

## Reviewer 2 Comments

### **Overall Evaluation**

*This manuscript investigates chlorophyll-a (Chl-a) responses to marine heatwaves (MHWs) in the South China Sea using satellite observations, reanalysis products, and a Synergistic-Unique-Redundant Decomposition (SURD) framework. The authors identify contrasting summer Chl-a responses in the Pearl River Estuary (PRE) and Vietnam Upwelling Area (VUA), and propose distinct physical mechanisms linking MHWs to these biological responses.*

*Overall, this is a well-organised and generally well-written manuscript. The study addresses an important question, namely whether ecosystem responses to MHWs are driven primarily by temperature anomalies (or heat stress) themselves or by associated physical changes in the marine environment. The application of SURD provides an interesting and novel approach for investigating interacting drivers.*

*I found the results for the VUA relatively convincing, with the proposed mechanism linking weakened upwelling, reduced nutrient supply and negative chlorophyll anomalies appearing physically consistent. However, I have more concerns regarding the interpretation of the PRE results, where the proposed plume-retention mechanism is more speculative and appears less directly supported by the available observations (e.g. nutrients). I also think the manuscript would benefit from a more careful discussion of the limitations of using satellite-derived surface chlorophyll as a proxy for phytoplankton biomass and ecosystem productivity. The manuscript addresses an exciting and important research question that is highly relevant to current oceanographic research, particularly given the increasing occurrence of marine heatwaves and growing interest in their ecosystem impacts. The study fits well within the scope of Ocean Science and presents a novel application of the SURD framework to a challenging physical-biological problem. Subject to the comments below, the manuscript is potentially suitable for publication following revision.*

**Response:** Thank you for the overall assessment and for pointing out the main issues. We have addressed your concerns in detail and revised the corresponding sections of the manuscript accordingly.

### **Major Comment 1:**

One of my major issues with the manuscript is that surface chlorophyll does not necessarily represent biomass changes. Throughout the manuscript, changes in Chl-a are frequently interpreted as changes in phytoplankton biomass or productivity. However, increases in chlorophyll concentration within a layer can arise through several mechanisms such as increased phytoplankton biomass, increased chlorophyll existing cells through physiological light acclimation (Masuda et al, 2021), or through changes in mixed-layer depth and vertical redistribution of existing phytoplankton biomass (e.g. concentrating or diluting existing chlorophyll). For example, shoaling of the mixed layer may increase surface chlorophyll concentrations simply by concentrating existing phytoplankton into a thinner layer, without any increase in biomass or production. Conversely, entrainment of low-chlorophyll water can dilute surface concentrations. The manuscript should discuss these

possibilities more explicitly. In particular, do the authors consider whether the positive PRE anomalies or negative VUA anomalies may partly reflect changes in vertical redistribution rather than changes in biomass? Chlorophyll (from the reanalysis data product) integrated over depth might support the analysis. Additionally, the authors should outline the typical vertical structure of chlorophyll in summer as marine heatwaves have been shown to alter the vertical structure of chlorophyll (Li et al, 2025: Vertical structure of chlorophyll-a during marine heatwaves in the California Current Ecosystem | Communications Earth & Environment). The introduction contains little discussion of the vertical chlorophyll structure of the region.

***Response:***

Thank you for this insightful comment. We agree that satellite-derived surface Chl-a cannot be interpreted directly as changes in phytoplankton biomass or primary productivity. The manuscript has been revised accordingly.

To clarify that surface Chl-a alone cannot represent Chl-a variability throughout the upper water column, we added regional context on the summer vertical Chl-a structure of the South China Sea in the Introduction. The revised text describes the pronounced subsurface chlorophyll maximum in summer and cites previous observations of contrasting surface and subsurface Chl-a responses during MHWs.

Indeed, in our study, vertical redistribution is a key process regulating surface Chl-a anomalies during summer MHWs. To further support this point, we have now examined the vertical Chl-a structure and compared surface anomalies with water-column mean anomalies in the VUA and PRE. Water-column mean Chl-a is substantially less affected by vertical distribution. This comparison therefore helps assess the contribution of vertical redistribution to surface Chl-a anomalies.

The vertically resolved Chl-a data were obtained from the CMEMS Global Ocean Biogeochemistry Hindcast product (GLOBAL\_MULTIYEAR\_BGC\_001\_029). Overall, although the magnitudes of the model-derived and satellite-derived surface anomalies differ, the hindcast reproduces the observed anomaly sign in both regions, with negative surface Chl-a anomalies in the VUA and positive anomalies in the PRE (Figs. S5 and S6). This agreement indicates that the hindcast can, to some extent, be used to assess the contribution of vertical redistribution to the observed surface Chl-a responses.

**I VUA**

In the VUA, analysis of the SURD results indicates that weakened upwelling and enhanced stratification play important roles in causing the negative Chl-a anomaly (Sect. 3.3.1). In the revised manuscript, additional evidence from the vertical Chl-a structure further supports this point. The climatological vertical profile shows a pronounced subsurface Chl-a maximum at approximately 50–70 m (Fig. S5a). Due to the strong climatological summer upwelling (Fig. 6b), upward transport of this high-Chl-a subsurface water contributes to the climatological high-Chl-a conditions in the VUA (Fig. 6e). However, during MHWs, weakened upwelling reduced this upward transport, and the enhanced stratification suppressed the vertical exchange between surface and subsurface waters, thereby contributing to negative surface Chl-a anomalies.

