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Hawai‘i Cyclonic Eddies and Blue Marlin Catch Patterns[1]

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This research describes a case study in which results of the 1995 annual Hawaiian International Billfish Tournament (HIBT) are examined with respect to prevailing oceanographic conditions. In particular, we consider the presence and role of counterclockwise rotating vortices, or cyclonic eddies, that spin up on time scales of 50–70 days in response to a combination of the Hawaiian Islands' topography and the prevailing northeasterly tradewinds in the lee of the islands. These mesoscale (~10^2 km) features are nowhere more conspicuous or frequent than in the Alenuihaha Channel between Maui and the Big Island of Hawai‘i. Cyclonic eddies in subtropical waters, such as those around Hawai‘i, vertically displace the underlying nutricline into the overlying, nutrient-depleted euphotic zone, creating localized, biologically enhanced patches.

By examining the HIBT fish-catch data with concurrent oceanographic information mapping the fishing grounds, we offer insights into how these dynamic features may influence pelagic fish distribution. A cyclonic eddy dominated ocean conditions during the weeklong 1995 HIBT, and the resulting distribution of fish catch differed significantly from the tournament's average historical catch patterns. Within the tournament fishing area, well-mixed surface layers and strong current flows induced by the eddy's presence characterized inshore waters, where the highest catches of the prized Pacific blue marlin (Makaira mazara) occurred. This suggests possible direct (e.g., physiological limitations) or indirect (e.g., prey availability) biological responses of blue marlin to the prevailing environment.

[1]"Hawaii cyclonic eddies and blue marlin catch patterns" is adapted from the original article that appeared in the Journal of Oceanography, 58(5):739-745, 2002.

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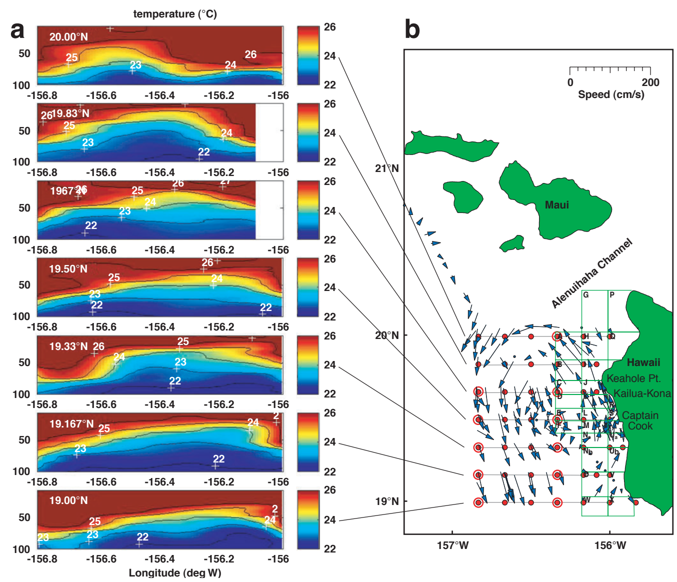

Figure 1. (a) Temperature sections with respect to depth for seven zonal sampling lines aboard the *Townsend Cromwell*, July 26–August 5, 1995. (b) Oceanographic station sampling grid (filled red dots); WOCE drifter deployment positions (red circles) and schematic vector representation of estimated current 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.

