



Two-decadal variability of photosynthetically active radiation over the Arabian Sea and its biogeochemical implications

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Abstract

Photosynthetically Active Radiation (PAR) plays a critical role in regulating marine primary productivity and air–sea interactions. This study investigates the spatiotemporal variability of PAR over the eastern Arabian Sea (62°E–75°E and 10°N–25°N) using 21 years (2002–2023) of satellite-derived observations. Monthly PAR data from MODIS-Aqua were analyzed to derive climatology, seasonal cycles, anomalies, and long-term trends. Results reveal pronounced monthly and seasonal variability in PAR in the eastern Arabian Sea. The 21-year averaged monthly PAR time series showed a declining trend for March ($p = 0.0061$ and Sen's slope = $-0.04 \text{ Einstein m}^{-2} \text{ day}^{-1} \text{ yr}^{-1}$), October ($p = 0.009$ and Sen's slope = $-0.11 \text{ Einstein m}^{-2} \text{ day}^{-1} \text{ yr}^{-1}$), and December ($p = 0.0033$ and Sen's slope = $-0.09 \text{ Einstein m}^{-2} \text{ day}^{-1} \text{ yr}^{-1}$) which has the potential to alter primary productivity in these months. Seasonal PAR time series showed maximum during Spring, and a significant decadal decline in Winter (Sen's slope = $-0.0535 \text{ Einstein m}^{-2} \text{ day}^{-1} \text{ yr}^{-1}$, $p = 0.016$, Mann-Kendall test). Two decadal Time series investigation of PAR anomaly and Climate mode indices (Niño 3.4 and the Dipole Mode Index) suggests that the Indo-Pacific climate state influences PAR anomalies in the eastern Arabian Sea, but it is not the sole driver. Overall, trend analysis indicates region-specific changes in PAR, with implications for phytoplankton productivity and biogeochemical cycling. The findings highlight the combined influence of atmospheric forcing and ocean dynamics on light availability in the Arabian Sea.

Keywords: Photosynthetically absorbed radiation (PAR), Arabia Sea (AS), Niño 3.4 index, Dipole Mode Index

Introduction

The solar energy flux reaching the ocean surface in the spectral range of 400–700 nm is defined as photosynthetically available (or active) radiation (PAR) (Kirk, 1994) [20]. PAR serves as a crucial indicator for determining the primary production, and health of an aquatic ecosystem (Kirk, 1994; Falkowski *et al.*, 2004) [11, 20]. Knowledge of spatial and temporal distribution of PAR is essential as it directly influence the carbon, nutrient, and oxygen biogeochemical cycles, and helps to address major climate issues like the fate of atmospheric carbon dioxide (Tan and Frouin, 2019) [51]. Baring chemical process, PAR by warming the upper ocean assists the physical processes through the generation of density contrast between the mixed layer and deeper layers (Nakamoto *et al.*, 2000, 2001; Miller *et al.*, 2003; Shell *et al.*, 2003; Ballabrera-Poy *et al.*, 2007) [5, 31, 34, 35, 49].

Satellite remote sensing has emerged as an indispensable tool for estimating PAR over oceanic and terrestrial surfaces at broad spatial and temporal scales. In contrast, *in situ* PAR observations remain restricted largely to research cruises, yielding sparse point measurements. *In situ* measurements are also logistically demanding to carry out observations for complete seasonal cycles, and inadequate for resolving the basin-scale spatial heterogeneity governing regional productivity regimes (Kinkade *et al.*, 2001). Currently, PAR data can be retrieved regularly from various space borne radiometers such as SeaWiFS, MODIS-Aqua, MODIS-Terra, MERIS, and VIIRS etc. (Tan and Frouin, 2019) [51]. The Ocean Biology Processing Group (OBPG) at the National Aeronautics and Space Administration (NASA) regularly produces daily, monthly, seasonal, and annual

PAR record as standard Level-2 and Level-3 products, and are publicly accessible through the NASA's Ocean Color portal (<https://oceancolor.gsfc.nasa.gov>; Group (2025)). Validations against *in situ* radiometric benchmarks indicate typical relative root-mean-square (RMS) differences of 10–30% and relative biases of 4–9% (Frouin and McPherson, 2012; Frouin *et al.*, 2012; Laliberté *et al.*, 2016; Somayajula *et al.*, 2018) [13, 26, 50]. Furthermore, multi-sensor data merging across disparate orbital overpass times substantially mitigates diurnal sampling bias and improves daily PAR accuracy (Frouin *et al.*, 2012) [13]. PAR variability at the ocean surface is primarily driven by the solar zenith angle and cloud transmittance, with aerosol optical thickness and surface albedo acting as secondary controls. (Bergman and Salby, 1996; Rossow and Schiffer, 1999) [6, 42].