In the VUA, the 0–300 m plotting range encompasses the full model-resolved water column (Fig. S5a). When averaged over the full water column, the water-column anomaly is only  $-0.006 \text{ mg m}^{-3}$ , substantially smaller in magnitude than the model-derived surface anomaly of  $-0.077 \text{ mg m}^{-3}$  (Fig. S5c). The much weaker water-column mean anomaly can partly reflect that vertical redistribution makes an important contribution to the surface Chl-a response in the VUA.

It should be noted that Chl-a anomalies were negative throughout approximately the upper 60 m during MHWs (Fig. S5a, b). Because the climatological Chl-a concentration is higher in the upper 0–60 m than in the deeper water, the negative anomalies throughout the upper 60 m cannot be explained by vertical redistribution alone. This result suggests that other unresolved processes may also contribute to the surface Chl-a response in the VUA. Given that the causality leak in the SURD analysis for the VUA Chl-a anomalies is not zero (Fig. 5b), these unresolved processes quite possibly represent the remaining causality leak.

In summary, vertical redistribution is an important process contributing to the surface Chl-a anomalies in the VUA, but it cannot fully account for the observed change.

## **II PRE**

In the PRE, the main analysis indicates that plume retention and enhanced upper-ocean stratification are important physical processes associated with the positive surface Chl-a anomaly (Sect. 3.3.2). The climatological profile is strongly surface intensified, with Chl-a concentrations generally decreasing from the surface toward deeper water (Fig. S6a). During summer MHWs, widespread mixed-layer shoaling indicates enhanced upper-ocean stratification (Fig. S7). The stronger stratification suppressed vertical exchange between the relatively high-Chl-a upper layer and the lower-Chl-a water below, favouring higher Chl-a concentrations near the surface. Consistent with this process, the satellite observations and the hindcast product both show positive surface Chl-a anomalies in PRE (Fig. S6b). In addition, the positive surface Chl-a anomaly was much larger in magnitude than the water-column mean anomaly, with the latter being close to zero ( $-0.004 \text{ mg m}^{-3}$ ; Fig. S6c). The above analyses support the interpretation that vertical redistribution contributes to the positive surface Chl-a response in the PRE.

Based on these analyses, we revised the manuscript throughout to avoid interpreting surface Chl-a anomalies directly as changes in phytoplankton biomass or primary productivity. The vertical Chl-a and MLD diagnostics are now incorporated into the regional analyses of the VUA and PRE to assess the possible contribution of vertical redistribution to the observed surface Chl-a responses. Sect. 3.5 has also been revised to explicitly discuss the limitations of using surface Chl-a as an indicator of phytoplankton biomass or productivity, including the potential influence of physiological photoacclimation and other unresolved biological and biogeochemical processes. The vertical Chl-a diagnostics are provided in Figs. S5–S6, and the MLD diagnostics are provided in Fig. S7.

### ***Changes in the manuscript:***

**Sect. 1 (Introduction), Lines 38–43:**

“During boreal summer, the SCS commonly exhibits a pronounced subsurface chlorophyll maximum, with substantial spatial variability in its depth and magnitude (Xu et al., 2022). During the record-breaking 2020 SCS MHW, reduced surface Chl-a coincided with increased subsurface Chl-a (Zheng et al., 2024), and Chl-a responses differed among MHWs with different vertical structures (Yuan et al., 2024). MHW-related changes in vertical Chl-a structure have also been reported in other oceanic regions (Li et al., 2025). Surface Chl-a alone may therefore not fully capture the underlying biological response.”

Sect. 3.3.1 (Suppressed upwelling in the VUA), Lines 280–281:

“These negative Chl-a anomalies spatially coincide with the summer climatological high-Chl-a belt (Fig. 6e), suggesting that MHWs may suppress surface Chl-a in this climatologically high-Chl-a region.”

Lines 305–306:

“Together, these processes restrict the upward supply of nutrients to the upper ocean and are consistent with the observed negative surface Chl-a anomalies (He et al., 2023; Ma and Chen, 2025).”

Lines 307–322:

“The vertical Chl-a from the CMEMS BGC Hindcast product (Sect. 2.2) was used to further examine the negative surface Chl-a anomalies in the VUA. Although the magnitude differs from the satellite observations, the BGC hindcast also shows a negative surface Chl-a anomaly in the VUA (Fig. S5), supporting its use for examining the vertical structure of the response. The climatological vertical profile shows a pronounced subsurface Chl-a maximum at approximately 50–70 m (Fig. S5a). Strong climatological summer upwelling (Fig. 6b) transports subsurface high-Chl-a water upward, contributing to the high climatological Chl-a in the VUA (Fig. 6e). During MHWs, weakened upwelling (Fig. 6g) reduced this upward transport, while enhanced stratification (Fig. 7i) suppressed vertical exchange, thereby contributing to the negative surface Chl-a anomalies.

When averaged over the full water column, the water-column anomaly is only  $-0.006 \text{ mg m}^{-3}$ , substantially smaller in magnitude than the model-derived surface anomaly of  $-0.077 \text{ mg m}^{-3}$  (Fig. S5c). The much weaker water-column mean anomaly suggests that vertical redistribution associated with weakened upwelling and enhanced stratification contributed to the surface Chl-a response in the VUA.

Chl-a anomalies were negative throughout approximately the upper 60 m, where climatological Chl-a concentrations are higher than in deeper water (Fig. S5a, b). This broad upper-ocean decrease suggests that vertical redistribution alone may not fully explain the observed response. Other unresolved processes may also contribute to the surface Chl-a response in the VUA. Given that the causality leak in the SURD analysis for the VUA Chl-a anomalies is not zero (Fig. 5b), these unresolved processes may contribute to the remaining causality leak.”

