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Hawaii Cyclonic Eddies and Blue Marlin Catches: The Case Study of the 1995 Hawaiian International Billfish Tournament

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The combination of prevailing northeasterly tradewinds and island topography results in the formation of vigorous, westward propagating cyclonic eddies in the lee of the Hawaiian Islands on time scales of 50–70 days. These mesoscale (~10^2 km) features are nowhere more conspicuous or spin up more frequently than in the Alenuihaha Channel between the Island of Maui and the Big Island of Hawaii. Cyclonic eddies in subtropical waters such as those around Hawaii vertically displace the underlying nutricline into the overlying, nutrient-depleted euphotic zone creating localized biologically enhanced patches. Insight into how these eddies may directly influence pelagic fish distribution is provided by examination of recreational fish catch data coinciding with the presence of eddies on the fishing grounds. We highlight the 1995 Hawaii International Billfish Tournament in which a cyclonic eddy dominated the ocean conditions during the weeklong event and the fish catch distribution differed significantly from the average historical tournament catch patterns. On the tournament fishing grounds, well-mixed surface layers and strong current flows induced by the eddy's presence characterized the inshore waters where the highest catches of the prized Pacific blue marlin (*Makaira mazara*) occurred, suggesting possible direct (e.g., physiological limitations) or indirect (e.g., prey availability) biological responses of blue marlin to the prevailing environment.

Keywords:
· Cyclonic eddies,
· AVHRR SST,
· hydrography,
· currents,
· Pacific blue marlin,
· tournament catches.

1. Introduction

Ocean activity has long been recognized to play a key role in the distribution, migration, availability, and catchability of large pelagic fishes such as marlin (Olson *et al.*, 1994). Ocean fronts and eddies in particular have been shown to attract and sustain these large, rapidly swimming animals (Owen, 1981). In Hawaiian waters, the combination of prevailing northeasterly tradewinds and island topography encourages the generation of vigorous eddies on the leeward side of the islands creating the potential for productive fishing areas. These physical features are nowhere more conspicuous and occur more frequently than off the west Kona coast of the Big Island, site of the Hawaiian International Billfish Tournament (HIBT) (Patzert, 1969; Lumpkin, 1998). Like other open-ocean eddies, their biological impact can be significant, although Hawaii's open-ocean, wind-driven features dynamically contrast with the well-studied cold core current-generated eddies such as those that spin off the Gulf Stream or the Kuroshio. These latter features characteristically trap or isolate an adjacent water mass retaining its developed floristic composition.

During the 1995 HIBT, an oceanographic survey was conducted off the southwest Kona coast, with the primary objective of mapping the prevailing oceanographic features and determining whether and if so, to what degree these conditions influenced tournament billfish catches. The oceanographic data were collected aboard the National Oceanic and Atmospheric Administration (NOAA) ship *Townsend Cromwell* (TC) over an area about 10,300 km^2. The sampled region extended well beyond the limits of the tournament fishing activity (Fig. 1) but nevertheless proved critical in providing insight into prevail-

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ing mesoscale (10^2 to 10^3 km) oceanographic processes; e.g., eddies. Information on current speeds and direction and water temperature and salinity were compared to the daily catch record for the HIBT provided by the Pacific Ocean Research Foundation (PORF) to evaluate the relationship between the oceanography and billfish catchability. The results are presented here.

2. Methods

Shipboard oceanographic measurements were made aboard the TC over a survey area about 93 km (50 nmi) by 111 km (60 nmi) off the southwest Kona coast of Hawaii during 29 July–4 August 1995 (Fig. 1). Hydrographic data (pressure, temperature, and conductivity) were acquired with 1000 m deep casts using a SeaBird 9/11+ Conductivity-Temperature-Depth (CTD) system. Local-scale currents were measured with a 153 kHz hull-mounted RDI acoustic Doppler current profiler (ADCP) along the survey track and to a depth of about 350 m and processed with the Common Oceanographic Data Analysis System (CODAS) subroutines(1). Additionally, 11 WOCE drifters were deployed within the eddy field (Fig. 1). Satellite sea surface temperature (SST) was evaluated using Advanced Very-High Resolution Radiometer (AVHRR) images from the NOAA Polar-Orbiting Environmental Satellites. Drifter specifications and data processing of drifter and satellite remotely sensed SST are detailed in Lumpkin (1998).

