

**BIOPHYSICAL VARIABILITY IN THE NORTH INDIAN
OCEAN USING A COUPLED
PHYSICAL-BIOGEOCHEMICAL MODEL**

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by

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Centre for Atmospheric Sciences

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QUOTATIONS

*The joy of discovery is certainly
the liveliest that the mind of man
can ever feel.*

- Claude Bernard -

DEDICATION

To my beloved parents
(Narasimhulu Naidu & Seethamma)

CERTIFICATE

This is to certify that the thesis entitled "**Biophysical variability in the north Indian Ocean using a coupled physical-biogeochemical model**", submitted by **Mr. Seelanki Vivek**, to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a bona fide record of the research work done by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Place: New Delhi

Date: 14-12-2022



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Place: New Delhi

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Seelanki Vivek

ABSTRACT

Indian Ocean (IO) circulation and its biological processes are largely different from those in the other oceans. The two distinct features of the IO have a significant impact on its biological processes. The first is the northern land boundary, which stretches southward to at least 26°N , with the Indian subcontinent dividing the north Indian Ocean (NIO) into two basins namely, the Arabian Sea (AS) in the west and the Bay of Bengal (BoB) in the east. The second unique feature is the seasonal reversal of surface winds north of 10°S in the IO. The winds are southwesterly during summer monsoon season (June-September) which is accompanied with substantial precipitation across the northern half of the basin and Indian sub-continent. The winter monsoon season (December-February) experiences northeasterly surface winds. In response to the change in wind direction, the surface currents over the NIO also undergo a seasonal reversal in the northern part of the IO. The biological productivity of ocean is primarily governed by the availability of nutrients in the near-surface sun-lit layers. Ocean upwelling process brings the subsurface cold and often nutrient rich water to the surface and, therefore, enhances biological productivity. The physical foundation that leads to significant biogeochemical variability throughout the basin is provided by the yearly evolution of oceanic current patterns and upwelling distributions that form in response to wind forcing.

In recent decades, the IO has been found to have a significant influence on regional and global climate variability. As a result, improving our knowledge of the biophysical (i.e. physical and biological) processes in the IO through observational and modelling studies has become essential for both science and society. In the present thesis, a coupled physical-biogeochemical model comprising of the Regional Ocean Modelling System (ROMS) and Bio-Fennel (the biogeochemical (BGC) model component) is used to study the biophysical variability of the NIO at various temporal scales. The coupled physical-biogeochemical model is configured with

a $1/4^\circ \times 1/4^\circ$ horizontal grid resolution, 40 vertical sigma levels, and an eddy-permitting resolution over the IO region covering from 30°E to 120°E and 30°S to 30°N . In order to calculate the surface heat and momentum fluxes as surface forcing fields, the daily mean values of meteorological parameters are acquired from the NCEP and QuikSCAT/ASCAT data.

In chapter 2, sixteen models from the ‘Coupled Climate Model Intercomparison Project phase 5’ (CMIP5) are assessed for their capability in simulating the Chlorophyll-a (Chl-a) concentration against satellite observations and regional coupled physical-biogeochemical model (ROMS + Bio-Fennel) over the NIO. The sixteen CMIP5 models are categorized into three groups based on their relative skill. Group-A models overestimated the phytoplankton bloom over prominent productive regions, whereas the Group-B and Group-C models mostly failed to reproduce the bloom in the NIO. However, the regional coupled model captured the phase of the bloom intensity in all seasons as noticed in observations. The observed annual variations were poorly simulated by all the CMIP5 models. Group-A models showed a negative bias in Chl-a concentration over the northern AS (NAS) and a positive bias in Chl-a simulation off Somalia over the western IO (WIO). High Chl-a associated with the coastal upwelling along the west coasts of India and off Sri Lanka was poorly simulated by CMIP5 models. In contrast, the regional coupled model has a low positive Chl-a bias. The study highlights the regional deficiency in CMIP5 climate models in simulating Chl-a and the need for improved coupled physical-biogeochemical models over the NIO.

