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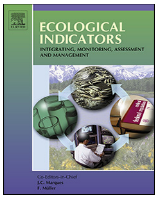

Original Articles

Environmental indicators to reduce loggerhead turtle bycatch offshore of Southern California

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ABSTRACT

Extreme climatic events are expected to become more frequent under current conditions of increasing global temperatures and climate variability. A key challenge of fisheries management is understanding and planning for the effect of anomalous oceanic conditions on the distributions of protected species and their interactions with fishing gear. Atypical marine states can cause non-target species to shift outside of their normal distribution patterns, leading to unwanted bycatch events that threaten fisheries sustainability. Environmental indicators can serve as early warning signals that allow for proactive management responses before significant bycatch occurs. Marine heatwaves in the Pacific have caused shifts in the distributions of endangered loggerhead turtles *(Caretta caretta)*, increasing overlap with California's Drift Gillnet fishery and thereby the risk of turtle bycatch events. To reduce bycatch, a fishery closure offshore of Southern California – The Loggerhead Conservation Area – Is enacted when an El Niño event has been declared and local sea surface temperatures (SSTs) are warmer than normal. However, this regulation was based on qualitative assessment of bycatch that occurred during past El Niño events, and no explicit threshold for SST anomalies was defined. Additionally, closures enacted under the current regulation rely on structured expert decision-making. Providing a quantitative indicator could help to refine future decisions. We developed and evaluated potential new indicators to guide the Loggerhead Conservation Area closure timing based on thermal indices in three different regions: the equatorial Pacific, regional areas offshore of Southern California, and temperate pelagic areas off the US west coast. Our objectives were to: 1) quantify thermal indicators and their respective thresholds to guide closure timing, and 2) hindcast closure scenarios based on these indicator thresholds to evaluate efficacy in terms of opportunity costs to fishers and ability to avoid turtle interactions. The best indicator in terms of avoiding historical turtle interactions while minimizing opportunity cost to fishers was a six-month average local SST anomaly indicator with closures enacted above a threshold of 0.77 °C. This result can improve upon the current closure guidelines by providing a quantified and spatially-explicit indicator and threshold to supplement the structured decision-making process. Our analysis demonstrates a novel approach to developing fisheries management strategies for species with a paucity of data. Issues with data comprehensiveness are frequently present in fisheries management exercises, and precautionary approaches are needed to allow adherence with legislation while considering the best available science.

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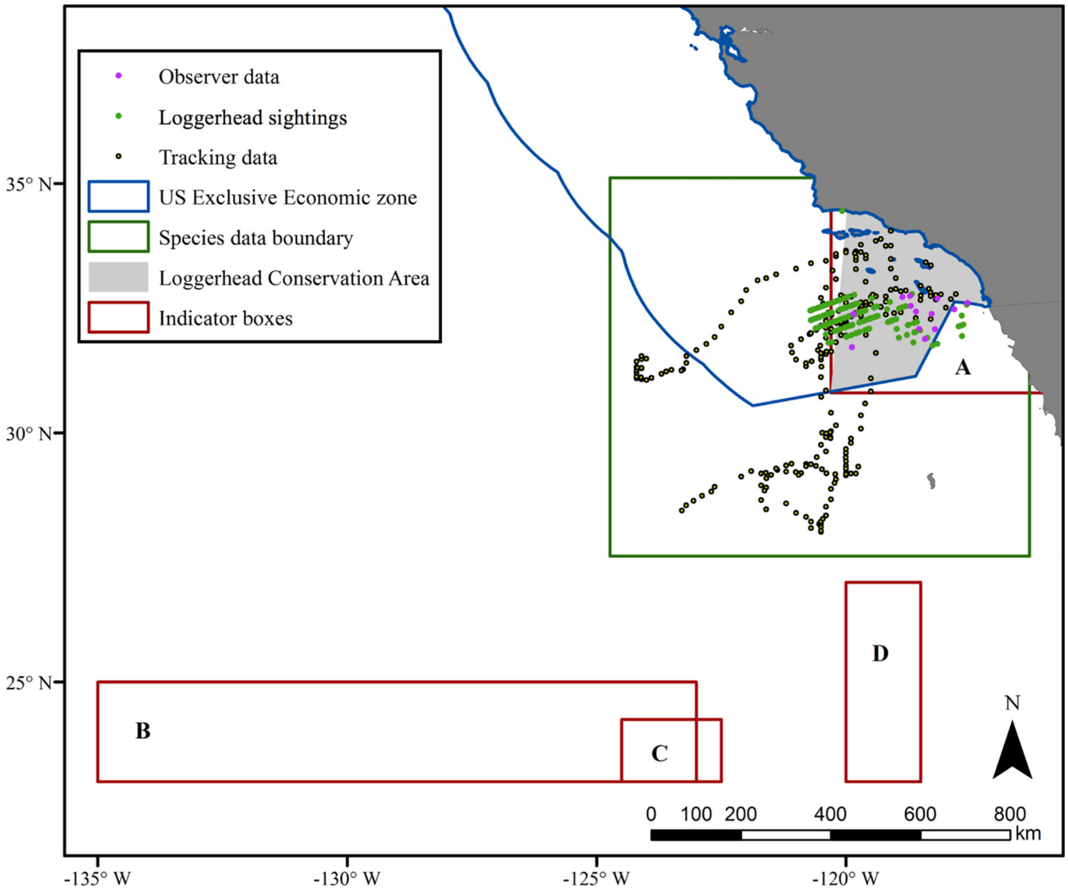

Fig. 1. The study area. The map shows the extent of the three loggerhead datasets, management boundaries, and the boxes used to define the local SST anomaly (A) and pelagic SST (B-D) indicators.

1. Introduction

The current rate of increase in oceanic and atmospheric heat content has increased the frequency and duration of marine heatwaves, or "prolonged discrete anomalously warm water events" (Hobday et al., 2016); a trend that is expected to continue (Oliver et al., 2018) in conjunction with changes in the strength, direction, and variability of major ocean currents (Hoegh-Guldberg and Bruno, 2010). These anomalous marine states can significantly alter the distributions of marine species as they shift to remain within their thermal tolerance limits or to exploit resources in newly suitable habitat (Ling, 2008; Wernberg et al., 2013). Changes in ecosystem structure can have direct impacts on marine fisheries, both in terms of target catch composition (Pearcy, 1987; Glynn, 1988; Ñiquen and Bouchon, 2004) and unwanted interactions with non-target species, or bycatch (MacKenzie et al., 2014).