Daily catch records for the 1995 HIBT were provided by the Pacific Ocean Research Foundation (PORF) to evaluate the relationship between the oceanography and fishing activity. Pacific blue marlin (*Makaira mazara*) catches are presented principally as a proportion of total catch. Ideally, some measure of catch with effort would have been preferred; however, no information on fishing effort is available. We therefore relied on historical catch as a guidance to "typical" blue marlin catch and distribution patterns. To examine the null hypothesis that there is no difference between the historical catch patterns and those observed in 1995 with the eddy present, we computed the chi-square statistic (X^2) on an 11×2 contingency table of positive catch cells from the historical and the 1995 data for goodness of fit. Individual statistical areas with expectation values <1 were pooled geographically to limit bias in the chi-square contingency analysis; specifically, these areas included those located farthest offshore (**A** through **F**), close inshore off Captain Cook (**R** and **S**), and offshore southwest (**M**-**N**-**O**).

3. Results

3.1 The oceanography

During the 1995 HIBT, ocean conditions off the Kona coast of Hawaii were dominated by the presence of a cyclonic eddy and provided insight into how these mesoscale features might influence the distribution and catchability of large pelagic fishes.

As evidenced in the AVHRR imagery, the eddy formed shortly before 8 July in the immediate lee of Hawaii. The AVHRR imagery from 6 July (not shown) showed an undisturbed warm pool, but by 8 July cold water in the Alenuihaha Channel west of Keahole Point had begun rotating cyclonically (Fig. 2(a)). Over the next 10 days, the eddy drifted to the southwest but then turned to the east and propagated directly into the west coast of Hawaii. By the week of the billfish tournament and TC survey, the eddy was asymmetrically centered about 37 km (20 nmi) off Kailua-Kona, occupying a region of about 111 km (60 nmi) in diameter and pressed tightly against the island (Fig. 2(b)). Interestingly, during this week, the cyclonic eddy uncharacteristically appeared in satellite imagery as a warm core feature; shipboard surface temperature measurements corroborated the phenomena (see Fig. 5). Because of the eddy's residence in Hawaii's wind shadow, diurnal warming appeared to have created a thin layer of warm water overlying the entrained parcel of upwelled cooler water, resulting in the warm core surface expression (Figs. 2(b) and 2(c)). Once the eddy propagated back offshore out of the island's wind shadow, the cold core surface expression could be observed in satellite images (Fig. 2(d)).

Through the water column on the tournament grounds, well-defined surface mixed layers and strong current flows at the eddy periphery characterized inshore waters surveyed south of Keahole Point (Fig. 1). Vertical shear was steepest in the surface 75 m resulting in current speeds exceeding 60 $\text{cm}\cdot\text{sec}^{-1}$ (1.2 knots) in waters closest to shore off Kailua-Kona and Captain Cook (Fig. 1); vertical cross-sections of the north-south (v) component of current velocity from shipboard ADCP with respect to depth are presented for the zonal sections along the 19°30′ N and 19°40′ N latitudes (Fig. 3). In deeper waters, current speeds in the main eddy flow measured about 40 $\text{cm}\cdot\text{sec}^{-1}$ (0.78 knots) and diminished rapidly (approaching zero horizontal velocity) towards the eddy center (Figs. 1 and 3). At these rates, passively advected particles would complete one revolution around the gyre in about 6.5 days (157 h). Mixed layer depths also extended to a maximum depth of about 75 m corresponding with the shear profile (Fig. 1). In the absence of wind-generated turbulence, inshore surface mixed layers were thus ascribed directly to the eddy energy and the water

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(1)The public domain Common Oceanographic Data Analysis System (CODAS) software package is available at http://ilikai.soest.hawaii.edu/sadcp/

