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Research Article

Thermal accumulation indicator as a dynamic ocean management tool in the Gulf of Ulloa, Mexico

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ABSTRACT. This study examines the occurrence of cumulative cold events in the Gulf of Ulloa, Baja California Sur, defined as sea surface temperatures (SST < 18°C) for ≥5 consecutive days, as a basis for developing an operational environmental indicator to support adaptive fisheries management and reduce sea turtle bycatch. High-resolution MUR satellite data (1.1 km²) from 2003-2023 were analyzed to generate climatologies, annual maps, and spatial accumulations that reveal critical areas and temporal patterns of thermal persistence. Results indicate a clear seasonal pattern, with the highest frequency of cold events between March and June, coinciding with intensified coastal upwelling and the residence of juvenile *Caretta caretta*. Interannual variability was pronounced: cold years (e.g. 2008, 2011, 2022) showed widespread event coverage, while warm ENSO phases (2014-2016) exhibited minimal incidence. The cumulative analysis revealed up to 84 cold events in the northern coastal sectors of the gulf and identified 18 critical polygons of persistent conditions that overlap zones of turtle-fishery interaction. The proposed indicator is both replicable and scalable, consistent with the principles of Dynamic Ocean Management. It provides near-real-time environmental information to anticipate sea turtles' ecological vulnerability and support conservation decisions without impairing local fisheries or relying on static fishery closures.

Keywords: *Caretta caretta*; cumulative cold events; environmental indicators; dynamic ocean management; fisheries conservation; Gulf of Ulloa

INTRODUCTION

The Gulf of Ulloa (GU), located along the western coast of Baja California Sur, is one of the most productive marine regions in the Mexican Pacific and is directly influenced by the California Current (CC). This productivity has supported the development of important small-scale fisheries while providing suitable habitats for ecologically valuable species such as the loggerhead turtle (*Caretta caretta*). Several studies have documented the recurrent presence of this species in the region, particularly during its juvenile stage, due to abundant food availability and the area's oceanographic characteristics (Seminoff et al. 2002).

In recent years, the GU has received national and international attention due to increased sea turtle strandings, prompting the Mexican government to implement conservation measures and fishing restrictions. However, these measures have largely relied on fixed spatial and temporal closures that do not

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always reflect the region's dynamic environmental conditions (Salinas-Zavala et al. 2020). A key aspect of this issue lies in how thermal risk is defined. While traditional approaches use instantaneous sea surface temperature (SST) thresholds, here we propose a cumulative indicator that accounts for the persistence of cold conditions (SST < 18°C for ≥5 consecutive days). This approach reflects the ectothermic nature of sea turtles: adverse physiological effects such as lethargy, immunosuppression, reduced swimming capacity, and cold-stunning are not triggered by short-term exposures but require sustained thermal inertia in the environment (Schwartz 1978, Sieg 2010). In other words, seawater temperature behaves as a quasi-conservative property at short time scales, and it is the temporal accumulation, rather than instantaneous fluctuation, that determines ecological risk.

This framework aligns with the concept of Dynamic Ocean Management (DOM), which promotes adapting management measures to the ocean's changing spatio-temporal conditions. Unlike traditional static management schemes, DOM favors flexible, near-real-time interventions that integrate updated environmental, biological, and fisheries information (Lewison et al. 2015, Maxwell et al. 2015, Dunn et al. 2016). Incorporating cumulative indicators provides a better representation of the relationship between persistent oceanographic processes, such as the upwelling systems of the CC, and the physiological responses of marine organisms, in this case *C. caretta*, whose residence in the GU depends on stable foraging habitats. Accordingly, this study analyzes cumulative cold SST events to develop a robust environmental indicator with direct implications for understanding ecological vulnerability and for designing dynamic management tools in the GU.