Sect. 3.3.2 (Horizontal plume retention in the PRE), Lines 376–391:

“Where nutrient availability remained sufficient, plume retention together with a warmer and more stratified surface environment could favour the observed positive surface Chl-a anomalies. Such a response would be consistent with the strong dependence of phytoplankton responses to warming on nutrient availability (Marañón et al., 2018) and with evidence that MHWs can promote phytoplankton blooms in nutrient-rich coastal waters (Hayashida et al., 2020). Although the selected physical variables support the plume-retention interpretation, the relatively high causality leak in the PRE suggests that unresolved biogeochemical processes may also contribute to local Chl-a variability.”

“The vertical Chl-a diagnostics are also consistent with this stratification-related interpretation. Both the satellite observations and the BGC hindcast show positive surface Chl-a anomalies in the PRE (Fig. S6b). This agreement

supports the use of the BGC hindcast to further examine the vertical structure of the PRE response. Under climatological conditions, Chl-a is concentrated near the surface (Fig. S6a), while widespread mixed-layer shoaling during summer MHWs indicates enhanced upper-ocean stratification (Fig. S7). The stronger stratification suppresses vertical exchange between the relatively high-Chl-a upper layer and the lower-Chl-a water below, favouring higher Chl-a concentrations near the surface. Within the BGC hindcast, the positive surface Chl-a anomaly is much larger in magnitude than the water-column mean anomaly, which is close to zero ( $-0.004 \text{ mg m}^{-3}$ ; Fig. S6c). This difference supports a contribution from vertical redistribution to the positive surface Chl-a response in the PRE.”

Sect. 3.5 (Causal leakage and uncertainty in SURD-based interpretation), Lines 491–496:

“These methodological checks cannot resolve uncertainties associated with omitted biological processes or with the biological interpretation of surface Chl-a itself. Satellite-derived surface Chl-a is not a direct measure of phytoplankton biomass or primary productivity. Physiological photoacclimation can alter cellular chlorophyll content independently of proportional biomass changes (Masuda et al., 2021). Accordingly, the physical pathways identified here should be interpreted as processes associated with the observed surface Chl-a anomalies, rather than as direct evidence of changes in phytoplankton biomass or productivity.”

Changes in the Supplementary Material:

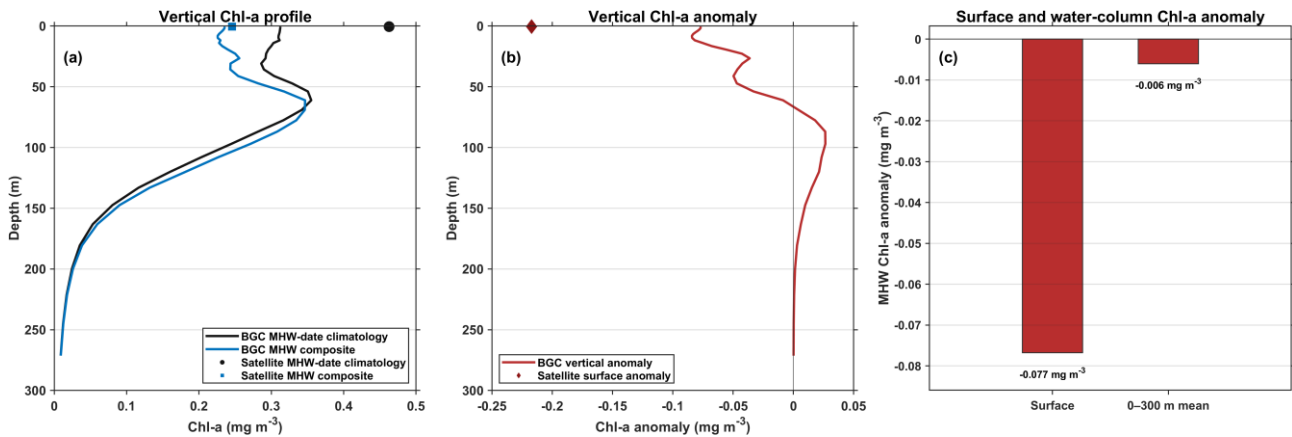


Figure S5. Vertical Chl-a structure in the VUA core response region during summer MHWs. (a) BGC MHW-date climatological profile (black) and MHW composite profile (blue), with satellite surface values shown by the circle and square. (b) BGC vertical Chl-a anomaly, with the satellite surface anomaly shown by the diamond. (c) BGC surface Chl-a anomaly and available water-column mean anomaly.

