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Observed anomalous chlorophyll-*a* bloom in the northern Arabian Sea during winter 2008

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Abstract

The observed interannual variability of winter chlorophyll-*a* (chl-*a*) bloom in the northern Arabian Sea (AS) using the remote sensing data of Sea-viewing Wide Field-of-View Sensor (SeaWiFS) and Aqua Moderate Resolution Imaging Spectro radiometer (MODIS) was analyzed for the period 1997–2010. We show that the strongest winter bloom in the 13-year record occurred in February 2008, with regional mean chl-*a* concentration in the north-central AS (14°N–20°N and 60°E–68°E) being 35% higher than any other winter peak, and open-ocean values exceeding 2 mg m^{-3}. The bloom was initiated during an episode of intense winter monsoon forcing, characterized by surface cooling exceeding 1 °C and deepening of the upper-ocean mixed layer and thermocline depth (D23). Analysis of aerosol optical depth (AOD), sea surface temperature, winds, and subsurface thermal structure indicates that the chl-*a* increase clearly preceded major dust events. This shows that dust deposition did not trigger the February 2008 bloom. Instead, convective mixing associated with anomalous winter cooling was the primary driver of bloom initiation, while atmospheric input, if any, was limited to a possible secondary role in sustaining and enhancing *bloom event* later in the month. The February 2008 event highlights the sensitivity of Arabian Sea winter productivity to episodic intensification of winter monsoon winds and associated convective mixing, with implications for future ecosystem responses under increasing climate variability.

1. Introduction

The Arabian Sea (AS), a semi-enclosed basin bounded to the north, is one of the most biologically productive regions of the world's oceans. The biogeochemistry of the AS is mainly driven by semiannual wind reversals associated with the monsoon cycle that result in two periods of elevated biological productivity: southwest (summer) and northeast (winter) monsoons (Prasanna Kumar *et al* 2001, Wiggert *et al* 2002). The growth of phytoplankton, a primary food source for most fauna in the marine ecosystems, depends on the availability of sunlight and nutrients such as nitrogen, phosphorus, iron, etc. Sunlight is not a limiting factor in the tropical Indian Ocean; instead, the phytoplankton production is limited by the availability of nutrients (Prasanna Kumar *et al* 2002). The different mechanisms responsible for nutrient injection into the near-surface mixed layer include: coastal upwelling, Ekman pumping which elevates the nutricline into the euphotic zone, wind stirring and convective overturning (Madhupratap *et al* 1996) that deepen the mixed layer and entrain subsurface nutrients, advection of nutrient-rich waters, river discharge and atmospheric deposition of mineral aerosols (Kuttippurath *et al* 2023). The summer chlorophyll-*a* (chl-*a*) bloom in the AS results from a combination of processes such as upwelling along the coasts of Somalia and Arabia and southwest India, advection from the upwelling region into the central AS, Ekman pumping associated with the cyclonic wind stress curl northwest of the Findlater Jet and wind-driven mixing. Together, these processes supply subsurface nutrients to the euphotic zone (Madhupratap *et al* 1996, Prasanna Kumar *et al* 2001).

In contrast, during winter, enhanced sea-surface cooling associated with dry continental northeasterly winds drives convective overturning, deepening the mixed layer and increasing the vertical supply of nutrients into the near-surface ocean. This convection-driven nutrient entrainment has been identified as the dominant control on winter phytoplankton productivity in the Arabian Sea (Madhupratap *et al* 1996).

The atmospheric deposition of mineral dust into the ocean represents an additional source of nutrients, including phosphate, silicate and iron, and has been shown to enhance chl-*a* concentrations in the northern AS (Patra *et al* 2007, Singh *et al* 2008). Deserts of southwest Asia produce large quantities of mineral dust particles, which enter the atmosphere and are transported over long distances to the AS by prevailing winds (Kuttippurath *et al* 2023). Measures and Vink (1999) showed that aeolian iron supply can stimulate biological production in nutrient-rich upwelled waters off the western AS coast, particularly in offshore-advected waters. However, the relative importance of atmospheric deposition versus physical mixing varies strongly in space and time and depends on the sequencing of atmospheric and oceanic processes.

Recent studies have documented substantial spatial heterogeneity and interannual variability in winter phytoplankton blooms across the AS on basin-wide, multi-decadal scales (Anjaneyan *et al* 2023, Yang *et al* 2024). These trend-focused analyses show long-term changes in bloom magnitude and phenology but do not resolve the short-term physical sequencing and causality during individual extreme events. In contrast, event-scale analyses provide critical insight into the dominant processes working during anomalous years.

The present study aims to determine the dominant physical drivers responsible for the event- specific anomalously high chl-*a* observed during February 2008 in the northern and north-central AS, using a multi-sensor dataset including SeaWiFS and MODIS ocean-color, sea surface temperature (SST), surface winds, aerosol optical depth (AOD) and Argo-derived thermocline depth. By explicitly resolving the timing of chl-*a*, SST, wind, and dust variability, this study evaluates whether atmospheric deposition acted as a trigger or whether physical mixing dominated bloom initiation.

