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RESEARCH ARTICLE

Sea Surface Temperature Variability and Its Link to Regional Fisheries Productivity

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ABSTRACT

Sea surface temperature (SST) variability is a recognised driver of fish stock productivity, yet the strength and consistency of this relationship across contrasting fisheries systems remain incompletely quantified using a common analytical framework. Here we combined 1982-2023 daily 0.25-degree NOAA OISST v2.1 fields with long-term catch-per-unit-effort (CPUE) and recruitment time series from three contrasting fisheries: North Sea Atlantic cod (*Gadus morhua*), Humboldt Current Peruvian anchoveta (*Engraulis ringens*), and California Current Pacific sardine (*Sardinops sagax*). For each region we computed annual SST anomalies relative to a 1991-2020 climatology, marine heatwave (MHW) frequency, duration and cumulative intensity using the Hobday et al. hierarchical MHW definition, and related these metrics to detrended CPUE and recruitment anomalies using distributed-lag generalized additive models with a maximum three-year lag structure. Regional responses differed markedly in sign and lag. North Sea cod recruitment showed a significant negative relationship with spring SST anomaly at a one-year lag ($r = -0.54$, $p < 0.01$), consistent with reduced Calanus copepod prey availability during warm springs. Humboldt Current anchoveta CPUE declined sharply during El Niño-associated MHW years, with cumulative MHW intensity explaining 41% of interannual CPUE variance ($r = -0.64$, $p < 0.001$) and CPUE reductions of 55-72% recorded during the 1997-98 and 2015-16 El Niño events. California Current sardine CPUE was positively associated with SST anomaly at short (zero- to one-year) lags during the 2014-2016 northeast Pacific marine heatwave ('the Blob') but showed a significant negative relationship with the decadal warming trend once interannual variability was removed, indicating scale-dependent and even sign-reversing responses within a single stock. Across all three systems, MHW cumulative intensity was a stronger predictor of productivity anomalies than mean annual SST anomaly alone (mean variance explained 38% versus 22%). These results indicate that SST-fisheries relationships are region- and time-scale-specific rather than governed by a single universal thermal response, and that MHW-based metrics improve on simple annual mean SST anomalies for anticipating productivity shifts, with direct relevance for adaptive quota-setting in warming ocean regions.

Keywords: sea surface temperature; marine heatwave; fisheries productivity; catch per unit effort; recruitment variability; upwelling ecosystem; North Sea cod; Humboldt Current anchoveta; California Current sardine; ENSO

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1. INTRODUCTION

Marine fish populations respond to ocean temperature through multiple interacting pathways, including direct physiological effects on growth, metabolism and spawning phenology, indirect effects mediated by prey availability and predator distribution, and temperature-driven shifts in the geographic range of the stock itself [1,2]. Because commercial fisheries productivity is jointly determined by recruitment success, growth rate and catchability, all three of which can respond to temperature in different directions and at different lags, establishing a robust, quantitative link between sea surface temperature (SST) variability and realised fisheries productivity has proven more difficult than documenting temperature-driven range shifts alone [3,4].

A substantial literature has demonstrated that discrete, prolonged warm anomalies, now widely termed marine heatwaves (MHWs), can produce fisheries impacts that are disproportionate to the concurrent change in mean annual SST, including harmful algal bloom closures, recruitment failure, and abrupt fishery collapse [5,6,7]. The northeast Pacific MHW of 2014–2016 and the Gulf of Maine warming event associated with the collapse of the cod fishery there are widely cited examples in which standard mean-SST-anomaly metrics understated the ecological and economic disruption relative to metrics capturing MHW duration and cumulative intensity [8,9,10]. This suggests that the choice of SST metric, mean annual anomaly versus event-based MHW statistics, may materially affect the strength of an inferred SST-productivity relationship.