A key challenge of ecosystem-based fisheries management is providing the tools to understand and plan for the effect of anomalous oceanic conditions on the distributions of marine species and their interactions with fishing fleets. To implement ecosystem-based fisheries management, timely information on significant fluctuations in ecosystem condition is required. Environmental indicators – Time-series of physical or biological variables that communicate information on environmental state – Can serve as early warning signals that allow for adaptive management to address interactions between marine species and fishing fleets before significant impacts occur (Skern-Mauritzen et al., 2016). Management actions such as time/area closures or input/output controls are triggered when indicators cross threshold values, i.e. predefined reference points over or below which negative fisheries impacts have been demonstrated to occur. For example, a sandeel (*Ammodytes marinus*) fishery in the northwestern North Sea is closed when seabird colony productivity falls below a threshold level (Wright et al., 2002). Temperature is used as a scaling factor in the harvest control rule for the Pacific sardine (*Sardinops sagax*) stock, which is more productive under warmer temperatures and less productive under cooler conditions (Kvamsdal et al., 2016). In an anchovy (*Engraulis encrasicholus*) fishery in the Mediterranean Sea, a chlorophyll-a index is used to inform growth rates in the stock model (GFCM, 2012). Similar approaches can be employed to avoid protected species bycatch events when driven by environmental conditions. For example, a dynamic ocean management tool – TurtleWatch (Howell et al., 2008) – Uses a temperature window to help Hawaii-based pelagic longline fishers reduce bycatch likelihood by avoiding waters that are thermally suitable for vulnerable loggerhead turtles (*Caretta caretta*).

Loggerhead bycatch in California's Drift Gillnet Fishery has been managed through implementing regulations using temperature-based guidelines since 2003 (50 CFR §660.713 (c)(2)). Loggerheads have been known to enter waters offshore of Southern California during anomalously warm years, resulting in overlap with the Drift Gillnet Fishery and increased likelihood of bycatch events. However, the mechanisms driving loggerheads to utilize this habitat are unknown (Eguchi et al., 2018). In the North Pacific, loggerheads emerge from nesting beaches in Japan and move to juvenile habitats in oceanic waters of the Central North Pacific (Polovina et al., 2000). An unknown proportion of these turtles transition from the Central North Pacific to the eastern Pacific (Tomaszewicz et al., 2015; Briscoe et al., 2016), where a foraging hotspot is present along the Pacific coast of the Baja California Peninsula, Mexico. Large numbers of loggerheads may also be present farther north, in the Southern California Bight region, where they reside for unknown periods often coinciding with warm water periods (Allen et al., 2013; Eguchi et al., 2018).

Two hypotheses have been proposed to explain periodic loggerhead presence offshore of Southern California. First, loggerheads in developmental areas off of Baja, Mexico may migrate northward. Warm Pacific Equatorial Water enters the near-shore region south of Southern California and is advected northward by the California Undercurrent, a subsurface poleward current running along the North American west coast. During the fall of 2015, an increase of loggerhead sightings offshore of Southern California coincided with anomalously warm waters associated with the 2014–16 North Pacific marine heat wave (Bond et al., 2015; Zaba and Rudnick, 2016; Rudnick et al., 2017; Jacox et al., 2016; Eguchi et al., 2018). Second, turtles offshore of Southern California may migrate eastward from the Central North Pacific. Under this hypothesis, warming waters in the Eastern North Pacific form an ecological bridge that allows juveniles to move eastward to access the more productive waters offshore of Southern California (Briscoe et al., 2016; Briscoe et al., 2017). A study of body sizes and stable isotope values indicates that loggerheads off California most likely have Central Pacific origins (Allen et al., 2013), although the long-term constancy of this pattern warrants further study.

The Drift Gillnet Fishery targets swordfish (*Xiphias gladius*) in waters offshore of Central and Southern California. Since the 1990s, 16 loggerhead bycatch events have been recorded in the fishery, all of which occurred in Southern California. To reduce loggerhead bycatch offshore of Southern California, a federally mandated closure – The Loggerhead Conservation Area (Fig. 1) – Was implemented in 2003 (50 CFR §660.713). Under this regulation, the National Marine Fisheries Service is required to enact the fishery closure in months between June and August when there are warmer than normal sea surface temperatures (SSTs) present offshore of Southern California for years during which an El Niño event has been forecast declared (50 CFR §660.713 (c)(2)). Specifically, SST data from the second and third months prior to the closure month are used to determine whether warm conditions associated with El Niño are present offshore of Southern California. For example, temperatures in March and April are used to determine the closure status in June. Since the guidelines went into effect, the closure has been enacted during three full month periods: August 2014, June-August 2015, and June-August 2016 (over seven months closed in total).

However, these closure guidelines were developed based on relatively few loggerhead bycatch events, all of which occurred in anomalously warm ocean conditions. Furthermore, the closure guidelines are qualitative in nature (“temperatures warmer than normal”), with no explicit closure threshold or region for temperature observation. Since the initial guideline definition, additional data have been collected on loggerheads in the area via aerial surveys, shipboard surveys, sighting reports from the public and satellite telemetry. With these additional data, we aimed to re-examine the relationships between loggerhead presence offshore of Southern California and thermal indicators to provide a quantitative and spatially explicit indicator and threshold to inform Loggerhead Conservation Area closure timing. Our objectives were to 1) quantify the thermal indicators and their respective thresholds to guide Loggerhead Conservation Area closure timing, and 2) hindcast closure scenarios based on these indicator thresholds to evaluate efficacy in terms of opportunity costs to fishers and ability to avoid turtle interactions. Despite much evidence demonstrating the influence of the fluctuating environment on stock status (Hannesson, 2007; Ottersen et al., 2013; Vert-pre et al., 2013), environmental indicators are infrequently included in operational fisheries management (Kvamsdal et al., 2016). Our study seeks to demonstrate the feasibility of the explicit incorporation of an environmental metric into fisheries regulation, thereby aiding a movement towards fisheries management strategies that are responsive to climate variability and change.