Context

Several applications of DOM have been successfully implemented across the Pacific to reduce sea turtle bycatch. One example is the TurtleWatch Program in Hawaii, a tool that issues thermal alerts based on turtles' preferred temperature range, allowing longline fleets to temporarily relocate their operations and reduce interactions with these reptiles (Howell et al. 2008). Similarly, the EcoCast model in California combines environmental indicators and *C. caretta* distribution models to propose dynamic fishery closures (Hazen et al. 2018). This approach has proven effective in reducing bycatch while minimizing the economic impact on fishing fleets (Welch et al. 2020). More recently, Schroeder et al. (2022) developed the Habitat Compression Index (HCI). This dynamic indicator identifies high-risk zones within upwelling systems, where thermal habitats contract and the probability of human-activity interactions increases.

These approaches illustrate how near-real-time integration of environmental data can support adaptive management. However, in the GU, the juvenile population of *C. caretta* exhibits prolonged residence at foraging grounds rather than latitudinal migration, as observed in other regions (Polovina et al. 2006). Therefore, this study proposes that the persistence of cold events (SST < 18°C for ≥5 consecutive days) serves as a thermal indicator, as such accumulated conditions represent a critical negative factor for the physiology, health, and behavior of sea turtles (Schwartz 1978, Sieg 2010). Monitoring these events may provide an early-warning tool to anticipate risk conditions, justify dynamic fishing closures, and support both sea turtle conservation and the socioeconomic viability of local communities.

MATERIALS AND METHODS

Study area

This analysis was conducted in the GU, Baja California Sur, Mexico. Although no official cartographic delimitation exists (Cortés-Ortiz et al. 2006, Ibarra-Rivera 2016), the region is generally recognized as extending between Punta Abreojos and Cabo San Lázaro. For this study, the area was defined as the region between 24.71-26.90°N and 114.40-112.00°W (Fig. 1). The GU lies under the influence of the CC, characterized by strong coastal upwelling and high primary productivity (Lynn & Simpson 1987, Lluch-Belda 2000). In addition to its ecological importance, the region is of significant socioeconomic importance, supporting small-scale fisheries and coastal communities that are highly dependent on marine resources (Salinas-Zavala et al. 2022).

Definition of a cumulative cold event

Based on the ectothermic physiology of sea turtles, a cold event was defined as any grid cell in which SST remained below 18°C for five or more consecutive days. This threshold was established because short-term exposures do not produce significant physiological effects, whereas prolonged exposures can induce lethargy, reduced swimming capacity, immunosuppression, or increased vulnerability to fishing nets (Schwartz 1978, Sieg 2010). The criterion of five consecutive days was empirically validated by analyzing

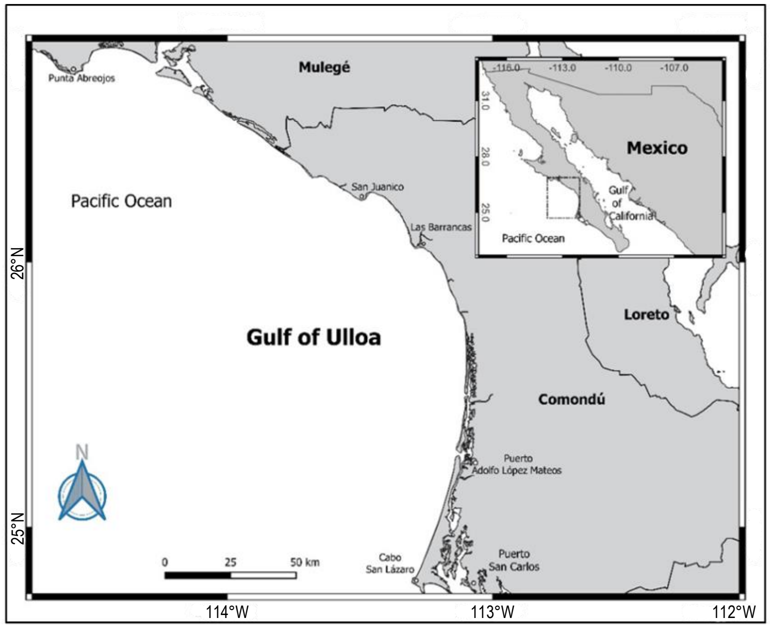

Figure 1. Location of the Gulf of Ulloa, Baja California Sur, Mexico. The inset map shows the location of the study area within northwestern Mexico.