We focus on the period 1997–2010 because it represents the longest continuous record of SeaWiFS observations with overlapping MODIS coverage, avoiding inter-sensor discontinuities following the termination of SeaWiFS after 2010 (Djavidnia *et al* 2010). Within this record, February 2008 exhibits the strongest winter bloom, making it an ideal case for process-level investigation. February 2008 was also the coldest winter month in the record, with an SST anomaly of −0.85 °C, indicating unusually strong convective cooling (Parekh, 2010). This combination of exceptional biological and physical anomalies provides a natural experiment to isolate the mechanisms driving extreme winter blooms in the Arabian Sea.

The datasets and methodology are discussed in section 2. The results and discussion are presented in section 3, followed by the conclusions in section 4.

2. Data and methodology

Throughout this analysis, we focus on variability of bio-physical properties over a region in the central AS bounded by 14 °N-20 °N and 60 °E-68 °E (box shown in figure 1(b)). Retaining this region as the focal point allows examination of observed changes in bio-physical parameters (chl-*a* and SST) associated with the anomalously high chl-*a* bloom during February 2008. This study used SeaWiFS (September 1997–December 2010) and MODIS-Aqua (January 2003–December 2010) 8-day composite and monthly Level-3 chl-*a* data at 9-km spatial resolution (https://oceancolor.gsfc.nasa.gov).

Because the two sensors overlap only during 2003–2010, no direct merging was performed. Each dataset was analysed independently, and consistency across the overlap period was verified using the documented global RMS difference (0.137) and bias (0.074, SeaWiFS higher) reported by Djavidnia *et al* 2010. To avoid inter-sensor discontinuities associated with the termination of SeaWiFS, the analysis is restricted to 1997–2010.

The SST used in this study was obtained from the daily and monthly Tropical Rainfall Measurement Mission (TRMM) Microwave Imager (TMI) observation for January 1998–December 2010.

The Level 3 daily gridded (0.25° × 0.25°) wind vector data from the QuikSCAT scatterometer were used for the selected period. Vertical temperature profiles were obtained from Argo profiling floats within the study region. The Argo floats are equipped with a CTD sensor for measuring temperature and salinity. These floats were parked at a depth of 1000 m, and profiles were conducted at a water depth of 2000 m every 10 days. Data transmission occurred when the floats reached the surface. To ensure data quality, temperature, and salinity measurements were subjected to quality control procedures.