2. Methods

2.1. Loggerhead distribution data

This study used fisheries dependent and independent datasets. Loggerhead bycatch events (n = 16 turtles) in the California Drift Gillnet Fishery have been recorded since 1990 through the observer program managed by the National Marine Fisheries Service’s West Coast Regional Office. Independent datasets (hereafter: sighted turtles) included an aerial line-transect survey during September and October 2015 (n = 215 turtles, see details of survey methodology in Eguchi et al., 2018), a citizen science loggerhead sighting hotline from April 2015 to July (Briscoe et al., 2017), and a satellite telemetry study conducted by National Marine Fisheries Service’s Southwest Fisheries Science Center in 2015 and 2016 (n = 3 tagged turtles).

2.2. Indicator selection and quantification

Three indicator groups were evaluated to test the two loggerhead presence hypotheses over a variety of spatial and temporal scales: El Niño indicators, local SST anomaly indicators, and a pelagic SST indicator. The El Niño indicators were selected to test the effect of broad scale climate forcing on loggerhead distribution. The local SST anomaly indicator was selected to test if local conditions drive turtle presence in waters offshore of Southern California, either by allowing turtles to enter the relatively more productive nearshore environment to exploit resources during anomalously warm periods (e.g. red crabs, *Pleuronocodes planipes*, Eguchi et al., 2018), or by providing a closer-to-shore route for turtles transiting between the Central North Pacific and Baja California Sur, Mexico. The final indicator, pelagic SST, was selected as a proxy for environmental mechanisms that operate over scales intermediate (hundreds of kilometers) to the broad climate forcing captured by the El Niño indicators and regional mechanisms captured by the local SST anomaly indicators.

The El Niño indicators were quantified using the monthly Niño-3.4 index, a time-series of temperature anomalies in the Niño-3.4 region (from 170 °W to 120 °W and 5 °S to 5 °N; http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/detrend.nino34.ascii.txt). The local SST anomaly indicators were quantified using a data assimilative implementation of the Regional Ocean Modeling System (ROMS) configured for the California Current System (Moore et al., 2013; Neveu et al., 2016). Monthly ROMS SST anomalies were averaged over box A (Fig. 1 and Table 1). Three different smoothing windows were applied to the El Niño and local SST anomaly data to account for different lags of turtle response to environmental fluctuations, such as the transiting time to reach waters offshore of Southern California or the time it takes turtles to aggregate in high enough densities to be detected in the datasets. The smoothing windows were: one-month (i.e. conditions in the month directly preceding the closure month), two-months (i.e. the average condition in the second and third months preceding the closure month, as in the existing rule), and six-months (i.e. the average condition in the six months preceding the closure month). For the El Niño indicators, thresholds were the mean Niño-3.4 index value calculated across the same smoothing window (one-month, two-months, or six-

Table 1
Coordinates of the boxes used to define the local SST anomaly (A) and pelagic SST (B–D) indicators. Box letters are consistent with Fig. 1.

	Coordinates (decimal degrees)			
Box name	North	East	South	West
Local anomaly box (A)	34.5	−116	30.8	−120.3
Pelagic SST box (B)	25	−123	23	−135
Pelagic SST box (C)	24.25	−122.5	23	−124.5
Pelagic SST box (D)	27	−118.5	23	−120

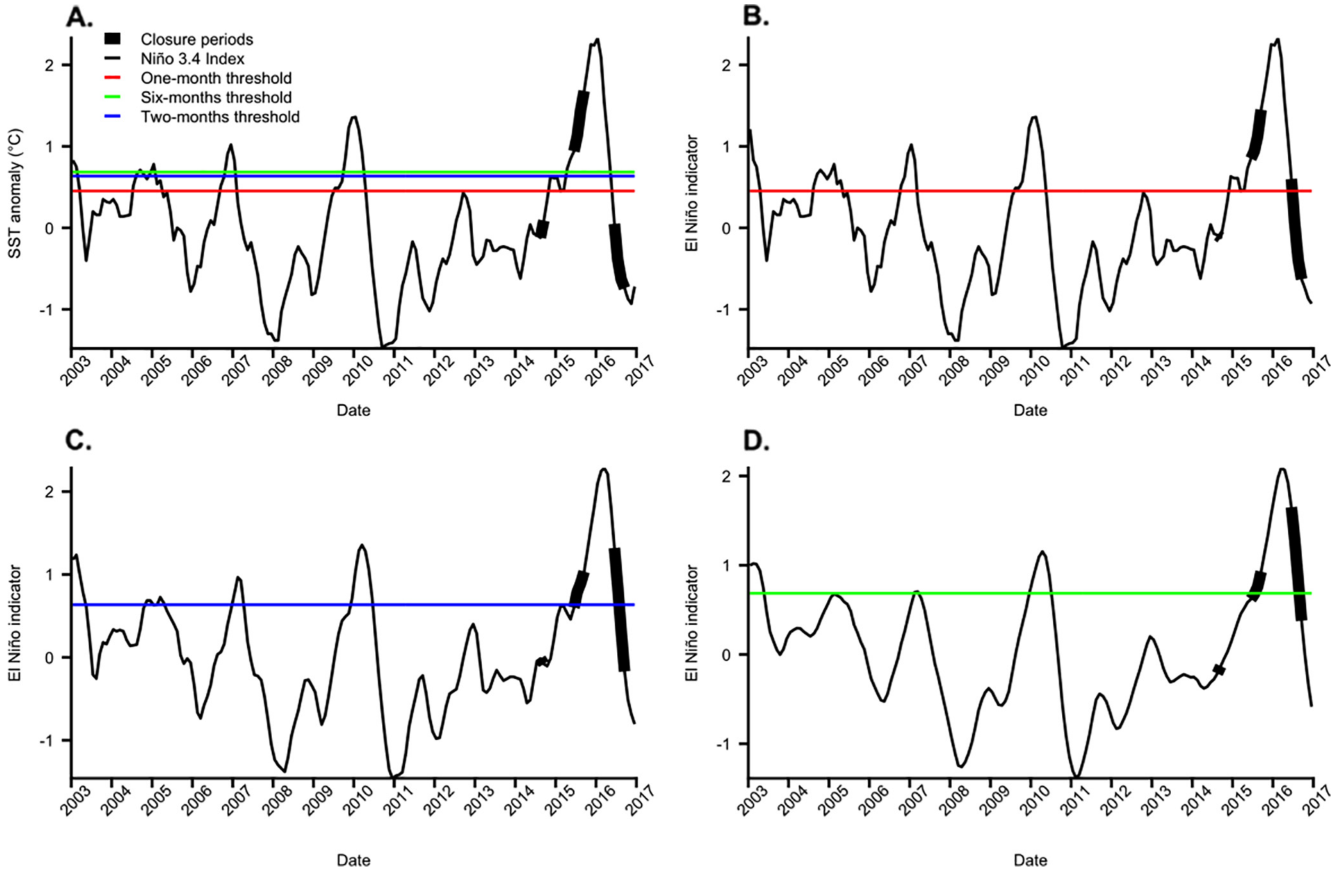

Fig. 2. The El Niño indicators and thresholds. (A) The raw Niño-3.4 index. (B) One-month average indicator. (C) Two-month average indicator. (D) Six-month average indicator. Thresholds are the averages of Niño-3.4 index values in monthly windows preceding the three historical closure periods (thick black line segments). Closures would be enacted when indicator values exceed thresholds.

months) preceding the three full month historical closure periods (August 2014, June-August 2015, and June-August 2016). For the local SST anomaly indicators, thresholds were the minimum monthly anomaly value within the smoothing window preceding the three historical closure periods.