strandings reported by Federal Attorney for Environmental Protection (PROFEPA, by its Spanish acronym) in the GU, obtained through the Mexican transparency system (request No. 330024423001504). Salinas-Zavala et al. (2020) demonstrated that when the number of days with SST < 18°C was compared with the monthly number of *C. caretta* strandings, the relationship followed an exponential pattern: as the number of cold days increased (up to a maximum observed of 31), the number of strandings rose sharply. Mortality began to increase noticeably after five consecutive cold days, thereby providing an operational justification for this threshold as an indicator of cumulative thermal risk.

Satellite data and processing

SST data were obtained from the Multi-scale Ultra-high Resolution (MUR) product, version 4.1, generated by the Jet Propulsion Laboratory (NASA-JPL), available at https://podaac.jpl.nasa.gov/dataset /MUR-JPL-L4-GLOB-v4.1, with a spatial resolution of 1.1 km² and daily coverage. Data download and the spatial subsetting for the GU region were automated using an R script (López-Ramírez et al. 2024).

Generation of spatial products

From the daily time series, the following products were derived:

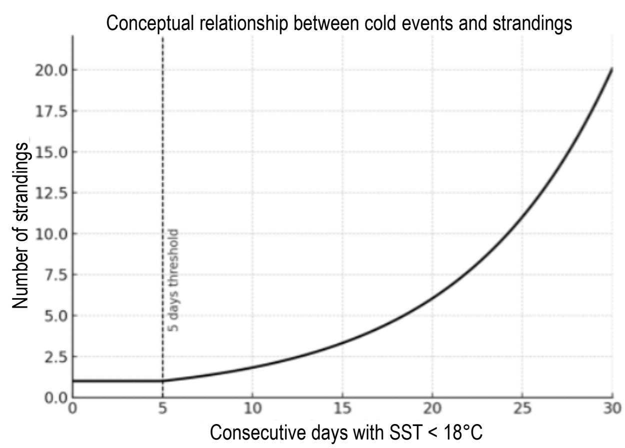

Figure 2. Conceptual relationship between the number of consecutive days with sea surface temperature (SST) < 18°C and the number of *Caretta caretta* strandings in the Gulf of Ulloa. The schematic model illustrates that the exponential increase is associated with prolonged cold-event duration, highlighting a critical threshold of five consecutive days (Salinas-Zavala et al. 2020).

- Monthly climatology of average cold events per cell (to identify seasonality).
- Annual sum of cold events per cell (to assess persistence and interannual variability).

Spatial processing was conducted in QGIS (QGIS Development Team 2024), using zonal statistics and map algebra functions to average and aggregate event counts per grid cell.

Identification of critical zones

Critical zones were defined as regions that experienced at least one cold event per year on average during 2003-2023, with emphasis on March-June, when coastal upwelling intensifies. These areas were compared with the known distribution of *C. caretta* and historical stranding patterns in the region (Salinas-Zavala et al. 2020). Interannual anomalies were also calculated by comparing each year's monthly climatology to identify exceptionally cold periods.

The overall workflow for building the cumulative thermal indicator is summarized (Fig. 3).

The diagram illustrates the sequential process followed in this study, including satellite data download and processing workflow, spatial filtering for the GU, detection of cold events (SST < 18°C for ≥5 consecutive days), generation of spatial products such as climatology and annual maps, and the identification of critical persistence zones. This methodological scheme ensures reproducibility and facilitates future applications of the indicator to other regions of the Mexican Pacific.

