

Ignoring marine heatwaves legacy effects underestimates carbon export loss in a major upwelling system

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Ignoring marine heatwaves legacy effects underestimates carbon export loss in a major upwelling system

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Marine heatwaves (MHWs) are intensifying globally yet their cumulative impact on the ocean's biological carbon pump remains poorly constrained. Current climate assessments evaluate MHWs as discrete physical events, assuming biological impacts recover with the cessation of the thermal anomaly. Here, using 25 years of daily satellite observations (1998–2022) across the Canary Current upwelling system (CanEBUS), one of the most productive ocean regions, we reveal a persistent physical-biogeochemical decoupling. We estimate that MHWs suppressed a cumulative ~154 Tg of particulate organic carbon (POC) export. Notably, accounting for post-MHW legacy effects amplifies this estimate by ~175%, demonstrating that conventional event-based assessments systematically underestimate the true biogeochemical cost of MHWs. Furthermore, annual export deficits scale robustly with accumulated MHW thermal stress ($r^2 = 0.65-0.71$). Under sustained warming, projected annual POC deficits including legacy effects are expected to exceed 46 Tg C yr⁻¹ in the CanEBUS by 2100. Given that EBUS collectively supports a disproportionate fraction of oceanic export production, MHW-driven biological pump suppression represents a substantial, previously overlooked feedback on regional carbon sequestration with potential global implications. Our findings highlight the urgent need for Earth System Models to incorporate biogeochemical recovery inertia to accurately project the future ocean carbon sink.

Most of the atmospheric carbon entering the ocean via photosynthesis is eventually respired back to CO₂ in the surface layers of the water column. Yet a considerable fraction escapes surface remineralization and is subsequently exported to the dark ocean (> 200 m) as part of the biological carbon pump¹. Temperature exerts fundamental control over this pump by regulating the key metabolic balance between primary production (PP), the main source of particulate organic carbon (POC) in the ocean, and respiration, which determines the fraction of POC remineralized in the water column. Ocean warming generally accelerates metabolic and microbial processes, enhancing organic carbon remineralization

and thereby reducing export efficiency²⁻⁴. Warmer temperatures can also transiently stimulate PP by promoting nutrient recycling or community shifts⁵. Therefore, abrupt temperature anomalies such as those occurring during marine heatwaves (MHWs)—discrete events of abnormally high ocean temperatures that can persist from days to months and can extend over large spatial scales⁶—, have the potential to profoundly disrupt established carbon cycling dynamics.

Anthropogenic ocean warming is intensifying the frequency, duration, and spatial extent of extreme and compound events^{7,8}, including MHWs for which projections indicate further strengthening in the coming decades⁹⁻¹¹. These events have already triggered devastating impacts on marine ecosystems and coastal economies¹²⁻¹⁶. Nevertheless, their influence on carbon export, and the efficiency of the biological carbon pump, remains poorly constrained, with regional assessments in highly dynamic and productive regions as eastern boundary upwelling systems (EBUS) still scarce¹⁷.

EBUS play indeed an outsized role in global carbon export, contributing roughly 10% of the global ocean's new productivity despite covering only 1–2% of ocean area^{18,19}. In these systems, upwelling of cold, nutrient-rich waters fuels intense PP, generating large carbon fluxes that can be readily remineralized by microbial activity in the upper layers or sequestered to depth^{20,21}. While the upwelling can partially buffer regional ocean warming^{22,23}, recent assessments using high-resolution Earth system simulations indicate a substantial increase in the frequency and intensity of MHWs in these regions²⁴. Despite their ecological and biogeochemical relevance, the full extent of MHW-driven changes on carbon export, a critical climate metric, remains elusive in EBUS¹⁵, which hampers our ability to predict the biogeochemical consequences of global warming in these ecologically and economically critical systems.

Here, we address this gap by leveraging 25 years (1998 to 2022) of daily multi-satellite observations to provide the first systematic quantification of the cumulative carbon export deficit associated with MHWs in the Canary Current (CanEBUS), the second most productive EBUS of the world oceans²⁵. Our primary objective is to quantify the cumulative impact of extreme thermal events altering the efficiency of the biological carbon pump. By establishing whether MHWs act merely as transient disturbances or as persistent regulators of carbon fluxes, we provide a process-based basis for predicting how a warmer and more variable ocean will reshape the efficiency of carbon sequestration and associated climate feedbacks in the coming decades in EBUS.

Long-term CanEBUS dynamics

We estimate pixelwise decadal trends using Theil-Sen slopes on daily satellite data available from 1998 to 2022 (Methods; $n=6561$ grid-points $\times$ 9131 time steps). Spatial trend maps (Fig. 1) evidence a clear pattern of general warming of the sea surface throughout most of the CanEBUS ($+0.078 \pm 0.038^{\circ}\text{C decade}^{-1}$; 92% pixels with $p<0.05$, Mann-Kendall), peaking at $+0.22^{\circ}\text{C decade}^{-1}$ south of Cape Blanc, which aligns with previous multi-decadal assessments (e.g., ^{26,27}). Nonetheless, trends also indicate localized nearshore cooling (negative trends, in blue) extending offshore, particularly in the permanent upwelling^{28,29} and Cape Blanc areas ($\sim 21\text{--}26^{\circ}\text{N}$). This pattern is compatible with upwelling strengthening, although whether this reflects a broader intensification of coastal upwelling — as hypothesized by Bakun³⁰—remains under debate^{26,31}. Similar cooling signals have been recently observed in the four main EBUS of the world ocean, i.e., the Canary, California, Perú-Humboldt, and Benguela systems, yet with some discrepancies^{27,32,33}.