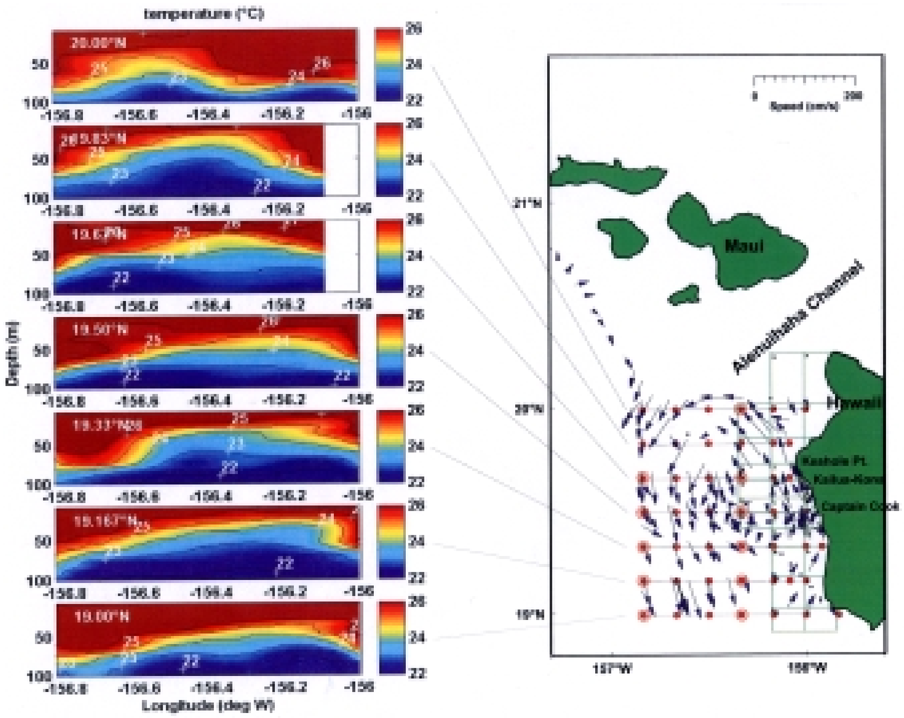

Fig. 1. (a) Temperature sections with respect to depth for seven zonal sampling lines aboard the *Townsend Cromwell* (TC), 26 July–5 August 1995. (b) Oceanographic station sampling grid (filled red dots); WOCE drifter deployment positions (second red circles) and schematic vector representation of estimated current velocities and direction along the TC cruise track. Current vectors have length scales to reflect relative velocities current speeds and direction averaged over the upper 21–100 m. Green gridlines correspond to statistical areas for the HIBT.

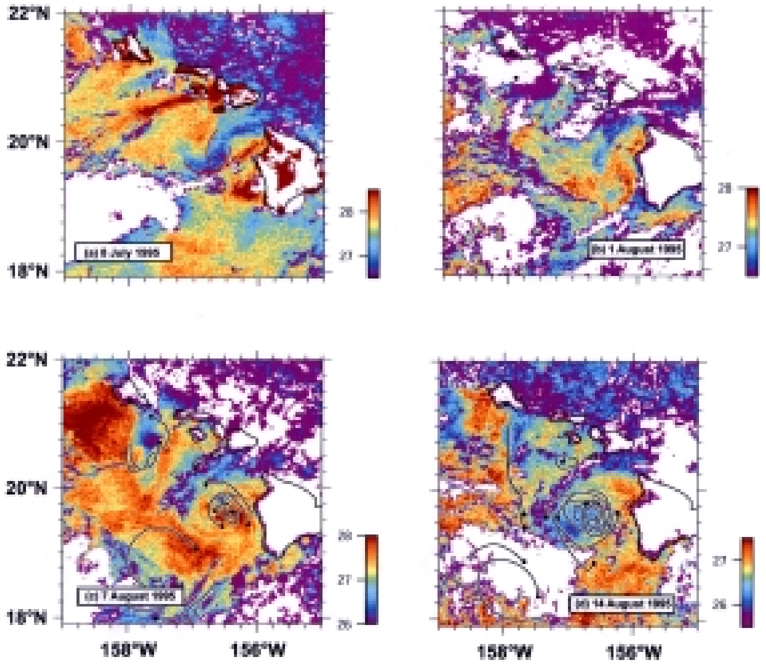

Fig. 2. AVHRR SST images (°C) for (a) 8 July, (b) 1 August–tournament week, (c) 7 August, and (d) 14 August. Concurrent drifter positions (points, with lines showing previous five days) are overlaid SST in (c) and (d). Temperatures colder than 22°C have been flagged as clouds (white).

mass occupying the tournament region composed largely of recirculated or well-mixed water advected or carried in from offshore.

In contrast, the water column of the eddy interior offshore was well stratified with virtually no evidence of surface mixing (Fig. 1). Localized fronts characteristically formed at the interface of the eddy periphery and core over a relatively narrow spatial scale of about 2 km (*ca*. 1 nmi) (Figs. 1 and 3). With respect to the fishing grounds, the front was positioned *ca*. 18 to 22 km (10 to 12 nmi) offshore.

