Where do the billfish go? Using recreational catch data to relate local and basin scale environmental conditions to billfish occurrence in the Eastern Tropical Pacific

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Abstract
Recreational fisheries in the Eastern Tropical Pacific (ETP) have increased in popularity since the 1970s, contributing to the eco-tourism industries of many Central American economies. However, pelagic gamefish face several direct and indirect threats which can affect population health and sustainability. We use daily catch logs from three recreational fishing lodges in Guatemala, Costa Rica, and Panama as records of change in blue marlin (Makaira nigricans) and sailfish (Istiophorus platypterus) sightings per unit effort (SPUE) between 2010 and 2019. Using cross-correlational analysis, we compared billfish SPUE to the El Niño Southern Oscillation (ENSO) Index and local oceanographic conditions (sea surface temperature [SST] and chlorophyll [chl a]) to understand how billfish availability to recreational fishers is related to environmental conditions at different time lags. Blue marlin occurrence was negatively correlated with the ENSO at time lags of 9–22 months in Guatemala and Costa Rica, while sailfish occurrence was positively correlated with ENSO at time lags of 5–10 months in all three regions. Cross-correlations with local SST were similar to ENSO patterns; however, results were unclear and nonsignificant for local chl a. By comparing recreational fisher SPUE to reported catch per unit effort (CPUE) of these two species by the international longline and purse seine fisheries, we show possible offshore movement of fish stocks during the 2016 warming event. Recreational fishing records provide an alternative way to monitor the occurrence of targeted fish species. By determining correlations of these species to environmental conditions, we begin to distinguish the effects of natural variability in the environment, from direct anthropogenic impacts.

KEYWORDS
cross-correlation, ENSO, Istiophorus platypterus, Makaira nigricans, oceanography, recreational fisheries, time series analysis

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1 | INTRODUCTION

Marine fish face a number of direct and indirect anthropogenic threats which can affect population health and sustainability (Halpern et al., 2008). Direct threats include overfishing and bycatch, while indirect effects include changes in habitat availability, food webs, and climate (Halpern et al., 2015). Specifically, changes in climate and oceanography such as warming ocean temperatures, depletion of oxygen, and changes in productivity can cause shifts in the spatial distributions of fish populations (Pinsky et al., 2013). It is often difficult to tease apart the effects of a changing climate, which may impact the distribution and therefore accessibility of the fish to fishers, from the more direct human impacts on fish populations such as stock depletion and incidental take. These factors make the management of fish stocks challenging, particularly in areas with a variety of competing interests. Here, we use daily sighting reports of two recreationally targeted billfish species, sailfish (Istiophorus platypterus) and blue marlin (Makaira nigricans), from fishing lodges in Central America, to better understand the response of these species to ocean basin scale and regional scale climatic variation.

Sailfish and blue marlin are two species of highly migratory billfish that exist throughout the world's subtropical and tropical marine waters (Goodyear et al., 2008; Goodyear, 2016; Hoolihan et al., 2011). Although their Atlantic counterparts are well studied and documented (Kerstetter et al., 2011; Kraus et al., 2011; Kraus & Rooker, 2007; Lam et al., 2016), fewer studies exist on Pacific populations to date. Both species are transboundary in the region of the Eastern Tropical Pacific (ETP) (Carlisle et al., 2017; Ehrhardt & Fitchett, 2006; Prince & Goodyear, 2006; Su et al., 2011), exposing individuals to a variety of fishing pressures and regulations, as well as international waters in areas beyond national jurisdiction (ABNJ). However, although highly migratory, these species associate with continental shelf breaks and seamounts, which are easily identifiable by recreational sport fishers and the commercial industry (Campbell et al., 2003; Morato et al., 2010; Richert et al., 2017).

Blue marlin and sailfish distribution and occurrence in the ETP is hypothesized to be related to physical and oceanographic variables like sea surface temperature (SST), oceanic fronts and eddies, current speed, and oxygen content (Block et al., 1992; Carlisle et al., 2017; Ehrhardt & Fitchett, 2006; Farchadi et al., 2019; Prince et al., 2017; Su et al., 2011). Seasonal shifts in blue marlin distribution have been related to changes in SST, mixed layer depth (MLD), and chlorophyll a concentrations in the greater Pacific Ocean (Su et al., 2011). While these environmental conditions may directly affect the physiology of blue marlin and sailfish, it is possible they are indirectly related to prey distribution as well. For example, blue marlin and sailfish primarily feed on small tunas (Shimose et al., 2006), and squids (Ehrhardt & Fitchett, 2006), and prey occurrence can be strongly influenced by ocean climate oscillations like the El Niño Southern Oscillation (ENSO) (Lehodey et al., 1997; Pedraza & Díaz Ochoa, 2006). However, we lack the fine scale understanding of how prey occurrence and distribution are affected by local and ocean basin scale environmental variability along the coast of Central America at this time.