In chapter 3, the coupled model interannual simulations were performed for the period of 2000-2017. The model simulations are validated with respect to *in-situ* observations and satellite data over the BoB. The BoB is known to have high primary productivity at its northwestern margin close to the coast with an offshore extent of $\sim 400 \text{ km}$ during the Indian summer monsoon season. This coastal productivity is mainly caused due to the near-surface nutrient availability maintained by the local coastal upwelling process. The surface winds in the IO significantly vary during El-Niño/La-Niña and Indian Ocean dipole (IOD). The sea surface temperature (SST) and Chl-a anomalies in the western BoB are analyzed

for the period of 18 years (2000 to 2017) using the coupled model and observations. All considered positive IOD (pIOD) years show distinct behavior of biophysical features in the western BoB during the study period. The co-occurrence years of pIOD and El-Niño modes are associated with contrasting biophysical anomalies. In the analyzed pIOD events, years 2006 and 2012 show an enhancement in the Chl-a anomalies whereas, the other two years (2015 and 2017) experience Chl-a decrement. The western BoB was anomalously warmer during 2015 and 2017 pIOD years compared to the other two pIOD years (2006, 2012). This inconsistent response of biophysical features associated with pIOD years is investigated in terms of local surface flux (momentum, heat, and freshwater) changes over the western BoB. The combined impact of local surface flux changes during the individual years remains the major contributing factor affecting the upper-ocean stratification. Ultimately, the stratification changes are responsible for the observed inconsistent response of biophysical features by significantly altering the upper-ocean mixing, upwelling, and nutrient availability in the western BoB.

In chapter 4, the coupled model interannual simulations were performed for 19 years (2000 to 2018) over the AS. The model simulations are validated with respect to satellite and *in-situ* (Bio-Argo, gridded Argo) observations over the AS domain including the NAS. The NAS is a highly productive basin in the IO. The marked seasonal variation of surface winds has the major control on the oceanic primary productivity in the NAS. The coupled physical-biogeochemical model used to examine the control of marine physical processes on the primary productivity in the NAS. It is found that the pure positive IOD (PPIOD) events had positive anomalies, whereas a co-occurrence of El-Niño and positive IOD (CEPIOD) events lead to negative anomalies in winter-time Chl-a concentration. The CEPIOD events are characterized by weaker winter convective mixing than in PPIOD events. The evolution of this discrepancy in the convective mixing process is sufficiently explained by the presence of weaker northeasterly (dry and cold) winds and a lower amount of net heat flux loss during CEPIOD as compared to the PPIOD events. During PPIOD, higher convective mixing resulted in intense surface cooling, a deeper mixed layer depth (MLD), increased nutrients supply towards surface, and a stronger winter bloom. Whereas, weak convective mixing

cause warming and a shallow MLD leading to weak winter bloom in CEPIOD. The interannual variability in the NAS region, including Chl-a concentration, is more strongly related to El-Niño forcing than to pIOD.

In chapter 5, an attempt is made to provide a better understanding of the tropical cyclones' (TCs) interactions with the surface as well as subsurface oceanic physical and biological features along the tracks of TCs. The coupled physical-biogeochemical model simulations are performed to analyze the before-, during-, and after-cyclone conditions of both, the physical and biological features in the NIO. The different surface and subsurface physical and biological features along the track of TCs depicted a cyclone-generated surface phytoplankton bloom and associated decline of dissolved oxygen (DO). It is found that the intense cyclonic wind stress caused upwelling in the wake of cyclone track. The excess surface fresh-water flux due to precipitation establishes stronger stratification in the coastal region. This enhanced stratification restricts the supply of nutrients to the euphotic zone and, hence, limits the surface primary productivity. The passage of two TCs sequentially makes the upper-ocean water column cooler (SST drops by 3°-6°C) and higher primary productivity (Chl-a up to 6 mg.m^{-3}) compared to the passage of single TC. The primary productivity on the surface persists more than two weeks after the passage of sequential TCs, due to TC generated upwelling and mixing, which is favorable for shoaling of nutrients and higher consumption of DO.