Because sea-surface temperature and nutrient levels change very little throughout the year in most tropical and subtropical oceans, seasonal variations in PAR and the upper water column's physical structure primarily drive regional productivity (Kumar and Narvekar, 2005; Lozier *et al.*, 2011) [22, 28]. The Arabian Sea (AS) provides an ideal setting to examine these dynamics. Situated within the tropical belt, it experiences intense air–sea interactions across seasonal to interannual timescales. This strong coupling ultimately shapes the light and nutrient conditions that govern local phytoplankton communities (Lakshmi *et al.*, 2021) [25]. The semi-annual reversal of the southwest and northeast monsoons drives larger seasonal swings in surface currents, temperature, and nutrient injection in the AS than in any other ocean basin. (McCreary *et al.*, 2009), combining an unusually strong, twice-reversing wind field with pronounced seasonal changes in cloud cover,

atmospheric dust loading, and mixed-layer depth (Kinkade *et al.*, 2001). These monsoon-driven processes generate substantial variability in cloud cover, which in turn produces complex spatial and temporal patterns in the PAR field reaching the sea surface. Variations in cloud fraction,

aerosol loading, and atmospheric circulation collectively modulate the solar radiation reaching the ocean surface which shapes the underwater light field, ultimately dictating the timing and magnitude of primary productivity across the basin (Lévy *et al.*, 2007; McCreary *et al.*, 2009).

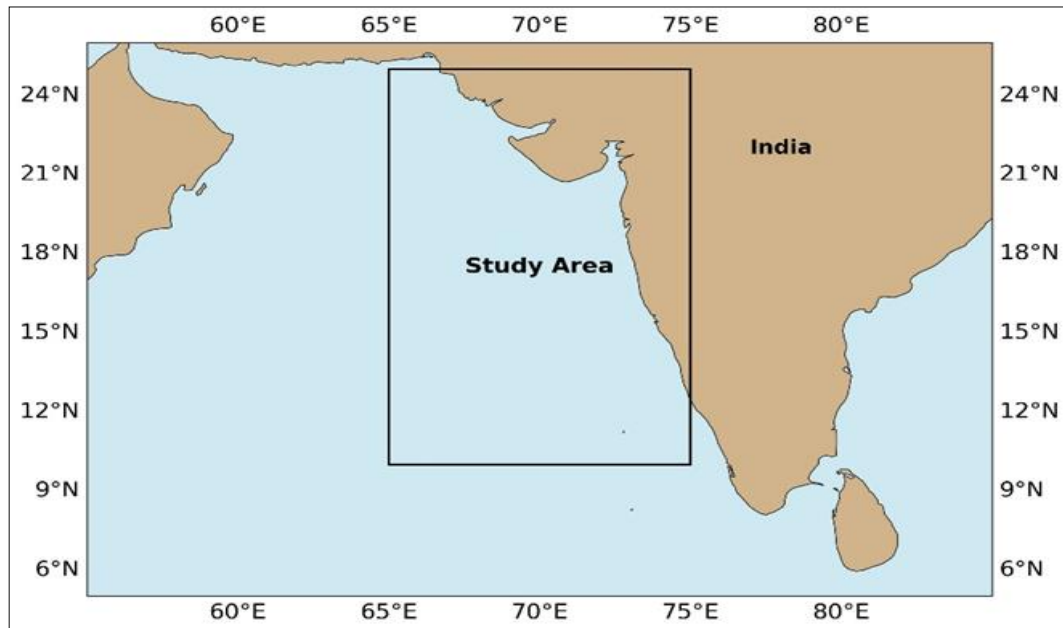


Fig 1: Study area

Addressing this challenge requires long-term understanding of PAR in the AS. This study aims to: (1) quantify climatological and seasonal variability of PAR in the AS; (2) examine interannual variability and climate linkages of PAR in the AS; (3) assess long-term trends of PAR and its implications for marine productivity in the AS.

Methodology

Study area

The Arabian Sea

The study area bounded approximately between 62°E and 75°E longitude and 10°N and 25°N latitude encompasses the eastern Arabian Sea (Fig. 1). The Arabian Sea is one of the most dynamic and productive marine regions of the northern Indian Ocean (Kumar and Narvekar, 2005)^[22]. The Arabian Sea is geographically bounded by the Arabian Peninsula to the west, India to the east, and Pakistan and Iran to the north (Nair *et al.*, 1989)^[33]. Variability in sea surface temperature and monsoon upwelling has played a major role in shaping the oceanographic conditions of the basin over time (Emeis *et al.*, 1995)^[10]. Numerous studies report that AS circulation is strongly controlled by the seasonal monsoon system, which reverses regional winds and currents during the summer and winter monsoons (Schott and McCreary Jr, 2001; Shankar *et al.*, 2002)^[46, 48]. Strong winds during the southwest monsoon trigger intense coastal upwelling in the AS along Somalia, Oman, and the west coast of India, pumping nutrient-rich deep waters into the surface layer (Ajith Joseph *et al.*, 2018