Surface chlorophyll-a (Chl-a) shows widespread declines across coastal upwelling zones over the study period (Fig. 1b), reaching rates of up to $-0.7\text{ mg Chl m}^{-3}\text{ decade}^{-1}$ off the Mauritanian coast. The largest declines coincide spatially with the strongest SST increases in the permanent upwelling region, extending from the southern Western Saharan coast to offshore areas near Cape Verde—an area characterized by wintertime upwelling²⁸ and the convergence of northern and southern waters at Cape Blanc³⁴. This spatial decoupling between warming and Chl-a³⁵ underscores the complexity of climate change impacts on EBUS, where coastal upwelling buffering effects coexist with alterations in nutrient supply and stratification. Export production (EP) mirrored Chl-a trends closely (Fig. 1c), emphasizing their coupled link. Declining EP despite persistent upwelling aligns with recent findings suggesting that sustained warming is eroding the ocean's capacity to sequester carbon in productive boundary systems^{36,37}. In contrast, the open ocean shows minimal long-term change, with slight increases in Chl-a and EP, possibly reflecting shifts in stratification or nutrient recycling under warming conditions^{38,39} and indicating that coastal upwelling, not the open ocean, concentrates the largest climate-driven changes.

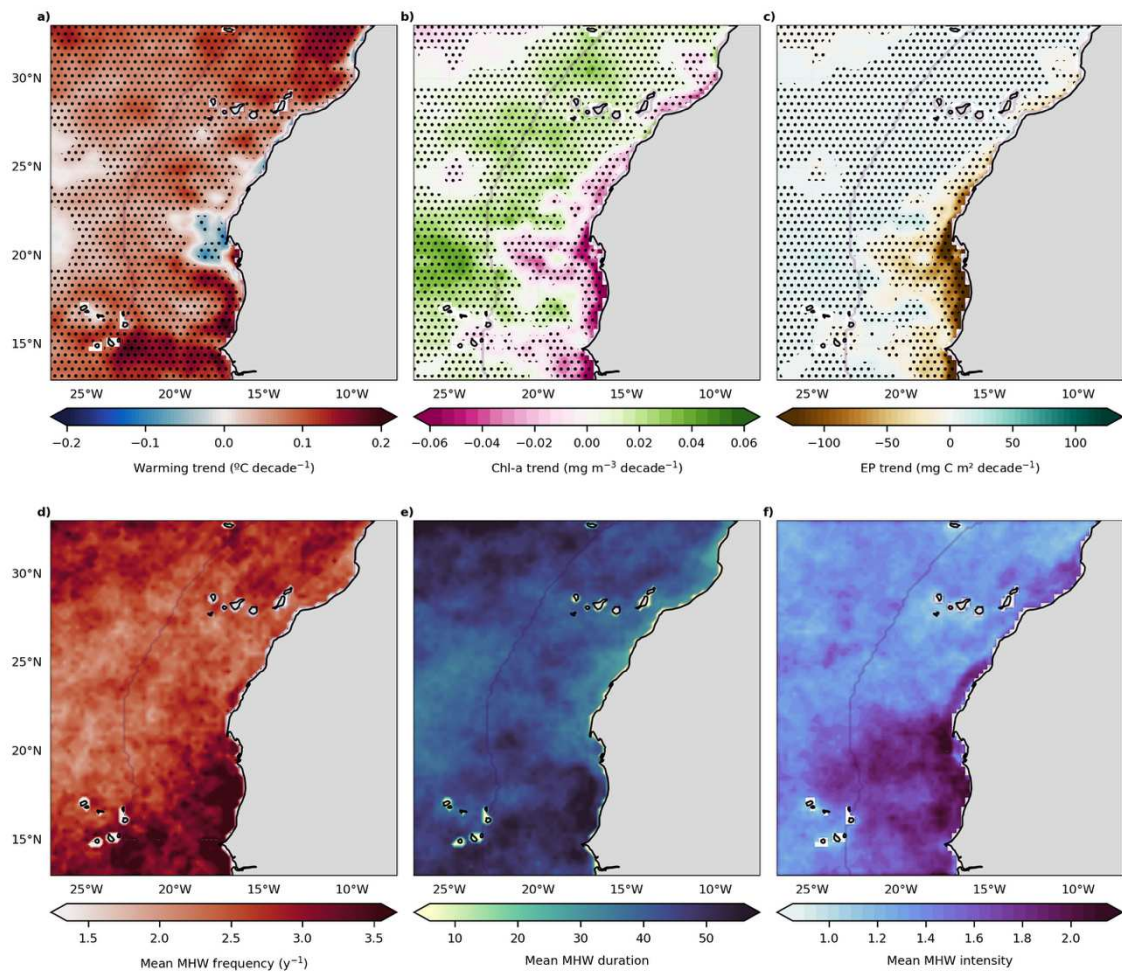


Figure 1. Long-term trends and marine heatwaves regime. Satellite-derived Thiel-Sen trends (1998–2022) in (a) sea surface temperature ($^{\circ}\text{C decade}^{-1}$), (b) surface chlorophyll-a ($\text{mg m}^{-3} \text{ decade}^{-1}$), and (c) export production ($\text{mg C m}^{-2} \text{ d}^{-1} \text{ decade}^{-1}$), computed from daily observations. Marine heatwaves regime characteristics including (d) mean annual number of MHW events, (e) mean annual MHW duration and (f) mean annual MHW intensity ($^{\circ}\text{C}$ above the seasonally varying 90th-percentile threshold) are displayed. All metrics are spatially resolved across the northwest African CanEBUS. Stippling in (a–c) indicates grid cells where trends are statistically significant at the 95% confidence level. Black contours indicate the oceanic region within 600 km from the African coast (see Fig. 2).

Superimposed on these long-term patterns, MHWs manifest as recurring extreme warming episodes throughout the study period. Regionally, CanEBUS averaged 1.82 ± 1.29 MHW events yr^{-1} , with the Mauritanian coast exhibiting the highest mean frequency (> 3.6 events yr^{-1} , Fig. 1d). The longest MHW episodes, exceeding ~ 50 days, cluster predominantly in the northern open ocean region (Fig. 1e). South of the Canary Islands—within the Canary Eddy Corridor⁴⁰ (Fig. 1e)—, MHW duration shows a local enhancement relative to adjacent coastal waters, consistent with modelling studies indicating mesoscale features as drivers of MHWs^{41,42}. Near the coast, MHWs tend to be more transient, though their intensity remains relatively high despite coastal buffering²⁴, reflecting distinct shelf-to-open-ocean drivers and dynamics^{41,43}. South of $\sim 21^{\circ}\text{N}$, MHWs are characterized by numerous high intensity

episodes (Fig. 1f) that can occur within a single upwelling season, potentially imposing repeated thermal stress on coastal phytoplankton communities. In this region, intensity and duration remain relatively high.