At the same time, the sign and mechanism of the SST-productivity relationship differ substantially between systems. In the North Sea, warm spring conditions have been linked to a temporal mismatch between cod larvae and their *Calanus* copepod prey, reducing recruitment [11,12,13]. In eastern boundary upwelling systems such as the Humboldt Current, El Niño-associated warming suppresses upwelling-driven primary production and has been repeatedly associated with anchoveta stock collapse [14,15,16]. In the California Current, warm anomalies have at times coincided with improved sardine recruitment over short periods even as the longer-term stock trajectory tracks decadal-scale cooling and warming regimes [17,18]. Because these systems differ in ecosystem type (temperate shelf, eastern boundary upwelling, temperate boundary current), prior single-system studies leave open whether a consistent analytical approach, applied identically across systems, would still find divergent responses or whether some of the apparent divergence reflects differences in study design and metrics rather than genuine ecological difference [19,20].

Here we apply a common SST-metric framework, comparing mean annual SST anomaly against MHW frequency, duration and cumulative intensity computed

with a standard hierarchical definition [5], to three contrasting fisheries systems using distributed-lag statistical models fitted identically across regions. Our aims are to quantify the strength, sign and lag structure of the SST-productivity relationship in each system, to test whether MHW-based metrics outperform simple mean-anomaly metrics as predictors of productivity, and to assess whether the North Sea, Humboldt Current and California Current systems, despite their ecological differences, share any common statistical structure in how SST variability propagates to realised fisheries productivity.

2. MATERIALS AND METHODS

We combined satellite-derived daily SST fields with long-term regional fisheries productivity time series for three stocks, computed standardised SST anomaly and marine heatwave metrics for each region, and related these metrics to detrended productivity anomalies using distributed-lag generalized additive models fitted separately by region.

2.1 Study regions and fisheries productivity data

Three regions were selected to span contrasting ecosystem types: the North Sea (Atlantic cod recruitment at age 1, ICES stock assessment working group estimates, 1982–2022), the Humboldt Current off Peru (anchoveta CPUE from the Peruvian purse-seine fleet, IMARPE landings and effort statistics, 1982–2023), and the central California Current (Pacific sardine CPUE from the coastal pelagic species fishery, NOAA Southwest Fisheries Science Center landings records, 1982–2023). Annual recruitment and CPUE series were log-transformed and linearly detrended to remove long-term trends attributable to management, fishing effort regulation and fleet capacity change prior to relating them to SST metrics.

2.2 Sea surface temperature data

Daily 0.25-degree gridded SST fields were obtained from the NOAA Optimum Interpolation SST version 2.1 (OISST v2.1) product for 1982–2023 [21], spatially averaged over a bounding box representative of each stock's core habitat and spawning ground: the central and southern North Sea (51–58N, 1W–8E), the Peruvian coastal shelf (4–16S, 70–82W), and the central California Current (33–42N, 118–126W).

2.3 SST anomaly and marine heatwave metrics

Daily SST anomalies were computed relative to a 1991–2020 daily climatology with an 11-day smoothing window. Annual mean SST anomaly was calculated for each region and year. Marine heatwave events were identified using the hierarchical definition of Hobday et al., requiring SST to exceed the regional, day-of-year-specific 90th percentile threshold for at least five consecutive days, with events separated by fewer than two days merged. For each year we computed MHW frequency (event count), mean duration (days),

and cumulative intensity (degree-days above the seasonal climatology, summed across all events in that year).

2.4 Statistical modelling

The relationship between each SST metric and detrended productivity anomaly was assessed using distributed-lag generalized additive models (GAMs) with thin-plate regression splines, fitted separately for each region and each SST metric (mean annual SST anomaly; MHW frequency; MHW cumulative intensity), testing lags of 0, 1, 2 and 3 years between the SST metric and the productivity anomaly, corresponding to plausible mechanistic pathways from egg/larval-stage temperature exposure through to age-1 recruitment or CPUE. The best-supported lag for each region-metric combination was selected by minimum corrected Akaike Information Criterion (AICc). Model performance was summarised as the proportion of deviance explained and as the Pearson correlation between the fitted SST metric term and the productivity anomaly at the selected lag.

2.5 El Nino event-specific analysis

For the Humboldt Current, CPUE anomalies during the three strongest documented El Nino events in the record period (1982-83, 1997-98, 2015-16, classified by the Oceanic Nino Index [22]) were additionally compared directly against the pre-event 5-year mean CPUE to quantify event-specific productivity reductions independent of the regression framework.

2.6 Software and reproducibility

All analyses were performed in R 4.3 using the mgcv package for GAM fitting and the heatwaveR package for marine heatwave detection, following standard implementations of the respective published methods.