To quantify the pelagic SST indicator, data from a monthly SST satellite product generated by NOAA CoastWatch-West Coast and NOAA Southwest Fisheries Science Center from data provide by NASA's Jet Propulsion Laboratory (JPL MUR MEaSUREs Project, 2010) at 0.01° resolution were downloaded from Environmental Research Division's ERDDAP (Simons, 2017, https://coastwatch.pfeg.noaa.gov/erddap/griddap/jplMURSST41mday). These data were used to construct a gridded time-series of mean monthly SST for each calendar month from 2003 to 2017. Monthly SST time-series in each grid cell were correlated with a time-series of yearly turtle sightings between 2003 and 2017, which was generated by combining all loggerhead distribution datasets (see Section 2.1, Table A1, Appendix A), to produce monthly spatial correlation maps. Two methods were tested to handle years with no turtle sightings ($n = 7$): 1) turtles were assumed to be absent, and 2) years with no sightings were removed. This analysis identified parts of the ocean that were highly correlated with turtle presence offshore of Southern California. Areas with high correlation coefficients (> 0.75) for both methods of handling years with no turtle sightings were further explored to find areas of persistently high correlation across months in order to define candidate pelagic SST boxes (e.g. a box that has persistent correlation across January, February, and March). Then for each month, the box most correlated with turtle presence offshore of Southern California was identified, and its monthly threshold was calculated as the mean of SST in that month within the box across years when turtles were seen offshore of Southern California (Table A1, Appendix A).

2.3. Hindcasting indicator efficacy

To test relative indicator efficacy, three hindcast metrics were used: the opportunity cost to fishers (i.e. the number of months the closure was enacted between 2003 and 2017, the same time period over which the current guidelines have been employed), the overlap with sighted turtles, and the proportion of historical bycatch avoided. To evaluate each metric, the seven indicators (the El Niño indicators and local SST anomaly indicators, each calculated over three smoothing windows, and the pelagic SST indicator) were hindcast, and thresholds were used to determine closure status. Because the monthly SST dataset used to quantify the pelagic SST indicator only spans 2003-present, an SST product generated by NOAA CoastWatch-West Coast and NOAA Southwest Fisheries Science Center (https://coastwatch.pfeg.noaa.gov/erddap/griddap/erdPH2sstamday) at ~0.04° resolution from data provided by the Pathfinder program (Casey et al., 2010) was utilized to hindcast earlier dates. The current guidelines consider local temperatures and El Niño declarations in tandem; therefore an eighth indicator that combined El Niño and local SST anomalies was also considered. In the combined indicator scenario, thresholds for both the six month El Niño and local SST anomaly indicators must be exceeded in order for the closure to be enacted. Two closure window scenarios were hindcast and compared, 1) a partial closure window scenario in which the closure may be enacted in June, July, and/or August (following the current guidelines), and 2) a full closure window scenario in which the closure may be enacted in any month of the year.

3. Results

3.1. Indicator quantification and evaluation

During the time period the current guidelines have been in effect (2003–2017), there have been six El Niño events (2002–03, 2004–05, 2006–07, 2009–10, 2014–15, and 2015–16), defined by at least five straight months of Oceanic Niño Index values above 0.5. Niño-3.4 anomaly thresholds for the El Niño indicators (Fig. 2) increased with smoothing window width: 0.45 (one-month threshold), 0.64 (two-months threshold), and 0.69 (six-month threshold). This trend derives from the fact that closures are enacted during summer months when Niño-3.4 anomalies are generally small, while longer averaging times capture winter/spring periods closer to the peak strength of El Niño events. Under the full closure window scenario, the declared El Niño events of 2002–03, 2006–07, 2009–10, and 2015–16 each would have resulted in enacted closures for the three El Niño indicators (Fig. 2). Also under the full closure window scenario, weak El Niños in 2004–05 and 2014–15 would have resulted in closures under the one-month indicator (Fig. 2B), and the 2004–05 event would have resulted in an additional closure under the two-month indicator (Fig. 2C).

Thresholds for the local SST anomaly indicators (Fig. 3) were 0.92 (one-month threshold), 1.40 (two-month threshold), and 0.77 (six-month threshold). These thresholds are sensitive to the monthly SST fluctuations of 2014–2016, as each threshold is derived from a different set of months. The two-month threshold uses an SST anomaly from May 2014, which was relatively warm compared to the SST anomalies used by the one-month and six-month thresholds in May 2016 and February 2014, respectively. In all three cases, closures would have been enacted each year from 2014 to 2016 (Fig. 3). El Niño events prior to 2014 had weaker impacts on SST anomalies offshore of Southern California and would not have triggered closures, with the exception of the 2006–07 event under the one-month indicator and the full closure window scenario (Fig. 3B).

Spatial correlation analyses between loggerhead presence offshore of Southern California and pelagic SST (Fig. A1, Appendix A) revealed three areas with high correlations (> 0.75) that persisted across several months: pelagic box B for July – September, pelagic box C for May – July, and pelagic box D for January – May (Fig. 1, Table 1, Fig. A2. Appendix A, Table 1). Of the three pelagic boxes, box B had SST most strongly correlated with turtle presence offshore of Southern California in July, August, and October-December ($0.45 \le R \le 0.93$), box C was most strongly correlated in February, June, and September ($0.86 \le R \le 0.91$), and box D was most strongly correlated in January and March through May ($0.80 \le R \le 0.84$) (Table A2, Appendix A). Thresholds (calculated as the mean temperature across years turtles were seen offshore of Southern California) for the most correlated box in each month ranged from 18.88 °C in March in box D to 23.12 °C in September in box C (Table A2, Appendix A). Based on these thresholds, closures would have been enacted in 2003–04, 2009, and 2014–16 under the full window closure scenario (Fig. 4).