^[1]; Chowdhury *et al.*, 2021). Monsoon-driven processes significantly enhance phytoplankton growth and primary productivity, making the Arabian Sea one of the most biologically productive ocean basins in the world (Wiggert *et al.*, 2005)^[53]. Driven by high biological productivity and organic matter decomposition, the Arabian Sea hosts one of

the world's strongest Oxygen Minimum Zones (OMZs) where severe oxygen depletion at intermediate depths profoundly influences the basin's nitrogen cycling and denitrification (Resplandy *et al.*, 2012)^[41]. In addition to its oceanographic importance, the Arabian Sea has a major influence on the Indian monsoon system through air–sea interactions, heat exchange, and moisture transport. Recent studies suggest increasing warming trends, marine heatwaves, and cyclone intensification in the region due to climate change. This region is widely regarded as a biogeochemical hotspot within the global ocean, owing to the combined influence of a strong, reversing monsoon system, an intense and shallow oxygen OMZ, and pronounced seasonal coastal upwelling (Naik and Naik, 2022)^[32]. Because these physical forcings interact directly with nitrogen, carbon, and oxygen cycling, the eastern Arabian Sea has become a natural laboratory for biogeochemical research with global significance, from marine nitrogen-loss budgets to projections of ocean deoxygenation and acidification under climate change.

Data accumulation and processing

For this study, PAR data were obtained from the Moderate Resolution Imaging Spectroradiometer aboard NASA's Aqua satellite (MODISA). Specifically, level-3 datasets, with a spatial resolution of 4 km from September 2002 to August 2023 were downloaded from NASA's Ocean Color Web (<https://oceancolor.gsfc.nasa.gov/l3/>) which is maintained by the NASA's Ocean Biology Processing Group (OBPG) (Group (2025)). MODISA launched in 2002, is a passive optical sensor with 36 spectral bands and a 1–2-day global repeat cycle, well suited to monitor the ocean-color products (King *et al.*, 2003)^[17]. The NASA's OBPG generates a standard PAR product from MODISA using an algorithm developed by Frouin, Franz, and Werdell (Frouin

et al., 2003) ^[12]. MODISA has provided near-continuous ocean-colour observations since July 2002 ^[48], and its PAR product forms part of the standard Level-3 global mapped suite generated and distributed by NASA's Ocean Biology Processing Group (OBPG) through the Ocean Biology Distributed Active Archive Center (OB. DAAC; Group (2025)). The PAR data suite provides satellite-based estimates of the downwelling solar radiation in the 400–700 nm range available for photosynthesis at the ocean surface, quantifying the daily amount of usable light (King *et al.*, 2003) ^[17]. All data files are obtained in netCDF format which was processed for subsetting, spatial averaging, and time series construction using the required packages of Python software. In this study, we have defined the season as Fall (September, October, November), Winter (December, January, February), Spring (Mar, April, May), and Summer (June, July, August). Monthly sea surface temperature (SST) anomaly indices i.e. Niño 3.4 index and the Dipole Mode Index (DMI) were obtained from the National Oceanic and Atmospheric Administration (NOAA) (Saji and Yamagata, 2003 ^[44]; (<https://psl.noaa.gov/>; Data accessed on 11 June, 2026). The Niño 3.4 index measures area-averaged SST anomalies across the central-eastern equatorial Pacific region

(5°N–5°S, 170°W–120°W)

serves as a primary metric for monitoring, defining, and classifying the warm (El Niño) and cool (La Niña) phases of the El Niño–Southern Oscillation (ENSO) cycle (Rayner *et al.*, 2003) ^[40]. The Dipole Mode Index (DMI), introduced by Saji *et al.* (1999) ^[43], is the standard metric used to monitor the Indian Ocean Dipole (IOD). It calculates the difference in sea surface temperature (SST) anomalies between two specific regions: the western equatorial Indian Ocean (50°E–70°E, 10°S–10°N) and the southeastern equatorial Indian Ocean (90°E–110°E, 10°S–0°) (Saji and Yamagata, 2003) ^[44].

Statistical analysis

To test the significance of monotonic trends in monthly PAR, the non-parametric Mann-Kendall test was performed. The magnitude of the trend was then estimated using Sen's slope, a robust, non-parametric estimator defined by the median of the slopes computed across all pairs of observations (Sen, 1968) ^[47], which limits the influence of outliers on the estimates. Differences in mean among seasons were tested with the Friedman test, followed by pairwise Wilcoxon signed-rank tests (Zimmerman and Zumbo, 1993) ^[55].

Results and Discussions

Long-term trends in monthly PAR

Month	n	Mean	SD	Min	Max
Jan	21	41.43	0.64	39.92	42.40
Feb	21	47.64	0.49	46.57	48.24
Mar	21	53.34	0.51	51.96	53.93
Apr	21	56.56	0.53	55.33	57.27
May	21	55.03	1.81	50.35	57.23
Jun	21	45.25	2.20	40.01	49.71
Jul	21	42.08	2.03	39.56	47.44
Aug	21	43.91	2.67	36.73	49.32
Sep	21	45.91	2.21	42.27	50.33
Oct	21	45.48	1.30	41.88	47.36
Nov	21	41.05	1.60	37.03	43.03
Dec	21	38.81	1.07	36.20	40.33