The ETP provides a particularly interesting ecosystem to study both anthropogenic impacts and the effects of interannual and intra-annual environmental availability on marine fish populations. The ETP is significantly influenced by the ENSO cycle. El Niño conditions cause increased water temperature and a deepened mixed layer leading to decreases in the availability of nutrients, primary productivity, and likely shifts in the distribution of billfish (Ballance et al., 2006; Barber & Chavez, 1983; Prince et al., 2017; Prince & Goodyear, 2006; Stramma et al., 2012). La Niña conditions result in increased equatorial upwelling and extend low oxygen waters, which are thought to prevent blue marlin from migrating to certain areas in the ETP and restricting blue marlin to areas around the equator (Carlisle et al., 2017; Farchadi et al., 2019). As a result, the spatial distribution of suitable habitat for blue marlin and sailfish changes both horizontally and vertically in response to these conditions (Carlisle et al., 2017; Farchadi et al., 2019).

Central American countries such as Guatemala, Costa Rica, and Panama have taken advantage of the relatively high abundance of billfish species via the sport fishing industry (Ehrhardt & Fitchett, 2006). As a result, sport fishing has become an essential part of the ecotourism industry and an important source of income for residents of these countries (Gentner, 2007; Holland et al., 1998). But as is common in many parts of the world, perceived conflicts of interest (in terms of setting catch limits and setting management goals) occur between the sport fishing industry and the robust international and domestic commercial fisheries (Berkes, 1984; Cooke & Cowx, 2006). Catches of blue marlin and sailfish have been highly variable in the ETP, and stock assessments for blue marlin (IATTC, 2019) and sailfish (Hinton & Maunder, 2011) in this region estimate populations are likely overexploited, but little information about the recreational sport fisheries has been documented in the literature. In the absence of more direct sources of population and spatial information on billfish species, such as regular population surveys and observations from satellite tags or acoustic telemetry, other novel sources of data may be useful to demonstrate trends in the distributions of these species. Here we analyze catch and release records of blue marlin and sailfish occurrence (“sightings”) from fishing lodges in Guatemala, Costa Rica, and Panama to determine if correlations exist between ocean basin scale and regional scale environmental variability and billfish occurrence. By quantifying the response of these species to regional and ocean basin scale environmental conditions, we can begin to distinguish the effects of variability in the natural environment from direct anthropogenic impacts to medium-term (5–10 + years) population trends to better inform long-term trends.

2 | METHODS

We identified multiyear archives of daily logbook records from three sport fishing lodges located in Guatemala, Costa Rica, and Panama. Within lodges, boats are outfitted with comparable engines and fishing equipment, allowing us to consider boat-days as a reasonable indicator of sightings effort. However, among the three lodges, boat
engine size, and therefore the accessible fishing footprint, differed at each lodge. Therefore, comparisons of datasets among the lodges should be made with caution. These lodges operate under regular fishing schedules, with boat charters generally leaving around the same time every morning and returning around the same time each evening. Trips targeting blue marlin and sailfish will generally use two strategies: surface trawling (lures, baited hooks, and teasers trail behind a boat) and live baiting (live baitfish are tethered to a hooked line which trails behind a boat). Captains will target aggregations of bait associated with floating debris, bathymetric features like seamounts, and roaming schools of tuna or other baitfish. Blue marlin, sailfish, various tunas, and dorado (mahi-mahi, Coryphaena hippurus) may co-occur in these areas. While we cannot directly account for the species captains and fishers are targeting, in general, most offshore trips are targeting blue marlin and sailfish consistently using similar methods throughout the year within and among lodges. Inshore fishing trips differ in location and in fishing method. Targeted inshore species include roosterfish (Nematistius pectoralis), snapper (various species), and jack (various species). It is unlikely that a blue marlin or sailfish was caught while targeting these inshore species.