Together, the combination of warming, coastal Chl-a decline, and an emerging hotspot of frequent and intense MHWs south of 21° N, creates background conditions that favour the accumulation of MHW-driven export losses.

Thermal stress impact Chl-a and carbon export

To elucidate the biological and biogeochemical impacts of MHWs in CanEBUS, we quantified anomalies in surface Chl-a and EP during MHW days relative to non-MHW climatological conditions (Supplementary Fig. 1). These anomaly patterns closely mirrored MHW intensity distribution (Fig. 1f), revealing sharp Chl-a and EP declines concentrated in coastal upwelling cores, where thermal extremes coincide with peak nutrient-driven productivity.

The response of Chl-a and EP to MHWs varies substantially across seasons and latitude (Fig. 2). During MHW events, both variables are negatively impacted relative to non-MHW climatological conditions across the domain, but the decline is strongly amplified south of 21° N, particularly in winter when MHW intensity peaks (>4° C). This seasonal alignment suggests a potential vulnerability of winter phytoplankton blooms^{28,44} to episodic thermal extremes. Such events could disrupt upwelling-driven nutrient supply by reinforcing surface stratification⁴⁵, potentially suppressing carbon export precisely when the system is most productive.

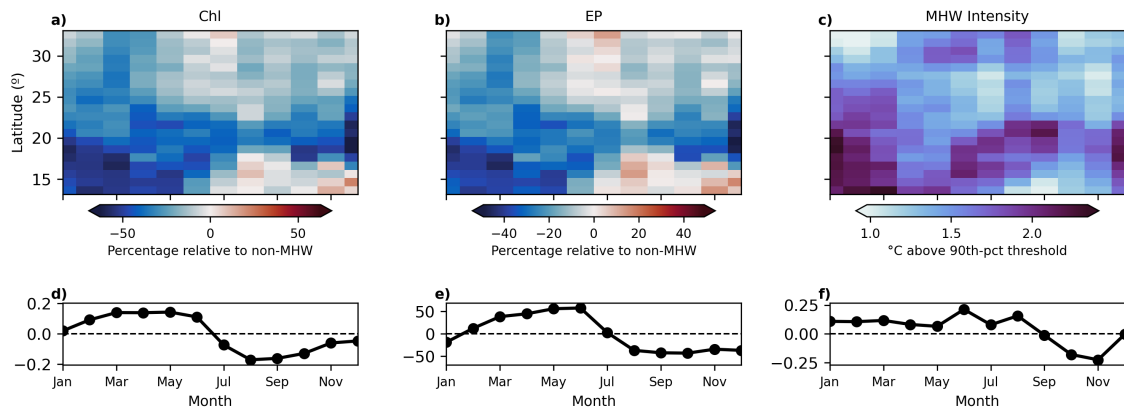


Figure 2. Seasonal and latitudinal modulation of phytoplankton and carbon export responses to marine heatwaves. (a, b) Mean percentage anomalies of surface Chl-a and EP during MHWs relative to non-MHW climatological conditions (1998 to 2022), binned into 1° latitude bands and averaged zonally over the first 600 km from the African coast. Negative values indicate suppression relative to the seasonal climatological baseline. (c) Corresponding MHW mean intensity (°C above threshold) in the same latitude–season space. (d–f) Longitude- and latitude-area-weighted seasonal cycles of Chl-a, EP and MHW intensity, respectively, integrated across the full CanEBUS domain.

Latitudinal differences in MHW-driven Chl-a and EP suppression reflect contrasting upwelling regimes and their capacity to buffer thermal stress. Between ~20-26° N, permanent upwelling of cold, nutrient-rich subsurface waters partially offsets intense MHW-induced stratification. Similarly, summer months show weaker impacts of MHW occurrences, suggesting that strong upwelling counteracts thermal stress. In contrast, the southern region, where upwelling is mainly restricted to winter and spring^{46,47}, emerges as highly sensitive to thermal extremes, exhibiting the largest declines in surface Chl-a and EP, occurring during the annual maxima of both variables (Fig. 2d, e).

Subregional impacts and recovery dynamics

To clarify the causal role of intense MHWs (Category III-IV, see Methods) in driving declines in Chl-a and EP, and their regional responses, we selected four key subregions: Permanent Upwelling (PU), Seasonal Upwelling (SU), Southern Region (SR) and Open Ocean (OO) (see Methods). For each subregion, the most intense weighted-average event was selected and represented together with EP anomalies (Fig. 3a-h). In the PU, the most intense MHW event reached an SST anomaly of + 4.81 °C and was accompanied by large reductions in EP (Fig. 3a, e) and Chl-a (not shown). In this region, mean EP recovery after intense events (Category III-IV) is relatively short (10-15 days; Fig. 3i), likely reflecting the buffering effects of upwelling that helps to restore nutrient supply and partially compensates MHW-induced stratification.

In contrast, the SR is subject to slightly lower SST anomalies (+ 3.08 °C during the most intense event) and EP suppression (- 87% relative to 15 days mean before the most intense event), but substantially prolonged mean recovery times (45-75 days, Fig. 3l). In this region, conditions persist long after the thermal event dissipates, potentially suggesting slower nutrient injection to counteract MHW-driven export suppression, allowing MHW-driven export suppression to accumulate.