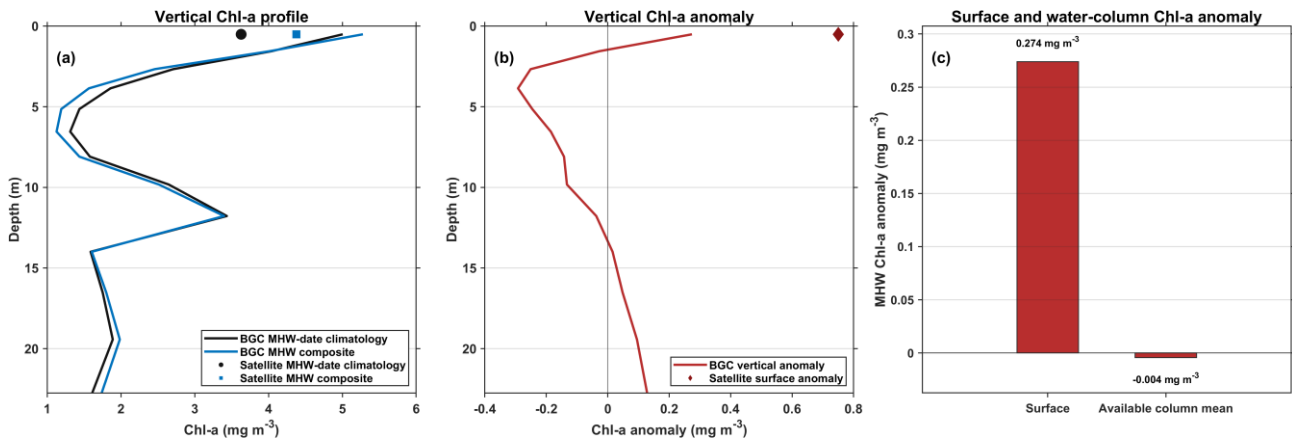


Figure S6. Vertical Chl-a structure in the PRE core response region during summer MHWs. (a) BGC MHW-date climatological profile (black) and MHW composite profile (blue), with satellite surface values shown by the circle and square. (b) BGC vertical Chl-a anomaly, with the satellite surface anomaly shown by the diamond. (c) BGC surface Chl-a anomaly and available water-column mean anomaly.

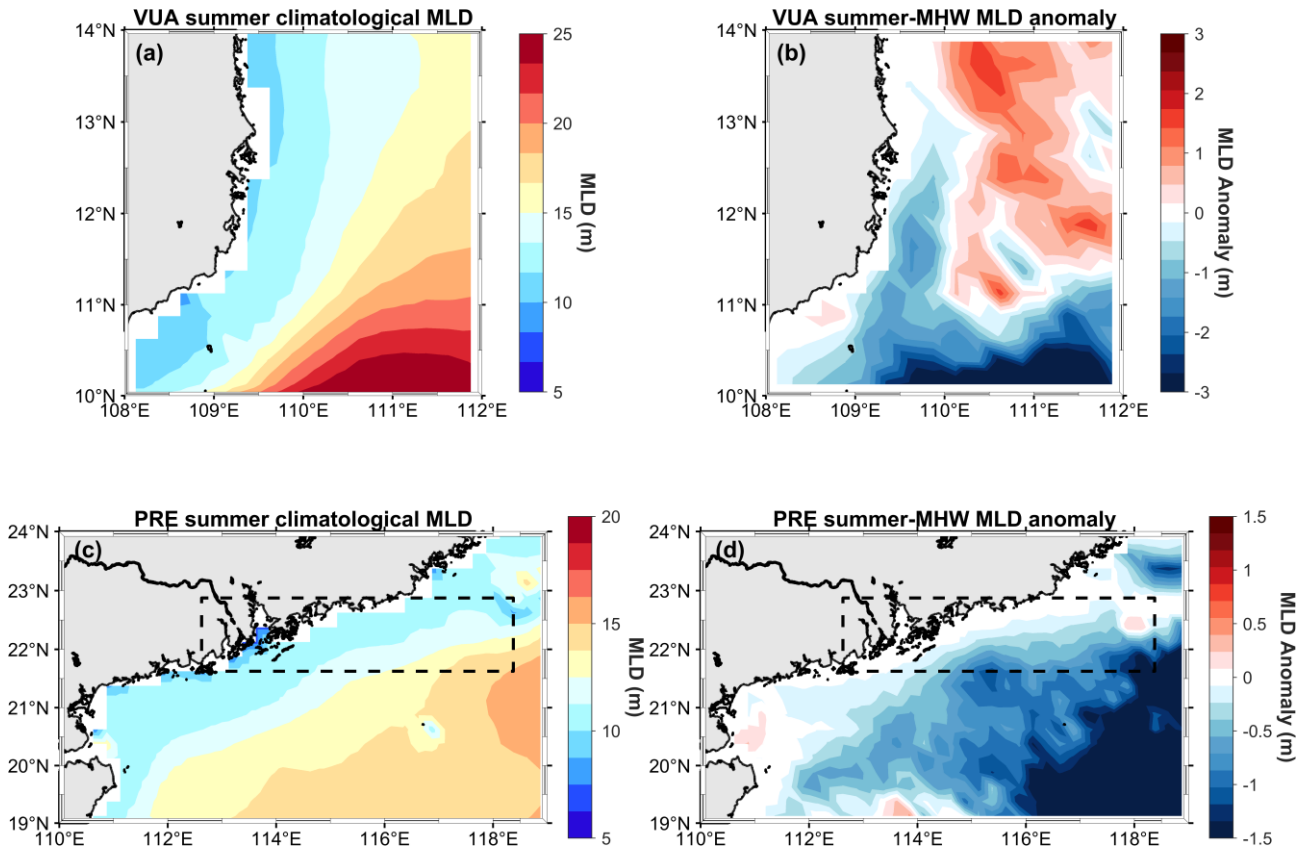


Figure S7. Summer climatological MLD and MHW-related MLD anomalies in the VUA and PRE. Panels show summer climatological MLD in (a) the VUA and (c) the PRE, with the corresponding MHW-related anomalies in (b) and (d), respectively. Negative anomalies indicate mixed-layer shoaling. The dashed box marks the PRE analysis region.