3.2. Hindcasting indicator efficacy

The El Niño/local anomaly combined indicator had the lowest opportunity cost to fishers, resulting in closures 3.6% and 10.7% of the time across the 2003–2017 time-series under the partial and full closure windows, respectively (Table 2). This was closely followed by the two-month and six-month local SST anomaly indicators, resulting in closures 2.4% & 11.9% and 5.4% & 18.5% of the time under the partial

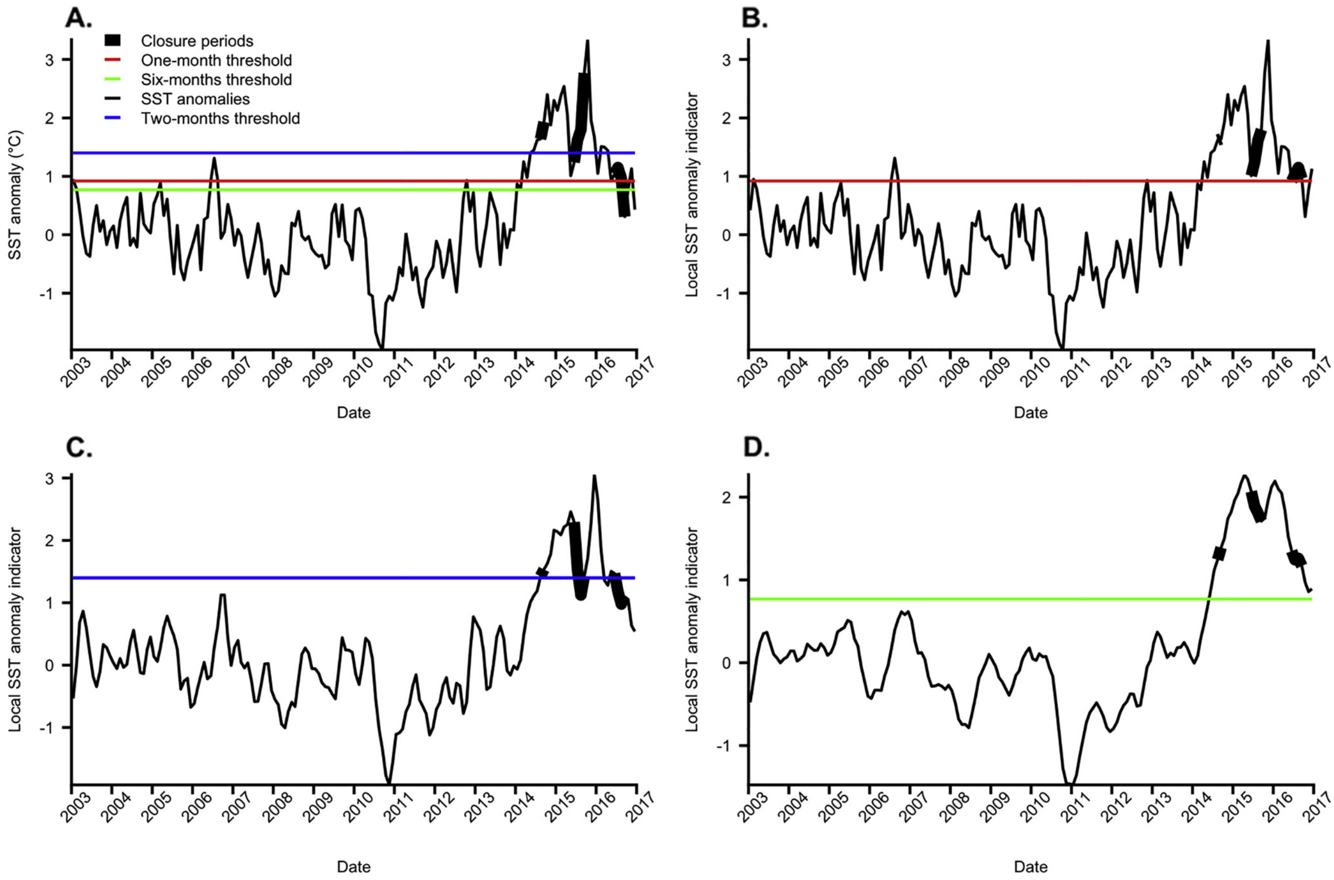

Fig. 3. The local SST indicators and thresholds. (A) The raw ROMS SST anomalies. (B) One-month indicator. (C) Two-month average indicator. (D) Six-month average indicator. Thresholds are the minimum monthly ROMS SST anomaly values in monthly windows preceding the three historical closure periods (thick black line segments). Closures would be enacted when indicator values exceed thresholds.

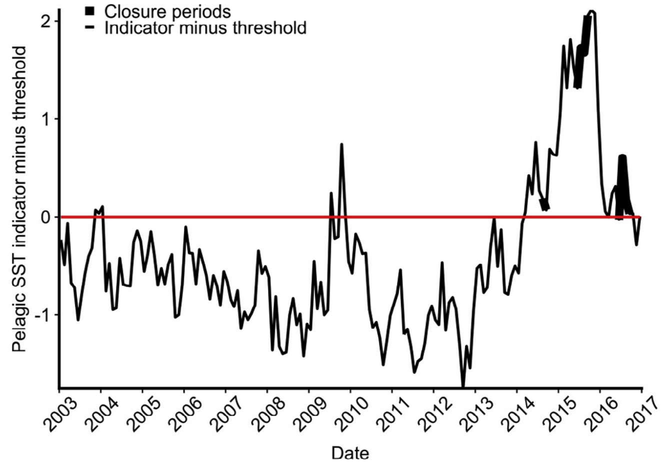

Fig. 4. The pelagic SST indicator and threshold. Time-series shows the monthly SST value in the box most correlated with turtle presence in waters offshore of Southern California (i.e. the indicator), minus the threshold. For each month, thresholds are the average monthly temperature calculated across years turtles were seen offshore of Southern California. Closures would be enacted when the time-series is greater than zero (i.e. when indicator values exceed thresholds).

and full closure window scenarios, respectively. All eight indictors (the El Niño indicators and local SST anomaly indicators, each calculated over three smoothing windows, the pelagic SST indicator, and the El Niño/local anomaly combined indicator) overlapped with the majority of sighted turtles under the full closure window scenario (minimum of 95.1% avoided in the two-month local SST anomaly indicator), largely due to the coincidence of elevated turtle sightings with anomalous warming in 2015 that resulted in closures for all indicators. Overlap with sighted turtles decreased to 6.7–10.8% under the partial closure window scenario. Under the full closure window scenario, the six-month local SST anomaly indicator outperformed all other indicators by 30–55% in terms of avoided bycatch, avoiding all but two historical bycatch events, in 2001 and 2006 (Table 2, Fig. 5). Under the partial closure window scenario, seven historical bycatch events were not avoided. Due to superior performance in terms of low opportunity cost and avoidance of both sighted and bycaught turtles (Fig. 5), the six-month local SST anomaly indicator (Fig. 3D) was selected as the best indicator to inform closure timing.