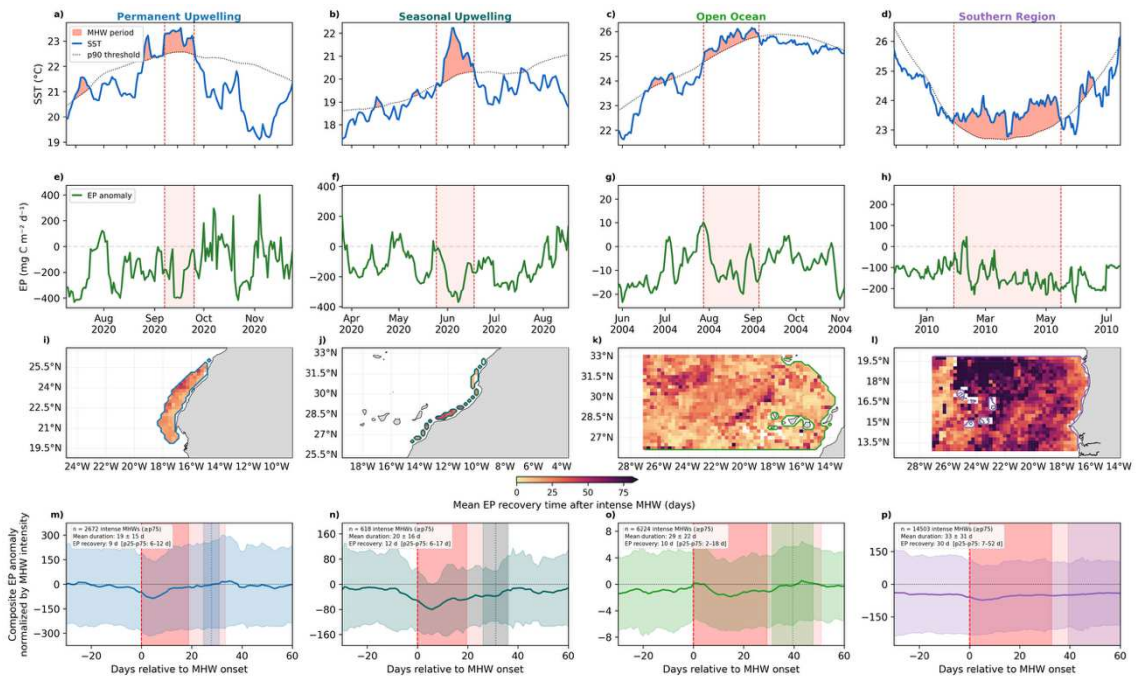


Figure 3: Subregional impacts, recovery dynamics, and responses of export production to intense marine heatwave events. Regional area-weighted time series of SST (a–d) and EP anomalies (e–h) during the weighted-average most intense MHW event of the studied period (1998–2022) for the Permanent Upwelling, Seasonal Upwelling, Open Ocean, and Southern Region subregions, respectively. Spatial distribution maps of EP recovery time (days) following intense (Category III–IV) MHW events (i–l). Recovery is defined as the first post-event day on which the EP anomaly returns to the climatological baseline (anomaly = 0) for three consecutive days, computed with a ± 15 -day smoothing window following Hobday et al. (2016). For each grid cell, the mean recovery time across all qualifying events is displayed. Composite daily EP anomalies normalized by mean MHW intensity (m–p), centred on MHW onset (day 0). Solid lines represent the composite mean; dark shading denotes ± 1 standard deviation across events; red shading marks mean MHW duration ± 1 standard deviation. Negative lag values indicate days prior to thermal onset. Only events with mean intensity at or above the 75th percentile of the domain-wide MHW intensity distribution are included. Event counts (n) and mean durations are annotated in each panel.

The composite analysis of EP anomalies normalized by MHW intensity (Fig. 3m–p) reveals a broadly consistent temporal structure across PU, SU and OO subregions. EP suppression typically begins within ~ 2 –3 days after the MHW onset. Maximum decline occurs around the 5th–7th day, while recovery begins after 9 to 12 days from mean MHW offset. This lagged response is consistent with the time required for thermal stratification to reduce nutrient fluxes⁴⁸, and to propagate the effects to phytoplankton community^{49,50}. By contrast, the composite analysis of the SR region differs by displaying a flatter EP response to MHW, but much longer recovery times (30 days on average), as seen before. We define legacy effects as the persistent suppression of carbon export extending beyond the formal offset of the thermal anomaly, lasting until the biological carbon pump returns to climatological baseline conditions for three consecutive days (see Methods).

Overall, in PU and SU, intense but relatively short-lived events generate sharp yet transient EP anomalies that the system can largely dissipate within weeks.

Conversely, in the SR, even moderately intense MHWs translate into disproportionately large cumulative export deficits because slow recovery stretches negative EP anomalies well beyond MHW offset.

Discussion

Ocean warming and Chl-a decline across CanEBUS are spatially heterogeneous, modulated by upwelling seasonality and mesoscale dynamics²⁶ (Fig. 1). Within the coastal permanent upwelling region (~21 to 26° N), nearshore cooling co-occurs with Chl-a and EP decreases, suggesting that possible upwelling intensification can coexist with declining carbon export. These losses are partly linked to recurrent occurrences of relatively short but intense MHWs that transiently disrupt the upwelling, especially during wintertime (Fig. 2). South of Cape Blanc, however, the overlap between stronger sea-surface warming, more intense and persistent marine heatwaves, and steeper export production declines identifies a hotspot of thermal vulnerability within the system.

The lagged response of EP to MHW onset (Fig. 3m-p) suggests that MHWs suppress export production primarily by reorganizing upper-ocean structure, rather than by directly inhibiting photosynthesis⁵¹ (Supplementary Fig. 2). A plausible mechanism is enhanced stratification, as it can weaken the efficiency of nutrient resupply to the euphotic zone⁵², with downstream consequences for phytoplankton biomass and export. This interpretation is consistent with evidence that MHW-induced changes in vertical structure can favour smaller phytoplankton cells over the larger taxa that typically dominate nutrient rich coastal upwelling waters^{53,54}. Because these larger cells contribute disproportionately to POC export^{55,56}, a shift towards smaller-celled communities would further reduce export efficiency. Although the satellite-based anomaly framework cannot directly resolve upper-ocean stratification or nutrient dynamics, the spatial correspondence between MHW intensity, negative EP anomalies, delayed recovery, and cumulative thermal stress is consistent with a dominant role of MHW-driven upper-ocean restructuring in driving the observed export deficits.

