

Reviewer 3 Comments

General Comments

The paper focuses on determining the physical mechanisms of the impact of Marine heatwaves (MHW) on chlorophyll-a in the South China Sea using a statistical method that quantifies causality and suited for complex interactions, instead of simpler linear approaches. The results show that in addition to heat stress, the chlorophyll-a is also forced by regional physical pathways rather a dominant independent driver. This approach could be applied to other marginal seas affected by MHWs. The paper is well-written, and the methods are sound overall. I recommend minor revision. My main concern with the study is about addressing why the Chl-a responses to MHW were only looked at seasonally (see line by line comments for details). It is also unclear why some large-scale driver (like the WNPSH) connects to the summer MHWs. These points need to be addressed. My specific comments are below:

Response: Thank you for the overall assessment and for highlighting these concerns. We have revised the manuscript accordingly. Detailed responses are provided in the corresponding comments below.

Comment 1 (Line 74):

Do you mean two representative ecosystem regions?

Response:

Thank you for pointing this out. We intended to describe the PRE and VUA as two regions representing contrasting oceanographic settings within the SCS, rather than to imply that they are representative ecosystem regions. We have revised the sentence accordingly.

Changes in the manuscript:

Sect. 2.1, Lines 84:

“This study focuses on two regions within the SCS that represent contrasting oceanographic settings.”

Comment 2 (Line 57):

Was SURF method applied before to understand MHW or marine extremes drivers? Was it applied more widely in oceanography studies. Please provide references.

Response:

Thank you for this comment. We interpret “SURF” as referring to the SURD method used in this study. SURD is a recently developed framework and, to our knowledge, we are not aware of previous applications specifically to MHWs or other marine extremes. Its application in oceanographic research also remains limited. In the original study, SURD was evaluated in a range of complex nonlinear systems and applied to the turbulent energy cascade, demonstrating its ability to resolve unique, redundant, and synergistic causal information in a multiscale fluid system (Martínez-Sánchez et al., 2024).

More recent studies have begun to apply SURD to climate and environmental problems, including precipitation forecasting in Arctic maritime environments (Panja et al., 2025), multivariate drivers of vapor pressure deficit in China (Han et al., 2025), and the influence of large-scale climate oscillations on meteorological drought in the Yangtze River Basin (Ren et al., 2026). These studies indicate that SURD is beginning to be used for multivariate climate and environmental systems characterized by strongly coupled and potentially nonlinear interactions. We have added this context and the corresponding references to the Introduction.

Changes in the manuscript:

Introduction, Lines 65–68:

“To address these limitations, this study applies the Synergistic–Unique–Redundant Decomposition (SURD) method (Martínez-Sánchez et al., 2024). More recent applications have extended the framework to climate and environmental problems, including Arctic precipitation forecasting, vapor pressure deficit, and meteorological drought (Panja et al., 2025; Han et al., 2025; Ren et al., 2026).”

References added:

Han, Y., Zhou, P., Lv, Q., Cui, R., and Meng, L.: Synergistic drivers and threshold effects of vapor pressure deficit in China: An integrated framework of causal inference and machine learning, *J. Environ. Manag.*, 395, 127739, <https://doi.org/10.1016/j.jenvman.2025.127739>, 2025.

Panja, M., Das, D., Chakraborty, T., Ray, A., Athulya, R., Hens, C., Dana, S. K., Murukesh, N., and Ghosh, D.: Forecasting precipitation in the Arctic using probabilistic machine learning informed by causal climate drivers, *Chaos*, 35, 113108, <https://doi.org/10.1063/5.0297336>, 2025.

Ren, K., Guo, W., Wang, F., Qu, J., Ming, T., and Fang, W.: Synergistic-unique-redundant decomposition of the causal influences of four large-scale climate oscillations on meteorological drought in the Yangtze River Basin, *Stoch. Environ. Res. Risk Assess.*, 40, 128, <https://doi.org/10.1007/s00477-026-03255-6>, 2026.

Comment 3 (Line 95):

What is the method used to determine MLD, using a temperature or density threshold? What's the threshold?

Response:

Thank you for pointing this out. The MLD used in this study was obtained directly from the CMEMS GLORYS12V1 reanalysis rather than calculated independently. In this product, MLD is defined using a density criterion relative to 10 m depth, with the density increment corresponding to a 0.2 °C temperature decrease under local conditions (Drévillon et al., 2023). We have added this definition to Sect. 2.2.

Changes in the manuscript:

Sect. 2.2, Lines 107–109:

“The GLORYS12V1 MLD is defined using a density criterion relative to 10 m depth, with the density increment corresponding to a 0.2 °C temperature decrease under local conditions (Drévillon et al., 2023).”

Comment 4 (Line 125):

Add the definition for each MHW metric: frequency, duration

Response:

Thank you for this suggestion. We have revised Sect. 2.3.1 to explicitly define the four MHW metrics used in the study, including frequency, total days, duration, and cumulative intensity, and to clarify how these metrics were averaged over the analysis period.

Changes in the manuscript:

Sect. 2.3.1, Lines 147–151:

“Frequency was defined as the annual number of MHW events, total days as the annual number of MHW days, duration as the length of an individual MHW event, and cumulative intensity as the sum of daily SST anomalies relative to the climatological mean over an individual MHW event (Hobday et al., 2016). Frequency and total days were then averaged over 1998 to 2024 at each grid cell. Duration and cumulative intensity were first calculated for each grid-cell event and then averaged over all events detected at that grid cell during 1998 to 2024.”

Comment 5 (Line 129):

Change analysi to analysis.

Response:

Thanks. The typographical error has been corrected.