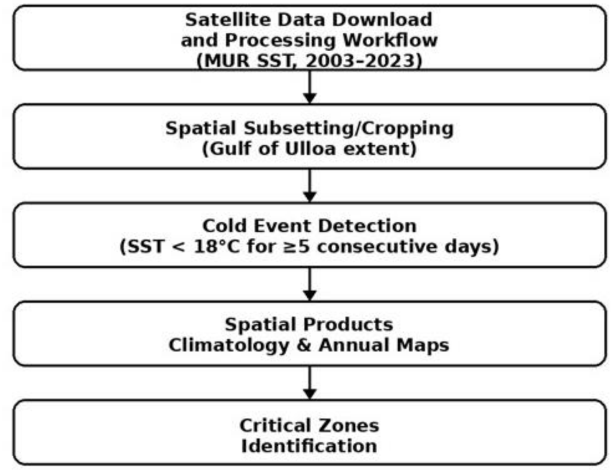

Figure 3. Methodological workflow used for the construction of the cumulative thermal indicator in the Gulf of Ulloa. The procedure included downloading daily Mur SST data (2003-2023), spatial subsetting of the study area, detection of cold events (SST < 18°C for ≥5 consecutive days), generation of spatial products (monthly climatology and annual maps), and identification of critical cold-event persistence zones.

RESULTS

The spatial analysis of SST in the GU revealed a high recurrence of cumulative cold events throughout the 2003-2023 period. These events occurred more frequently between March and June. They were mainly concentrated in the northern and coastal sectors of the study area, reflecting the seasonal intensification of coastal upwelling driven by alongshore winds and Ekman transport under the influence of the CC system. Interannual variability was pronounced. Figure 4 shows four representative years: (a) 2008, a cold year with extensive occurrence of cumulative events along the entire coastal zone; (b) 2015, an El Niño year with minimal presence of cold events, restricted to isolated oceanic areas; (c) 2011, a La Niña year with maximum persistence of cold events covering most of the northern and central GU; and (d) 2014, a warm anomaly year associated with the onset of the northeastern Pacific 'Warm Blob' (Cavole et al. 2016). These contrasts demonstrate how cold ENSO phases favor the intensification of events, whereas warm phases drastically reduce their incidence.

The total accumulation over the full period (2003-2023) reached 84 events in some grid cells in the northern and coastal sectors (Fig. 5). In contrast, the lowest values (<20) were observed in the southernmost portion and in deeper offshore areas. This pattern reveals marked spatial heterogeneity: northern coastal zones experience recurrent cold conditions, while central offshore areas exhibit an intermediate number of events. The spatial distribution reflects the influence of the CC and the locations of persistent coastal upwelling systems.

The monthly climatology (Fig. 6) confirmed a well-defined seasonal cycle: cold events were systematically concentrated between March and June, with a peak in April and May.

From July onward, the events became restricted to isolated offshore areas and nearly disappeared between September and November. In January, the regional cooling cycle resumed. This pattern coincides with the period of highest juvenile *C. caretta* residence in the GU, reinforcing the relevance of the cumulative indicator during this critical temporal window.

Finally, based on spatial recurrence, 18 critical polygons were identified (Fig. 7). These were distributed mainly across the northern and central GU, corresponding to areas where interactions between juvenile loggerhead turtles (*C. caretta*) and coastal fisheries have been historically documented (Peckham et al. 2007, Salinas-Zavala et al. 2020).