MHW impacts on export production persist well beyond the period of anomalous warming. Negative export anomalies remain after event offset (Fig. 3m-p), indicating that recovery of the biological carbon pump requires not only the cessation of thermal stress but also the re-establishment of vertical structure and thus nutrient supply. Recovery is relatively rapid in the core upwelling zone, consistent with thermal buffering by recurrent upwelling^{57,58}. In contrast, recovery is more prolonged south of Cape Blanc, suggesting that biogeochemical recovery

time is a first-order control on cumulative carbon-export loss, in addition to event intensity and duration.

Over 1998–2022, MHWs were associated with a cumulative export deficit of 153.84 Tg C across the CanEBUS, equivalent to approximately 3% of climatological EP (Fig. 4). Based only on days formally classified as MHWs, the mean annual deficit was 6.15 ± 8.24 Tg C yr⁻¹ (Fig. 4a, b), with considerable interannual variability (Fig. 4b). However, when post-event recovery periods were included, this estimate rose to 16.92 ± 16.78 Tg C yr⁻¹, indicating that legacy effects substantially amplify the cumulative loss of export production (Fig. 4b) and thus constitute a key component of biological carbon pump weakening. This amplification was particularly pronounced south of 21° N. This southern region, spanning Cape Blanc to Cape Verde, accounted for 87% of the total MHW-driven EP deficit when including post-event deficit (Fig. 4c), despite occupying roughly 25% of the study domain, consistent with the coincidence of stronger and longer MHWs with the productive winter season. These results were robust across three distinct export efficiency parametrizations^{59–61} (Supplementary Fig. 3).

At the global scale, the gravitational biological carbon pump transfers a considerable amount of carbon from the surface ocean to depth^{56,62,63}, with EBUS making a disproportionate contribution through both vertical and lateral export pathways^{20,64,65}. The CanEBUS is among the most productive of these systems, playing a key role in sequestering carbon to depth^{21,66}. Similar patterns of long-term decline under increasing MHW stress are now emerging in other EBUS^{14,24,33}, suggesting that our findings may have broader applicability. In this context, the carbon export deficit computed in this study could represent a substantial and still underappreciated component of future changes in the ocean carbon sink.

We further identify a robust relationship between annual carbon export deficit and cumulative MHW heat stress ($r^2 = 0.65$ when legacy effects are included, $r^2 = 0.71$ for MHW days only; Fig. 4c), that is, the annual combination of MHW duration (in days) and intensity (in °C). This metric is similar to degree heating weeks, which is used to quantify thermal stress accumulation in marine ecosystems^{67,68} (e.g., coral reefs) linking thermal extremes to biogeochemical impacts. This relationship implies that the strength of the MHW-driven export deficit can be predicted from the accumulation of thermal stress over a given year. Assuming that cumulative MHW heat stress continues to increase linearly through the 21st century — consistent with the observed trend over the study period (1998–2022) — we project the annual deficit of carbon export accounting for legacy effects could rise 30.21 ± 2.59 Tg C yr⁻¹ by 2050, and 46.81 ± 4.55 Tg C yr⁻¹ by 2100 (Fig. 4d). These values should be regarded as conservative lower bounds, as multi-model ensembles from the 6th Coupled Model Intercomparison Project (CMIP6) project an acceleration of ocean

warming and a near-permanent MHW state by the end of the 21st century under high-emission scenarios⁶⁹, alongside increases in MHW frequency, duration and intensity^{9,70}. Future work coupling this statistical framework with CMIP6 projections would provide more constrained uncertainty bounds. If this intensity-deficit relationship is robust across all EBUS, continued warming is likely to further enhance the export deficit in these regions.