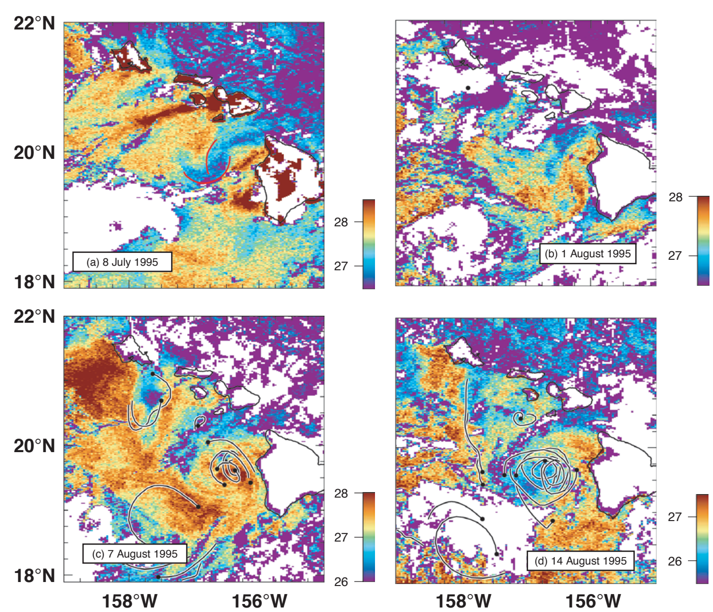

Figure 2. AVHRR SST images (°C) for (a) July 8; (b) August 1– tournament week; (c) August 7; and D) August 14. Concurrent drifter positions (points, with lines showing previous five days) are overlaid SST in (c) and (d). Temperatures colder than 22°C have been flagged as clouds (white).

A Mesoscale Eddy off the Big Island

Ocean activity has long been recognized to play a key role in the distribution, migration, availability and catchability of large pelagic fish 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 formation of vigorous eddies or current swirls on the leeward side of the islands, which in turn creates the potential for productive fishing areas. These eddies are nowhere more conspicuous or frequent 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, the biological impact of the Hawai'i eddies can be significant, although their open-ocean, wind-driven features contrast dynamically with those of the well-studied cold-core current-generated eddies such as those that spin off the Gulf Stream or the Kuroshio. The latter variety characteristically will 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 to map prevailing oceanographic features and determine if these conditions influenced tournament billfish catches (and if so, to what degree). Data were collected aboard the NOAA ship Townsend Cromwell (TC) over an area of about 10,300 km^2. The sampled region extended well beyond the limits of the tournament (Fig. 1), but proved critical nevertheless in providing insight into mesoscale (10^2 to 10^3 km) oceanographic processes such as eddies. To evaluate the relationship between the oceanography and billfish catchability, information on current speeds, direction, water temperature and salinity were compared to the daily catch record for the HIBT provided by the Pacific Ocean Research Foundation (PORF). The results are presented here.

Studying the 1995 Eddy

Shipboard oceanographic measurements were made aboard the TC between July 4 and August 1995 over an area of about 93 by 111 km (50 by 60 nmi) off the southwest Kona coast of Hawai'i (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 subroutines from the Common Oceanographic Data Analysis System (CODAS). Additionally, 11 drifters from the World Ocean Circulation Experiment 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 PORF to evaluate the relationship between area oceanography and fishing activity. Pacific blue marlin (*Makaira mazara*) catches are presented principally as a proportion of total catch, and though some measure of catch with effort would have been preferred, no information on fishing effort was available; we therefore relied on historical catch information 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 11x2 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 southwest offshore (**M-N-O**) (Fig. 4).

Characteristics of the Eddy

As evidenced in the AVHRR imagery, the eddy formed shortly before July 8 in the immediate lee of Hawai'i. AVHRR imagery from July 6 (not shown) showed an undisturbed warm pool, but by July 8 cold water in the Alenuihaha Channel west of Keahole Point had begun rotating cyclonically (Fig. 2a). 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 Hawai'i. 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. 2b). Interestingly, the cyclonic eddy during this week appeared uncharacteristically in satellite imagery as a warm core feature, and shipboard surface-temperature measurements corroborated the phenomena (see Fig. 5). Because of the eddy's residence in Hawai'i'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 (Fig. 2b, c). Once the eddy propagated back offshore out of the island's wind shadow, the cold core surface expression could once again be observed in satellite images (Fig. 2d).