In chapter 6, the impact of pandemic-driven lockdown on ocean biophysical parameters is investigated using coupled model and observations. The unprecedented nationwide lockdown due to the 'coronavirus disease 2019' (COVID-19) affected humans and the environment in different ways. It provided an opportunity to examine the effect of reduced transportation and other anthropogenic activities on the environment. The impact of lockdown on Chl-a concentration, an index of primary productivity, over the NIO is investigated using the observations and a physical-biogeochemical model. A comparison of the observed and model-simulated data during the lockdown period (March–June, 2020) and pre-pandemic period (March–June, 2019) shows significant differences in the physical

(temperature and salinity) and biological (Chl-a, nutrient, and dissolved oxygen concentration) parameters over the western AS, western BoB, and regions off Sri Lanka. During the pandemic, the reduced anthropogenic activities led to a decrease in Chl-a concentration in the coastal regions of western BoB. The enhanced aerosol/dust transport due to stronger westerly winds enhanced phytoplankton biomass in the WAS in May–June of the pandemic period.

सार

हिंद महासागर (आईओ) परिसंचरण और इसकी जैविक प्रक्रियाएं काफी हद तक दूसरे महासागरों से भिन्न हैं। आईओ की दो विशिष्ट विशेषताएं महत्वपूर्ण हैं। पहली उत्तरी भूमि सीमा है, जो भारतीय उपमहाद्वीप को विभाजित करते हुए दक्षिण की ओर कम से कम २६°एन तक फैला हुआ है और उत्तर हिंद महासागर (एनआईओ) को दो बेसिनों में, अर्थात् अरब सागर (एएस) पश्चिम में और पूर्व में बंगाल की खाड़ी (बीओबी)। दूसरी अनूठी विशेषता आईओ में १०°एस के उत्तर में सतही हवाओं का मौसमी उत्क्रमण है। हवाएँ गर्मियों के मानसून के मौसम (जून-सितंबर) के दौरान दक्षिण-पश्चिम में बेसिन के उत्तरी आधे हिस्से और भारतीय उपमहाद्वीप में पर्याप्त वर्षा करती हैं। शीतकालीन मानसून (दिसंबर-फरवरी) उत्तरपूर्वी सतही हवाएँ अनुभव करता है। हवा की दिशा में परिवर्तन के जवाब में, एनआईओ के ऊपर की सतह की धाराएँ भी उत्तर आईओ में एक मौसमी उत्क्रमण से गुजरती हैं। महासागर की जैविक उत्पादकता मुख्य रूप निकट-सतह धूप से प्रकाशित परतों में पोषक तत्वों की उपलब्धता से नियंत्रित होती है। महासागर अपवेलिंग प्रक्रिया उपसतह के ठंडा और अक्सर पोषक तत्वों से भरपूर पानी को सतह पर लाता है और, इसलिए, जैविक उत्पादकता को बढ़ाता है। भौतिक प्रक्रियाएं जो आगे पूरे बेसिन में महत्वपूर्ण जैव-रासायनिक परिवर्तनशीलता लाती हैं। महासागरीय वर्तमान पैटर्न का वार्षिक विकास और हवा के दबाव के जवाब में अपवेलिंग वितरण को निर्धारित करती हैं।

हाल के दशकों में, आईओ का क्षेत्रीय और वैश्विक जलवायु परिवर्तनशीलता पर महत्वपूर्ण प्रभाव पाया गया है। नतीजतन, आईओ में बायोफिजिकल (यानी भौतिक और जैविक) प्रक्रियाएं के बारे में हमारे ज्ञान में सुधार अवलोकन और मॉडलिंग अध्ययन विज्ञान के माध्यम से आवश्यक हो गया है। वर्तमान थीसिस में, एक युग्मित भौतिक-जैव-रासायनिक मॉडल जिसमें क्षेत्रीय महासागर मॉडलिंग प्रणाली (रोम्स) और जैव-सॉफ़ (जैव-भू-रासायनिक (बीजीसी) मॉडल घटक) शामिल हैं, का उपयोग विभिन्न लौकिक पैमानों पर एनआईओ की जैवभौतिक परिवर्तनशीलता का अध्ययन करने के लिए किया जाता है। युग्मित भौतिक-जैव-रासायनिक मॉडल को $9/8^\circ \times 9/8^\circ$ क्षैतिज ग्रिड रिज़ॉल्यूशन, ४० लंबवत सिग्मा स्तरों और ३०°इ से १२०°इ और ३०°एस से ३०°एन को कवर करने वाले आईओ क्षेत्र पर एक एडी-अनुमति रिज़ॉल्यूशन के साथ कॉन्फ़िगर किया गया है। सरफेस फोर्सिंग फ़ील्ड के रूप में सरफेस हीट और मोमेंटम फ्लक्स की गणना करने के लिए, मौसम संबंधी मापदंडों के दैनिक माध्य मान एनसीईपी और क्विकसैट/एससीएटी डेटा से प्राप्त किए जाते हैं।