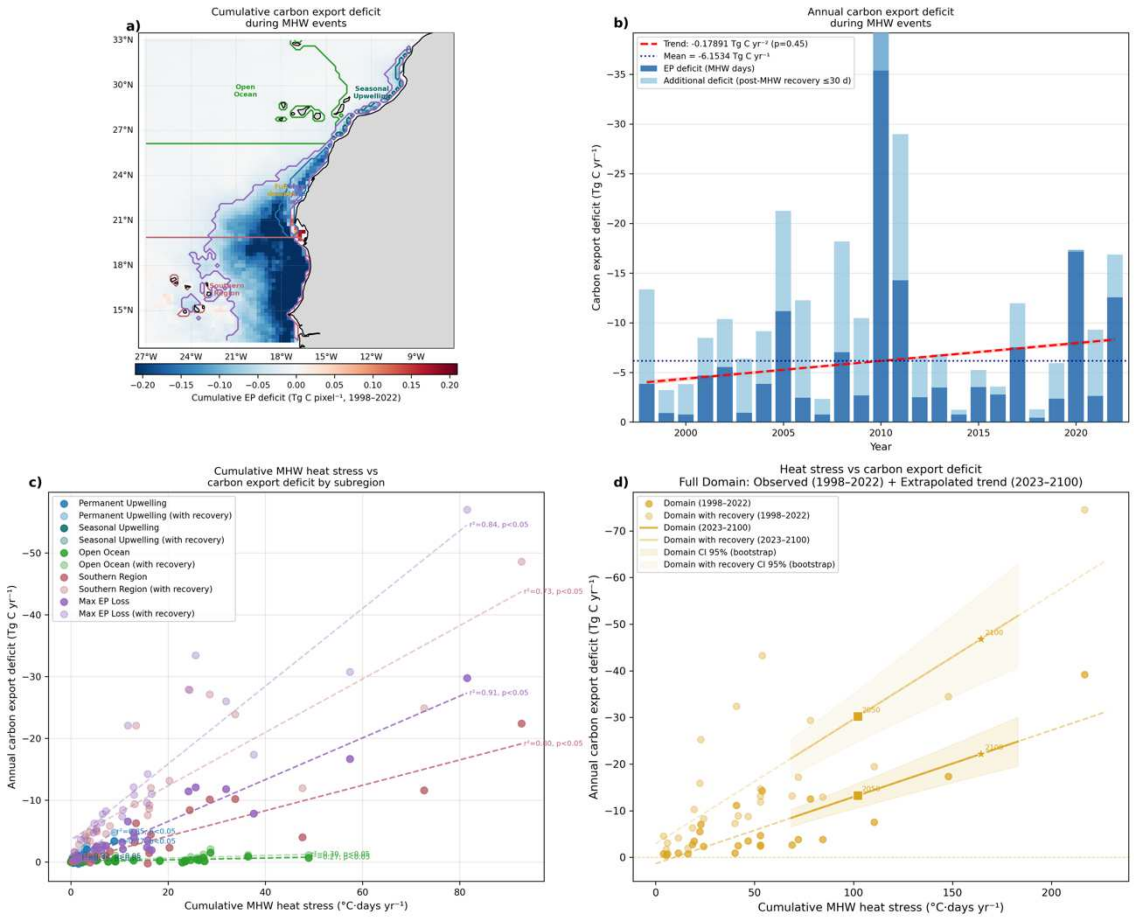


Figure 4: Carbon export deficit driven by MHWs in the CanEBUS. (a) Cumulative spatial distribution of export production (EP) deficit (Tg C pixel^{-1}) attributable to MHW events. (b) Annual carbon export deficit (Tg C yr^{-1}) attributable to MHW periods (dark blue) and the post-MHW recovery phase (light blue). The dashed red line indicates the linear trend. (c) Relationship between annual mean MHW thermal stresses ($^{\circ}\text{C day yr}^{-1}$) and annual carbon export deficit with and without accounting for legacy effects across subregions. Solid lines indicate OLS regressions with 95% bootstrapping-based confidence bands. A subregion where pixels fall within the top quartile (25% most affected) of carbon export deficit is also shown. (d) Under the assumption of linear increase in MHW heat stress, the relationship between annual mean MHW thermal stress ($^{\circ}\text{C day yr}^{-1}$) and carbon export deficit (with and without legacy effects) is projected into the future (2023–2115). Square and star markers indicate projected values at 2050 (2035 to 2065 mean) and 2100 (2085 to 2115 mean), respectively.

Several caveats merit consideration. First, EP was inferred from satellite-derived NPP using empirical export-efficiency parameterisations. Although our comparison with two alternative parameterisations yields consistent relative MHW-driven suppression (Supplementary Fig. 3), absolute fluxes and deficits remain model

dependent. Satellite derived NPP algorithms used here have been recently validated against *in situ* measurements within the region⁷¹, providing reliability for characterizing regional carbon export. Second, satellite observations inform only on the surface layer, thus only the gravitational component of the biological carbon pump associated with POC is derived. Our estimates may therefore be conservative as MHW-driven thermal stratification could also suppress other effective carbon export pathways, including mixing-driven flux mechanisms that facilitate the export of low-sinking POC and dissolved organic carbon^{62,72}. In addition, the fate of sinking POC at depth is not resolved by our satellite-derived estimates and, hence, the consequences for longer-term sequestration remain to be determined depending on the organic carbon turnover rate⁷³. Finally, legacy effect estimates are sensitive to the choice of recovery window, with annual deficits ranging from $13.66 \pm 13.78 \text{ Tg C yr}^{-1}$ (1 day) to $20.95 \pm 19.14 \text{ Tg C yr}^{-1}$ (5 days; Supplementary Table 1). Importantly, the relationship between MHW thermal stress and annual EP deficit remains robust across all windows ($r^2 = 0.64\text{--}0.66$), and the dominant contribution of the SR increases consistently with increasing recovery window length. This is consistent with the substantially longer recovery times documented in that subregion (Fig. 3l).

Most studies have focused on the impacts of individual MHW events (e.g., ^{74,75}), whereas their cumulative biogeochemical consequences remain poorly resolved. Using more than two decades of satellite-derived export production, we show that MHWs weaken the biological carbon pump and thereby reduce the capacity of a major eastern boundary upwelling system to buffer atmospheric carbon dioxide. Strikingly, accounting for post-MHW legacy effects increases the cumulative export deficit by 175% compared with estimates based only on MHW days, indicating that the biogeochemical footprint of extreme warming extends well beyond the thermal event itself. Our results therefore suggest that the carbon-cycle impacts of extreme thermal events may be systematically underestimated in current large-scale assessments, particularly where lagged ecosystem and biogeochemical responses are not explicitly represented. If widespread across upwelling systems, these hidden deficits would imply that MHWs are not only transient disturbances but persistent regulators of ocean carbon sequestration with relevant climate implications.

Methods

1. Study region

This study focuses on the Canary Current Eastern Boundary Upwelling System (CanEBUS), spanning 13–33° N and 7–27° W. This latitudinal range captures the strong biogeographic and hydrographic gradients that characterize CanEBUS and its associated productivity regimes. It encompasses major subdomains of the system, including the Western Saharan and Mauritanian–Senegalese sectors as defined by Arístegui et al.²⁸.

According to regional characteristics, decadal trends, and MHW signatures, four subregions were selected. (1) Permanent Upwelling (PU) is considered between 20 and 26° N, where SST is colder than 20.5 °C, and Chl-a is higher than 0.6 mg Chl m⁻³. (2) Seasonal Upwelling (SU) is considered north of 26° N, where SST is colder than 20.5 °C, and Chl-a is higher than 0.6 mg Chl m⁻³. (3) Open Ocean (OO) is considered north of 26° N, where upwelling is not present. (4) Southern Region (SR) is considered the region south of 20 °N. In addition, Fig. 4 displays a fifth subregion consisting of all pixels within the 25th percentile of higher EP suppression.

2. Satellite data

We used multiple long-term satellite products to characterize the physical and biological environment of the CanEBUS. Daily sea surface temperature (SST) was obtained from the Global Ocean OSTIA Sea Surface Temperature and Sea Ice Reprocessed analysis product⁷⁶ from the UK Met Office, with a spatial resolution of ~0.05° as provided by GRAFCAN/Biodiversity Service GOBCAN. This dataset (1982 to 2025) was used to detect MHWs.