The average values and standard deviations of monthly PAR for 21-year period were shown in Table 1. The minimum PAR was obtained in the month of December whereas, maximum was for April. In general, monthly average PAR values remained higher for March, April, and May as compared to other calendar months. Analysis of 21 years of monthly PAR (September 2002 to August 2023) revealed statistically significant monotonic trends (Fig. 2; Mann-Kendall test, $p < 0.05$) in 3 of the 12 calendar months, namely March (Fig. 1; $p = 0.0061$ and Sen's slope = -0.04 Einstein $\text{m}^{-2} \text{day}^{-1} \text{yr}^{-1}$), October (Fig. 1; $p = 0.009$ and Sen's slope = -0.11 Einstein $\text{m}^{-2} \text{day}^{-1} \text{yr}^{-1}$), and December (Fig. 1; $p = 0.0033$ and Sen's slope = -0.09 Einstein $\text{m}^{-2} \text{day}^{-1} \text{yr}^{-1}$). In every case the slope was negative, indicating a decline in PAR. The annual rates of change ranged from -0.11 in October to -0.04 Einstein $\text{m}^{-2} \text{day}^{-1}$ in March. The strongest decline occurred in the month of October (Sen's slope = -0.11 Einstein $\text{m}^{-2} \text{day}^{-1} \text{yr}^{-1}$, 95% CI: -0.19 to -0.03 ; $p = 0.009$). The remaining months showed no significant trend. This indicates that no monotonic change could be detected against natural interannual variability. Long-term changes in surface radiation are well documented previously. Surface

observations showed a decline in solar radiation over land up to about 1990 ("global dimming"), followed by a widespread brightening from the late 1980s, and this reversal is consistent with changes in cloudiness and atmospheric transmission (Wild, 2009) ^[54]. The direction and timing of these changes differ between regions, so global patterns cannot be assumed to apply locally. In India, Padma Kumari *et al.* (2007) ^[37] found that solar dimming offset surface warming. This trend is driven by aerosols, particularly atmospheric brown clouds, which disrupt the broader South Asian climate and hydrological cycle (Ramanathan *et al.*, 2005) ^[39]. The declines found here are therefore consistent with a role for increased aerosol loading and/or changes in cloud cover however, the present analysis does not include cloud or aerosol data, so it cannot separate these contributions. Testing these explanations requires the same period of cloud fraction, aerosol optical depth and precipitation data for Arabian Sea. As PAR is the energy source for photosynthesis, a persistent decline during March, October and December could affect primary productivity in the study region however, the ecological significance depends on whether light is the limiting factor in those months.

