

General Comments:

Dear authors

Thank-you for your full responses to referee comments and your revised manuscript incorporating them. I don't need to return it to the referees but am asking for minor revision according to the "Detailed comments" below, after which I expect to take a final look before publication.

Yours sincerely

John Huthnance (editor)

Response: Thank you for your careful evaluation of our manuscript and for providing the constructive comments. We have revised the manuscript accordingly and addressed each point in the detailed responses below.

Comment 1:

Lines 29-30. “. . destructive potential including Arctic precipitation forecasting, vapor pressure deficit, . .” does not read well. Omit “forecasting”? “destructive potential” → “potential adverse effects”? What is “destructive” (or adverse) about Arctic precipitation (forecasting)?

Response:

Thank you for pointing this out. We agree that the previous wording was unclear. We have revised the Introduction (Lines 28–32) by removing the phrase “Arctic precipitation forecasting, vapor pressure deficit, and meteorological drought” from this sentence and rephrasing the text to clarify that the potential adverse effects refer to impacts of MHWs on the marine biosphere.

Changes in the manuscript:

1 Introduction, Lines 28–32:

“As global warming intensifies during the twenty-first century, MHWs are projected to increase nonlinearly in spatial extent (Oliver et al., 2018; Yao et al., 2020), with potentially adverse effects on the marine biosphere, including shellfish diseases and mollusk mortality (Jones et al., 2018; Oliver et al., 2017), coral reef bleaching (Le Nohaïc et al., 2017), functional extinction of kelp forests (Wernberg et al., 2016), harmful algal blooms, and mass strandings of marine mammals and seabirds (Cavole et al., 2016).”

Comment 2:

Table 1. In the second column (headed “Variable”), where there are two rows listing variables from the same source, the line spacing should be reduced to strengthen the association with the source in the third column (CMEMS GLORYS12V1, two ERA5 products). Similarly for the bottom two rows in columns 1 and 3 to associate with EPV in column 2 and columns 4, 5.

Response:

We have reformatted Table 1 by reducing line spacing within multi-variable entries and adjusting the alignment of corresponding cells to improve the association between variables, data sources, and resolutions.

Changes in the manuscript:

Table 1:

Category	Variable	Source / Product ID	Temporal resolution	Spatial resolution
Ocean physics	SST	NOAA OISST v2.1	Daily	$0.25^{\circ} \times 0.25^{\circ}$
	salinity, currents (u, v), MLD, temperature	CMEMS GLORYS12V1	Daily	$1/12^{\circ} \times 1/12^{\circ}$
	SLA	CMEMS SEALEVEL L4	Daily	$0.25^{\circ} \times 0.25^{\circ}$
Ocean biology	Chl-a	CMEMS GlobColour L4	Daily	$4 \text{ km} \times 4 \text{ km}$
	Chl-a (vertical)	CMEMS BGC Hindcast	Daily	$0.25^{\circ} \times 0.25^{\circ}$
Atmosphere	10 m wind (u, v), SWR, precipitation	ERA5 single levels	Daily	$0.25^{\circ} \times 0.25^{\circ}$
	GH500, 850 hPa wind (u, v)	ERA5 pressure level	Daily	$0.25^{\circ} \times 0.25^{\circ}$
Derived variable	EPV	ERA5 10 m wind stress curl	Daily	$0.25^{\circ} \times 0.25^{\circ}$

Comment 3:

Figure 7. The grey shading for “bathymetry” with Brunt-Väisälä frequency is different from that for salinity and temperature. I suppose it must be related to the CMEMS GLORYS12V1 reanalysis grid and values available to calculate Brunt-Väisälä frequency. This might be commented, c.f. Figure S1.

Response:

Thank you for pointing this out. We have clarified the meaning of the grey shading in Figure 7 by revising the caption to indicate that it represents seafloor bathymetry or masked grid cells, consistent with the description used in Figure S1.

Changes in the manuscript:

Figure 7 caption, Lines 342–343:

“Grey shading at the bottom of each panel represents seafloor bathymetry or masked grid cells.”