Changes in the manuscript:

Sect. 2.3.2 title:

“SURD causality analysis”

Comment 6 (Section 2.3.2):

Add what function package and programming language does the SURD method could be implemented from.

Response:

We have revised Sect. 2.3.2 to specify the programming language and function used for the SURD implementation.

Changes in the manuscript:

Sect. 2.3.2, Lines 161–162:

“The SURD decomposition was implemented in Python using the surd function provided by Martínez-Sánchez et al. (2024).”

Comment 7 (Figure 2):

Add boxes to indicate both regions PRE and VUA.

Response:

Thanks for pointing this out. We have revised Fig. 2 by adding boxes to indicate the PRE and VUA study regions.

Changes in the manuscript:

Figure 2 caption revised accordingly:

“Black rectangles indicate the PRE and VUA study regions.”

Comment 8 (Section 3.2):

Why the Chl-a responses to MHW were only looked at seasonally while the MHW are computed on an annual basis. It'd interesting to examine the Chl-a anomalies for the whole period and not just per season.

Response:

Thank you for this comment. MHW events were identified continuously from the daily SST record throughout 1998–2024, without restricting the detection to individual season. We then classified the MHW events according to season and events by their occurrence season and examined the associated Chl-a responses separately for each season. This seasonal separation was adopted because the physical and biological background states of the SCS vary substantially among seasons. Pooling all MHW events into a single annual Chl-a composite could therefore mask season-specific response patterns.

The seasonal composites show that summer exhibits the clearest regional contrast, with positive Chl-a anomalies in the PRE and negative anomalies in the VUA (Fig. 4). Because the subsequent mechanism analysis was designed to explain this summer contrast, we retained the seasonally resolved composites rather than adding a pooled annual Chl-a composite. We have clarified this rationale and the transition from the seasonal screening to the summer-focused mechanism analysis in Sect. 3.2.

Changes in the manuscript:

Sect. 3.2, Lines 250–253:

“Because the SCS exhibits strong seasonal variability in both physical conditions and Chl-a background states, pooling MHW responses across seasons could mask these season-specific contrasts. The summer composite anomalies in both regions also lay outside the variability observed under comparable non-MHW summer conditions (Fig. S3). We therefore focus the subsequent mechanistic analysis on summer, when the clearest contrast emerges between the PRE and VUA.”

Comment 9 (Line 212-233):

From "Cumulative SST ..." To move to Methods.

Response:

Thank you for this suggestion. We reorganized the relevant material by moving the methodological description from the former Sect. 4.1 to the Methods section rather than relocating the original text verbatim. The description of how SST_CUM and the other physical variables entered the SURD analysis, together with

the construction and selection of the four-variable subsets, is now presented in Sect. 2.3.2. Discussion of unresolved processes and methodological limitations remains in Sect. 3.5.

Changes in the manuscript:

Methods, Sects. 2.3.1–2.3.2:

The methodological description was reorganized and consolidated, including the use of SST_CUM and the other physical variables in the SURD analysis, together with the construction and selection of the four-variable subsets.

Results and Discussion, Sect. 3.5:

The discussion of unresolved processes and methodological limitations was retained and expanded

Comment 10 (Line 347):

Please give a brief definition for the western Northern Pacific subtropical high and a justification rationale on why it was thought to impact the summer MHWs (for example, is this a commonly reported driver for these events in the region?)

Response:

Thank you for this suggestion. We have added a brief definition of the WNPSH and clarified why its anomalous intensification and westward extension are relevant to summer MHWs in the SCS. Previous studies have linked the associated anticyclonic circulation to enhanced surface shortwave heating and weakened summer SCS monsoon, the latter of which can suppress wind-driven upwelling and the midwestern SCS cold filament, thereby reducing ocean cooling. Together, these processes can increase sea surface temperature and hence favour MHW development and persistence. These points have been incorporated into Sect. 3.4.

Changes in the manuscript:

Sect. 3.4, Lines 410–418:

“The WNPSH is the western sector of the North Pacific subtropical high and an important component of the summer atmospheric circulation over East Asia. Here, GH500 denotes 500 hPa geopotential height, expressed in geopotential metres (gpm), and the 5875 gpm contour is used as a proxy for the WNPSH extent (Basconcillo and Moon, 2022; Nie et al., 2024). Anomalous intensification and westward extension of the WNPSH are typically accompanied by an anomalous anticyclonic circulation over the western North Pacific and SCS. Associated subsidence can suppress convection and cloud cover, thereby increasing incoming shortwave radiation at the sea surface (Tan et al., 2022; Li et al., 2022). The accompanying wind anomalies can also weaken the SCS summer monsoon and suppress wind-driven upwelling and the midwestern SCS cold filament (Yao and Wang, 2021; Song et al., 2023). These processes reduce local ocean cooling and favour the development and persistence of summer MHWs in the SCS.”

Comment 11 (Sections 3 and 4):

These sections should be merged and renamed Results & Discussion as the authors are presenting results in section but also comparing and discussing them relative to previous findings. Additionally

former subsection 4.3 is mainly about the limitation of the SURD method (which fits for a discussion).

Response:

Thank you for this suggestion. We have merged the former Results and Discussion sections into a single “Results and Discussion” section (Sect. 3) and reorganized the subsection structure accordingly. In the revised manuscript, the causality leakage and uncertainty in the SURD interpretation are discussed in Sect. 3.5.

Changes in the manuscript:

Sections 3 and 4:

The former Results and Discussion sections have been merged into a single “Results and Discussion” section.

Sect. 3.5:

The discussion of causality leakage, methodological limitations, and unresolved processes has been retained within the combined section.