4. Discussion

We developed and explored a suite of environmental indicators designed to inform the timing of the Loggerhead Conservation Area closure to reduce loggerhead bycatch in California's Drift Gillnet Fishery. We found the six-month local SST anomaly indicator (Figs. 3D and 5) to have the highest overlap with loggerhead presence offshore of Southern California with a low opportunity cost to fishers. Notably, while an expected strong El Niño in 2014–15 largely failed to materialize, waters offshore of Southern California were extremely warm owing to a separate event – The northeast Pacific warm anomaly commonly referred to as 'the Blob' (Bond et al., 2015; Zaba and Rudnick, 2016), which coincided with elevated loggerhead sightings. In cases like this and others, temperatures along the US west coast are not necessarily closely tied to ENSO variability (Fiedler and Mantua, 2017). The local SST anomaly indicator enables tracking of turtle responses to warm events independent of El Niño. While El Niño events were reflected in all indicators to some degree, the El Niño based indicators had decreased ability to avoid turtle interactions despite increased opportunity cost. Additionally, the pelagic SST indicator also had a decreased ability to avoid turtle interactions. These results postulate that turtles are most directly responding to local temperature conditions as opposed to broad-scale climate forcing (tested via the El Niño indicators) or intermediate mechanisms proxied by the pelagic SST indicators; however, given paucity of the loggerhead datasets, more distribution data are needed to fully parse out the environmental mechanisms driving loggerheads to waters offshore of Southern California.

The strength of the six-month local SST anomaly indicator over the two-and one-month local SST anomaly indicators suggests that loggerhead presence offshore of Southern California is tied not just to warm temperatures, but to persistently warm temperatures. However, additional information on loggerhead residency time offshore of Southern California and movement data on eastward migrating juveniles is needed to understand the ecological processes captured by the six-month lag. One possible mechanism for the delay in response is the transiting time it takes turtles in the Central Pacific or off the Baja California Peninsula to reach warming waters offshore of Southern California. Another possible mechanism is that it takes several months of locally suitable thermal conditions for turtles to aggregate offshore of Southern California in high enough densities to be detected in the sightings and/or fisheries data sets. Additional tagging studies and stable isotope analyses (e.g. Allen et al., 2013) could help elucidate the processes underpinning loggerhead habitat usage offshore of Southern California.

4.1. Operationalizing the indicator

Environmental indicators must be sophisticated enough to accurately capture information on ecosystem state, yet simple and cost-effective enough to be integrated into management schemes. These dual objectives can be in direct competition – Indicator quality can come at a cost of increased complexity (Hilborn, 2012), which can lead to implementation barriers (e.g. increased monitoring costs, challenges communicating information to managers and stakeholders). We tested

Table 2

Evaluating the efficacy of thermal indicator groups. Hindcast closure scenarios based on indicator thresholds were used to quantify opportunity costs to fishers (number of months between 2003 and 2017 in which the closure was enacted), overlap with sighted turtles, and ability to avoid turtle bycatch. Bolded values indicate the best performing indicator for each evaluation metric. Values for each metric under the partial and closure window scenarios are shown separated by a "/", respectively. Percent overlap with the seven months the closure was historically enacted is shown in the far-right column.

	Indicator	Opportunity cost	Overlap with sighted turtles	% Bycatch avoided	Overlap
El Niño	One-month average	3.6/27.4%	10.8/100.0%	25.0/43.8%	57.1%
	Two-months average	4.2/28.0%	**10.8/100.0%**	37.5%/50.0%	71.4%
	Six-months average	6.5/28.0%	10.8/98.9%	43.8%/56.3%	85.7%
Local	One-month average	6.5/21.4%	**10.8/100.0%**	37.5%/50.0%	100.0%
	Two-months average	2.4/11.9%	6.7/95.1%	37.5%/50.0%	57.1%
	Six-months average	5.4/18.5%	**10.8/100.0%**	56.3%/87.5%	100.0%
	Pelagic SST	5.4/22.0%	10.4/99.6%	25.0%/31.3%	85.7%
	El Niño/local anomaly combo	**3.6/10.7%**	10.8/98.9%	43.8%/56.3%	85.7%
	Possible totals	168 months	268 sightings	16 bycatch events	7 closures

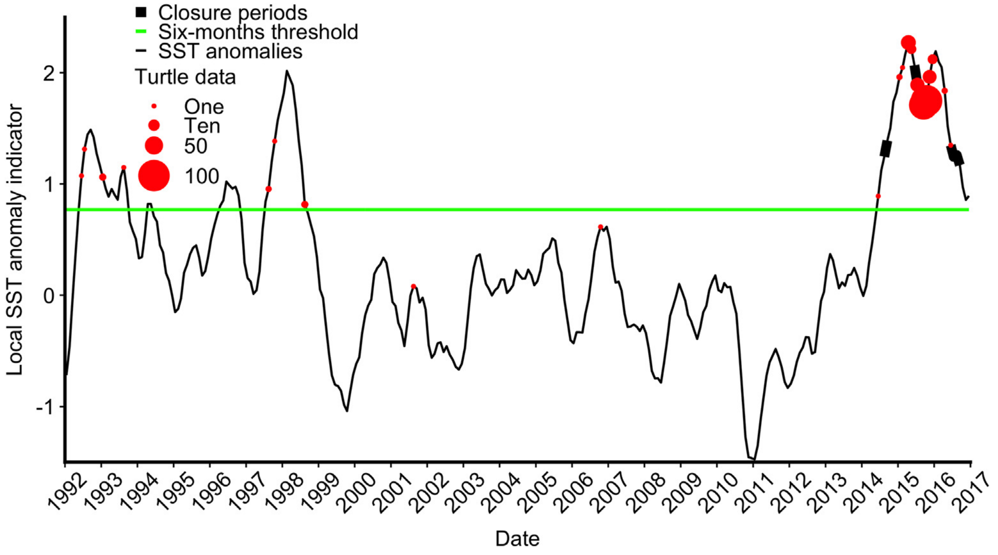

Fig. 5. The local SST anomaly indicator based on temperature conditions in the six months preceding closures, 1992–2017. Plot demonstrates the indicator's hindcast ability to avoid turtle interactions. Closures would be enacted when indicator values exceed the threshold. Turtle data include fisheries dependent (1992–2006) and independent (2015–2017) data within the Loggerhead Conservation Area.