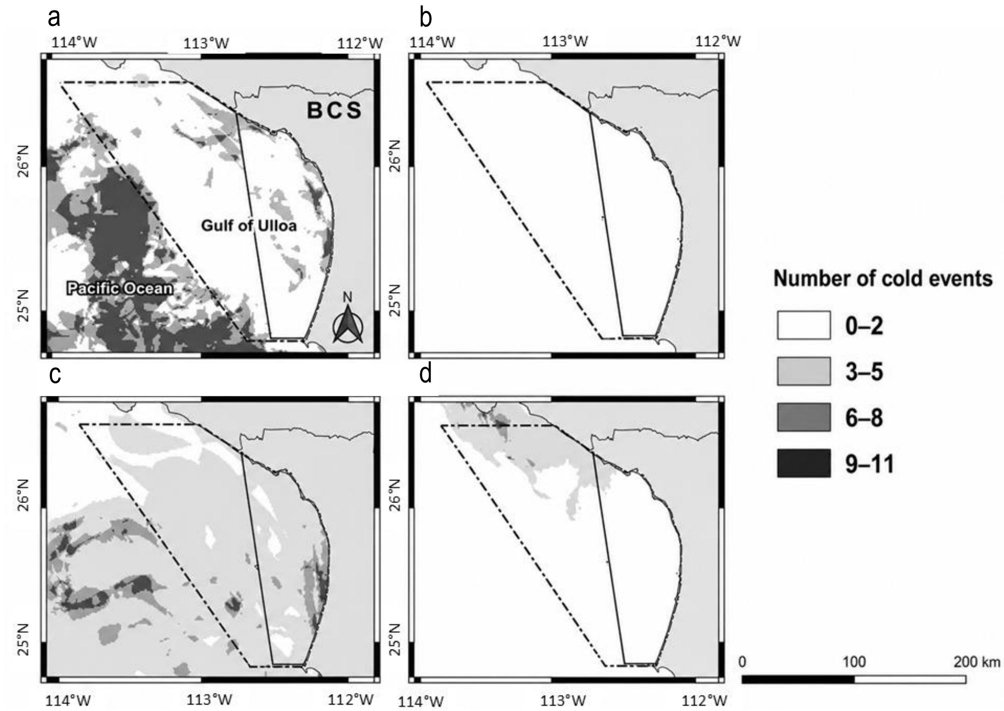

Figure 4. Representative annual maps of cumulative cold events in the Gulf of Ulloa under different climatic conditions: a) 2008, the coolest year; b) 2015, an El Niño year with minimal cold-event occurrence; c) 2011, a La Niña year with extensive cold-event persistence; and d) 2014, a year influenced by the northeastern Pacific marine heatwave ("Warm Blob") showing intermediate conditions. Grayscale intensity indicates the number of cold events (SST < 18°C for ≥5 consecutive days).

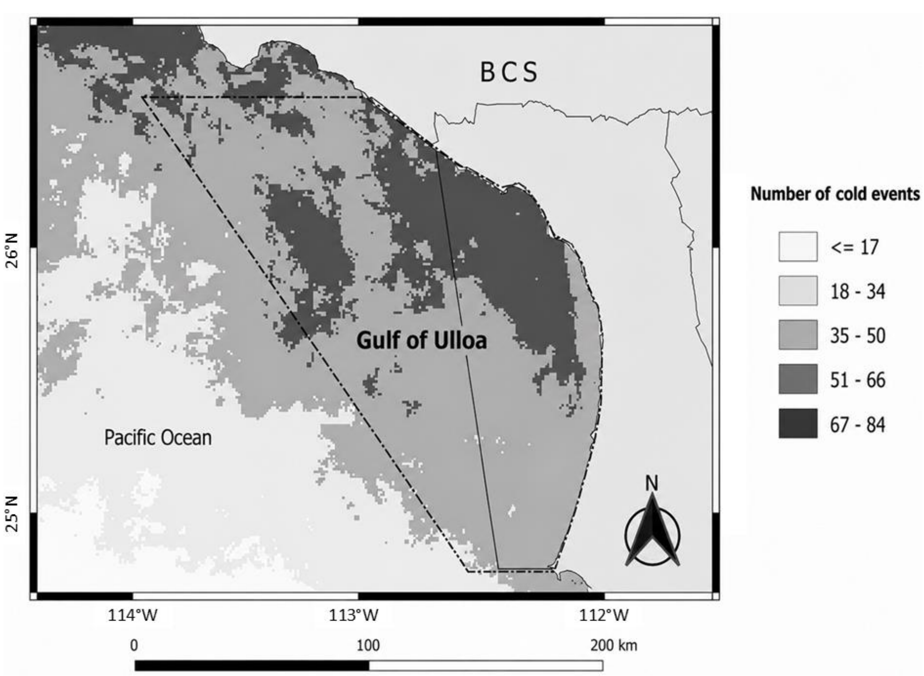

Figure 5. Total accumulation of cold events per grid cell in the Gulf of Ulloa during the 2003-2023 period. Grayscale intensity indicates the cumulative number of cold events (SST < 18°C for ≥5 consecutive days), highlighting the recurrent persistence of cold conditions in the northern and coastal sectors of the study area.