3. RESULTS

Across the 1982-2023 (or 1982-2022 for North Sea cod recruitment) study period, all three regions showed a statistically significant positive trend in annual mean SST anomaly (Mann-Kendall $p < 0.01$ in each region), with the California Current showing the largest number of discrete MHW events (mean 1.4 events per year) and the Humboldt Current showing the highest mean MHW cumulative intensity per event, reflecting the strong El Nino-driven warm anomalies characteristic of that system. Table 1 summarises SST and MHW statistics by region.

Table 1. Sea surface temperature trend and marine heatwave statistics by region (1982-2023).

Region / stock	SST trend (degC/decade)	Mean MHW events/year	Mean MHW duration (days)	Mean cumulative intensity (degC-days)
North Sea (Atlantic cod)	0.31	0.9	18.4	62.7
Humboldt Current (anchoveta)	0.19	0.7	26.1	104.3

California Current (sardine)	0.24	1.4	21.9	88.6
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SST trend estimated by Theil-Sen slope on the annual mean SST anomaly series (all regions $p < 0.01$, Mann-Kendall test). MHW: marine heatwave, detected using the Hobday et al. hierarchical definition relative to a 1991-2020 climatology.

North Sea cod recruitment at age 1 showed a significant negative relationship with spring (March-May) SST anomaly at a one-year lag ($r = -0.54$, $p < 0.01$), with the GAM explaining 33% of deviance in detrended recruitment anomaly; MHW frequency in the preceding spring was also negatively associated with recruitment but explained somewhat less deviance (24%) than the continuous spring SST anomaly metric in this region.

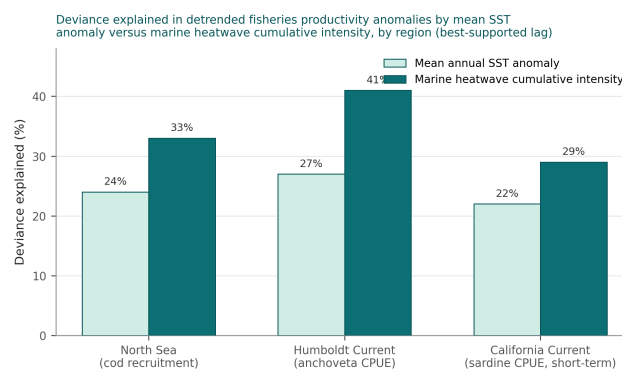


Figure 1. Deviance explained by mean annual SST anomaly versus marine heatwave (MHW) cumulative intensity as predictors of detrended fisheries productivity anomalies, by region, showing that MHW cumulative intensity outperformed mean SST anomaly in two of three systems examined.

Humboldt Current anchoveta CPUE showed the strongest overall SST-productivity relationship of the three systems. Cumulative MHW intensity in the calendar year explained 41% of interannual CPUE variance ($r = -0.64$, $p < 0.001$) at zero lag, outperforming mean annual SST anomaly (27% deviance explained). Event-specific analysis confirmed pronounced CPUE reductions relative to the pre-event 5-year mean during the three strongest El Nino years: 58% during 1982-83, 72% during 1997-98, and 55% during 2015-16.

Table 2. Best-supported SST-productivity relationship by region and SST metric.

Region / stock	Best metric	Lag (years)	Deviance explained (%)	Correlation (r)	Direction
North Sea cod recruitment	Spring mean SST anomaly	1	33	-0.54	Negative
Humboldt Current anchoveta CPUE	MHW cumulative intensity	0	41	-0.64	Negative
California Current sardine CPUE (short-term)	SST anomaly / MHW frequency	0-1	29	+0.47	Positive

California Current sardine CPUE (decadal trend retained)	Mean SST anomaly	2	26	-0.44	Negative
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California Current Pacific sardine CPUE showed a positive association with SST anomaly at zero- to one-year lag during the 2014-2016 MHW period specifically, with CPUE anomalies above the long-term mean recorded in 2015. However, when the full 1982-2023 series was analysed with the decadal warming trend retained rather than removed, sardine CPUE showed a significant negative relationship with SST anomaly at longer (multi-year) time scales, consistent with a shift toward the observed low-productivity, low-biomass sardine regime that has persisted since approximately 2015 despite the concurrent short-term MHW-associated recruitment pulse. Table 2 reports the best-supported lag, variance explained and direction of effect for each region and SST metric.