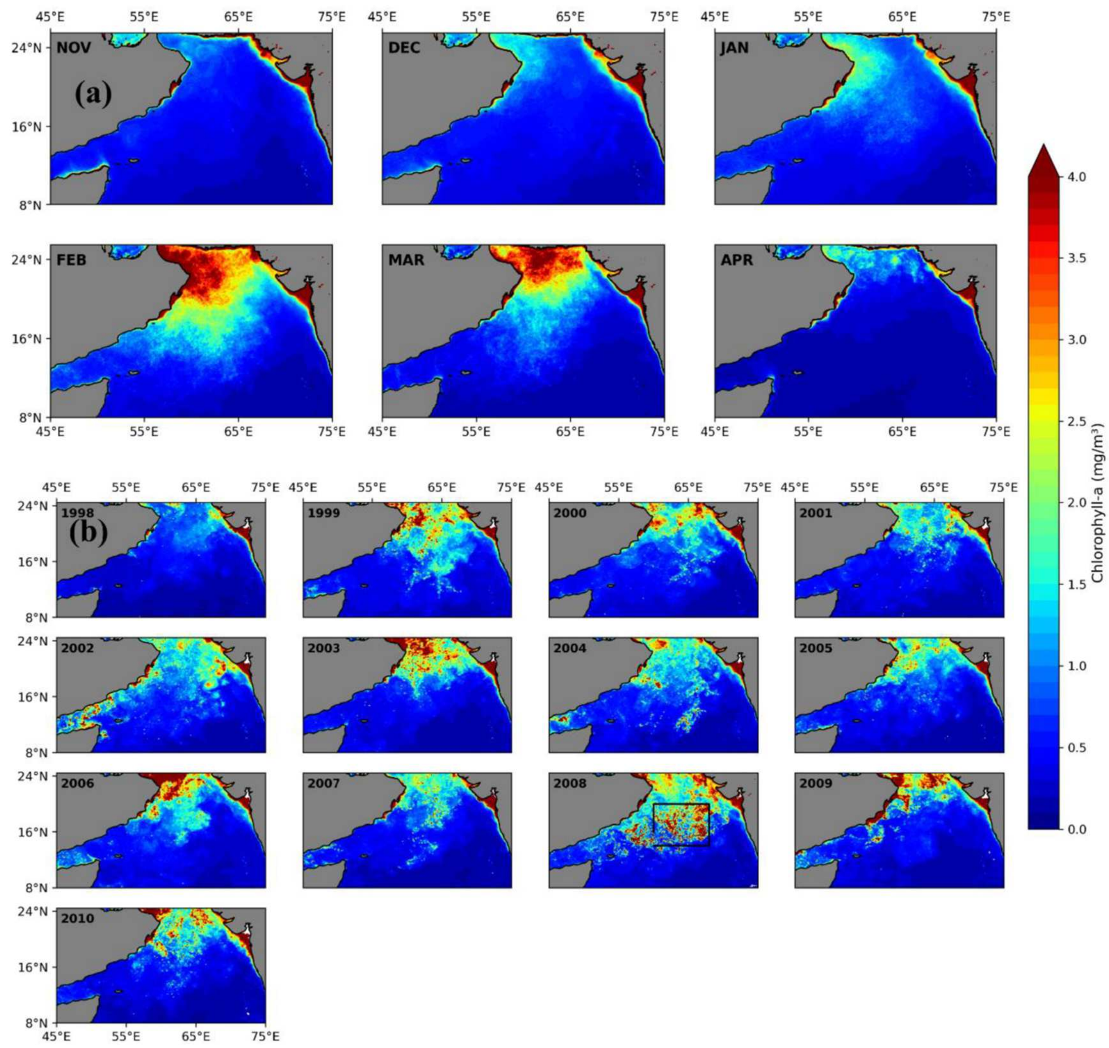

Figure 1. (a) Spatial distribution of monthly climatology of chl-*a* during November to April in the AS. The color bar shows the value of chl-*a* in mg m^{-3}. (b) Interannual variability of spatial distribution of chl-*a* during the month of February for the years 1998–2010. The box highlights the study region (14–20°N and 60–68°E).

We used the TropFlux daily net air-sea heat flux product for the year 1989–2010 on a 1° regular grid (Praveen Kumar *et al* 2012). Argo profiles were subjected to standard delayed-mode quality control, excluding profiles with QC flags 3, 4, or 9. Thermocline depth was estimated as the depth of the 23°C isotherm (D23), a widely used proxy in the AS for mixed-layer entrainment depth. Depth interpolation used a 1-m vertical grid [obtained through the Giovanni System (https://giovanni.gsfc.nasa.gov/)].

The MODIS Aqua AOD at 550 nm was used as an indicator of atmospheric dust loading, obtained through NASA Giovanni. AOD is treated here as a qualitative proxy for dust presence, not a quantitative iron-flux estimate, consistent with earlier AS dust studies (Patra *et al* 2007, Singh *et al* 2008). We added this clarification because direct dust-to-iron flux conversion requires chemistry-aerosol modelling, which is beyond the scope of this study.

Percent change between months was computed as:

$$\Delta\% = \frac{\text{Month}_2 - \text{Month}_1}{\text{Month}_1} \times 100$$

Using spatially averaged monthly chl-*a* within 14–20°N and 60–68°E.

All anomalies (SST, chl-*a*, AOD, wind speed) were computed relative to the 1998–2010 monthly climatology for each variable. Relationships between chl-*a* and environmental variables (SST, D23, AOD, wind speed) are described in terms of qualitative co-variability and temporal sequencing. No formal statistical correlation tests were applied, as the analysis focuses on diagnosing physical consistency during an extreme event rather than establishing basin-scale statistical relationships.

3. Results and discussion

3.1. Inter-annual variability of chl-*a* bloom during winter

The evolution of the monthly climatology of chl-*a* concentration in the AS for the November–April period is shown in figure 1(a). The chl-*a* concentrations show an increase from December over the northern AS with the onset of winter, with values of more than 3 mg m^{-3} during February–March. Afterwards, the chl-*a* concentrations decrease to less than 1 mg m^{-3} during April. Winter peak intensities are observed in the northern AS during February, in agreement with earlier studies (Lévy *et al* 2007). This seasonal evolution reflects the dominant role of wintertime convective mixing in regulating nutrient availability in the northern AS.

This broader pattern is consistent with the findings of Anjaneyan *et al* (2023), who reported pronounced spatial and interannual variability in winter–spring chl-*a* across the Arabian Sea, with different sub-regions responding to distinct physical drivers. Our analysis focuses on one such dynamically sensitive region in the north-central AS, allowing process-level interpretation of an extreme winter bloom within this heterogeneous basin-scale context.

The observed interannual variability of chl-*a* from November to March for the years 1998–2010 in the northern AS is shown in table 1. From November to December, absolute chl-*a* increases from ~0.30–0.44 mg m^{-3} to ~0.34–0.69 mg m^{-3} across different years, corresponding to percentage changes of 10%–60% (and 116% in 1998–99 due to a very low November baseline). From December to January, chl-*a* varies from ~0.34–0.69 mg m^{-3} to ~0.40–1.18 mg m^{-3}, giving changes between −20% and 90%. During the height of winter bloom in February, the monthly mean chl-*a* increases sharply from January to February by 30%–100% in most years, except 2004 and 2009, when changes were weak or negative. In most years, chl-*a* decreases from February to March (−56% to 0%), followed by a continued decline until the onset of the summer monsoon.