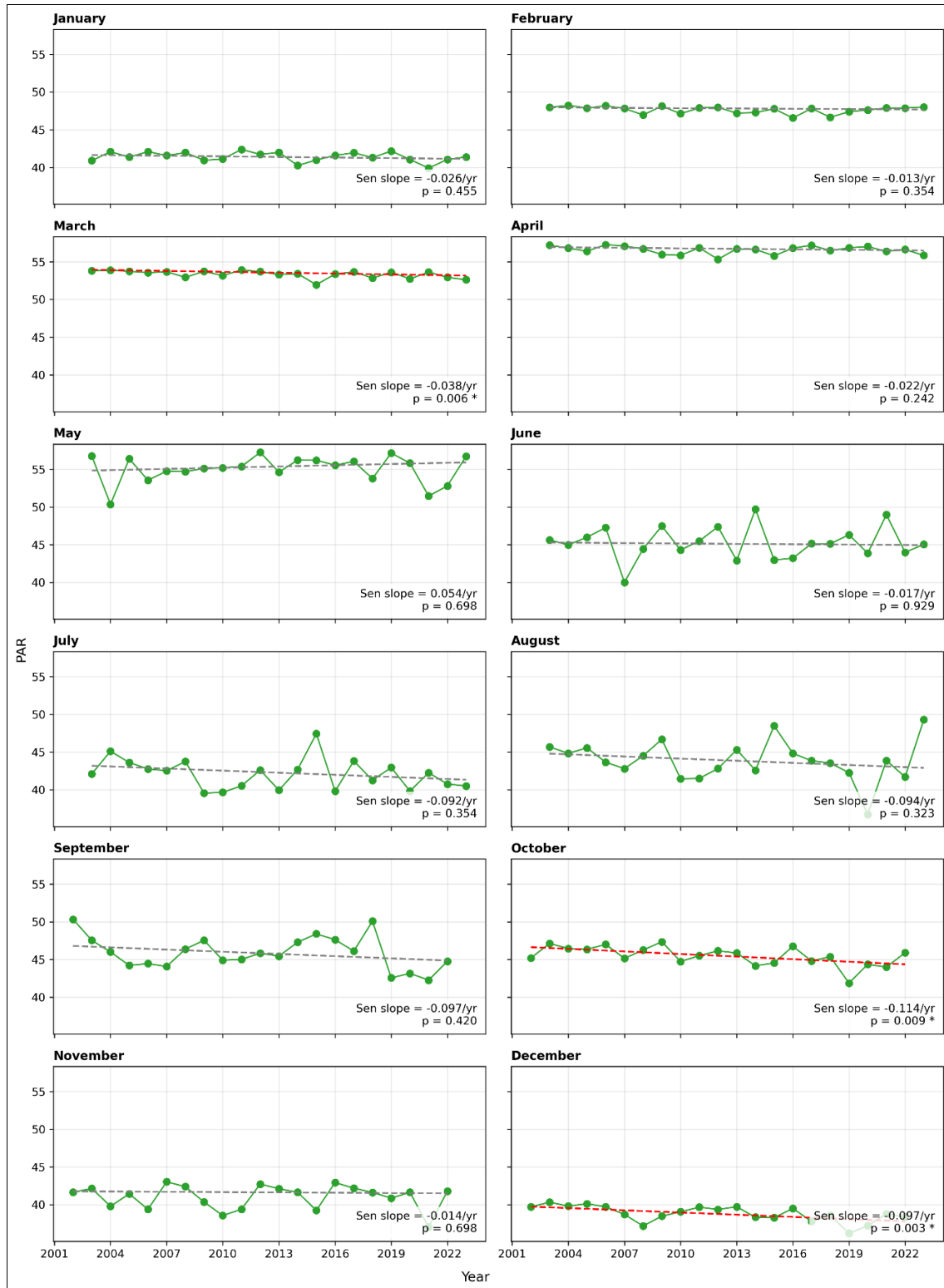


Fig 2: Monthly time series of PAR (Einstein $\text{m}^{-2} \text{day}^{-1}$) in the eastern Arabian Sea

Seasonal contrast

PAR exhibits a strong seasonal cycle in the present study (Fig. 3). The primary maximum occurs during the Spring (March-May), with PAR reaching 54.98 ± 0.61 Einstein $\text{m}^{-2} \text{day}^{-1}$ (Fig. 3), when the sun is near its zenith over the northern tropics and skies are largely clear (Kirk, 2011). In rest of the seasons, PAR values were comparable (Fig. 3; Summer: 43.74 ± 1.49 Einstein $\text{m}^{-2} \text{day}^{-1}$; Fall: 44.14 ± 1.24 Einstein $\text{m}^{-2} \text{day}^{-1}$; Winter: 42.63 ± 0.54 Einstein $\text{m}^{-2} \text{day}^{-1}$). This decline is driven mainly by dense, deep monsoon cloud cover along the west coast of India, which strongly

attenuates surface irradiance (Frouin *et al.*, 2003, 2012) [12, 13]. The eastern AS is affected more than the open central basin because orographic uplift along the Western Ghats intensifies rainfall and cloudiness near the coast (Schott and McCreary Jr, 2001) [46].

Seasonal trend analysis of PAR over the eastern Arabian Sea (2002-2021) [25, 48] revealed a statistically significant declining trend only in winter (Sen's slope = -0.0535 Einstein $\text{m}^{-2} \text{day}^{-1} \text{yr}^{-1}$, $p = 0.016$, Mann-Kendall test), corresponding to a cumulative decrease of approximately 1.1 Einstein $\text{m}^{-2} \text{day}^{-1}$ over the 21-year record. Fall

exhibited the largest negative slope ($-0.079 \text{ Einstein m}^{-2} \text{ day}^{-1} \text{ yr}^{-1}$) but did not reach significance ($p = 0.176$), while spring and summer showed weak, non-significant declines ($p = 0.531$ and 0.612 , respectively).

The consistently negative sign across all seasons suggests a general, if not uniformly significant, downward tendency in surface PAR, most pronounced during winter.