Surface chlorophyll-a (Chl-a) concentrations were derived from the daily, multi-sensor Copernicus-GlobColour biogeochemical analysis (1997 to 2025), with a spatial resolution of ~0.05°, as provided by GRAFCAN/Biodiversity Service GOBCAN. Daily photosynthetically active radiation (PAR) data were obtained from the recent Castant et al.⁷⁷ gridded dataset (1998 to 2022; ~0.25° resolution).

Net primary production (NPP) was estimated using the Eppley–VGPM algorithm, chosen for its demonstrated accuracy in Eastern Boundary Upwelling Systems, particularly the Canary region⁷¹.

The analysis period (1998 to 2022) was selected based on the temporal overlap among satellite products, enabling robust identification of both long-term trends and extreme thermal anomalies. All datasets were interpolated to a common 0.25° latitude - longitude grid for consistency and subsequent analysis.

3. MHW definition

Marine heatwaves were identified following the definition of Hobday et al.⁶, as periods of at least five consecutive days with abnormally warm daily SST that exceed the 90th percentile of daily climatological mean. The climatology (mean and 90th percentile) used a 31-day centred running mean over a 30-year OSTIA record (January 1st, 1982, to December 31st, 2011) (see ⁷⁸) for robust smoothing of intra-day variability.

To assess event intensity, we applied the Hobday et al.⁷⁹ categorical framework: SST anomalies that exceed a unit, twice, three times and four times the 90th percentile anomaly from the climatological normal are designated as Categories I (modest), II (strong), III (severe) and IV (extreme) events, respectively. This classification enables the evaluation of both the frequency and severity of temperature extremes across CanEBUS.

A binary mask indicating for each pixel days with MHW conditions (“1”) and days with non-MHW conditions (“0”) was used for further computations.

4. Estimation of the carbon export production

Carbon export production (EP) was derived from satellite-based NPP using the empirical model developed by Dunne et al.⁵⁹, which relates EP to NPP through an export efficiency factor (E_f) and the depth of the euphotic layer (Z_{Eu}):

$$E_f = -0.0101xSST + 0.0582x \ln \frac{NPP}{Z_{Eu}} + 0.419$$

$$EP = NPPx \begin{cases} 0.04 & \text{if } E_f < 0.04 \\ 0.72 & \text{if } E_f > 0.72 \\ E_f & \end{cases}$$

This model was parameterized using global compilations of sediment trap, ²³⁴Th flux, and ¹⁴C-based production data. The depth of the euphotic layer was estimated following the optical approach of Morel and Berthon⁸⁰ using Chl-a observations, as implemented in the Eppley-VGPM framework. The Dunne model was selected because it outperforms alternative formulations in reproducing satellite-derived export fluxes when evaluated against global in situ datasets⁸¹.

To test the robustness of our results dependent on this parameterization, two additional parameterizations were used to compute the relative change (%) of EP suppression driven by MHWs. Parameterizations by Laws et al.⁶¹ and Henson et al.⁶⁰ were utilized.

5. Decadal trends

Long-term changes in SST, Chl-a, and EP were quantified pixelwise using the non-parametric Theil–Sen estimator⁸², which is considered robust to outliers and non-normal data distributions. The method computes the slopes between all possible pairs of observations in a variable’s time series, with the median of these slopes representing the overall trend.

Significance levels for the detected trends were evaluated using the Mann–Kendall test, which assesses whether data exhibit a statistically significant monotonic increase or decrease over time. This combination provides robust detection of linear and non-linear changes in environmental variables commonly affected by intra-annual variability and long-term climate forcing.

6. Recovery times

Post-MHW EP recovery time was defined at each grid cell as the first post-event day on which the EP anomaly (smoothed with a ± 15 -day centred moving average) remained at or above the climatological baseline ($\Delta EP \geq 0$) for three consecutive days (adapted from Hobday et al.⁶). For each grid cell, recovery time was averaged across all qualifying Category III–IV events occurring between 1998 and 2022.

7. Quantification of MHW-driven carbon export deficit

To quantify the reduction in biological carbon export associated with MHW events, we computed the absolute daily anomaly of EP relative to a non-MHW climatological baseline. For each grid cell, the climatological reference was defined as the mean EP for each calendar day of the year, computed exclusively over non-MHW days across the full study period (1998–2022), following the baseline approach of Hobday et al.⁷⁹. To remove high-frequency noise whilst preserving the seasonal cycle, the resulting day-of-year climatology was smoothed using a centred ± 15 -day running mean (with circular padding at year boundaries to avoid artefacts).

The daily EP anomaly for each grid cell was then defined as:

$$\Delta EP_{i,t} = EP_{i,t} - \bar{EP}_{i,doy(t)}$$

where $EP_{i,t}$ is the observed EP at pixel i on day t , and $\bar{EP}_{i,doy(t)}$ is the smoothed climatological value for the corresponding day of year. Negative values of $\Delta EP_{i,t}$ indicate a deficit in carbon export relative to non-MHW conditions. Anomalies were retained only for days identified as MHW days based on the binary MHW mask described in Section 3.

The domain-integrated carbon export deficit was obtained by multiplying the daily EP anomaly at each pixel by its corresponding surface area, accounting for the spherical geometry of the Earth:

$$A_i = R^2 \cos(\phi_i) \Delta\lambda \Delta\phi$$

where R is the Earth's radius (6.371×10^6 m), ϕ_i is the central latitude of pixel i , and $\Delta\lambda$ and $\Delta\phi$ are the zonal and meridional grid spacings in radians, respectively. The resulting deficit was integrated temporally to yield annual carbon export deficit estimates expressed in Tg C yr⁻¹:

$$\Delta C_{year} = \sum_i \sum_{t \in MHW} \Delta EP_{i,t} \cdot A_i \cdot 10^{-18}$$

where the factor 10^{-18} converts from mg C to Tg C.