Since the chl-*a* reaches its annual winter maximum during February, we examined the interannual variability of the spatial distribution of surface chl-*a* in the northern AS during February for 13 years (1998-2010; figure 1(b)). Marked year-to-year variability is evident, with February 2008 exhibiting the highest spatially averaged chl-*a* concentration in the entire record. The SST anomaly during February 2008 also shows the strongest cooling (−0.85 °C). Previous studies have reported an inverse co-variability between SST and chl-*a* in the AS (Prakash *et al* 2012). This region of anomalously high chl-*a* during February 2008 is examined in greater detail below to identify the dominant physical drivers of bloom initiation and evolution.

The monthly time series of surface chl-*a* (SeaWiFS: 1998–2010; MODIS: 2002–2010) and SST from TRMM-TMI are shown in figure 2(a). The primary chl-*a* peak occurs during August–September (summer monsoon), while a secondary peak occur during February (winter). During January 2008, chl-*a* exceeded 1 mg m^{-3} in the northern AS, and by February it expanded across 60°E–68°E, with an intensity exceeding that of the 1999 winter bloom (figure 1(b)). The February 2008 bloom was stronger than all other winter blooms and comparable to, or exceeding, several summer peaks in the 13-year record.

The mean chl-*a* concentration during February 2008 was 35% higher than the maximum winter value observed in any other year (table 1). During this period, peak chl-*a* concentrations exceeded 2 mg m^{-3} in open ocean waters. The higher value of chl-*a* concentration in central AS (60 °E—68 °E and 14 °N—20 °N) is observed during the third week of January, 2008, and reached its peak during the third week of February. Chl-*a* remained elevated until early March before returning to climatological levels (0.1–0.5 mg m^{-3}).

The monthly variation of SST over the AS shows a semi-annual cycle, with primary maxima (minima) during April–May (July–August) and secondary maxima (minima) around October–November (January–February) (figure 2(a)). Periods of lower SST coincide with enhanced chl-*a*, indicating strong inverse co-variability rather than a statistical correlation. These SST extrema play a critical role in air–sea interaction and biological productivity in the basin (Graham and Barnett, 1987, Madhupratap *et al* 1996). The pronounced cooling during February 2008 (−0.85 °C) indicates unusually strong convective mixing, consistent with enhanced nutrient entrainment into the surface layer (Parekh 2010). The interannual time series of chl-a variation demonstrates a clear inverse co-variability between chl-*a* and SST anomalies during winter, consistent with the physical control of convective mixing on winter bloom intensity in the AS(figure 2(a)) .

3.2. Physical mechanisms of observed anomalous higher chl-*a*

We examined the co-variability of physical drivers (SST, surface wind speed anomaly, net air–sea heat flux, and D23 thermocline depth) to identify the dominant mechanism responsible for the February 2008 chl-*a* bloom. Prasanna Kumar *et al* (2001) observed that a decrease of 1°C in SST during winter can substantially enhance primary productivity in northern AS through convective mixing. Parekh (2010) showed that such extreme winter cooling events occurred only twice in the last three decades (1984 and February 2008) and linked them to

Table 1. (a) The chl-a concentrations (mg m-3) listed here are the spatial mean within 14°-20 °N,60°-68 °E. The mean concentration for each month during the November-March period has been calculated. (b) Mean TMI SSTA (°C) for February computed for the same region of table 1(b).

Chlorophyll-*a* concentration (mg m^{-3})												
Month	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09
(a)												
November	0.3	0.32	0.41	0.37	0.37	0.34	0.34	0.42	0.44	0.31	0.39	0.37
December	0.41	0.69	0.5	0.5	0.46	0.43	0.43	0.47	0.54	0.34	0.63	0.4
January	0.42	0.55	0.54	0.45	0.55	0.53	0.79	0.54	0.58	0.6	1.18	0.68
February	0.57	1.1	0.82	0.75	0.9	0.74	0.8	0.7	0.72	0.81	2.1	0.54
March	0.36	0.54	0.73	0.74	0.48	0.65	0.54	0.49	0.55	0.36	1.7	0.42
Winter Mean (Nov-Mar)	0.41	0.64	0.6	0.56	0.55	0.54	0.58	0.52	0.57	0.48	1.2	0.48
(b)												
Monthly mean TMI SSTA (°C)												
Month	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
February	−0.05	−0.02	−0.06	−0.26	−0.16	0.29	−0.04	−0.04	0.28	0.58	-0.85	0.34