अध्याय २ में, 'युग्मित जलवायु मॉडल इंटरकंपेरिसन प्रोजेक्ट चरण ५' (सीएमआईपी५) से सोलह मॉडलों का आकलन उपग्रह प्रेक्षणों और क्षेत्रीय अवलोकनों के विरुद्ध क्लोरोफिल-ए (सीएचएल-ए) सांद्रता का अनुकरण करने में उनकी क्षमता के लिए किया जाता है। सोलह सीएमआईपी५ मॉडलों को उनके सापेक्ष कौशल के आधार पर तीन समूहों में वर्गीकृत किया गया है। ग्रुप-ए मॉडल ने प्रमुख उत्पादक क्षेत्रों पर फाइटोप्लांकटन ब्लूम को अधिक अनुमानित किया, जबकि ग्रुप-बी और ग्रुप-सी मॉडल ज्यादातर एनआईओ में ब्लूम को पुनः उत्पन्न करने में विफल रहे। हालाँकि, क्षेत्रीय युग्मित मॉडल ने सभी मौसमों में खिलने की तीव्रता के चरण को दिखाया जैसा कि टिप्पणियों में देखा गया है। देखे गए वार्षिक बदलाव सभी सीएमआईपी५ मॉडल द्वारा खराब रूप से अनुकरण किए गए थे। ग्रुप-ए मॉडल ने उत्तरी एएस (एनएस) पर सीएचएल-ए एकाग्रता में नकारात्मक पूर्वाग्रह और पश्चिमी आईओ (डब्ल्यूआईओ) पर सोमालिया से सीएचएल-ए सिमुलेशन में सकारात्मक पूर्वाग्रह दिखाया। भारत के पश्चिमी तटों और श्रीलंका के तटीय अपवेलिंग से जुड़े उच्च सीएचएल-ए को सीएमआईपी५ मॉडल द्वारा खराब रूप से अनुकरण किया गया था। इसके विपरीत, क्षेत्रीय युग्मित मॉडल में कम सकारात्मक सीएचएल-ए पूर्वाग्रह है। अध्ययन में सीएमआईपी५ जलवायु मॉडल में क्षेत्रीय कमी पर प्रकाश डाला गया है जो सीएचएल-ए का अनुकरण करता है और एनआईओ पर युग्मित भौतिक-जैव-रासायनिक मॉडल में सुधार की आवश्यकता है।