3.2 The 1995 HIBT catch

Fish catches, inclusive of fish landed and those tagged and released, were extracted directly from the HIBT daily catch record for the tournament week 31 July to 4 August 1995. Location of fish capture was reported only to a spatial resolution of the HIBT statistical sampling grid (Figs. 1, 4 and 5). A total of 89 fish were caught: 80 Pacific blue marlin; 6 yellowfin tuna, *Thunnus albacares*; and 3 striped marlin, *Tetrapturus audax*. For blue marlin specifically, the concentration of catches occurred in statistical areal blocks "**S**" where 20.0% were landed, "**L**" with 18.75%, and "**K**", "**T**", and "**U**" each with 13.75% of the total marlin catch (Fig. 4). As mentioned above, no fishing effort data are available to help interpret catch information. For comparative purposes, the proportions of the total historical blue marlin catch for each statistical area from 1959 to 1994 are also presented (Fig. 4). Although there is probably some interannual variability over the 36-year tournament history, the catch per area of pooled data provides a good perspective towards the general trend of where fish were caught. The chi-square goodness of fit statistic computed for the contingency table comparing the historical and the 1995 catch patterns by statistical area suggested strong evidence for anomalous catch patterns in the 1995 HIBT ($X^2 = 36.59$, $df = 10$, $p < 0.0005$). For the 1995 HIBT, the concentration of catches was centered farther south than normal and curiously, there was a notable absence of any catch in area "**I**", historically the most productive "grounds" typically targeted by experienced anglers. In the case of area "**I**", the absence of catch may be a reflection of reduced effort, however, one may expect that the annually returning, experienced anglers would likely expend considerable search time (i.e., fishing effort) on the "grounds" traditionally associated with best catches[2].

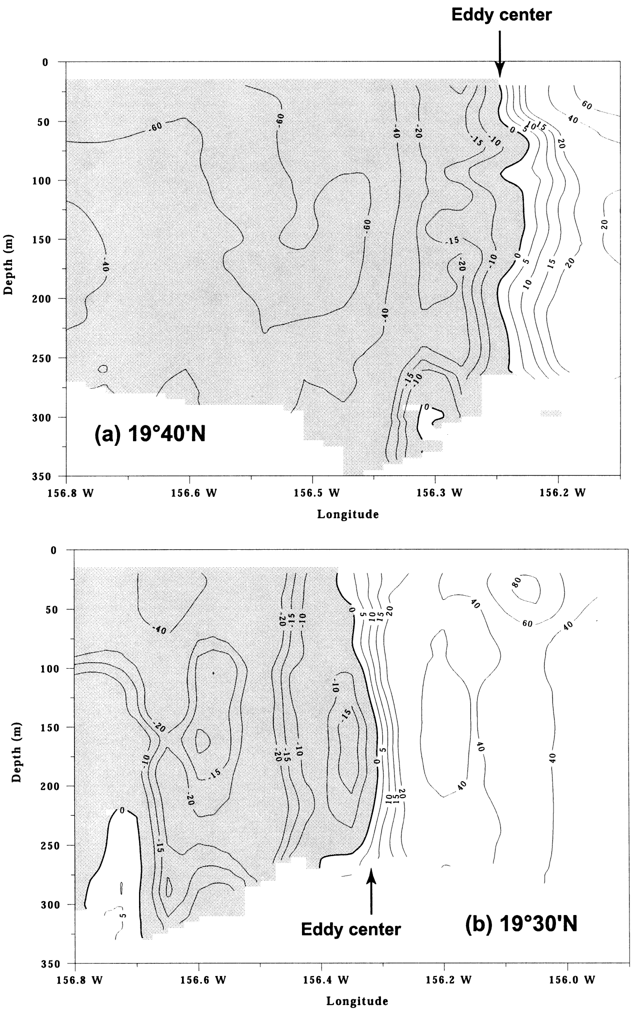

Fig. 3. Vertical profiles of depth-averaged estimated north-south components ("*v*") of current velocities (a) off Captain Cook; i.e., along 19°30′ N and between *ca*. 156°00′ W and 156°50′ W, 2 August 1995 and (b) off Kailua-Kona; i.e., along 19°40′ N and between *ca*. 156°00′ W and 156°50′ W, 3 August 1995. White areas represent net northward flow and shaded areas represent net southward flow.