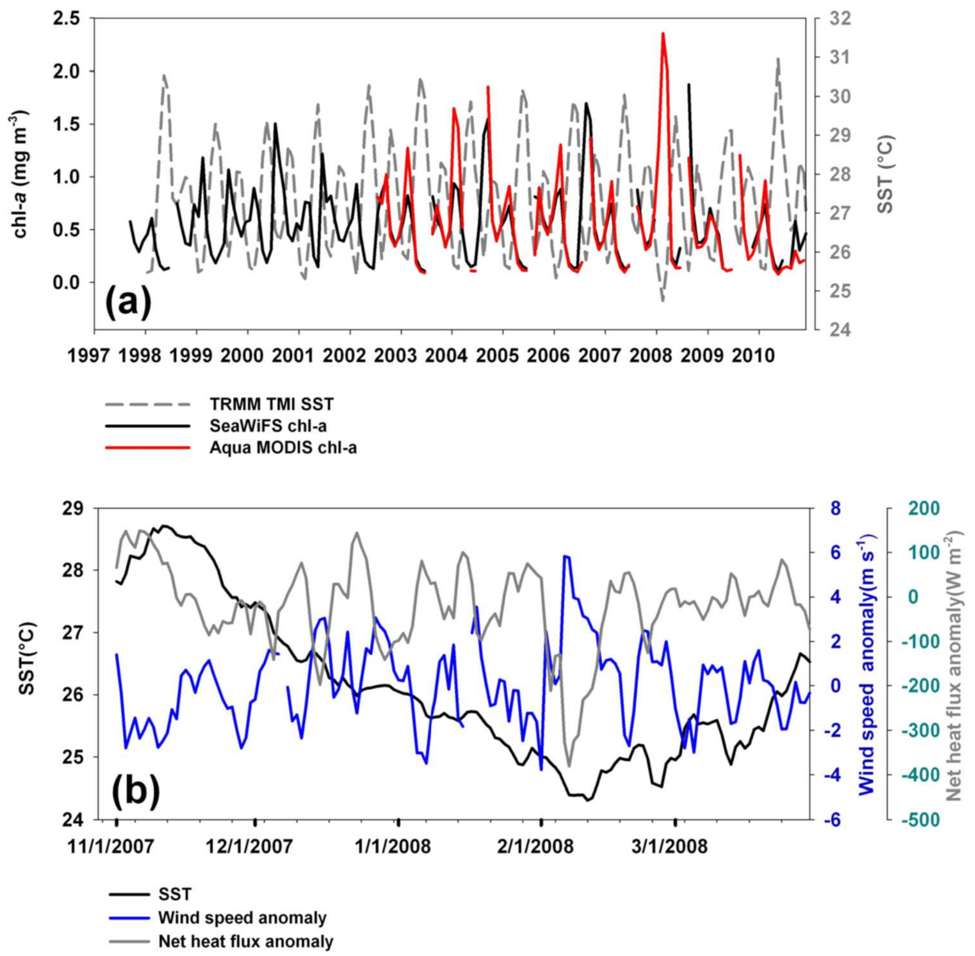

Figure 2. (a) Time series of monthly chl-*a* concentration obtained from SeaWiFs (1998- 2010, Black) and Aqua MODIS (2002–2010, Red) and SST (Grey) obtained from TRMM-TMI in the study region shown in figure 1(b). (b) Time series of daily SST (Black), Net heat flux anomaly(Grey) and wind speed anomaly(Blue) during November 2007 to March 2008, averaged over the study region.

anomalously strong northwesterly winds. The February 2008 bloom coincided with one of these rare cooling events and therefore provides a clear opportunity to isolate the physical drivers of an extreme winter bloom.

Anjaneyan *et al* (2023) also highlighted substantial interannual variability in winter–spring chl-*a* anomalies across the AS, with convective cooling and mixed-layer deepening identified as dominant controls in open-ocean regions. The pronounced cooling (−0.8 °C) and mixed-layer deepening observed in February 2008 within our study region are fully consistent with this basin-scale framework, while allowing process-level interpretation at the event scale. During winter in the AS, nutrient supply to the euphotic zone is primarily governed by convective entrainment associated with surface cooling and wind-driven mixing (Madhupratap *et al* 1996). While atmospheric dust deposition can supply additional nutrients to the surface ocean (Duce and Tindale 1991, Singh *et al* 2008), its potential influence depends critically on its timing relative to bloom initiation.

The key question, therefore, is whether the anomalous February 2008 bloom was initiated by physical mixing processes or by atmospheric dust deposition. To address this, the observed co-variability of the SST, surface winds, thermocline depth (D23), net heat flux anomaly, and chl-*a* is shown in figures 2(b), 3 and 4. Figure 2(b) shows the daily SST, wind speed anomaly, and net heat flux anomaly from November 2007 to March 2008. Surface wind speed anomalies exceeded 4 m s^{-1} during the third week of January and strengthened again during early February, reaching values greater than 6 m s^{-1}. These strong winds produced pronounced negative net heat-flux anomalies (up to −400 W m^{-2}), indicating intense oceanic heat loss relative to climatology.