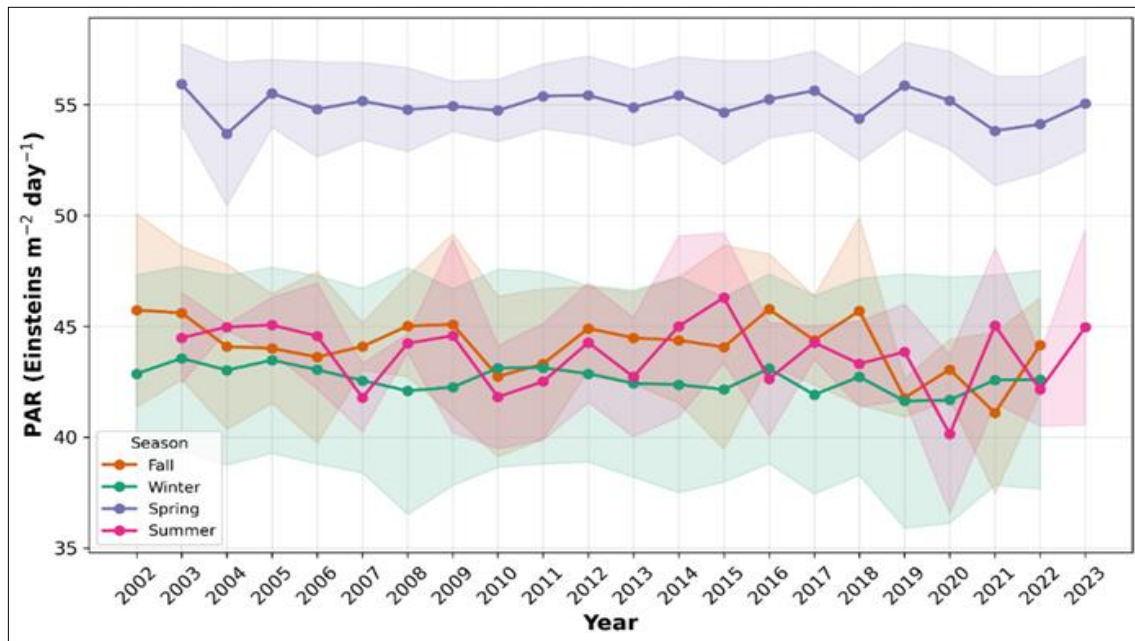


Fig 3: Seasonal cycle of PAR in the eastern Arabian Sea

The seasonal light regime interacts with the region's strong physical forcing. Monsoonal upwelling along India's southwest coast brings nutrient-rich water to the surface, boosting biological productivity even when PAR hits its annual minimum. This indicates that nutrient supply, not light availability, limits production at this time (Kumar *et al.*, 2000; Sankar *et al.*, 2011)^[21, 45]. In contrast, during the pre-monsoon and winter months, PAR is high but the water column is strongly stratified and nutrient-poor, and winter cooling in the northeastern Arabian Sea can deepen the mixed layer and trigger convective mixing and blooms of *Noctiluca* (Kumar *et al.*, 2001; do Rosário Gomes *et al.*, 2014)^[9, 23]. This decoupling of PAR from chlorophyll seasonality is a defining characteristic of the Arabian Sea, underscoring the need for careful consideration when interpreting regional light-productivity relationships.

PAR climatology of the study area

The 21-year monthly PAR climatology (2002^[48]-2023) showed a distinct annual cycle over the study region (Fig. 4). Consistent with earlier studies in the Arabian Sea, Arnone *et al.* (1998)^[2] observed a bimodal PAR cycle, with seasonal maxima occurring in May and October and minima in December and July. Specifically, our observed December minimum aligns with their recorded winter minimum, whereas our April maximum precedes their May peak by approximately one month (Fig. 4). From December to April, PAR increases by 18 % in the present study. This rise follows the northward shift of the sun, longer days, and the clear skies that precede the summer monsoon. Arnone *et al.* (1998)^[2] reported that the maximum PAR originates in the southern Arabian Sea in April and migrates northward as the southwest

monsoon advances, reaching the northern Oman coast by August. Our observations are consistent with this finding. The February-to-March panels show PAR increasing over the whole domain, with the highest values in the south (Fig. 4). The pattern also suggests that the maximum of PAR is reached before the peak of cloudiness associated with the monsoon. The December minimum is expected because the sun is at its lowest elevation in the Northern Hemisphere and day length is shortest, so less solar radiation reaches the surface. Tan and Frouin, (2019)^[51] found that seasonal patterns in tropical PAR are related to solar position and the monsoon. The July minimum cannot be explained by solar geometry, since the Sun is then near its highest at these latitudes. It reflects the monsoon, when increased cloud cover and aerosols lower the light available at the sea surface (Arnone *et al.*, 1998)^[2]. In our data, the July value is 14 % below the April maxima. Clouds dominate in the monsoon-season causing reduction in PAR. Aerosol optical thickness also increases over the Arabian Sea during the summer monsoon, but its influence on PAR is expected to be smaller than that of monsoon cloudiness (Tan and Frouin, 2019)^[51].

The seasonal cycle of PAR is important because light is one of the main Component that controls phytoplankton growth. In the Arabian Sea, the winter minimum in December coincides with the northeast monsoon period, when convective mixing can bring nutrients into the surface layer in the north (Madhupratap *et al.*, 1996; Prakash and Ramesh, 2007; Kumar *et al.*, 2010)^[24, 29, 38]. Consequently, the spring PAR maximum precedes the southwest monsoon, a period when intense upwelling along the Indian coast and the Somali and Oman margins strongly drives regional biological productivity (Wiggert *et al.*, 2005)^[53]