the trade-off between comprehensiveness and complexity by evaluating two simple indicator groups (El Niño and local SST anomaly indicators) with single observation boxes and thresholds, and one complex indicator (the pelagic SST indicator), designed to capture loggerhead presence with highest possible precision (three observation boxes and 12 thresholds). The outperformance of the simple local SST anomaly indicator over the complex pelagic SST indicator demonstrates that comprehensiveness is not being sacrificed for simplicity in this case.

Under the current closure guidelines, environmental information is integrated with expert opinion and information on recent turtle sightings in a structured decision-making process to guide closure timing. We propose the six-month local SST anomaly indicator to inform, as opposed to replace, the current process. When the local SST anomaly threshold is exceeded, managers could decide to directly enact the closure, or to launch additional monitoring efforts (e.g. aerial or shipboard) to survey turtles offshore of Southern California to further inform managers about bycatch risk. Expert opinion provides an invaluable source of information regarding turtle behavior particularly in data-poor scenarios, and we stress the importance of maintaining this component of the structured decision-making process. Additionally, we have provided a comparison of the indicator's hindcast efficacy under partial closure window (June, July, and August, following the current guidelines) and full closure window (year-round) scenarios. It will fall to the managers to determine if the current closure window should be maintained, or if the increases in overlap with sighted turtles and historical bycatch avoidance warrant moving to a longer closure window.

To help with these determinations, we have developed a website that assembles information that may be useful for managers during the structured decision-making process and for fishers to determine closure status and the rationale behind it (https://coastwatch.pfeg.noaa.gov/loggerheads). The website displays the current environmental conditions within the Loggerhead Conservation Area, including SST and the SST anomaly, and conditions present for the last six months. The ENSO status, as reported by NOAA's Climate Prediction Center, and closure status of the Loggerhead Conservation Area can also be viewed. In addition, a data dashboard tool allows exploration of historical environmental data, conservation area closure dates, and ENSO status. The differences between the anomaly product used on the website, which is based on the GHRSST MUR satellite product (JPL MUR MEaSUREs, 2010), and the ROMS SST anomalies used to evaluate indicators in the present study are negligible (Fig. B1, Appendix B), thus the products are comparable for use in informing closure timing.

Ecosystem-based fisheries management requires continuous efforts to understand underlying species-environmental relationships and refine our representations of them. Indeed, as more data on loggerhead distribution along southern California become available, loggerhead thermal responses can be better constrained, enabling development of better indicators. To that end, we suggest that surveys of loggerhead and prey species (e.g. red crabs, Cavole et al., 2016) be conducted periodically. We also recommend that additional loggerhead tagging is conducted to better understand fine-scale movements of this endangered species within waters offshore of Southern California in relation to oceanographic conditions and prey abundance for further refinement of the management approaches described here.

4.2. Conclusions

We have developed an operationally feasible environmental indicator designed to help minimize loggerhead bycatch in an applied fisheries management scenario. Despite significant evidence that marine environment impacts stock productivity and distribution, a recent *meta*-analysis of applied fisheries management frameworks found that environmental drivers were only integrated for 2% of managed stocks (24/1250 reviewed stocks, Skern-Mauritzen et al., 2016). Although many proof-of-concept environmental indicators have been developed for fisheries management (e.g. Roth et al., 2007; Burke et al., 2013), they are infrequently implemented due in part to concerns regarding the non-stationarity of species-environmental relationships (e.g Pacific sardines, McClatchie et al., 2010; Deyle et al., 2013) confounded by a paucity of species distribution time-series data. However, issues with data comprehensiveness will likely always be present in fisheries management exercises, and precautionary approaches such as the present methodology are needed to allow adherence with legislation while incorporating the best available data. Additionally, climate change and variability are expected to increase the frequency of anomalous ocean states and potentially new fisheries – Protected species interactions, further necessitating the integration of environmental indicators into fisheries management plans.

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Version 5.2 (PFV5.2) data, obtained from the US National Oceanographic Data Center and GHRSST (http://pathfinder.nodc.noaa.gov) and 2) the Group for High Resolution Sea Surface Temperature (GHRSST) Multi-scale Ultra-high Resolution (MUR) data obtained from the THREDDS server at the NASA EOSDIS Physical Oceanography Distributed Active Archive Center (PO.DAAC), Jet Propulsion Laboratory, Pasadena, CA (https://thredds.jpl.nasa.gov/thredds)

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2018.11.001.

References

Allen, Camryn D., et al., 2013. Stable isotope analysis reveals migratory origin of loggerhead turtles in the Southern California Bight. Mar. Ecol. Prog. Ser. 472, 275–285.

Bond, Nicholas A., et al., 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophys. Res. Lett. 42 (9), 3414–3420.

Briscoe, Dana, K, et al., 2016. Multi-year tracking reveals extensive pelagic phase of juvenile loggerhead sea turtles in the North Pacific. Mov. Ecol. 4 (1), 23.

Briscoe, Dana K., et al., 2017. Ecological bridges and barriers in pelagic ecosystems. Deep Sea Res. Part II 140, 182–192.

Burke, Brian J., et al., 2013. Multivariate models of adult Pacific salmon returns. PLoS One 8 (1), e54134.

Casey, Kenneth S., 2010. The past, present and future of the AVHRR pathfinder SST program. In: Barale, V., Gower, J.F.R., Alberotanza, L. (Eds.), Oceanography from Space: Revisited. Springer DOI: 10.1007/978-90-481-8681-5_16.