Daily logs record raises (i.e., blue marlin and sailfish observed following or attacking the bait or lure), releases (i.e., mate handled the terminal leader on fishing tackle before fish was released or broke free), and harvests of various gamefish species. All lodges adhere to best practices for recreational catch and release billfish fisheries (e.g., using circle hooks for live baiting and keeping hooked billfish in the water at all times) and only harvesting species such as dorado and tuna (primarily yellowfin tuna; Thunnus albacares). A “release” inherently depends on the ability of the angler to maintain a sailfish or blue marlin on the line up to the boat. Previous work has shown that only 43% of fish raised are eventually “released” (Ehrhardt & Fitchett, 2006). Therefore, for the purpose of this study, we only considered sailfish or blue marlin raises to tackle as observations (or sightings), following Pohlot and Ehrhardt (2018).

2.1 Guatemalan trip logs

Daily trip logs from Casa Vieja, Puerto San José, Guatemala were available between January 2015 and December 2019. The fishing footprint of the lodge extends out to approximately 60 nautical miles from Puerto San José (13.91°, –90.78°, Figure 1), due to engine limitations and safety requirements of the resort. We categorized trip logs as offshore fishing, inshore fishing, or a mix of offshore and inshore fishing based on the species of fish documented and with guidance from an experienced local fisher (supporting information Figure S1). Trips targeting inshore species used methods that would not raise or land a sailfish or blue marlin and were therefore removed from the dataset before analysis. To standardize for differences in the number of boats fishing per day (fishing effort), we report sightings per unit effort (SPUE) as fish (sailfish or blue marlin) raised, divided by the number of boats that fished each day. To smooth out small-scale fluctuations in fishing effort over time and to allow SPUE to be compared to climate indices (reported monthly), we aggregated daily SPUE (raised fish per boat) by month.

**Figure 1** Study map. Inset maps show approximated fishing footprints (red polygons) for charter boats from Casa Vieja, Puerto San Jose, Guatemala, from Crocodile Bay Resort (Matapalo Rock), Puerto Jimenez, Costa Rica, and from Tropic Star Lodge, Piñas Bay, Panama.
2.2 | Costa Rican trip logs

Daily trip logs from Crocodile Bay Resort, Puerto Jimenez, Costa Rica were made available from February 2011 to December 2019. All offshore fishing occurred within 25 nautical miles of Matapalo Rock (8.37–83.28°, Figure 1), near the entrance of Golfo Dulce, Costa Rica, due to engine limitations and safety requirements of the resort. Similar to the dataset from Guatemala, records were labeled as “inshore,” “offshore,” or “mix” depending on the species documented or information noted about the trip in the database. Inshore trips target species using fishing methods that would not attract a blue marlin or sailfish and were excluded from our analysis. Daily raises of sailfish and blue marlin were converted to SPUE (raised fish per boat per day) and aggregated by month.

2.3 | Panama trip logs

Daily trip logs from Tropic Star Lodge, Piñas Bay, Panama, were made available from January 2010 to December 2019. Like the other lodges, trip logs consisted of a mix of inshore and offshore trips; however, only raises and releases of billfish were consistently recorded, preventing us from discerning inshore and offshore trips. This means that calculated SPUE for blue marlin and sailfish is likely underestimated, as inshore trips not targeting billfish were inevitably included in our analysis. All fishing takes place within approximately 40 miles from the lodge (7.55–78.20°, Figure 1). Daily raises of sailfish and blue marlin were converted to SPUE (raised fish per boat per day) and then aggregated by month.

2.4 | Missing records

Time series from all three regions included gaps in the records even after aggregating from daily to monthly SPUE due to incomplete data recording, missing data records, or month-long lodge closures. Missing data accounted for 6%–20% of the three time series. For most years, missing data time gaps ranged from 1 to 3 months; however, there was a 7-month gap in the time series from Panama in 2017 due to missing records. Because of the high variability in catches from 1 month to the next in all data series, we were not confident that imputation techniques to fill in data gaps would accurately predict actual conditions. Therefore, we restricted our analysis to methods that allowed for comparisons of time series that contain missing values.

2.5 | IATTC data

The Inter-American Tropical Tuna Commission (IATTC) is an international collaborative effort tasked with conserving and managing marine fisheries resources in the eastern Pacific Ocean. The commission collects data from commercial fisher members and cooperative nonmembers regarding the catch of tuna and tuna-like species like billfish, annually. These data are openly available to the public (https://www.iattc.org/PublicDomainData/IATTC-Catch-by-species1.htm, accessed 1 Nov 2020). These fisheries are primarily targeting tunas and swordfish, and blue marlin and sailfish are usually taken as bycatch. For comparison with the local SPUE of blue marlin and sailfish collected by recreational fishers, we extracted the reported number of blue marlin and sailfish caught by commercial longliners (reported for 5° × 5°) and purse seiners (reported for 1° × 1° grids), as well as fishing effort (number of 1000 hooks and number of sets). We aggregated data for all flags fishing between January 2010 to December 2019 in the Eastern Pacific Ocean (EPO) (supporting information Figure S2). These data were averaged across all grid cells to provide an ocean basin average catch per 1000 hooks and catch per set, hereafter referred to as catch per unit effort (CPUE). This created a time series to provide a general snapshot of offshore commercial catches during the time period of our study.