To obtain a conservative lower-bound estimate of total carbon sequestration loss, we additionally computed an extended deficit that encompasses the post-MHW recovery period. For each pixel and each MHW event, the deficit integration window was extended beyond the event termination date until the EP anomaly returned to the climatological baseline (i.e., $\Delta EP_{i,t} \geq 0$) for three consecutive days following event termination. This approach captures the lagged biological response to thermal stress that persists after SST has recovered, consistent with the delayed EP anomalies documented in Fig. 3. To assess the sensitivity of the legacy effect estimates to this choice, the analysis was repeated for the number of consecutive days (1, 3, and 5 days) for which EP anomaly returned to the climatological baseline after event termination (Supplementary Table 1).

Subregional carbon export deficits were computed by applying the spatial masks of the four CanEBUS subregions (Permanent Upwelling, Seasonal Upwelling, Open Ocean, and Southern Region; see section 1) to the daily deficit field prior to spatial integration. To contextualise the magnitude of the MHW-driven deficit, annual deficits were additionally expressed as a percentage of the non-MHW climatological EP integrated over each subregion. The linear trend in annual carbon export deficit over the study period was assessed using least-squares regression, with statistical significance evaluated at the 95% confidence level (two-tailed t -test, $n - 2$ degrees of freedom).

8. Projection MHW thermal stress and carbon export deficit

To project the future export production (EP) deficit, a statistical relationship ($r^2 = 0.65$ accounting for legacy, $r^2 = 0.71$ for formally defined MHW days only) was first established between annual marine heatwave (MHW) thermal stress ($^{\circ}\text{C} \cdot \text{days yr}^{-1}$, HS) and annual EP deficit (Tg C yr⁻¹) over the observed period 1998–2022 ($n = 25$ years). An ordinary least-squares (OLS) linear regression was fitted across years common to both time series, retaining only finite-valued observations:

$$\widehat{EP}_{\text{deficit}} = \beta_1 \cdot \text{HS} + \beta_0$$

where β_1 is the slope (Tg C per °C·day) and β_0 is the intercept. This regression was performed for two EP deficit scenarios: a baseline scenario based only on days strictly considered as MHW, and an alternative scenario incorporating post-MHW recovery dynamics. The residual standard error of each regression (s_ε) was computed as:

$$s_\varepsilon = \sqrt{\frac{\sum_i (y_i - \hat{y}_i)^2}{n - 2}}$$

A second OLS regression was applied to the observed HS time series (1998–2022) against calendar year to characterize its long-term linear trend. This trend was then extrapolated forward to 2115, yielding a projected HS trajectory for the period 2023–2115:

$$\widehat{\text{HS}}(t) = \alpha_1 \cdot t + \alpha_0$$

This extrapolation assumes that the linear trend in MHW thermal stress observed over 1998–2022 remains stationary throughout the projection period. Given model projection of MHW intensification, we thus assume this approach as a lower boundary.

Future EP deficit was projected by applying the regression equation to the extrapolated HS values. Projected values were averaged over two 30-year windows centred on mid-century (2035–2065) and end-of-century (2085–2115).

We use a parametric bootstrap ($N = 10000$) to quantify the uncertainty. For each iteration, regression coefficients were jointly drawn from their asymptotic multivariate normal distributions:

$$[\beta_1^{(b)}, \beta_0^{(b)}] \sim N(\hat{\beta}, \mathbf{V}_{\hat{\beta}})$$

where the coefficient covariance matrix is computed as:

$$\mathbf{V}_{\hat{\beta}} = s^2(\mathbf{X}'\mathbf{X}^{-1})$$

They were performed independently for the HS temporal trend regression and for each EP deficit regression (MHW days and MHW and recovery). The period-mean HS for each bootstrap iteration was computed from the drawn HS trend coefficients, and the resulting EP deficit projection additionally incorporated a draw from the residual noise distribution:

$$\varepsilon^{(b)} \sim N(0, s_\varepsilon)$$

The 95% confidence interval for each projected period was taken as the 2.5th and 97.5th percentiles of the bootstrap distribution, with the projected HS held fixed at its period-mean point estimate, isolating the uncertainty in the EP–HS statistical relationship from that of the HS projection. The latter was quantified separately by propagating the covariance of the HS trend regression coefficients through the bootstrap, and substantially exceeds the regression uncertainty (± 15.60 and $\pm 34.59 \text{ Tg C yr}^{-1}$ versus ± 2.59 and $\pm 4.59 \text{ Tg C yr}^{-1}$ at 2050 and 2100, respectively), reflecting the assumption that the linear HS trend observed over 25 years remains stationary throughout the projection horizon.

Data Availability and Reproducibility

All satellite datasets used in this study are publicly available. Daily Global Ocean OSTIA Sea Surface Temperature and Sea Ice Reprocessed Analysis (Worsfold et al., 2024) can be accessed through the Met Office Marine Data Portal (<https://www.metoffice.gov.uk/research/climate/maps-and-data/data/ostia>).

Chlorophyll-a data from the Copernicus-GlobColour biogeochemical analysis are available at <https://www.globcolour.info/>. Daily photosynthetically active radiation (PAR) grids can be requested to Castant et al.⁷⁷ corresponding authors. Details of the gridding algorithms, quality controls, and regional pre-processing are described in the corresponding references.

Interpolated data and estimates presented in the paper will be deposited in the Zenodo Data Repository (<https://zenodo.org/>), upon publication.

Code Availability

All statistical computations were performed in Python 3.13 using the packages xarray, pandas, scipy, and statsmodels. Spatial visualization and compositing analyses were carried out with Matplotlib and Cartopy. Custom computer code used to generate the results reported in this study is available upon reasonable request from the corresponding author.

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Author Contributions

Y.S.F. conceived and designed the study, performed all analyses, produced all figures, and wrote the manuscript. J.C.S. provided the pre-processed satellite data and the derived marine heatwave products. N.H.H. contributed to the conceptualization and framing of the study. All authors reviewed and approved the final version of the manuscript.

Competing Interests

The authors declare no competing interests.

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