अध्याय ३ में, २०००-२०१७ की अवधि के लिए युग्मित मॉडल इंटरएनुअल सिमुलेशन का प्रदर्शन किया गया था। बीओबी पर इन-सीटू अवलोकनों और उपग्रह डेटा के संबंध में मॉडल सिमुलेशन मान्य हैं। बीओबी को तट के करीब अपने उत्तर-पश्चिमी खाड़ी मार्जिन पर और भारतीय ग्रीष्मकालीन मानसून के मौसम के दौरान ~४०० किमी की अपतटीय सीमा के साथ उच्च प्राथमिक उत्पादकता के लिए जाना जाता है। यह तटीय उत्पादकता मुख्य रूप से स्थानीय तटीय उत्थान प्रक्रिया द्वारा बनाए रखी गई निकट-सतह पोषक उपलब्धता के कारण होती है। एल-नीनो/ला-नीना और हिंद महासागर द्विध्रुव (आईओडी) के दौरान आईओ में सतही हवाएं काफी भिन्न होती हैं। पश्चिमी बीओबी में समुद्र की सतह के तापमान (एसएसटी) और सीएचएल-ए विसंगतियों का युग्मित मॉडल और टिप्पणियों का उपयोग करके १८ वर्ष (२००० से २०१७) की अवधि के लिए विश्लेषण किया गया है। सभी माने गए सकारात्मक आईओडी (पीआईओडी) वर्ष अध्ययन अवधि के दौरान पश्चिमी बीओबी में जैव-भौतिक विशेषताओं के विशिष्ट व्यवहार को दर्शाते हैं। पीआईओडी और एल-नीनो मोड की सह-घटना के वर्ष विपरीत जैवभौतिक विसंगतियों से जुड़े हैं। विश्लेषित पीआईओडी में, वर्ष २००६ और २०१२ में सीएचएल-ए विसंगतियों में वृद्धि दिखाई देती है, जबकि अन्य दो वर्षों (२०१५ और २०१७) में सीएचएल-ए कमी का अनुभव होता है। अन्य दो पीआईओडी वर्षों (२००६, २०१२) की तुलना में २०१५ और २०१७ पीआईओडी वर्षों के दौरान पश्चिमी बीओबी असामान्य रूप से गर्म था। यह असंगत प्रतिक्रिया पश्चिमी बीओबी पर स्थानीय सतह प्रवाह (गति, गर्मी और मीठे पानी) के परिवर्तन के संदर्भ में पीआईओडी वर्षों से जुड़ी जैव-भौतिक विशेषताओं की जांच की जाती है। अलग-अलग वर्षों के

दौरान स्थानीय सतह के प्रवाह में परिवर्तन का संयुक्त प्रभाव ऊपरी सागर स्तरीकरण को प्रभावित करने वाला प्रमुख योगदान कारक बना है। अंततः, स्तरीकरण परिवर्तन पश्चिमी बीओबी में ऊपरी-समुद्र के मिश्रण, अपवेलिंग और पोषक तत्वों की उपलब्धता में उल्लेखनीय रूप से परिवर्तन करके जैव-भौतिक प्रक्रियाओं की असंगत प्रतिक्रिया के लिए जिम्मेदार हैं।

अध्याय ४ में, एएस के ऊपर १९ साल (२००० से २०१८) के लिए युग्मित मॉडल इंटरनैशनल सिमुलेशन का प्रदर्शन किया गया था। मॉडल सिमुलेशन को एनएएस सहित एएस डोमेन पर उपग्रह और इन-सीटू (बायो-आर्गो, ग्रेडेड आर्गो) टिप्पणियों के संबंध में मान्य किया गया है। आईओ में एनएएस एक अत्यधिक उत्पादक बेसिन है। सतही हवाओं की चिह्नित मौसमी भिन्नता का एनएएस में समुद्री प्राथमिक उत्पादकता पर प्रमुख नियंत्रण है। एनएएस में प्राथमिक उत्पादकता पर समुद्री भौतिक प्रक्रियाओं के नियंत्रण की जांच करने के लिए युग्मित भौतिक-जैव-रासायनिक मॉडल का उपयोग किया जाता है। यह पाया गया है कि शुद्ध सकारात्मक आईओडी (पीपीआईओडी) घटनाओं में सकारात्मक विसंगतियाँ थीं, जबकि एल-नीनो और सकारात्मक आईओडी (सीईपीआईओडी) घटनाओं की सह-घटना सर्दियों के समय सीएचएल-ए सांद्रता में नकारात्मक विसंगतियों को जन्म देती है। सीईपीआईओडी घटनाओं की विशेषता पीपीआईओडी घटनाओं की तुलना में कमजोर शीतकालीन संवहन मिश्रण है। संवहन मिश्रण प्रक्रिया में इस विसंगति के विकास को पीपीआईओडी घटनाओं की तुलना में कमजोर उत्तरपूर्वी (शुष्क और ठंडी) हवाओं की उपस्थिति और सीईपीआईओडी के दौरान शुद्ध ऊष्मा प्रवाह हानि की कम मात्रा द्वारा पर्याप्त रूप से समझाया गया है। पीपीआईओडी के दौरान, उच्च संवहन मिश्रण के परिणामस्वरूप तीव्र सतह शीतलन, एक गहरी मिश्रित परत गहराई (एमएलडी), सतह की ओर पोषक तत्वों की आपूर्ति में वृद्धि, और एक मजबूत शीतकालीन खिलना हुआ। जबकि, कमजोर संवहन मिश्रण से गर्माहट होती है और एक उथला एमएलडी सीईपीआईओडी में कमजोर सर्दियों के खिलने का कारण बनता है। एनएएस क्षेत्र में सीएचएल-ए सघनता सहित अंतर-वार्षिक परिवर्तनशीलता, पीआईओडी की तुलना में एल-नीनो से अधिक मजबूती से संबंधित है।