### Major Comment 2:

My other concern is that the interpretation of the PRE mechanism requires strengthening. The VUA interpretation is relatively straightforward, with weakened upwelling providing a plausible link between MHWs and reduced chlorophyll concentrations. I found the PRE mechanism less convincing; the authors argue that weakened winds promote retention of nutrient-rich plume waters, resulting in positive chlorophyll anomalies. While the hydrographic evidence for plume retention is plausible, the nutrient supply pathway remains inferred rather than demonstrated. The conclusions regarding nutrient-enhanced phytoplankton growth in the PRE should therefore be expressed more cautiously. I suggest clearly distinguishing between the evidence supporting plume retention and the more speculative inference that plume retention enhanced nutrient availability and phytoplankton growth.

**Response:**

We agree with the reviewer that the hydrographic evidence for plume influence or retention should be clearly distinguished from the inferred nutrient-support pathway in the PRE. We have therefore revised Sect. 3.3.2 to describe the negative nearshore SSS anomalies as being consistent with enhanced influence or local retention of low-salinity Pearl River plume water, rather than as direct evidence of plume retention. We also clarify that, although nutrient concentrations in the PRE usually covary negatively with salinity, nutrients were not directly observed during the MHW events. The proposed nutrient-support pathway is therefore treated as an inference rather than a directly demonstrated mechanism.

We also added a precipitation diagnostic for the PRE and nearby PRD. Local PRE precipitation did not increase during summer MHWs, and precipitation over the PRD showed no systematic enhancement around regional MHW establishment (Fig. S2), providing little support for enhanced rainfall as the primary explanation for the observed nearshore freshening. Corresponding revisions were made in Sect. 3.4, the Fig. 11 caption, the Abstract, and Sect. 4 (Conclusions), so that the hydrographic observations support a physically consistent plume-retention interpretation, whereas the associated nutrient pathway and its contribution to the positive Chl-a anomalies are described more cautiously.

***Changes in the manuscript:***

Abstract, Lines 17–21:

“In the Pearl River Estuary, enhanced incident shortwave radiation promoted rapid surface warming, while weakened wind-driven export favoured the nearshore retention of low-salinity plume water. The SURD results suggest that retained plume water likely strengthened surface-layer stratification and maintained relatively nutrient-rich surface conditions, potentially allowing plume retention to act synergistically with cumulative heat stress and favouring positive Chl-a anomalies. However, the associated nutrient pathway remains inferred rather than directly demonstrated.”

Sect. 3.3.2 (Horizontal plume retention in the PRE), Lines 356–360:

“Together, these spatial patterns support an enhanced influence or local retention of low-salinity Pearl River plume water near the coast. Precipitation anomalies provide little support for enhanced rainfall as the source of this freshening: local PRE precipitation did not increase during summer MHWs, and nearby PRD land precipitation likewise showed no systematic increase around regional MHW establishment (Fig. S2).”

Sect. 3.3.2, Lines 361–364:

“In the eutrophic PRE, nutrient concentrations often exhibit a negative correlation with salinity (Dai et al., 2008; Niu et al., 2020), so retention of Pearl River plume water could also maintain relatively nutrient-rich surface conditions. Because nutrient concentrations were not directly observed during the MHW events, this nutrient pathway remains inferred rather than directly demonstrated.”

Sect. 3.4 (Contrasting regional responses to the western North Pacific subtropical high), Lines 435–441:

“These conditions favour nearshore retention of low-salinity river plume water, consistent with the negative SSS anomalies in the plume-affected region (Fig. 9f). The absence of enhanced precipitation over the PRE and nearby PRD around these events further argues against anomalous rainfall as the primary cause of the nearshore freshening (Fig. S2). In the eutrophic PRE, retention of plume water could maintain favourable nutrient conditions for positive Chl-a anomalies, although this nutrient pathway was not directly resolved in the present analysis. Together, these processes provide a physically consistent framework for the simultaneous occurrence of elevated temperatures and positive Chl-a

anomalies in the PRE, linking radiative warming with wind-regulated plume retention and a plausible nutrient-mediated response.”

Fig. 11 caption:

“(b) In the PRE, enhanced shortwave radiation promotes surface warming and MHW development, while weakened wind-driven offshore transport favours nearshore retention of low-salinity river plume water, providing conditions associated with a positive Chl-a anomaly.”

Sect. 4 (Conclusions), Lines 511–515:

“Precipitation did not increase during the MHW events, further supporting plume retention rather than anomalous rainfall as a cause of the observed nearshore freshening. Enhanced shortwave radiation favoured rapid surface warming and MHW development in this shallow shelf region, while weakened wind-driven export favoured the nearshore retention of low-salinity plume water. This low-salinity surface layer likely strengthened upper-ocean stratification and hence favoured the positive surface Chl-a anomalies, although the associated nutrient pathway was not directly resolved.”