Cavole, Letícia M., et al., 2016. Biological impacts of the 2013–2015 warm-water anomaly in the Northeast Pacific: Winners, losers, and the future. Oceanography 29 (2), 273–285.

Deyle, Ethan R., et al., 2013),. Predicting climate effects on Pacific sardine. Proc. Natl. Acad. Sci. U.S.A. 110 (16), 6430–6435.

Eguchi, T., McClatchie, S., Wilson, C., Benson, S.R., LeRoux, R.A., Seminoff, J.A., 2018. Loggerhead turtles (*Caretta caretta*) along the United States west coast: Abundance, distribution, and anomalous warming of the North Pacific. Front. Mar. Sci. 5, 452. https://doi.org/10.3389/fmars.2018.00452.

Fiedler, Paul C., Mantua, Nathan J., 2017. How are warm and cool years in the California Current related to ENSO? J. Geophys. Res. Oceans 5936–5951.

GFCM (2012). Report of the working group on stock assessment of small pelagic species. General Fisheries Commission for the Mediterranean http://151.1.154.86/GfcmWebSite/SAC/SCSA/WG_Small_Pelagics/2012/docs.html.

Glynn, Peter W., 1988. El Niño-southern oscillation 1982–1983: nearshore population, community, and ecosystem responses. Annu. Rev. Ecol. Syst. 19 (1), 309–346.

Hannesson, Rögnvaldur, 2007. Geographical distribution of fish catches and temperature variations in the northeast Atlantic since 1945. Mar. Policy 31 (1), 32–39.

Hilborn, Ray, 2012. The evolution of quantitative marine fisheries management 1985–2010. Nat. Resour. Model. 25 (1), 122–144.

Hobday, Alistair J., et al., 2016. A hierarchical approach to defining marine heatwaves. Prog. Oceanogr. 141, 227–238.

Hoegh-Guldberg, Ove, Bruno, John F., 2010. The impact of climate change on the world's marine ecosystems. Science 328 (5985), 1523–1528.

Jacox, Michael G., et al., 2016. Impacts of the 2015–2016 El Niño on the California current system: early assessment and comparison to past events. Geophys. Res. Lett. 43 (13), 7072–7080.

Kvamsdal, Sturla F., et al., 2016. Harvest control rules in modern fisheries management. Elem Sci. Anthropocene 4, 000114.

Howell, Evan A., et al., 2008. TurtleWatch: a tool to aid in the bycatch reduction of loggerhead turtles Caretta caretta in the Hawaii-based pelagic longline fishery. Endanger. Species Res. 5 (2-3), 267–278.

JPL MUR MEaSUREs Project. "GHRSST Level 4 MUR Global Foundation Sea Surface Temperature Analysis." (2010): Ver. 2. PO.DAAC, CA, USA. Dataset accessed in 2017 at https://doi.org/10.5067/GHGMR-4FJ01.

Ling, S.D., 2008. Range expansion of a habitat-modifying species leads to loss of taxonomic diversity: a new and impoverished reef state. Oecologia 156 (4), 883–894.

MacKenzie, Brian R., et al., 2014. A cascade of warming impacts brings bluefin tuna to Greenland waters. Global Change Biol. 20 (8), 2484–2491.

McClatchie, Sam, et al., 2010. Re-assessment of the stock–recruit and temperature–recruit relationships for Pacific sardine (Sardinops sagax). Can. J. Fish. Aquat. Sci. 67 (11), 1782–1790.

Moore, Andrew M., et al., 2013. A 4D-Var analysis system for the California current: a prototype for an operational regional ocean data assimilation system. Vol. II In: Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications. Springer, Berlin, Heidelberg, pp. 345–366.

Neveu, Emilie, et al., 2016. An historical analysis of the California Current circulation using ROMS 4D-Var: System configuration and diagnostics. Ocean Model. 99, 133–151.

Ñiquen, Miguel, Bouchon, Marilú, 2004. Impact of El Niño events on pelagic fisheries in Peruvian waters. Deep Sea Res. Part II 51 (6-9), 563–574.

Oliver, E.C., et al., 2018. Longer and more frequent marine heatwaves over the past century. Nat. Commun. 9 (1), 1324.

Ottersen, Geir, et al., 2013. Temporal shifts in recruitment dynamics of North Atlantic fish stocks: effects of spawning stock and temperature. Mar. Ecol. Prog. Ser. 480, 205–225.

Pearcy, W.G., Schoener, Amy, 1987. Changes in the marine biota coincident with the 1982–1983 El Niño in the northeastern subarctic Pacific Ocean. J. Geophys. Res. Oceans 92 (C13), 14417–14428.

Polovina, Jeffrey J., et al., 2000. Turtles on the edge: movement of loggerhead turtles (Caretta caretta) along oceanic fronts, spanning longline fishing grounds in the central North Pacific, 1997–1998. Fish. Oceanogr. 9 (1), 71–82.

Roth, Jennifer E., et al., 2007. Chinook salmon (*Oncorhynchus tshawytscha*)—seabird covariation off central California and possible forecasting applications. Can. J. Fish. Aquat. Sci. 64 (8), 1080–1090.

Rudnick, Daniel L., et al., 2017. A climatology of the California Current System from a network of underwater gliders. Prog. Oceanogr. 154, 64–106.

Simons, R.A. 2017. ERDDAP. https://coastwatch.pfeg.noaa.gov/erddap. Monterey, CA: NOAA/NMFS/SWFSC/ERD.

Skern-Mauritzen, Mette, et al., 2016. Ecosystem processes are rarely included in tactical fisheries management. Fish Fish. 17 (1), 165–175.

Tomaszewicz, Calandra N. Turner, et al., 2015. Age and residency duration of loggerhead turtles at a North Pacific bycatch hotspot using skeletochronology. Biol. Conserv. 186, 134–142.

Vert-pre, Katyana A., et al., 2013),. Frequency and intensity of productivity regime shifts in marine fish stocks. Proc. Natl. Acad. Sci. U.S.A. 110 (5), 1779–1784.

Wernberg, Thomas, et al., 2013. An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. Nature Clim. Change 3 (1), 78.

Wright, P.J., et al., 2002, European Commission's annual report on the impact of the Northeast sandeel fishery closure and status report on the monitoring fishery in 2000 and 2001.

Zaba, Katherine D., Rudnick, Daniel L., 2016. The 2014–2015 warming anomaly in the Southern California Current System observed by underwater gliders. Geophys. Res. Lett. 43 (3), 1241–1248.