Correspondingly, daily TMI SST cooled from 28.5 °C in mid-November 2007 to a minimum of ~24.2 °C during early February 2008. This sustained cooling preceded the peak chl-*a* enhancement and is consistent with deep convective mixing and nutrient entrainment from below the mixed layer.

Figure 3 shows MODIS derived AOD at 550 nm, chl-*a* and Argo-derived thermocline depth (D23) during the winter of 2006–2007 and 2007–2008. The depth of the 23 °C isotherm during February 2008 was substantially deeper than in January 2007, indicating stronger and more persistent mixed-layer deepening. In

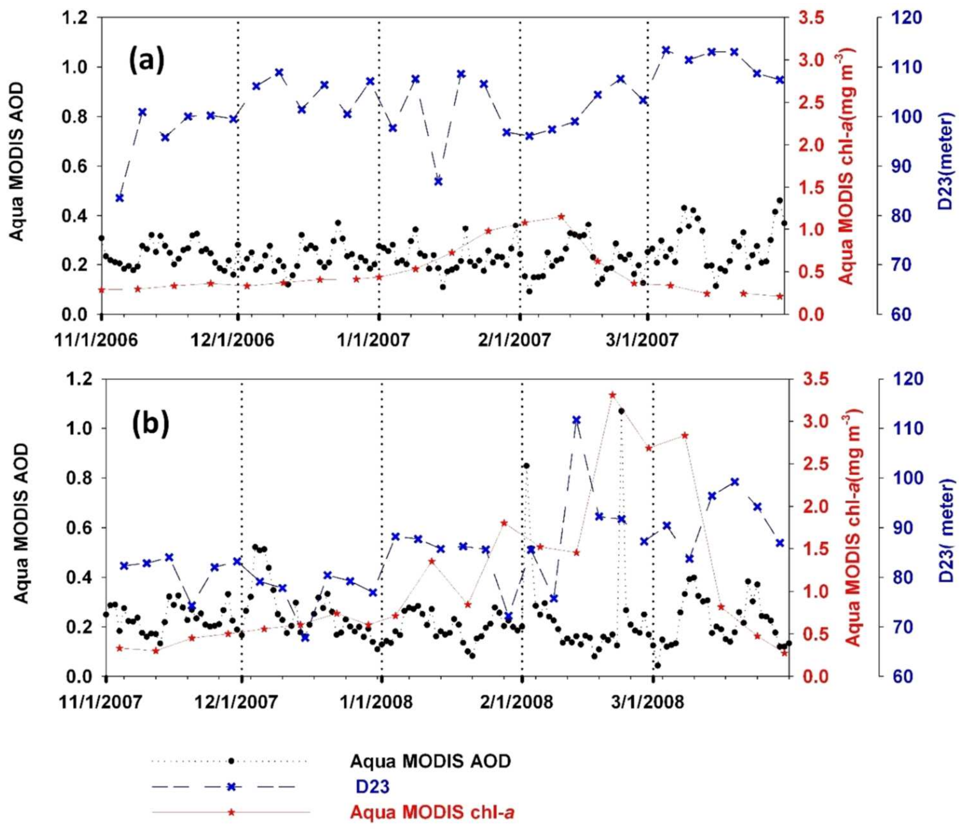

Figure 3. (a) Daily Aqua MODIS AOD at 550 nm (Black), weekly chl-a concentration (Red) obtained from Aqua MODIS and depths of 23°C(D23, proxy for thermocline depth) isotherm(Grey) derived from Argo float every 5 days averaged over the study region during November 2006 to March 2007. (b) Daily Aqua MODIS AOD at 550 nm (Black), weekly chl-a concentration (Red) obtained from Aqua MODIS and depths of 23°C(D23, proxy for thermocline depth) isotherm(Grey) derived from Argo float every 5 days averaged over the study region during November 2007 to March 2008.

January 2007, weaker cooling and less sustained heat loss resulted in only modest chl-*a* enhancement, reinforcing the dominant role of persistent convective forcing in 2008.

The wind speed anomaly shows positive values in the northeastern, northern, and central AS during the first week of February 2008. This led to densification due to enhanced evaporation associated with enhanced net heat loss in the study region. The consequent sinking and convection deepened the mixed layer and transported nutrients upwards into the euphotic zone. Figures 2(b) and 4 show that increased wind speed coincides with surface cooling and mixed-layer deepening, indicating a physical coupling between atmospheric forcing and chl-*a* enhancement rather than a causal inference based on correlation. Although atmospheric dust deposition can supply additional nutrients to the surface layer, the temporal evolution shown in figure 3(b) shows that the initial increase in chl-*a* clearly preceded the major AOD peaks in early and late February. This temporal mismatch indicates that dust deposition did not trigger the February 2008 bloom. Instead, convective cooling and associated mixed-layer deepening driven by anomalously strong winter winds were the dominant mechanisms initiating the bloom, while dust input, if any, may have played a secondary role in sustaining elevated chl-*a* levels later in the month.