Fig. S2 in the Supplement:

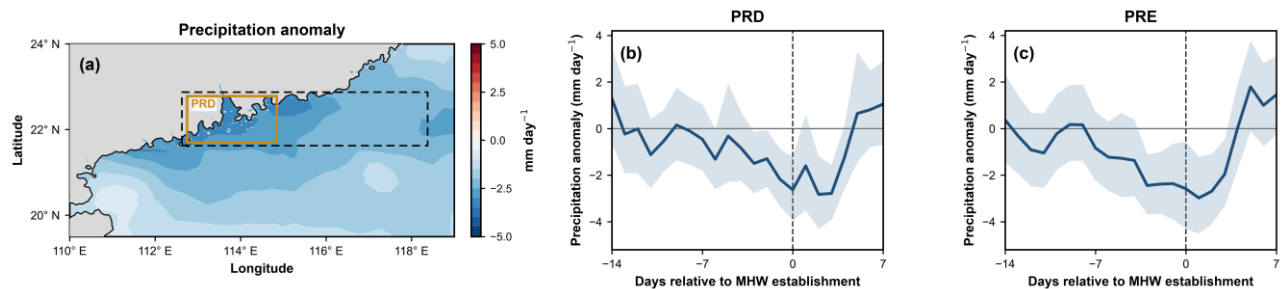


Figure S2. Precipitation anomalies associated with PRE summer MHWs. (a) Spatial composite of precipitation anomalies; the dashed and orange boxes mark the PRE analysis region and the PRD land region, respectively. (b, c) Composite precipitation anomalies over the PRD land region and PRE ocean region, respectively, relative to the regional MHW establishment date (day 0). Shading denotes the 95 % confidence interval.

### Major Comment 3:

Additionally, seasonal climatology is used to define chlorophyll anomalies during MHWs, but it is currently difficult to assess how unusual these anomalies are relative to normal summer variability. The authors should clarify whether the reported anomalies exceed the typical variability observed during the season and whether the high-chlorophyll belt described in the VUA represents episodic bloom activity.

### Response:

Thank you for this comment. Our additional analyses indicate that the summer MHW-related Chl-a responses in both regions are unusual relative to normal summer variability, while the climatological high-Chl-a belt in the VUA is a persistent summer feature rather than being primarily driven by episodic high-Chl-a observations.

First, we compared the observed summer MHW Chl-a composites in the VUA and PRE with duration- and seasonally matched non-MHW summer pseudo-events (Fig. S3). The VUA composite fell below the 5th

percentile of the matched non-MHW distribution, whereas the PRE composite exceeded the 95th percentile. These results place the negative VUA response and the positive PRE response outside the typical range of variability under comparable non-MHW summer conditions.

Second, we examined whether the climatological high-Chl-a belt in the VUA was dominated by episodic high-Chl-a events (Fig. S4). The belt remained evident in the summer median field and after excluding the upper 5 % and 10 % of daily Chl-a observations, although these upper-tail observations enhanced its magnitude. The persistence of the belt across these alternative characterizations indicates that it reflects the summer background state rather than being primarily generated by a small number of episodic high-Chl-a observations.

### ***Changes in the manuscript:***

Sect. 3.2 (Chl-a responses to MHWs), Lines 251–252:

“The summer composite anomalies in both regions also lay outside the variability observed under comparable non-MHW summer conditions (Fig. S3).”

Sect. 3.3.1 (Suppressed upwelling in the VUA), Lines 272–274:

“The high-Chl-a belt remains evident under alternative characterizations of the summer background state, suggesting that it is not primarily driven by a small number of episodic high-Chl-a observations (Fig. S4).”

Fig. S3 and Fig. S4 in the Supplement:

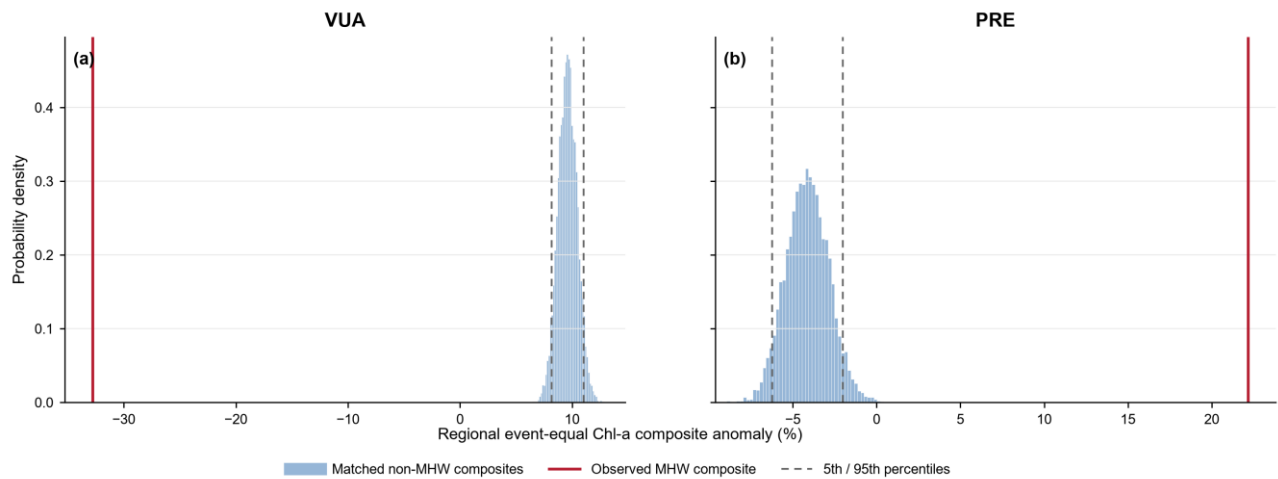


Figure S3. Summer MHW-related Chl-a composite anomalies relative to matched non-MHW summer conditions in the VUA and PRE. Blue histograms show the distributions of matched non-MHW regional composite anomalies in the (a) VUA and (b) PRE. Red vertical lines indicate the observed summer MHW composites, and grey dashed lines denote the 5th and 95th percentiles of the matched distributions.