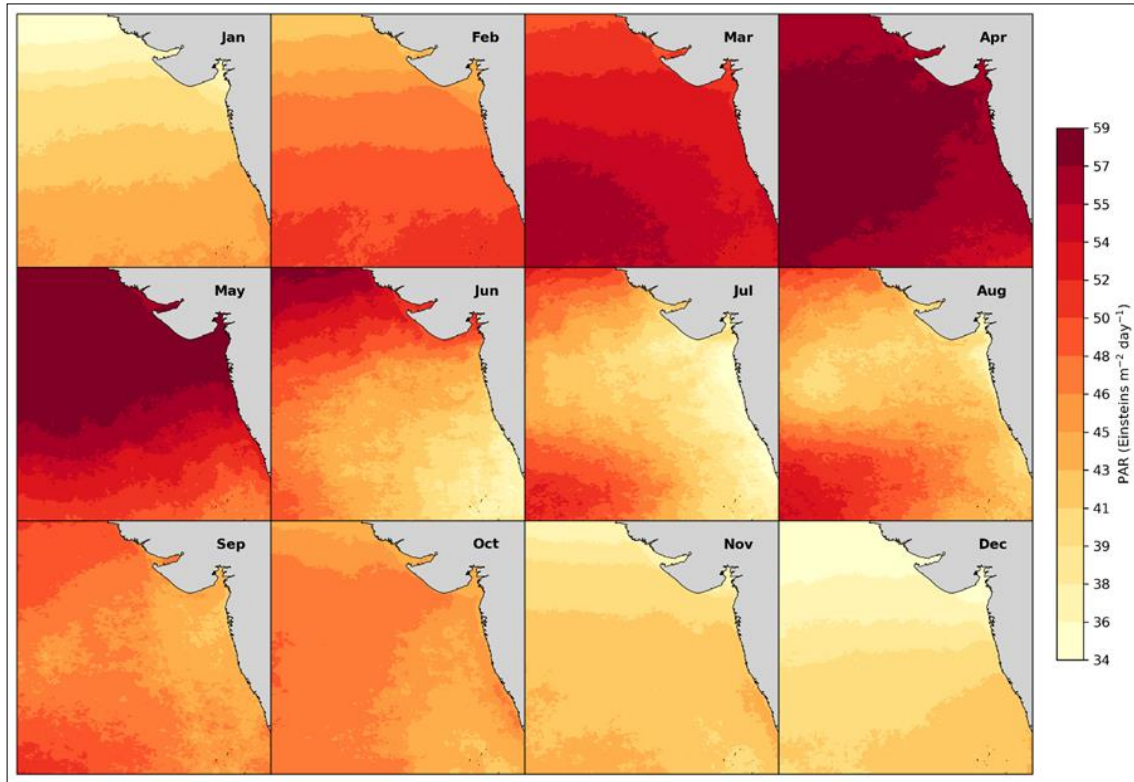


Fig 4: Monthly PAR climatology in the eastern Arabian Sea

Effect of climate indices on PAR

The 21-year record of monthly PAR anomalies over the eastern Arabian Sea (September 2002^[48] to August 2023; Fig. 5) is dominated by short-lived fluctuations. Most months fall within about ± 2 Einstein m⁻² day⁻¹, but excursions reach roughly $+5.4$ Einstein m⁻² day⁻¹ in mid-2015 and in the final month of the record, and about -7.2 Einstein m⁻² day⁻¹ in mid-2020. The climate indices show a different, low-frequency pattern. Niño 3.4 depicts warm

phases in 2002–03, 2004–05, 2006–07, 2009–10, 2015–16 (the strongest, near $+2.7$ °C), 2018–19 and 2023, and cool phases in 2007–08, 2010–12, 2016–18 and the prolonged 2020–23 La Niña. This chronology matches NOAA's criterion of ± 0.5 °C persisting for five consecutive overlapping seasons (Trenberth, 1997^[52]; Center, 2026). The DMI ranges from about -0.75 to $+0.96$ °C, with positive IOD peaks in 2006, 2019 and 2023 and negative excursions in 2016 and 2022

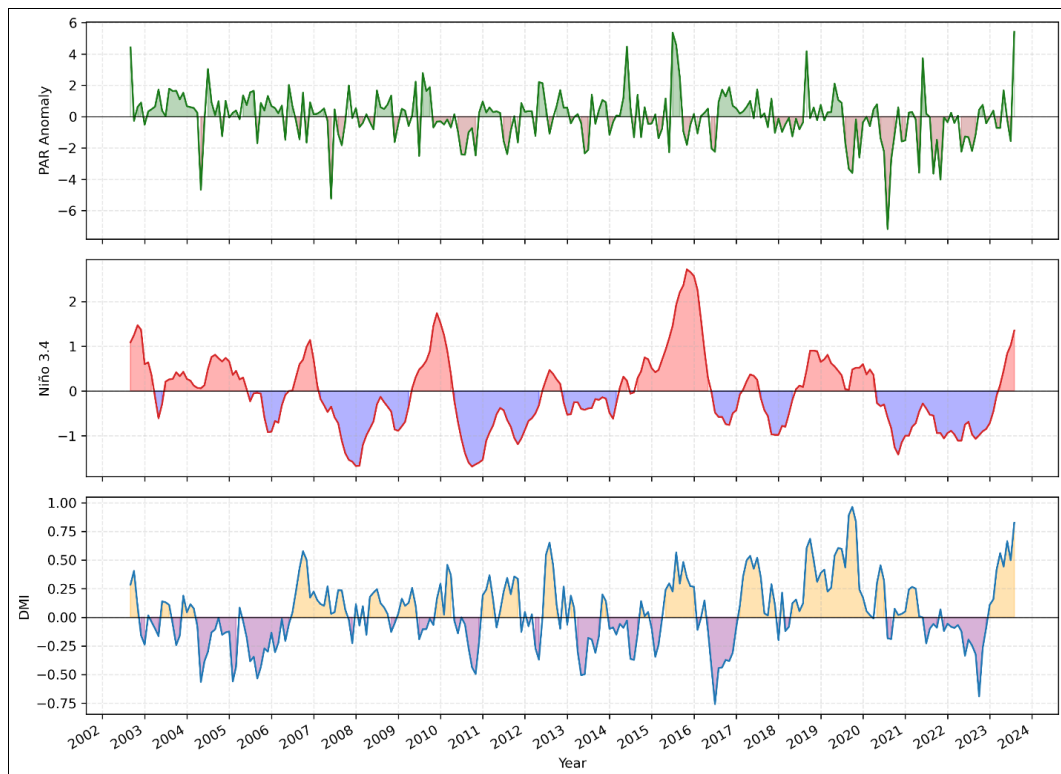


Fig 5: Time series of PAR anomaly (Einstein m⁻² day⁻¹), Niño 3.4 (°C) and DMI (°C) in the eastern Arabian Sea.