2.6 | Environmental data

To provide environmental context for the patterns in SPUE of sailfish and blue marlin recorded by these fishing operations, we used historical records of climate indices and sea surface conditions. We downloaded the Oceanic Niño Index (ONI) between January 2010 and December 2019 using the download_enso function in R (“rsol,” Albers & Campitelli, 2020). This monthly index is one of the primary measures of the ENSO, with values above 0.5 indicating El Niño conditions (east-central tropical Pacific Ocean is warmer than normal) and values below –0.5 indicating La Niña conditions (east-central tropical Pacific Ocean is cooler than normal). The ENSO is an ocean basin scale climate index that varies interannually and changes weather patterns and oceanographic conditions in the ETP.

While ocean basin scale climate variability is likely influencing the distribution of sailfish and blue marlin in the region, local scale oceanographic conditions are also expected to be related to SPUE (Kerstetter et al., 2011; Kraus et al., 2011; Kraus & Rooker, 2007; Lam et al., 2016). Daily composites of SST and chlorophyll a (CHL) concentrations collected by NASA’s MODIS-Aqua satellite platform were downloaded between January 2010 and December 2019 for the ETP (https://oceandata.sci.gsfc.nasa.gov). Remotely sensed sea surface conditions (4-km² resolution) within the fishing footprint around each resort were extracted to match the spatial extent of fishing effort (Figure 1). Because exact fishing location was not recorded within the trip logs, monthly averages of local SST and CHL were created for each fishing region to represent the average environmental conditions that existed for each month of the time series.

2.7 | Data analysis

Time series analysis assumes that input time series are stationary (i.e. have constant means and variance functions or no unit root; Zuur et al., 2007). The stationarity of environmental variables and fish
comparing anomalous conditions. More sophisticated seasonal dataset and allows for cross-correlation analysis to focus only on dataset. This effectively strips away baseline conditions from each environmental variables, we subtracted the monthly mean from each and Panama (supporting information Figure S4). To remove the step for local SST, blue marlin in Panama, and sailfish in Costa Rica this analysis revealed significant positive correlations after one time (supporting information Figure S3). When combined with the pacf, sailfish occurrence, as well as local environmental conditions et al., 2015).

Significant correlations were identified as peaks in the absolute value of the missing data from our time series. Both the acf and ccf functions are able to handle missing data gaps found in SPUE time series using the “na. pass” parameter, meaning correlations were only calculated for complete cases (Trapletti & Hornik, 2019).

All data analyses and visualizations were done in the R statistical environment version 4.0.2 (R Core Team, 2020).

3 | RESULTS

3.1 | Environmental conditions

Throughout the 10-year period for which we were able to obtain recreational trip logs, environmental conditions varied on both large and small spatiotemporal scales (Figure 3). During the first half of the study, ONI values reflected mild La Niña or neutral conditions, followed by a very strong El Niño in late 2015 to early 2016 (Figure 2). This strong warming event was followed by a few years of La Niña or neutral conditions before becoming a mild El Niño once again in 2018/2019 (Figure 2). The time series of local SST reflects seasonal cycles of heating and cooling of the surface ocean; however, on average, SSTs were directly related to latitude (i.e., Guatemala was warmer than Panama, Figure 2). Guatemala and Costa Rica experienced a slight increase in SST between approximately 2011–2016 followed by slight cooling; however, temperatures remained high in Guatemala for the duration of the time series (Figure 2). This warming and cooling pattern is less pronounced for Panama, which was consistently cooler (Figure 2). However, the warming event of 2015/2016 is evident in the record of SST in Panama as well (Figure 2). Observations varied among sites in the trend in local CHL (Figure 2). In Guatemala, a peak in local CHL occurred in late 2011, followed by a period of decreasing CHL that levels off around 2016 before peaking again in late 2018 (Figure 2). In Costa Rica, a peak in CHL was observed in late 2013, followed by a similar decreasing trend and then leveling off in 2016 (Figure 2). On average, local CHL in Panama appears low from 2011 to 2014, with sharp peaks in early 2016 and early 2019 (Figure 2).