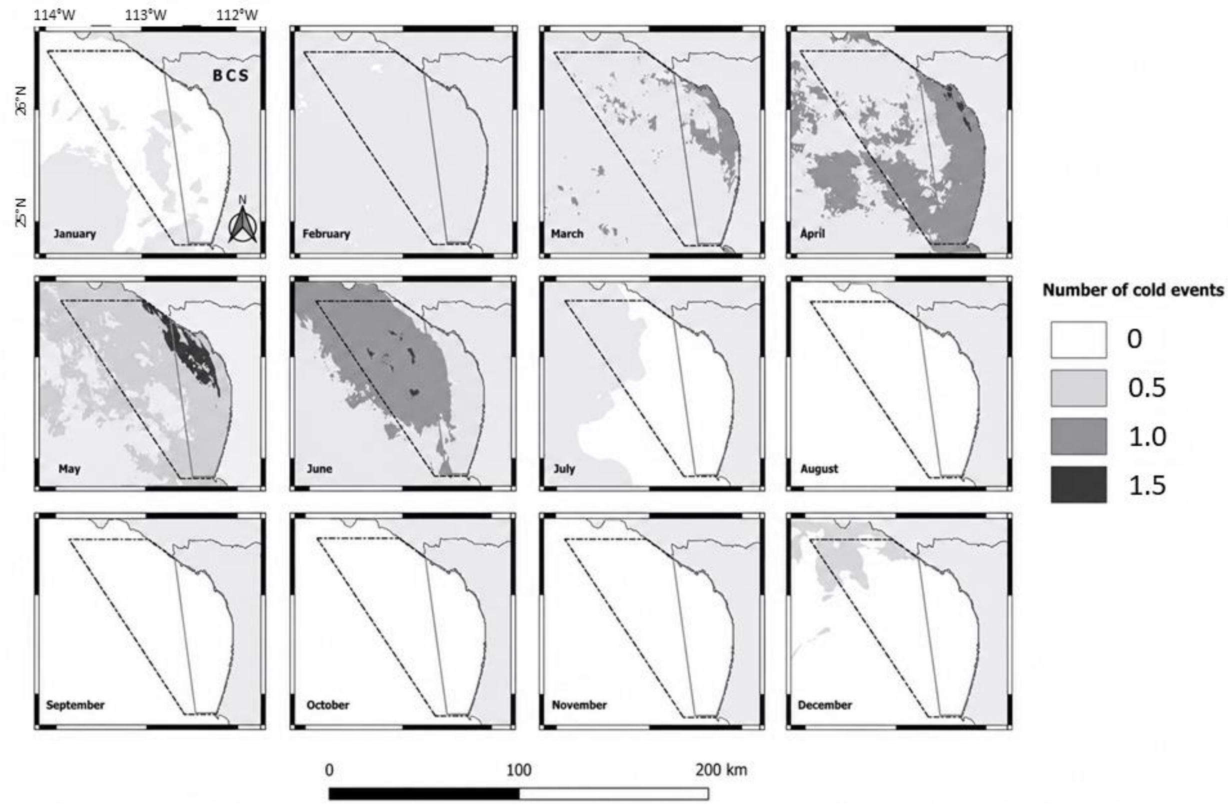

Figure 6. Monthly climatology of cumulative cold events in the Gulf of Ulloa during the 2003-2023 period. Grayscale intensity indicates the average monthly frequency of cold events (SST < 18°C for ≥5 consecutive days). The highest incidence and spatial extent of cold events occurred between March and June, particularly during April and May.