4. Discussion

The occurrence of oceanic eddies of this scale is not uncommon in waters adjacent to the west coast of the Big Island (Patzert, 1969; Lumpkin, 1998; Seki *et al*., 2001). When present, these eddies will dominate all other coastal currents, often creating extended periods of strong unidirectional coastwise flow (Robinson and Lobel, 1985). Within the fishing grounds (i.e., the 37 km (20 nmi) closest to shore), the eddy generally appeared as a strong north-northwest current running up the coast towards Keahole Point, where the flow turned west offshore, essentially following the island topography.

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[2] Davie, P. S. HIBT catch and fishing effort since 1959. A statistical perspective. 16 pp. Unpublished report available from the Hawaiian International Billfish Association and the Hawaii Data Center [hdc@aloha.net].

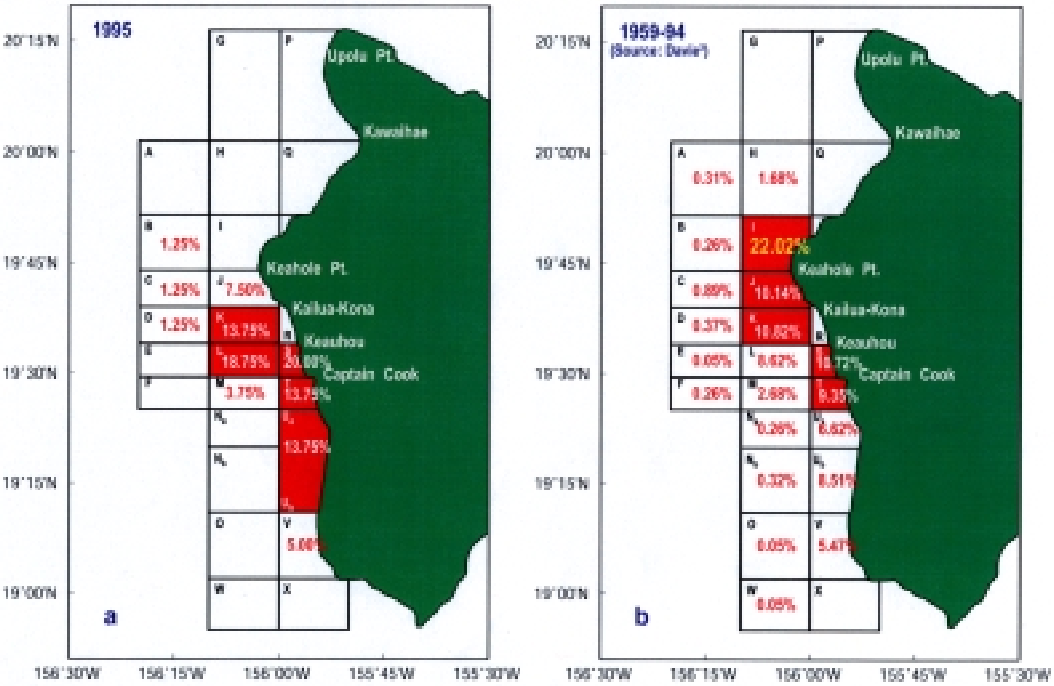

Fig. 4. Catch, as proportion of total catch, of Pacific blue marlin (*Makaira mazara*) by fishing area at the Hawaiian International Billfish Tournament for (a) 1995 and (b) 1959–1994 (Davie$^{(2)}$).