The anomalous winds during this period are associated with winter Shamal events, which are linked to mid-latitude disturbances propagating from west to east and typically follow the passage of cold fronts (Hubert *et al* 1983). These winds can reach speeds of 10–20 m s^{-1} and extend across the western Arabian Sea (Aboobacker *et al* 2011), enhancing surface cooling and enabling long-range aerosol transport (Rengarajan and Sarin 2004). During the first week of February, 2008 unlike other years, a strong anomalous northwesterly wind developed over the western and central AS (figure 4(c)). MODIS Aqua imagery confirms the presence of dust plumes transported from arid regions of Iran and Pakistan over the Gulf of Oman and the AS during 22-23 February 2008 (figure 4(a)–(b)), resulting in elevated AOD values (figure 3(b)). These Shamal-related strong northwesterly winds associated with the dust event enhanced latent heat loss from the ocean surface, as reflected in the large negative net heat-flux anomalies, thereby strengthening convective mixing and surface cooling.

Although dust transport accompanied these wind events, the timing of chl-*a* enhancement indicates that bloom initiation occurred prior to peak dust loading. Thus, dust storms are interpreted here as co-occuring

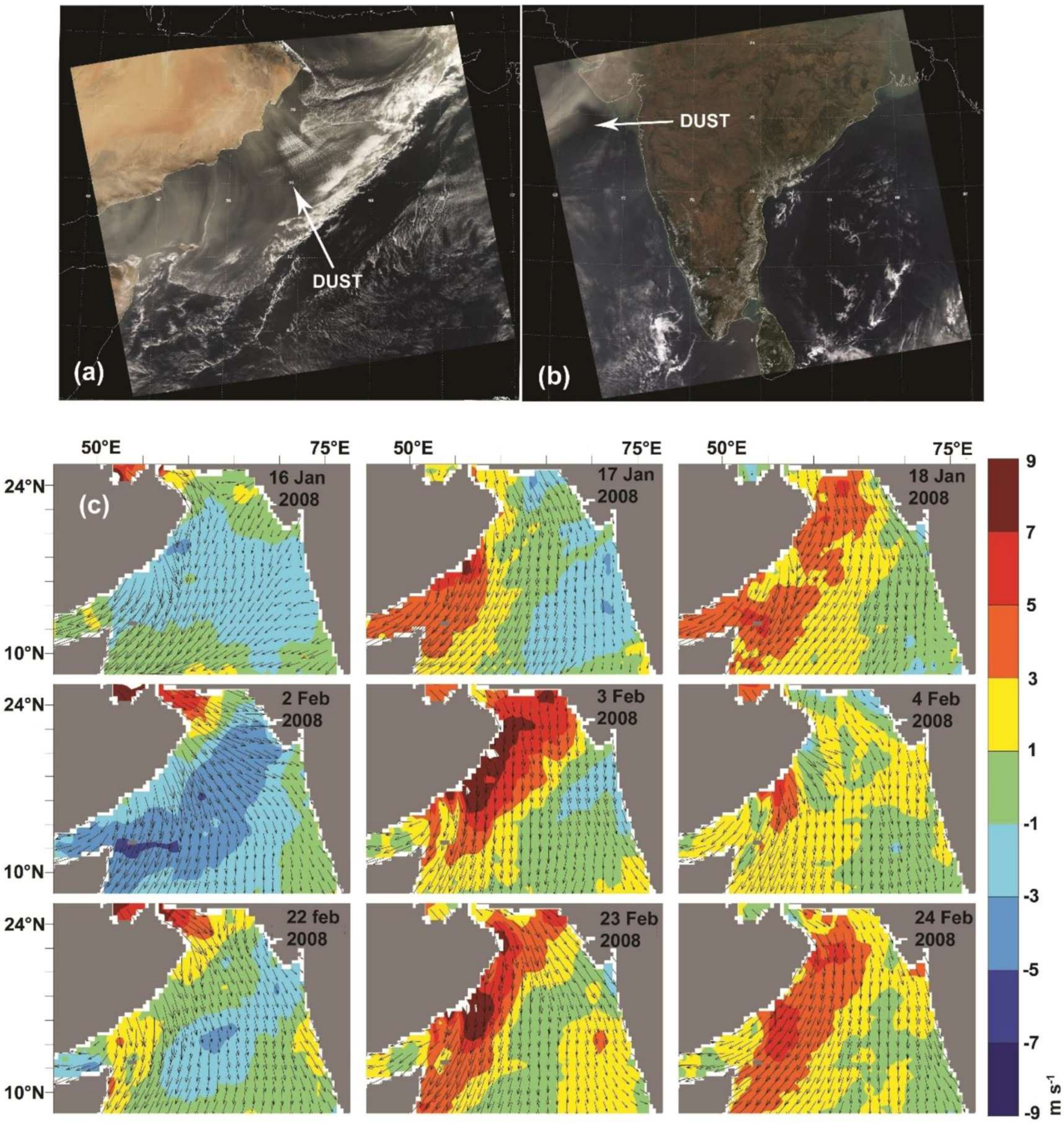

Figure 4. (a) True-visible Aqua MODIS image on 2 February in the AS, (b) True-Visible Aqua MODIS image on 23 February in the A S. The dust plume is highlighted by an arrow in both figures. (c) Daily wind speed anomaly in m s^{-1} and direction during the dust period. Arrows indicate the wind direction.