अध्याय ५ में, उष्णकटिबंधीय चक्रवातों (टीसी) की सतह के साथ-साथ उपसतह समुद्री भौतिक और जैविक विशेषताओं के साथ टीसी की हैक के साथ बातचीत की बेहतर समझ प्रदान करने का प्रयास किया गया है। युग्मित भौतिक-जैव-रासायनिक मॉडल सिमुलेशन एनआईओ में भौतिक और जैविक विशेषताओं दोनों के पहले-, दौरान- और चक्रवात के बाद की स्थितियों का विश्लेषण करने के लिए किया जाता है। टीसी के ट्रैक के साथ-साथ विभिन्न सतह और उपसतह भौतिक और जैविक विशेषताओं ने एक चक्रवात-जनित सतह फाइटोप्लांकटन ब्लूम और घुलित ऑक्सीजन (डीओ) की संबद्ध गिरावट को दर्शाया। यह पाया गया है कि तीव्र चक्रवाती हवा के तनाव के कारण चक्रवात ट्रैक के मद्देनजर उथल-पुथल मच गई। वर्षण के कारण अतिरिक्त सतही मीठे पानी का प्रवाह तटीय क्षेत्र में मजबूत स्तरीकरण स्थापित करता है। यह बढ़ा हुआ स्तरीकरण यूफोरिक ज़ोन में पोषक तत्वों की

आपूर्ति को प्रतिबंधित करता है और इसलिए, सतह की प्राथमिक उत्पादकता को सीमित करता है। एकल टीसी के पारित होने की तुलना में दो टीसी का मार्ग क्रमिक रूप से ऊपरी-महासागर के जल स्तंभ को ठंडा (एसएसटी ३°-६°सी तक गिरता है) और उच्च प्राथमिक उत्पादकता (सीएचएल-ए से ६ मिलीग्राम प्रति मीटर घन) बनाता है। सतह पर प्राथमिक उत्पादकता अनुक्रमिक टीसी के पारित होने के दो सप्ताह से अधिक समय तक बनी रहती है।

अध्याय ६ में, युग्मित मॉडल और प्रेक्षणों का उपयोग करके महासागर जैवभौतिक मापदंडों पर महामारी-संचालित लॉकडाउन के प्रभाव की जांच की गई है। 'कोरोनावायरस रोग २०१९' (कोविड-१९) के कारण अभूतपूर्व राष्ट्रव्यापी लॉकडाउन ने मनुष्यों और पर्यावरण को विभिन्न तरीकों से प्रभावित किया है। इसने पर्यावरण पर कम परिवहन और अन्य मानवजनित गतिविधियों के प्रभाव की जांच करने का अवसर प्रदान किया। प्राथमिक उत्पादकता के सूचकांक सीएचएल-ए पर लॉकडाउन के प्रभाव का एनआईओ पर अवलोकनों और एक भौतिक-जैव-भू-रासायनिक मॉडल का उपयोग करके जांच की जाती है। लॉकडाउन अवधि (मार्च-जून, २०२०) और पूर्व महामारी अवधि (मार्च-जून, २०१९) के दौरान देखे गए और मॉडल-सिम्युलेटेड डेटा की तुलना में भौतिक (तापमान और लवणता) और पश्चिमी एएस (डब्ल्यूएस), पश्चिमी बीओबी और श्रीलंका के क्षेत्रों पर जैविक (सीएचएल-ए, पोषक तत्व, और घुलित ऑक्सीजन सांद्रता) पैरामीटर महत्वपूर्ण अंतर दिखाई देता है। महामारी के दौरान, मानवजनित गतिविधियों में कमी के कारण पश्चिमी बीओबी के तटीय क्षेत्रों में सीएचएल-ए सांद्रता में कमी आई। महामारी की अवधि के मई-जून में डब्ल्यूएस में तेज हवाओं के कारण बढ़े हुए एरोसोल/धूल परिवहन ने फाइटोप्लांकटन बायोमास को बढ़ाया।