Through the water column on the tournament grounds, well-defined surface mixed layers and strong current flows at the periphery of the eddy 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 cm/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 latitudes 19°30'N and 19°40'N (Fig. 3). In deeper waters, current speeds in the main eddy flow measured about 40 cm/sec^{-1} (0.78 knots)[2] and diminished

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

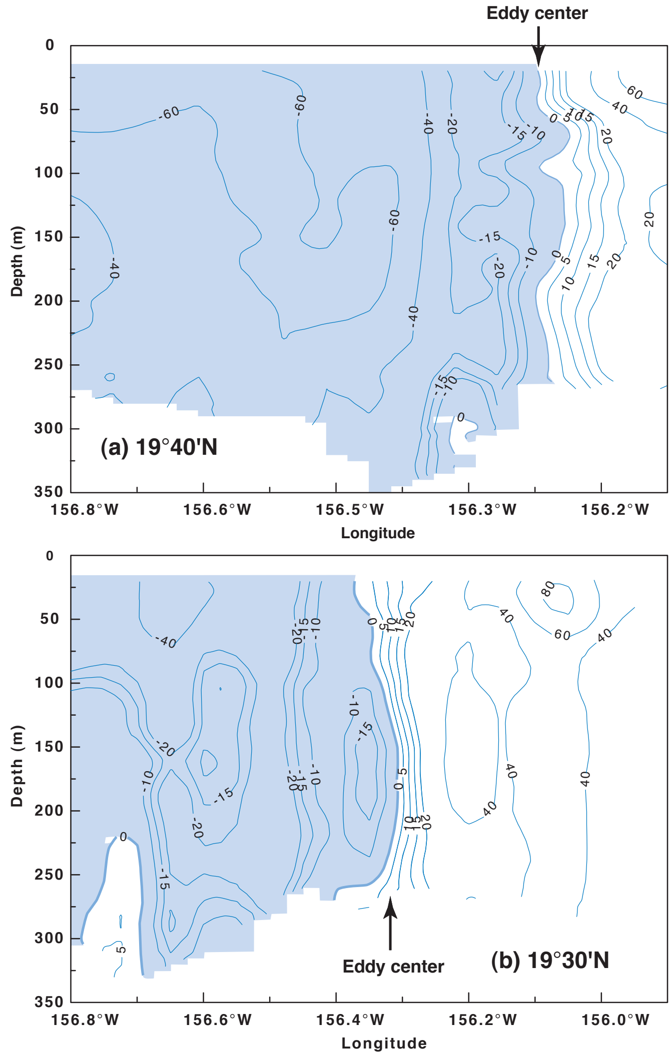

Figure 3. Vertical profiles of depth-averaged estimated north-south components ("v") of current velocities: (a) off Kailua-Kona (i.e., along 19°40′N and between ~156°00′W and 156°50′W, August 3, 1995; and (b) off Captain Cook (i.e., along 19°30′N and between ~156°00′W and 156°50′W, August 2, 1995. White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

rapidly (approaching zero horizontal velocity) towards the eddy center (Figs. 1, 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 mass occupying the tournament area composed largely of recirculated or well-mixed water advected or carried in from offshore.

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

The 1995 HIBT Catch

Fish catches, including those landed and those tagged and released, were extracted directly from the HIBT daily catch record for the tournament week July 31 to August 4, 1995. Location of fish capture was reported only to a spatial resolution of the HIBT statistical reporting grid (Figs. 1, 4, 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 area blocks "**S**," where 20.0% were landed, "**L**," with 18.75%, and "**K**," "**T**" and "**U**," each with 13.75% of the total 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 tournament's 36-year history, the catch per area of pooled data provides a good perspective on the general trend of where fish were caught. The chi-square goodness of fit statistic computed for the contingency table compared the historical and 1995 catch patterns by statistical area, and suggested strong evidence for anomalous catch patterns in the 1995 HIBT ($X^2 = 36.59$, df = 10, $p < 0.0005$). For the 1995 tournament, the concentration of catches was centered farther south than normal, and curiously, there was a notable absence of any catch in area "**I**," which historically is the most productive area targeted by experienced anglers. In this case, the absence of catch may reflect reduced effort, but one might expect that annually returning, experienced anglers would expend considerable fishing effort in the area traditionally associated with best catches.[3]

Oceanic eddies of this size are 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 dominate all other coastal currents, often creating extended periods of strong unidirectional coastwise flow (Robinson and Lobel, 1985). Within the fishing grounds, or 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 offshore to the west, essentially following the island's topography.