3.2 | Fisheries time series

3.2.1 | Guatemala

To document fishing off Guatemala, we obtained 4,803 daily trip logs from 1,149 fishing days which recorded blue marlin and sailfish raises between January 2015 and December 2019. Raises of these two species were generally higher in Guatemala than in Costa Rica or Panama, with total raises equaling 2483 and 112,533 for blue marlin and sailfish, respectively. In Guatemala, average SPUE by month was 0.62 (range = 0–3.67) for blue marlin and 20.31 (range = 1.5–46.54) for sailfish, and seasonality and interannual differences in monthly SPUE were evident throughout the time series (Figure 3). Blue marlin observations varied slightly throughout the year, with higher SPUEs in...
August through October (SPUE ≈ 1.5); however, variability among years was high during those months (Figures 3 and 4). Although the time series for Guatemala is relatively short, blue marlin occurrence did vary over time, with low SPUE (<1) observed in 2015 and 2017 (Figure 4). Due to the limited number of years in the Guatemala time series, it is unclear if seasonal peaks in blue marlin occurrence (SPUE > 2) are consistent; however, on average, SPUE appears to increase slightly over time (Figure 4). While interannual variability for sailfish SPUE was evident in Guatemala, catches were high (SPUE > 20) relative to the other locations nearly year-round; however, SPUE generally decreased in July and August (SPUE ≈10; Figure 3). Sailfish SPUE peaked in 2015 through mid-2016 (SPUE 25–45), followed by a sharp decline. SPUE remained lower through the remainder of the time series (SPUE ≈20; Figure 4). In general, sailfish SPUE declined towards the end of the time series, but it is not possible to conclude if this is anomalous for this region given the short time series.

### Costa Rica

Between February 2011 and December 2019, 7,241 daily trip diaries from 2,027 fishing days were logged from Crocodile Bay Resort in Puerto Jimenez, Costa Rica. During these trips, 2,144 blue marlin and 29,713 sailfish raises were documented. On average, 0.36 blue marlin (range = 0–2.1) and 2.85 sailfish (range = 0–12.45) were raised per boat per day (Figures 3 and 4). In general, we observed blue marlin SPUE peaks in May, August, and November (SPUE ≈0.5); however, a seasonal trend is less apparent and interannual variability was high (Figure 3). Conversely, sailfish SPUE was generally highest in January through April (SPUEs ≈4–5), peaking in March (Figure 3). On average, blue marlin SPUE decreased slightly between 2016 and 2018; however, SPUE appears to have increased after that time (Figure 4). On average, sailfish SPUE remained steady until mid-2015, when sailfish SPUE declined and did not recover to pre-2016 levels through the remainder of the time series (Figure 4).

### Panama

In Panama, 37,593 daily trip records were obtained from 2,843 fishing days between January 2010 and December 2019 from Tropic Star Lodge. During this time, 6,039 blue marlin and 18,153 sailfish raises were documented. On average, 0.16 blue marlin (range = 0–0.62) and 0.47 sailfish (range = 0–2.91) were sighted per boat per day each
month; however, sightings changed seasonally and between years (Figures 3 and 4). For both blue marlin and sailfish in Panama, SPUE was highest centered around August (SPUE blue marlin: ~0.25, sailfish: ~0.80) and January (SPUE blue marlin: ~0.35, sailfish: ~0.75) (Figure 3). No records exist for the month of October from Panama due to lodge closure (Figure 3). SPUE of blue marlin in Panama increased slightly around 2016 (Figure 4). The subsequent recovery in blue marlin SPUE observed for Guatemala and Costa Rica did not occur for the fishery in Panama (Figure 4). Throughout much the time series, catches of sailfish remained seasonally consistent, with a notable spike in 2016 (SPUE ~3) followed by a return to historic levels (Figure 4). However, missing data may be obscuring some of these observed patterns.