Comment 4:

Sections 3.3.1, 3.3.2 and figures 5, 8. For readers accustomed to variance attributable to “input variables” in multivariate regression, where typically four well-chosen inputs would account for a large majority of the regressed variable’s variance, the “causality leak” fractions in the SURD analysis leaks appear large, especially for the PRE Chl-a. Hence (I suppose) the caution expressed by the referees. Any statistical analysis, or previous experience with use of SURD, for levels of confidence to attach to the inferences here, would therefore be welcome.

Response:

Thank you for this important comment. We agree that the SURD results should be distinguished more clearly from variance attribution in multivariate regression. Multivariate regression evaluates how much of the variance in a target variable can be explained by a set of predictors, whereas SURD is based on information theory and quantifies the reduction in uncertainty of a future target provided by the selected drivers. The causality leak therefore should not be interpreted as unexplained variance in a regression framework. In SURD, the causality leak represents the fraction of target uncertainty that is not captured by the selected driver subset, whereas the unique, redundant, and synergistic contributions are normalized only within the information captured by the selected physical drivers. These contributions therefore represent relative information contributions rather than fractions of the total Chl-a variability.

The non-zero causality leak shows that the selected variables do not capture all processes affecting Chl-a. We discuss this limitation explicitly in Sect. 3.5. Nutrient and biological variables were not included in the SURD driver pool because we did not identify suitable long-term datasets that simultaneously provide daily resolution, spatial continuity, and consistent reliability across both study regions. Model-derived biogeochemical variables also remain uncertain in coastal and estuarine waters. We therefore focus the SURD analysis on physical drivers that can be resolved consistently over 1998–2024. The substantial causality leak in the

VUA and PRE further reinforces the need to consider unresolved biological, biogeochemical, and optical processes when interpreting the Chl-a response.

We also appreciate the suggestion to provide additional statistical support or context from previous SURD applications. The lag-sensitivity and bin-sensitivity analyses show that the selected variable subsets and the main SURD results remain stable under the tested settings. Direct comparison of contribution magnitudes across different SURD applications is not straightforward because these values depend on the selected variables, target variable, and regional processes. We therefore use these sensitivity analyses as the main check on the robustness of the present results.

Changes in the manuscript:

1 Introduction, Lines 67–70:

“Unlike variance attribution in multivariate regression, SURD is based on information theory and quantifies how much uncertainty in a future target is reduced by the selected drivers. The captured information is then decomposed into redundant, unique, and synergistic components, while the remaining target uncertainty is reported separately as the causality leak.”

Sect. 3.3.1 (Suppressed upwelling in the VUA), Lines 284–285:

“whereas EPV showed the largest unique information contribution among the selected physical drivers (12.9 %).”

Lines 287–288:

“This result identifies vertical transport as the dominant identified physical pathway associated with the Chl-a decline within the selected driver set.”

Sect. 3.3.2 (Horizontal plume retention in the PRE), Lines 350–351:

“whereas SSS provided the largest unique information contribution among the selected physical drivers (28.1 %; Fig. 8b).”

Sect. 3.5 (Causal leakage and uncertainty in SURD-based interpretation), Lines 466–467:

“The substantial causality leak in both regions also indicates that processes beyond the selected physical drivers, including biological, biogeochemical, and optical processes, should be considered when interpreting the observed Chl-a anomalies.”

Sect. 4 (Conclusions), Lines 507–509:

“In the VUA, the unique contribution of EPV within the selected physical drivers indicates that weakened upwelling was the dominant identified physical pathway associated with the negative Chl-a anomalies.”

Lines 512–513:

“In the PRE, SSS showed the largest unique information contribution among the selected physical drivers, and its synergy with SST_CUM, SLA, and u_wind supports a coupled radiative-warming and plume-retention interpretation.”

Comment 5:

Line 531. Only “around China”?

Response:

Thank you for pointing this out. We agree that the previous wording unnecessarily limited the potential application scope of the SURD-based framework. We have revised the sentence to refer to other marginal seas worldwide.

Changes in the manuscript:

Sect. 4 (Conclusions), Lines 534–536:

“Beyond the SCS, future applications of this SURD-based framework to other marginal seas worldwide could help assess whether MHW-driven Chl-a responses arise from similar or regionally distinct physical–biological pathways.”