atmospheric features of the Shamal wind event. The effect of dust storms are clearly reflected in AOD, with values reaching 0.8 on 2 February compared to a monthly mean of 0.3 (figure 3(b)). A dust storm of similar magnitude also affected the region during the third week of February 2008, with AOD peaking at 1.1 on 23 February.

Winter dust storms are relatively rare compared to summer in this region; however, during 2008 multiple events occurred under exceptionally dry winter conditions with reduced soil moisture across South Asia (Badarinath *et al* 2010). The predominant winter winds over the AS are typically northeasterly, but episodic strengthening of northwesterly winds during January–February is observed. Wind vectors and daily wind speed anomalies before and after the dust events of 17 January, 2 February, and 23 February 2008 (figure 4(c)) clearly show strong northwesterly winds over the Arabian Peninsula and northwestern AS, consistent with Shamal circulation.

Winter dust storms occurrence are relatively rare compared to summer in this region; however, during 2008 multiple dust events occurred under extremely dry winter conditions with reduced soil moisture across South Asia (Badarinath *et al* 2010). The predominant winter winds over the AS are north-easterly, but episodic strengthening of northwesterly winds during January–February is observed. .Wind vectors and daily wind speed anomalies before and after dust storm events of 17 January, 2 February, and 23 February 2008 (figure 4(c)) clearly show the presence of strong north-westerly winds over the Arabian Peninsula and north-western AS, which are associated with winter Shamal event.

Previous studies (Patra et al 2007, Singh et al 2008) reported that chl-*a* enhancement followed dust deposition by several days, indicating a causal dust-fertilisation mechanism. This study also corroborates the previous findings. The February 2008 event shows the, enhancement of chl-*a* after the dust peaks (figure 3(b)). It can be seen that D23 was deeper prior to the bloom event. This suggests that the triggering of the 2008 bloom was not due to dust , but rather a convection-driven event, with dust deposition potentially reinforcing chlorophyll-a levels during and after the bloom initiation.

Hence, the February 2008 bloom represents an extreme, physically driven winter event initiated by anomalous convective cooling and mixed-layer deepening. This event-scale interpretation complements basin-scale analyses (Anjaneyan et al 2023) by demonstrating how rare atmospheric forcing can generate exceptional biological responses within a spatially heterogeneous AS system.

4. Conclusions

The northern AS remains the most productive region during winter. This study examined the inter-annual variability of satellite-derived chl-*a* over the northern AS during 1997–2010 and identified an anomalously high chl-*a* over the northern AS during February 2008. February 2008 represents an extreme winter event, recording the strongest winter bloom in the entire SeaWiFS–MODIS record, with chl-*a* exceeding 2 mg m^{-3} and regional mean winter chl-*a* nearly 35% higher than any other year in the 13-year record. The observed chl-*a* variability was strongly associated with SST, AOD, air–sea heat flux anomalies, and thermocline depth variability, indicating dominant physical control on bloom initiation. The analysis of these parameters shows that the February 2008 bloom was primarily driven by intense Shamal-related north-westerly winds, strong negative net heat-flux anomalies (up to −400 W m^{-2}), and the resulting cooling and mixed-layer deepening that entrained nutrients into the euphotic zone. The associated convective mixing deepened the mixed layer and enhanced nutrient entrainment, consistent with previous studies on winter productivity in the AS.

Although multiple dust events occurred during January–February 2008 and elevated AOD values were observed, the increase in chl-*a* clearly preceded major AOD peaks. This temporal sequencing shows that dust deposition did not trigger the February 2008 bloom. Dust deposition likely played a secondary role by sustaining elevated chl-*a* levels later in February, rather than initiating the bloom.

Overall, the February 2008 event highlights the dominant role of wind-driven convective cooling and mixed layer deepening in generating extreme winter blooms in the northern AS. This event-scale analysis adds process-level insight to recent decadal studies by demonstrating how short-lived atmospheric anomalies can generate basin-relevant biological extremes. Such events may become increasingly important under future scenarios of enhanced winter monsoon wind variability, and targeted *in situ* nutrient measurements and coupled atmosphere–ocean biogeochemical modelling would help further quantify the relative contributions of physical forcing and atmospheric deposition during extreme bloom years.

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Data availability statement

No new data were created or analysed in this study.

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Data curation (equal), Formal analysis (equal), Methodology (equal), Validation (equal), Visualization (equal), Writing – original draft (equal)

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Supervision (equal), Writing – review & editing (equal)

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