Compared with the fishing-restriction zones established by the Mexican federal government (DOF 2023), including a Temporary Partial Fishing Refuge Zone covering 19,934 km² and a Specific Fishing Restriction Area covering 7,244 km², the 18 polygons identified in this study are considerably smaller and spatially focused. Rather than encompassing broad management areas, these polygons correspond to recurrent cold-event hotspots identified from 21 years of satellite observations, highlighting the potential value of a dynamic approach over large static management measures. These areas represent the primary candidates for permanent monitoring of cold events and for the design of dynamic ocean management strategies.

DISCUSSION

The study by Schroeder et al. (2022) proposed the HCI as a dynamic metric to anticipate high-risk areas within upwelling systems. Our approach complements this framework by proposing an indicator based on adverse thermal accumulation rather than spatial compression. This distinction is particularly relevant in the GU, where the juvenile population of *C. caretta* exhibits prolonged residence in foraging areas rather than latitudinal displacements, as observed in other sectors of the North Pacific. In this context, persistent cooling conditions alter turtles' physiology and behavior, increasing their vulnerability.

The results confirm that cumulative cold events (SST < 18°C for ≥5 consecutive days) occur frequently in specific GU areas (Figs. 2, 4), coinciding with regions of high *C. caretta* presence and with historical stranding patterns (Salinas-Zavala et al. 2020). The monthly climatology (Fig. 6) reinforces that the March-June period is critical, while the critical polygons identified (Fig. 7) demonstrate that risk is concentrated in much narrower zones than the fishing restriction areas currently imposed by the federal government. These findings highlight the usefulness of the indicator for guiding more precise and efficient dynamic manage-