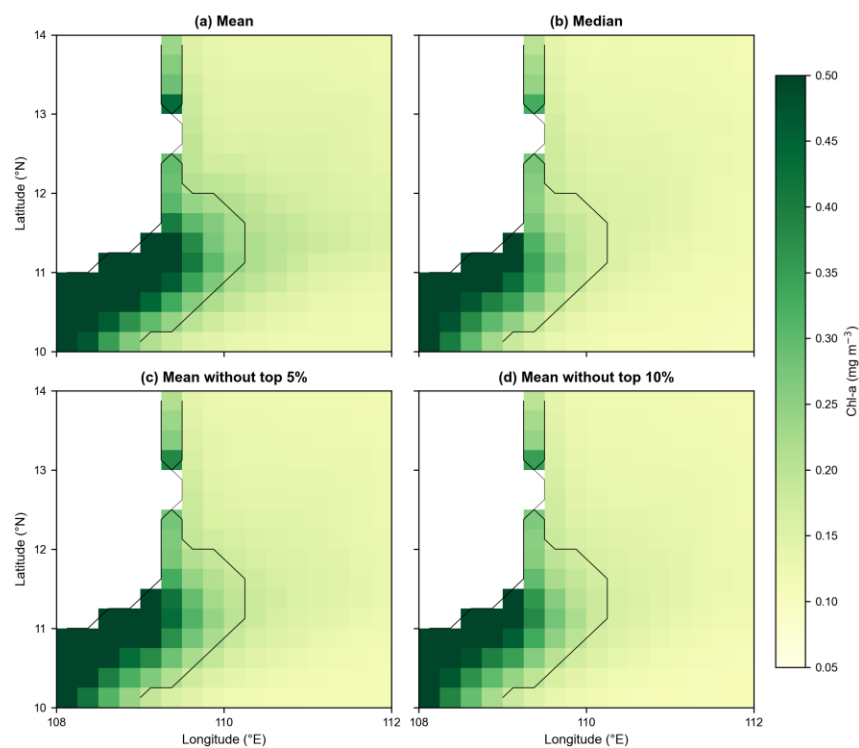


Figure S4. Sensitivity of the VUA summer high-Chl-a belt to alternative representations of the background Chl-a field. Panels show (a) the summer mean Chl-a climatology, (b) the summer median, and the summer mean after excluding the upper (c) 5 % and (d) 10 % of daily Chl-a observations at each grid cell. All panels use the same colour scale to facilitate comparison of the spatial structure and magnitude of the nearshore high-Chl-a belt.

#### ***Major Comment 4:***

The conclusions primarily summarise the results but provide relatively little discussion of their broader implications. What are the implications of reduced chlorophyll within the Vietnam upwelling system? Could these changes influence fisheries productivity? How might this relate to regional carbon cycling and export? Expanding the discussion of wider ecological implications would strengthen the significance of the study.

#### ***Response:***

Thank you for this suggestion. We have expanded the Conclusions to further discuss the broader ecological and biogeochemical implications of reduced Chl-a responses in the VUA. The revised text describes how MHW-induced Chl-a reductions may indicate weakened phytoplankton responses and potentially influence marine food-web support, fisheries productivity, and regional carbon cycling through changes in primary production and biological carbon export. Relevant literature has been added to support these broader implications. The corresponding revisions have been incorporated into Sect. 4 (Conclusions).

#### ***Changes in the manuscript:***

Sect. 4 (Conclusions), Lines 525–532:

“These findings highlight the importance of physical–biological coupling in shaping Chl-a responses to MHWs. Because Chl-a provides an indicator of phytoplankton conditions, and phytoplankton form the energetic foundation of

marine food webs, persistent Chl-a reductions may reduce energy availability for higher trophic levels and affect fisheries productivity in ecosystems (Ware and Thomson, 2005; Chassot et al., 2010). In addition, changes in Chl-a may indicate alterations in marine primary production and biological carbon export, with implications for regional carbon cycling (Richardson, 2019; Siegel et al., 2023). Beyond the SCS, future applications of this SURD-based framework to other marginal seas around China could help assess whether MHW-driven Chl-a responses arise from similar or regionally distinct physical–biological pathways.”

***Minor Comment 1:***

The manuscript would benefit from a brief discussion of chlorophyll as a proxy for phytoplankton biomass, including important limitations.

***Response:***

Thank you for this comment. This issue has been addressed together with Major Comment 1 on the biological interpretation of surface Chl-a. We have expanded Sect. 3.5 to clarify that satellite-derived surface Chl-a is not a direct measure of phytoplankton biomass or primary productivity, and that physiological photoacclimation and vertical redistribution can modify surface Chl-a independently of proportional biomass changes. Statements elsewhere in the manuscript that previously extended beyond this observational constraint have also been revised accordingly.

***Changes in the manuscript:***

Sect. 3.5 (Causal leakage and uncertainty in SURD-based interpretation), Lines 492–496:

“Satellite-derived surface Chl-a is not a direct measure of phytoplankton biomass or primary productivity. Physiological photoacclimation can alter cellular chlorophyll content independently of proportional biomass changes (Masuda et al., 2021). Accordingly, the physical pathways identified here should be interpreted as processes associated with the observed surface Chl-a anomalies, rather than as direct evidence of changes in phytoplankton biomass or productivity.”

***Minor Comment 2 (Sect. 2.3.1):***

Please explain why the 1982–2011 climatological baseline was selected for MHW detection. It would also be useful to note that the fixed baseline approach follows Hobday et al. (2016) and much of the MHW literature, but does not account for long-term warming and shifting temperature baselines.