A physical pathway linking these modes to PAR is plausible. PAR at the sea surface is controlled mainly by cloudiness and aerosol loading, and satellite PAR over the tropical oceans has been shown to vary interannually with El Niño–Southern Oscillation (ENSO) through changes in cloudiness, with monsoon-related patterns also evident in its seasonal cycle (Tan and Frouin, 2019)^[51]. Both ENSO and the IOD modulate the Indian summer monsoon, influencing rainfall patterns in a complementary manner where the IOD acts as a crucial mediator of the ENSO–monsoon relationship (Ashok *et al.*, 2001, 2004)^[3, 4]. One would therefore expect El Niño, which tends to weaken the monsoon, to favour clearer skies and positive PAR anomalies over the eastern Arabian Sea, and La Niña and positive IOD, which favour monsoon convection, to favour negative anomalies (Sankar *et al.*, 2011)^[45]. Several features of Fig.5 are compatible with this expectation. The large positive PAR anomalies in mid-2015 and at the end of the record both occur during strong El Niño phases. The 2015 monsoon was a drought year, with rainfall about 14% below normal (Nature India, 2026). In 2023^[16, 36], August was the driest on record with a 36% deficit (IMD, 2023), and that is when PAR jumps to its highest value in the record. At the other extreme, the deepest negative anomaly (about −7 in mid-2020) occurs during the onset of the 2020–23 La Niña. The cluster of negative anomalies of about −3.5 in late 2019 coincides with the peak of the strong 2019 positive IOD, when the DMI reached about +0.96 °C in October 2019. Both are consistent with enhanced cloudiness, although the present study alone cannot confirm this.

The Fig.5 equally shows that ENSO and IOD explain only part of the variability. Positive excursions of comparable size occur in 2014 (about +4.5, with Niño 3.4 near neutral), in 2018 (about +4.2) and in 2021 (about +3.7, under weak La Niña or neutral conditions). Pronounced negative anomalies occur in spring 2004 (about −4.7) and around May 2007 (about −5.2), when ENSO forcing was weak and, in 2007, the DMI was positive. Neither cool phases (2010–12) nor negative DMI intervals (2005, 2013–14) are accompanied by a uniform sign of PAR anomaly.

The current study suggests that the Indo-Pacific climate state contributes to, but does not by itself determine, PAR anomalies in the eastern Arabian Sea. The clearest correspondence appears in years with well-documented El Niño-related monsoon deficits (2015, 2023) and during the 2019–20 positive IOD to La Niña transition. Given that PAR determines light availability for phytoplankton, and both ENSO and the IOD are known to drive regional chlorophyll anomalies, these climate modes likely exert a combined influence on the interannual variability of the Indian Ocean's primary production (Currie *et al.*, 2013), such episodic changes in light may matter for productivity here. A complete understanding of cloud, aerosol and chlorophyll or primary production is required to understand this phenomenon completely.

Conclusion

This study examined the two decadal variability in monthly and seasonal time series, climatology, and anomalies of PAR, and assessed its linkage to large-scale climate modes through the Niño 3.4 index and DMI over the eastern AS. The 21-year averaged monthly PAR time series shows a pronounced and regular annual cycle, with a maximum in April and a minimum in December. The seasonal time series

shows that Spring receives the highest PAR and a comparable PAR in rest of the seasons. A steady decline was observed in 21 year averaged monthly PAR in March, October and December. The same decline was also observed in Winter season. Lower PAR in this region may reduce light-limited photosynthesis, especially during the winter monsoon (Nov-Feb), when the EAS has a convective-mixing bloom and mixed layers deepen. Phytoplankton in deep mixed layers are already near the light-limitation threshold, so a small drop in PAR may have huge impact on primary productivity in the study region. An observation of PAR anomalies and the climate mode indices revealed that the strongest alignment occurs during the 2019–20 transition from a positive IOD to La Niña, as well as in years with well-documented, El Niño-driven monsoon deficits like 2015 and 2023. These results have several implications as PAR is the energy source for photosynthesis hence, its inter-annual modulation by ENSO and the IOD is likely to affect primary productivity in the eastern AS. Seasonal PAR climatology and ENSO/IOD-related anomalies may also serve as a baseline for productivity monitoring and for early assessment of climate-driven stress. Overall, the study depicts PAR over the eastern Arabian Sea is dominated by a strong seasonal cycle, modulated on inter-annual scales by ENSO and the IOD, and understanding these links is essential for anticipating variations in light availability and ecosystem productivity under the changing climate conditions.

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