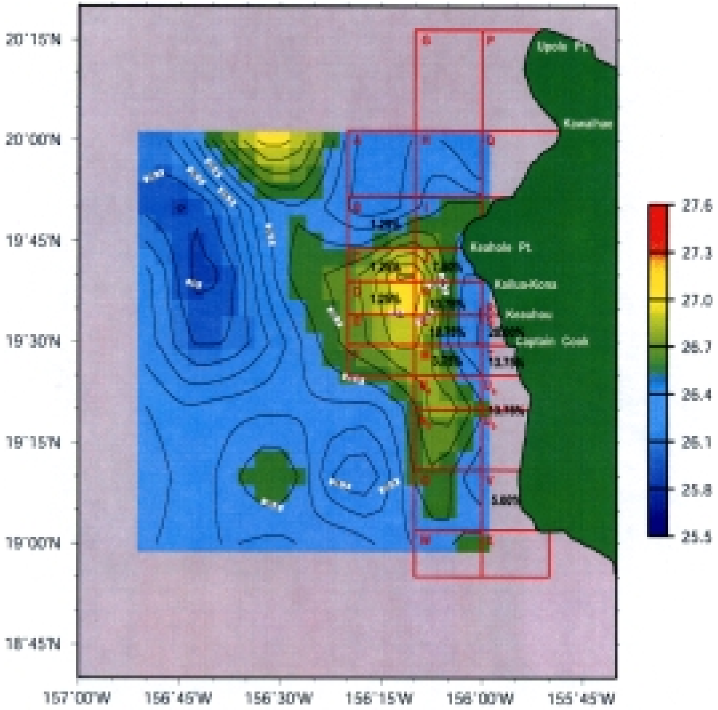

Fig. 5. Eddy structure mapped by horizontal sea surface temperature (SST) distribution, and proportion of total blue marlin catch per area at the 1995 HIBT.

Areas of highest blue marlin catches coincided with (1) regions over which the strongest fronts and surface thermohaline gradients were observed ("**L**" and "**K**") and (2) regions of strong coastwise currents and deep surface mixed layers inshore ("**S**", "**T**", and "**U**") (Fig. 5).

If catch patterns are reflecting responses to the prevailing environment, some insight into the underlying basis behind the development of these patterns may be gained from our existing understanding of blue marlin biology and ecology. For example, acoustic tracking studies conducted off Kona have shown that blue marlin exhibit a marked preference for the warm surface mixed layer above the thermocline and particularly where water temperature varied between 26° and 27°C (78.8°F–80.6°F) (Holland *et al*., 1990; Block *et al*., 1992). More importantly, while blue marlin are capable of ranging through the thermocline, they apparently rarely do so (Block *et al*., 1992). This would suggest that blue marlin migrating into waters south of Keahole Point during the tournament would have been compelled to confine their movements within the narrow swath between the coastline and the front interfacing the stratified eddy interior to remain in their preferred habitat. By limiting their horizontal movement between these bounds (essentially restricting their movement to the peripheral eddy flow), the catchability of the marlin likely increases.

The interplay between the ocean conditions and blue marlin foraging may prove an integral link to observed catch patterns. The physical environment may provide cues for marlin to locate prey, or more directly, may aggregate or concentrate food items. Movements and distribution of small tuna, which diet studies have shown to be a particularly favored food among blue marlin (Strasburg, 1970; Brock, 1984), can be strongly influenced by fronts and prevailing ocean conditions (Laurs *et al*., 1984; Fiedler and Bernard, 1987). Additionally, peculiar to the diet of blue marlin captured in coastal waters off Kona was the prevalence of larval and juvenile reef fish (Brock, 1984). Since these fish may be transported, carried along, or aggregated by local eddies and currents (Lobel and Robinson, 1986), an eddy field such as that observed in 1995, could create a unique feeding environment that would make these prey readily available.

Attempts to decipher catch patterns with respect to the environment also should consider the role of reproductive strategy in dictating blue marlin movement and distribution. Summer influx of blue marlin onto the fishing grounds appears to be directly tied to seasonal spawning migrations (Hopper, 1990). Conceivably, blue marlin spawning cues may have evolved to target oceanographic features, such as eddies, that are commonly found here during this time of year. Eddies, when present, could mechanically limit dispersal of young marlin (Owen, 1981; Lobel and Robinson, 1986), thereby helping to retain them within waters favorable to their growth and survival. During the survey, 9 blue marlin larvae(3) were caught in a mere 5 surface plankton tows made within 37 km (20 nmi) of the shore; none were taken in seven tows made 93 km (50 nmi) out.

In summary, a cyclonic eddy physically occupying some 8500 km^2 of surface area dominated the oceanography off the Kona coast of Hawaii during the 1995 HIBT. On the tournament grounds, well-mixed surface layers and strong current flows induced by the eddy presence characterized inshore waters surveyed south of Keahole Point. Offshore, localized fronts formed at the interface of the eddy periphery and core. Areas of high tournament fish catches seemed to coincide with both these eddy influenced inshore and frontal regions suggesting possible direct (e.g., physiological limitations) or indirect (e.g., prey availability) biological responses of blue marlin to the environment. Lack of information regarding the fishing effort unfortunately precludes our ability to fully investigate whether these catch patterns are a response to the change in physical environment or simply a chance outcome of effort allocation.

Acknowledgements

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(3)Equivocal diagnostic characters keep the larvae identification to blue marlin tentative; IDs courtesy of Bruce C. Mundy.

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