3.2.4 | Pacific Ocean—IATTC records

On an ocean basin scale, the CPUE of blue marlin from the IATTC commercial purse seine fishery peaked slightly around 2016 (CPUE ~0.15) but appear reasonably stable over time (Figure 4). Sailfish CPUE in the purse seine fishery peaked in 2010 (CPUE ~0.20) and 2016 (CPUE ~0.20) but is relatively low otherwise (Figure 4). Blue marlin CPUE was greater in the longline fishery than the purse seine fishery but similarly peaked slightly in 2016 (CPUE ~0.50; Figure 4). Sailfish CPUE in the purse seine fishery peaked early in the dataset and between 2016 and 2017 (CPUE ~0.25), however, remained low the rest of the time series (Figure 4). CPUE of sailfish was essentially non-existent in the longline fishery before 2016, after which there is a peak in CPUE (CPUE ~0.10) and increasing catches thereafter (Figure 4). Sailfish CPUE in the longline fishery appeared somewhat inversely related to SPUE from the recreational fishery towards the end of the time series, where increases in CPUE in the ocean basin scale longline fishery occurred at similar times as SPUE from the near-shore recreational fisheries decreased (Figure 4).

3.3 | Autocorrelation and cross-correlation

Autocorrelation was high for the ONI time series at lags of 1–7 months and was significantly negatively correlated at time lags of 2 and 5 years (supporting information Figure S3). Local SST was also highly autocorrelated in all three regions at lags of 1–2 months, which clearly reflects the seasonal heating and cooling cycles one would expect of the surface ocean (supporting information Figure S3). Patterns in the autocorrelation structure of local CHL reflect the expected annual seasonal nature of biological productivity in the
surface ocean (supporting information Figure S3). In general, the autocorrelation for blue marlin and sailfish SPUE reflected the approximate 6-month seasonal nature of their presence and absence in each region (supporting information Figure S3). The partial autocorrelation analysis indicated that for most variables, higher-order autocorrelations are effectively explained by the autocorrelation at the first time lag (supporting information Figure S4).

While local environmental conditions may be related to the relative abundance of the species in the footprint of various fisheries, it is also likely that time lags exist between environmental conditions and the abundance of blue marlin and sailfish within each study site. All environmental variables tested were significantly correlated with either blue marlin or sailfish in at least one of the three regions at some time lag, but correlations varied among species and sites.

Blue marlin were negatively correlated with the ONI at a time lag of approximately 9 months for Costa Rica and 22 months for Guatemala; however, at a time lag of approximately 20 months, blue marlin were weakly positively correlated with the ONI in Panama but this relationship is not significant at the 95% confidence level (Figure 5). At longer time lags (~3 years), there were weak negative correlations between sailfish and ONI in all three regions (Figure 6). Similar to the ONI, sailfish was positively correlated with sailfish SPUE at short time lags (< 1 year) and negatively correlated at time lags around 3 years in Costa Rica and Panama (Figure 5). The relationships between sailfish and local chlorophyll a concentrations were unclear for all three locations (Figure 6).

4 | DISCUSSION

Our paper presents evidence for relationships between environmental variables and the occurrence of blue marlin and sailfish as observed by recreational fishing lodges in the ETP. The results demonstrate that correlations exist between both local and ocean basin scale environmental predictors and the SPUE of blue marlin and sailfish to the recreational fisheries in Central America. In addition, we observed variability in interannual catch rates for both species in all regions and...
demonstrate that local oceanographic conditions can have opposite impacts on catches of these two billfishes, even among adjacent countries. While the time series are not long enough to definitively show increasing or decreasing trends in billfish occurrence in these regions, there is evidence that the strong El Niño event in 2015–2016 impacted the occurrence of blue marlin and sailfish in all three countries.

4.1 Impact of environmental variables on billfish occurrence in the ETP

Unsurprisingly, a strong El Niño event (2015–2016) is correlated with changes in the SPUE of sailfish and blue marlin within the ETP. The ENSO cycle is one of the most significant sources of environmental variability in the region (Pennington et al., 2006) and has been previously shown to affect the distribution of blue marlin and sailfish within the ETP and other regions of the Pacific Ocean (Carlisle et al., 2017; Ehrhardt & Fitchett, 2006; Farchadi et al., 2019; Hill et al., 2016). Average SSTs were relatively high in Guatemala and Costa Rica in 2015, at times exceeding 31°C, which approaches the maximum observed temperature range for blue marlin and sailfish (25–30°C; Block et al., 1992; Carlisle et al., 2017; Graves et al., 2002; Hoolihan et al., 2011; Su et al., 2008). In addition to increased SST, the oceanographic effects of an El Niño in this region include diminished primary productivity and a deepened thermocline (Ballance et al., 2006), which may affect the distribution of higher trophic level fish-like billfish either directly or indirectly (e.g., prey redistribution). Modeled pulses of primary productivity due to anomalous ocean warming and cooling events like the ENSO in the ETP have been found to propagate through the ecosystem for years and result in complex interactions and lagged effects scale proportionally to the trophic level of fish (Watters et al., 2003). This may support our findings that the impacts of climate scale oscillations, like ENSO, on billfish occurrence may be lagged in time.