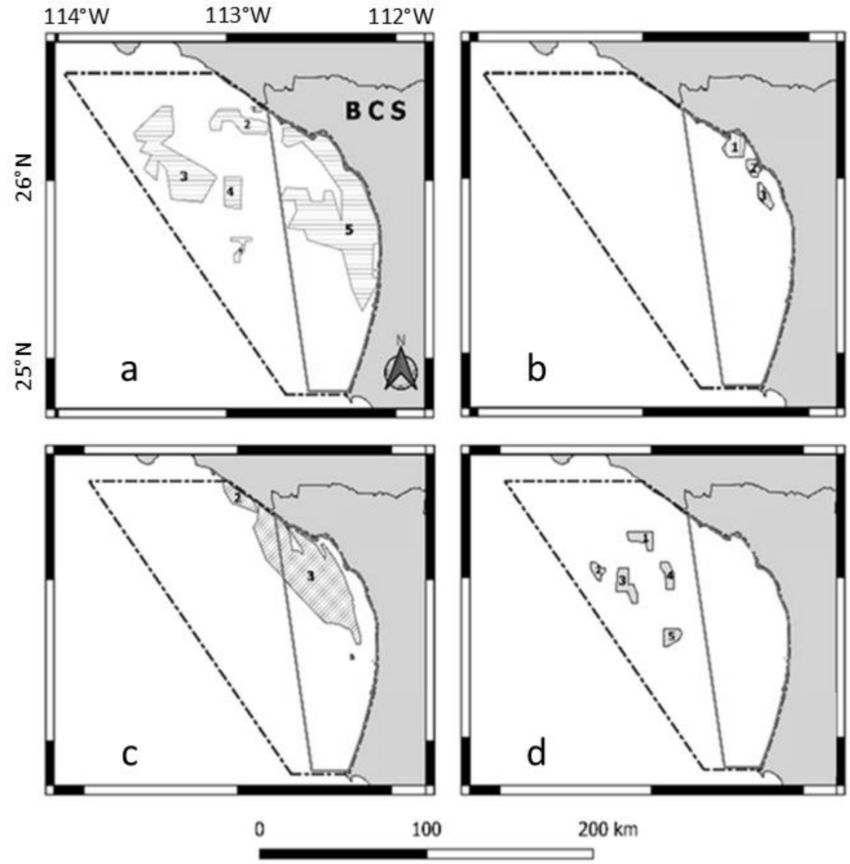

Figure 7. Proposed critical areas for permanent monitoring of cumulative cold events in the Gulf of Ulloa to support dynamic ocean management. Panels represent the seasonal distribution of critical polygons during: a) March, b) April, c) May, and d) June. These areas correspond to zones with recurrent persistence of cold events (SST < 18°C for ≥5 consecutive days) during the 2003-2023 period.

ment schemes. The criterion of five consecutive days is justified by both physiological evidence (Schwartz 1978, Sieg 2010) and empirical validation in the GU: the number of strandings increases exponentially as cold days accumulate, with five days representing the threshold at which adverse effects intensify (Salinas-Zavala et al. 2020). This dual validation confers robustness on the proposed indicator and distinguishes it from more generic metrics that rely solely on instantaneous SST thresholds. Unlike programs such as EcoCast in the USA, which rely on latitudinal distribution shifts (Welch et al. 2020), in the GU the risk does not depend on migratory movements but on persistent local conditions such as seasonal coastal upwelling, the accumulation of consecutive cold days (SST < 18°C), the resulting physiological vulnerability of juvenile *C. caretta* to prolonged cooling, and their extended residence within the region. This finding underscores the need to adapt dynamic indicators to the ecological particularities of each region.

This work contributes to the development of regional adaptive management tools, with potential replicability in other areas of the Mexican Pacific where critical megafauna habitats overlap with intensive extractive activities. However, the approach also has limitations: reliance on high-resolution, high-frequency satellite data; the need for institutional coordination to implement dynamic closures; and the need for acceptance by local fishing communities. Future work should integrate participatory processes, biological validations, and pilot applications to ensure its practical implementation.

In physical oceanography, temperature is considered a conservative variable at short time scales and in the absence of strong external forcing, since its variability is primarily driven by advection and diffusion rather than by instantaneous transformations (Lynn & Simpson 1987). In the GU context, the thermal inertia of the oceanic system acts as a risk modulator: adverse effects on ectotherms such as *C. caretta* depend not on instantaneous SST values but on the cumulative persistence of cold conditions. A sustained event can therefore be viewed as a form of "cumulative thermodynamic stress" that exceeds physiological thresholds, whereas short-term decreases do not have the same effect. This framework links ocean physics with ectotherm biology, strengthening the theoretical foundation of the proposed indicator.

CONCLUSIONS

Cumulative cold events (SST < 18°C for ≥5 consecutive days) occur frequently in the GU, particularly during spring, and represent a robust indicator of adverse environmental conditions for *C. caretta*. The five-day threshold is supported by both physiological evidence and the empirical relationship between cold days and strandings, providing scientific and operational reliability. The methodology enables the generation of near-real-time thermal risk maps using freely available satellite data, offering a practical and replicable tool for other systems along the Mexican Pacific. By focusing on thermal persistence rather than instantaneous thresholds, this approach enhances the ecological sensitivity of monitoring and aligns with best international practices in DOM. The proposed indicator constitutes an innovative regional-scale contribution, with the potential to guide more targeted dynamic fishery closures that reconcile sea turtle conservation with the socioeconomic viability of fishing communities.

Credit author contribution

C.A. Salinas-Zavala: conceptualization, validation, methodology, formal analysis, writing-original draft, funding acquisition; M.V. Morales-Zárate: formal analysis, methodology, validation, supervision, review and editing; F. Chávez-Juárez: formal analysis, validation, supervision, review and editing; M.M. Lara-Uc: formal analysis, supervision, review and editing; S. Martínez-Díaz: formal analysis, review and editing; J.A. López-Ramírez: data curation, methodology, formal analysis, review and editing. All authors have read and accepted the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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