***Response:***

Thank you for raising this point. We have clarified the rationale for using 1982–2011 as the climatological baseline in Sect. 2.3.1. The 1982–2011 period was adopted as a fixed 30-year reference period because this baseline has been widely used in MHW studies following the framework of Hobday et al. (2016), allowing our MHW definition to remain consistent with the established literature. The Chl-a record from 1998 onward determines the period over which biological responses can be analysed, whereas the SST climatology is used independently to define the seasonally varying threshold for MHW detection. These two periods therefore serve different methodological roles and do not need to coincide. We also now explicitly note that the use of

a fixed climatological baseline does not account for the long-term warming and shifting background temperature state (Chiswell, 2022).

**Changes in the manuscript:**

Methods, Sect. 2.3.1 (MHW identification and metric calculation), Lines 140–144:

“The period 1982 to 2011 was used as a fixed 30-year climatological baseline for calculating daily thresholds, consistent with the fixed-baseline approach widely used in MHW studies (Hobday et al., 2016; Chiswell, 2022). MHW detection was then applied to SST time series from 1998 to 2024. One limitation of this approach is that the climatological threshold remains fixed and therefore does not adjust to the long-term warming of the background climate (Chiswell, 2022).”

**Minor Comment 3 (Line 188):**

Consider changing to "both the PRE and VUA exhibit significantly higher median annual total MHW days and cumulative intensity..."

**Response:**

Thank you for this suggestion. We have revised the sentence accordingly in Sect. 3.1 (Lines 236–237).

**Minor Comment 4 (Line 200):**

Consider specifying "increases exceeding 40% relative to the climatological summer chlorophyll concentration."

**Response:**

Thank you for this suggestion. We have revised the sentence accordingly to clarify that the reported increase is relative to the climatological summer chlorophyll concentration (Sect. 3.2, Lines 248–249).

**Minor Comment 5 (Line 212):**

Why was cumulative SST intensity selected as the sole thermal-stress metric? The introduction contains little discussion of thermal stress mechanisms affecting phytoplankton physiology, despite this variable playing a central role in the SURD analysis.

**Response:**

Thank you for this comment. SST\_CUM was selected as the sole SST-derived thermal-stress metric because cumulative thermal exposure can better represent the prolonged stress experienced during persistent MHW events than single-day or event-averaged SST intensity. For example, short-duration and long-duration MHWs may have same mean or maximum SST intensity, whereas longer-lasting events can potentially induce stronger biological responses because of their prolonged thermal exposure. Therefore, SST\_CUM was used as a representative metric of cumulative thermal stress in the SURD analysis.

We have also expanded the Introduction to provide physiological context for temperature effects on phytoplankton. The revised text notes that phytoplankton physiological rates, including growth, generally increase toward taxon-specific thermal optima and decline once these optima are exceeded.

**Changes in the manuscript:**

Introduction, Lines 36–38:

“Temperature directly influences phytoplankton physiological rates, including growth, which generally increase toward taxon-specific thermal optima and decline once these optima are exceeded (Thomas et al., 2012; Coello-Camba and Agustí, 2017).”

Methods, Sect. 2.3.1, Lines 152–154:

“Separately, for the SURD analysis, we constructed a running cumulative SST anomaly metric (SST\_CUM) to represent the thermal exposure accumulated from MHW onset to each MHW day. SST\_CUM therefore evolves over the progression of an event rather than representing a single event-level value.”

**Minor Comment 6 (Lines 157-160):**

Please consider presenting the lag sensitivity results in supplementary material rather than only describing them in the text.

**Response:**

Thank you for this suggestion. We have added the lag-sensitivity results to the Supplement as Table S1. The results show that the same region-specific four-variable subsets were selected for response lags of 1, 2, and 3 days. We have also revised the description in Sect. 2.3.2 to clarify that this sensitivity test assesses the stability of the variable-subset selection across the tested response lags

**Changes in the manuscript:**

Sect. 2.3.2, Lines 207–209:

“Sensitivity tests for  $\tau = 1, 2$ , and 3 days showed that the selected region-specific variable subsets remained unchanged across the tested lags (Table S1). Given this limited sensitivity to the lag choice,  $\tau = 1$  day was retained for the main analysis.”

Changes in the Supplement:

Table S1. Sensitivity of the selected SURD variable subsets to the response lag.

| Region | Lag $\tau$ (days) | Main-analysis four-variable subset | Rank among candidate subsets |
|--------|-------------------|------------------------------------|------------------------------|
| VUA    | 1                 | SST_CUM, SSS, SLA, EPV             | 1                            |
| VUA    | 2                 | SST_CUM, SSS, SLA, EPV             | 1                            |
| VUA    | 3                 | SST_CUM, SSS, SLA, EPV             | 1                            |
| PRE    | 1                 | SST_CUM, SSS, SLA, u_wind          | 1                            |
| PRE    | 2                 | SST_CUM, SSS, SLA, u_wind          | 1                            |
| PRE    | 3                 | SST_CUM, SSS, SLA, u_wind          | 1                            |

Note: Candidate four-variable subsets were evaluated separately at each response lag using the mean causality leak across bin numbers 2–10. Rank 1 denotes the subset with the lowest mean causality leak at the corresponding lag.

**Minor Comment 7 (Figure 11):**

The schematic is helpful and effectively summarises the proposed mechanisms; however, the font size and labelling could be improved to aid readability.

**Response:**

Thank you for this suggestion. We have revised Fig. 11 by repositioning several labels and adjusting their placement relative to the corresponding schematic elements to improve readability and make the represented physical processes clearer.

***Changes in the manuscript:***

Figure 11 has been revised accordingly.