Previous work has shown that blue marlin and sailfish are feeding in the ETP (Ehrhardt & Fitchett, 2006; Shimose et al., 2006); therefore, it is likely that changes in the distribution and abundance of prey fish due to ENSO-related habitat constriction and expansion would impact predator distribution and abundance as well. Stomach content data suggest that blue marlin are also actively feeding on tunas and squid in the region (Rosas-Luis et al., 2016; Shimose et al., 2006). Skipjack tuna (Katsuwonus pelamis) make up a large portion of blue marlin’s diet in the Pacific (Shimose et al., 2006) and appear to shift
their distribution south of the equator during an El Niño in this region (Lehodey et al., 1997). This may also be influencing the lagged negative correlation between blue marlin and the ONI, as blue marlin are shifting their distribution out of these recreational fishing grounds in response to their prey.

SPUE in Guatemala and Costa Rica was low coincident with the highest reported SPUE in Panama. This may suggest that we are detecting a latitudinal movement of the distribution of blue marlin in the ETP, driven by local and climate scale warming events, similar to the findings of previous studies (Carlisle et al., 2017; Farchadi et al., 2019). Further supporting this, we observed relatively stable SSTs in Panama (around 28°C) throughout the time series, and SPUE of blue marlin similarly remained stable between 2015 and 2017, only decreasing in recent years. While previous studies have found blue marlin move north during El Niño events (Farchadi et al., 2019), the localized upwelling that occurs regularly off Panama (O’Dea et al., 2012) may provide a refuge of cooler water for blue marlin. In addition, CPUE of blue marlin and sailfish in the commercial longline and purse seine fisheries was relatively higher during the 2016 warming event, indicating that these species may have moved further offshore, into commercial fishing grounds, and out of the fishing range of the recreational fishing charters. A shift in occurrence from the coastal recreational fishery to the more offshore commercial fishery due to seasonal and climatic oscillations has been previously observed for sailfish off of Guatemala (Ehrhardt & Fitchett, 2006). The spikes in sailfish CPUE in both commercial fisheries in 2016 suggest that a

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**FIGURE 6** Cross-correlation structures for environmental variables (ONI: Oceanic Niño Index, local SST: sea surface temperature, and local CHL: chlorophyll a concentration) and sailfish sightings per unit effort (SPUE) from three regions in the Eastern Tropical Pacific (ETP). Dashed lines represent the critical value significance value ($r_{crit}$). Correlations surpassing the $r_{crit}$ represent the time lag in months for which a change (+/-) in the environmental condition precedes a change (+/-) in the sailfish SPUE.
similar shift in occurrence was observed in our datasets. Finally, it is important to consider that La Niña events may also affect the occurrence and distribution of blue marlin and sailfish in the ETP, as cold low oxygen waters from the equatorial upwelling have been found to restrict blue marlin habitat availability (Carlisle et al., 2017). As our time series only captured mild La Niña events, we are unable to determine how stronger La Niña events may impact the availability of blue marlin and sailfish for the more coastal recreational fisheries in the ETP.

Relationships between sailfish and the environmental variables included in this study were nearly inverse that of blue marlin in all three regions. While blue marlin SPUE was negatively correlated with the ONI, sailfish were positively correlated at time lags of less than a year, similar to the peak in sailfish SPUE observed in Guatemala after the 1997–1998 ENSO event (Ehrhardt & Fitchett, 2006). In Guatemala and Costa Rica, sailfish SPUE was higher when blue marlin SPUE was lower (and vice versa). This inverse relationship between species and environmental variables may be due to differences in the physiology and behavior of these two billfishes. The compressed body plan of sailfish may allow this species to dissipate heat more rapidly than blue marlin and therefore tolerate elevated water temperatures (Hoolihan et al., 2011). Sailfish are also more tightly associated with coastal waters and less transitory than blue marlin (Bubley et al., 2020), suggesting that these fish may be less likely to change their distributions in response to temporary changes in the oceanography. This may be further supported by the lack of this relationship in the consistently cooler Panamanian waters, where sailfish and blue marlin appear to co-occur more regularly throughout the year.

