoplankton community composition, carbon sequestration, and associated regulatory mechanisms in a floodplain Lake system. *Environ. Pollut.* 306, 119411. <https://doi.org/10.1016/j.envpol.2022.119411>.
- Jyothibabu, R., Arunpandi, N., Jagadeesan, L., Karnan, C., Lallu, K.R., Vinayachandran, P.N., 2018. Response of phytoplankton to heavy cloud cover and turbidity in the northern Bay of Bengal. *Sci. Rep.* 8 (1), 11282. <https://doi.org/10.1038/s41598-018-29586-1>.
- Kostadinov, T.S., Cabré, A., Vedantham, H., Marinov, I., Bracher, A., Brewin, R.J.W., Bricaud, A., Hirata, T., Hirawake, T., Hardman-Mountford, N.J., Mouw, C., Roy, S., Uitz, J., 2017. Inter-comparison of phytoplankton functional type phenology metrics derived from ocean color algorithms and Earth system models. *Remote Sens. Environ.* 190, 162–177. <https://doi.org/10.1016/j.rse.2016.11.014>.
- Krug, L.A., Platt, T., Sathyendranath, S., Barbosa, A.B., 2017. Unravelling region-specific environmental drivers of phytoplankton across a complex marine domain (off SW Iberia). *Rem. Sens. Environ.* 203, 162–184. <https://doi.org/10.1016/j.rse.2017.05.029>.
- Krug, L.A., Platt, T., Sathyendranath, S., Barbosa, A.B., 2018. Patterns and drivers of phytoplankton phenology off SW Iberia: a phenoregion based perspective. *Prog. Oceanogr.* 165, 233–256. <https://doi.org/10.1016/j.poccean.2018.06.010>.
- Lao, Q., Liu, S., Ling, Z., Jin, G., Chen, F., Chen, C., Zhu, Q., 2023. External dynamic mechanisms controlling the periodic offshore blooms in beibu gulf. *J. Geophys. Res., Oceans* 128 (6). <https://doi.org/10.1029/2023JC019689>.