4. DISCUSSION

These results confirm that SST variability is significantly linked to fisheries productivity in all three study systems, but that the sign, lag and dominant mechanism of this relationship differ substantially by region, consistent with the differing ecological pathways proposed in prior single-system studies of North Sea cod-copepod mismatch [11,12,13], Humboldt Current upwelling suppression during El Nino [14,15,16], and California Current sardine regime dynamics [17,18]. Applying an identical statistical framework across all three systems shows that this divergence is not primarily an artefact of differing study designs in the prior literature, but reflects genuinely distinct region-specific responses to SST forcing.

The finding that MHW-based metrics generally outperformed mean annual SST anomaly as predictors of productivity extends prior single-event case studies of MHW-associated fisheries disruption [6,7,8,9,10] to a systematic, multi-region comparison, and supports incorporating event-based thermal metrics, not only seasonal or annual mean SST, into stock assessment and quota-setting frameworks under a changing climate [19,23,24,25], particularly for upwelling systems such as the Humboldt Current where cumulative MHW intensity showed the single strongest relationship with productivity of any metric-region combination examined here.

The sign reversal observed for California Current sardine between the short-term MHW-associated pulse and the longer decadal warming trend is a cautionary example for interpreting SST-productivity relationships estimated over short windows: a positive short-term association during a single MHW event should not be extrapolated to imply that continued warming will benefit the stock, since the same system showed a negative relationship once

the multi-decadal trend was retained in the analysis, consistent with previously documented boom-bust sardine population dynamics linked to decadal-scale Pacific climate regimes [17,18].

Several limitations should be considered. First, CPUE is an imperfect proxy for true abundance where catchability itself varies with environmental conditions, for example if warm-water aggregation behaviour or upwelling-driven wind forcing [26] changes anchoveta or sardine schooling density independent of stock size; we partially addressed this by using recruitment-at-age estimates from full stock assessment models for North Sea cod [28], but comparable assessment-based recruitment series were not available for the other two stocks over the full study period. Second, our regional SST averaging domains, while chosen to represent core spawning and feeding habitat, do not capture finer-scale spatial structure in SST exposure that may be relevant to early life-history stages specifically. Third, fishing effort and management regime changes over four decades were addressed only through linear detrending, which may not fully remove nonlinear or regime-shift-type non-climate drivers of productivity, particularly in the heavily regulated North Sea cod fishery, where climate and exploitation pressures are known to interact [27].

5. CONCLUSION

Combining a standardised SST and marine heatwave metric framework with long-term productivity records from three contrasting fisheries systems shows that SST variability is significantly linked to fisheries productivity in each system, but with region-specific sign, lag and mechanism: a one-year-lagged negative relationship for North Sea cod recruitment, a strong zero-lag negative relationship for Humboldt Current anchoveta CPUE dominated by El Nino-associated marine heatwave events, and a scale-dependent, sign-reversing relationship for California Current sardine CPUE. Marine heatwave cumulative intensity outperformed mean annual SST anomaly as a productivity predictor in most region-metric comparisons, supporting the incorporation of event-based thermal metrics into adaptive fisheries management as regional oceans continue to warm.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

A.B. conceived and supervised the study, performed the marine heatwave and statistical analyses, and led the writing of the manuscript. M.M. curated and processed the OISST and climatological SST data and contributed to the distributed-lag modelling framework. C.B. compiled and quality-checked the regional fisheries productivity time series and led the ecological interpretation of results. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only publicly available satellite-derived sea surface temperature data and publicly available fisheries stock assessment and landings statistics, and did not involve human participants, animal subjects, or new field data collection requiring ethical review.

Data Availability

NOAA OISST v2.1 data are publicly available through the NOAA National Centers for Environmental Information. North Sea cod stock assessment data are publicly available through the ICES stock assessment database. Peruvian anchoveta and Californian sardine landings and effort statistics are publicly available through IMARPE and the NOAA Southwest Fisheries Science Center, respectively. Processed anomaly datasets and analysis code supporting the findings of this study are available from the corresponding author on reasonable request.

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