While we believe there may be physiological and behavioral factors driving the different responses to climate oscillations observed between the two species, it is important to note that our datasets may also capture changes in fisher behavior. While it is possible to catch both blue marlin and sailfish using similar gear, fishers may change their fishing gear, bait size, and fishing locations when they specifically target one species over the other. It is also possible that perceived changes in the availability of one species may redirect fishing effort to the other species (Thurstan et al., 2018). For example, if fishers believe it is a “bad year” for blue marlin, they may redirect fishing effort to target sailfish, artificially inflating sailfish sightings and deflating blue marlin sightings. To the same effect, in Panama, much of the fishing effort is shifted to the seasonal occurrence (January–February) of black marlin (Istiompax indica) in much shallower water, where blue marlin are rarely encountered. However, blue marlin are still regularly sighted in Panama in January and February, indicating that these records are still capturing their occurrence but perhaps underrepresenting the magnitude of their occurrence. In addition, there could be a shift in fishing trips occurring offshore versus inshore throughout the year that could affect sightings of blue marlin and sailfish. However, the number of inshore trips appears consistent throughout the year in Guatemala and Costa Rica and we do not believe that a shift in effort is a strong cause for concern here. For example, in the dataset from Costa Rica, when blue marlin CPUE is lowest (January–April), frequency of offshore trips is highest, and when inshore trips are more common (May–October), blue marlin SPUE is highest. Future work could seek to address these issues by capturing more specific measurements of effort and changes in the species fishers are targeting to better account for biases in the dataset.

4.2 Implications for conservation and management

The ETP and specifically the coastal waters accessible to recreational fishers off of Guatemala, Costa Rica, and Panama are considered the best billfish sport fisheries in the world (Ehrhardt & Fitchett, 2006). These fisheries contribute significantly to the local economies of these countries through the eco-tourism industry (Gentner, 2007; Holland et al., 1998). This industry benefits from high catch rates that attract anglers from across the globe (Pohlot & Ehrhardt, 2018), and therefore, understanding how environmental drivers at local and ocean basin scales impact the availability of these fish is important for fisheries management efforts.

Our study provides evidence that the occurrence of blue marlin and sailfish changes not only seasonally but also in relation to climate oscillations. Often when surveying a population, we assume that the distribution of species is sufficiently consistent across years (Campbell et al., 2003). However, when the migratory behavior of fish varies interannually, we need to understand how fish are redistributing in space and time to accurately capture their population status in surveys (Campbell et al., 2003). The most recent stock assessment for blue marlin from 2013 indicated that the species was exploited, and with growing commercial and recreational pressure on the species, it is likely that blue marlin are actually over exploited (IATTC, 2019). A stock assessment for sailfish was also attempted in 2011; however, the assessment was unable to determine the status of the stock due to a lack of life history and catch data for sailfish in this region (Hinton & Maunder, 2011). While the status of the stock of sailfish in the ETP is unclear, as commercial and recreational fishing pressure increases, it is highly likely that both sailfish and blue marlin restricted to the narrow epipelagic waters of the nearshore environment off of Central America will be susceptible to overexploitation (Goodyear et al., 2008; Prince & Goodyear, 2006).

5 Conclusions

In the absence of definitive formal population surveys for these two species, recreational fishing records provide an alternative way to monitor the occurrence of targeted species. While recreational fisheries are culturally, economically, and ecologically important throughout much of the world, our fundamental understanding of these fisheries is limited (Thurstan et al., 2018). Nontraditional data sources have been shown to inform fisheries management (Thurstan et al., 2018), and here we have shown that there appear to be correlations between blue marlin and sailfish observations and multiple environmental predictors. While the lodges included in this study represent only a small
subsection of the recreational fishing effort in Central America, they provide an important snapshot of trends in the relative occurrence of these fish. These records of fishing activity were particularly useful because individual trip logs were recorded; fishing was contained within a relatively narrow geographic range, and single day trips were relatively uniform in length. While the size of the boats used between lodges differed, within lodges boats were similar and fished using similar methods. This allowed us to account for effort and pool sightings data among boats within each region. In our study, we leveraged a latitudinal gradient of the recreational fishing areas to potentially identify shifts in the impacts of climate oscillations, as well as identify local oceanographic features that may resist climate scale oscillations and provide an area of refuge. However, to more definitively correlate various environmental variables with occurrence and distribution of blue marlin and sailfish, it is necessary to incorporate more detailed spatio-temporal data from satellite tagging studies.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHOR CONTRIBUTION
DH, HB, and LC conceived the research idea. DH and RL acquired data. DH performed data analysis and co-wrote manuscript with HB. All the coauthors participated in discussions and interpretations of the results.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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