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ABBREVIATIONS

<i>3D</i>	Three dimensional
<i>AAI</i>	Absorbing Aerosol Index
<i>AC</i>	Agulhas Current
<i>AMSR</i>	Advanced Microwave Scanning Radiometer
<i>AOD</i>	Aerosol Optical Depth
<i>AP</i>	Arabian Peninsula
<i>ARGO</i>	Array for Real-time Geostrophic Oceanography
<i>AS</i>	Arabian Sea
<i>ASCAT</i>	Advanced Scatterometer
<i>AVHRR</i>	Advanced Very High-Resolution Radiometer
<i>BGC</i>	Biogeochemical
<i>BLT</i>	Barrier Layer thickness
<i>BoB</i>	Bay of Bengal
<i>BOBMEX</i>	Bay of Bengal Monsoon Experiment
<i>CAS</i>	Central Arabian Sea
<i>CBoB</i>	Central Bay of Bengal
<i>CC</i>	Cold Class
<i>CDO</i>	Climate Data Operator
<i>CEPIOD</i>	Co-occurrence of El-Niño and Positive Indian Ocean Dipole
<i>Chl-a</i>	Chlorophyll-a
<i>CMIP5</i>	Coupled Model Intercomparison Project
<i>CO₂</i>	Carbon dioxide
<i>COVID-19</i>	Coronavirus Disease 2019
<i>D26</i>	Depth of 26°C isotherm
<i>DIC</i>	Dissolved Inorganic Carbon
<i>DJF</i>	December-January-February
<i>DO</i>	Dissolved Oxygen

<i>DUSMASS</i>	Dust Surface Mass Concentration
<i>EACC</i>	East African Coastal Current
<i>EC</i>	Equatorial Current
<i>EICC</i>	East Indian Coastal Current
<i>EIO</i>	Equatorial Indian Ocean
<i>EMT</i>	Ekman Mass Transport
<i>ENSO</i>	El Niño-Southern Oscillation
<i>EPV</i>	Ekman Pumping Velocity
<i>ESA</i>	European Space Agency
<i>ESCS</i>	Extremely Severe Cyclonic Storm
<i>ESM</i>	Earth System Model
<i>FORTTRAN</i>	FORmula TRANslation
<i>GLS</i>	Generic Length Scale
<i>HPC</i>	High-Performance Computing
<i>IIOE</i>	International Indian Ocean Expedition
<i>IITD</i>	Indian Institute of Technology Delhi
<i>ILD</i>	Isothermal Layer Depth
<i>IMD</i>	India Meteorological Department
<i>INCOIS</i>	Indian National Centre for Ocean Information Services
<i>IndOOS</i>	Indian Ocean Observing System
<i>IO</i>	Indian Ocean
<i>IOBM</i>	Indian Ocean Basin Mode
<i>IOD</i>	Indian Ocean Dipole
<i>ISMEX</i>	Indian Summer Monsoon Experiment
<i>JAXA</i>	Japan Aerospace Exploration Agency
<i>JGOFS</i>	Global Ocean Flux Study
<i>JJAS</i>	June-July-August-September
<i>KPP</i>	K-profile parameterization
<i>LDet</i>	Large Detritus
<i>LMD</i>	Large-McWilliams-Doney
<i>MAM</i>	March-April-May
<i>MERIS</i>	Medium Resolution Imaging Spectrometer

<i>MERRA-2</i>	Modern-Era Retrospective Analysis for Research and Applications, version 2
<i>MLD</i>	Mixed Layer Depth
<i>MLS</i>	Mixed layer Salinity
<i>MLT</i>	Mixed Layer Temperature
<i>MODIS</i>	Moderate Resolution Imaging Spectroradiometer
<i>MONEX</i>	Monsoon Experiment
<i>MONSOON</i>	Indo-Soviet Monsoon Experiment
<i>MONTBLEX</i>	Monsoon Trough Boundary Layer Experiment
<i>MPI</i>	Message Passing Interface
<i>MY</i>	Mellor-Yamada
<i>NAS</i>	Northern Arabian Sea
<i>NASA</i>	National Aeronautics and Space Administration
<i>NCEP</i>	National Center for Environmental Prediction
<i>NCL</i>	NCAR Command language
<i>NH₄</i>	Ammonium
<i>NHF</i>	Net Heat Flux
<i>NIO</i>	North Indian Ocean
<i>NIOA</i>	North Indian Ocean Atlas
<i>nIOD</i>	Negative Indian Ocean Dipole
<i>NIOP</i>	Netherlands Indian Ocean Program
<i>NMC</i>	Northeast Monsoon Current
<i>NO₂</i>	Nitrogen Dioxide
<i>NO₃</i>	Nitrate
<i>NOAA</i>	National Oceanic and Atmospheric Administration
<i>NODC</i>	National Oceanographic Data Center
<i>OC-CCI</i>	Ocean Color-Climate Change Initiative
<i>OGCM</i>	Ocean General Circulation Model
<i>OLCI</i>	Ocean and Land Colour Instrument
<i>OMI</i>	Ozone Monitoring Instrument
<i>OMZ</i>	Oxygen Minimum Zone
<i>ON</i>	October-November

<i>OSCAR</i>	Ocean Surface Current Analysis Real-time
<i>pCO₂</i>	Partial pressure of CO ₂
<i>Phy</i>	Phytoplankton
<i>pIOD</i>	Positive Indian Ocean Dipole
<i>PPIOD</i>	Pure Positive Indian Ocean Dipole
<i>R</i>	Correlation Coefficient
<i>RAMA</i>	Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction
<i>RMSE</i>	Root Mean Square Error
<i>ROMS</i>	Regional Ocean Modelling System
<i>SARS-CoV-2</i>	Severe acute respiratory syndrome coronavirus 2
<i>SC</i>	Somalia Current
<i>SCM</i>	Subsurface Chlorophyll Maxima
<i>SD</i>	Standard Deviation
<i>SDet</i>	Small Detritus
<i>SEAS</i>	South Eastern Arabian Sea
<i>SeaWiFS</i>	Sea-viewing Wide Field-of-view Sensor
<i>SECC</i>	South Equatorial Counter Current
<i>SH</i>	Southern Hemisphere
<i>SIO</i>	Southern Indian Ocean
<i>SMC</i>	Summer Monsoon Current
<i>SSHA</i>	Sea Surface Height Anomaly
<i>SSS</i>	Sea Surface Salinity
<i>SSSMAS</i>	Sea Salt Surface Mass Concentration
<i>SST</i>	Sea Surface Temperature
<i>SuCS</i>	Super Cyclonic Storm
<i>TC</i>	Tropical Cyclone
<i>TCHP</i>	Tropical Cyclone Heat Potential
<i>TMI</i>	TRMM Microwave Imager
<i>TRMM</i>	Tropical Rainfall Measuring Mission
<i>VIIRS</i>	Visible Infrared Imaging Radiometer Suite
<i>VSCS</i>	Very Severe Cyclonic Storm

<i>WAS</i>	Western Arabian Sea
<i>WC</i>	Warm Class
<i>WHO</i>	World Health Organization
<i>WICC</i>	West Indian Coastal Current
<i>WMO</i>	World Meteorological Organization
<i>WOA13</i>	World Ocean Atlas 2013
<i>WOA18</i>	World Ocean Atlas 2018
<i>Zoo</i>	Zooplankton