Species Response to Environment

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).

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[3]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 Hawai'i Data Center [hdc@aloha.net].

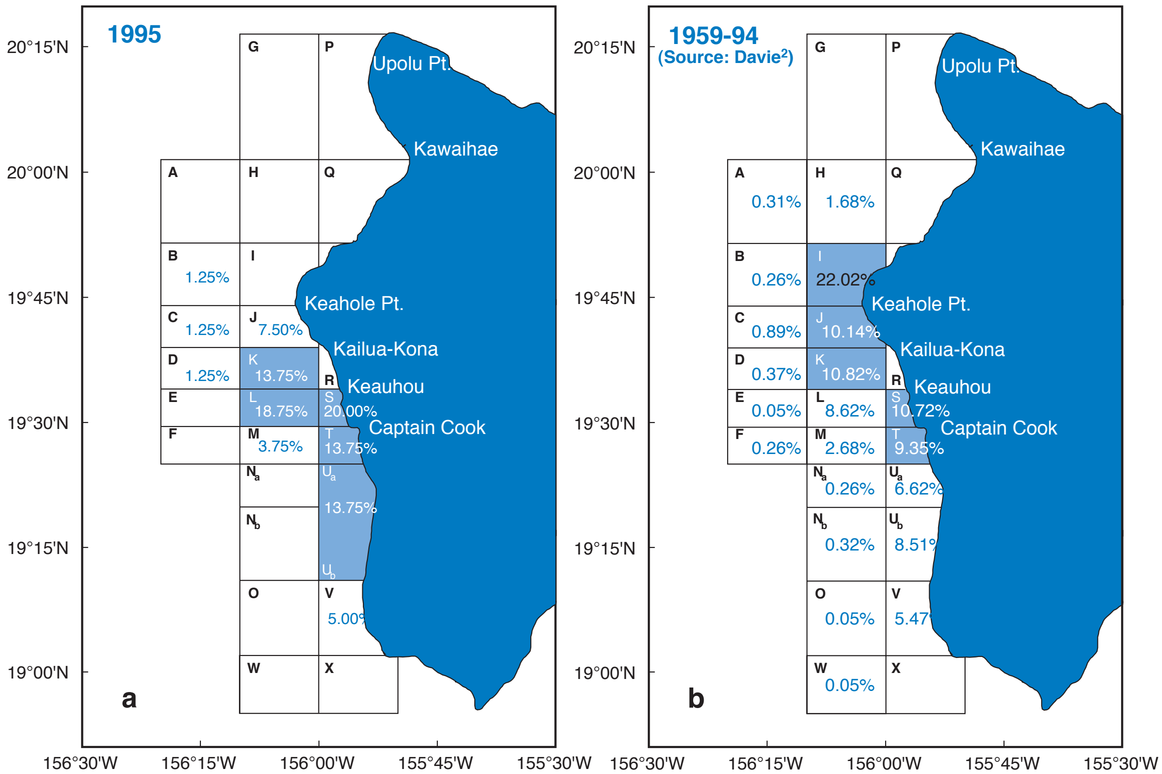

Figure 4. Catch, as proportion of total catch, of Pacific blue marlin (*Makaira mazara*) by fishing area at the Hawaiian International Billfish Tournament for (a) 1995; and (b) 1959–1994 (Davie: see reference in footnote 2).

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 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. When present, eddies 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[4] 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.

If catch patterns reflect responses to the environment, some insight into the system underlying 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, particularly where water temperature varies between 26 and 27°C (78.8– 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, to remain in their preferred habitat, 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. With horizontal movement constrained between these bounds (essentially within the peripheral eddy flow), the catchability of the marlin likely increases.

The interplay between ocean conditions and blue marlin foraging may prove an integral link to observed catch patterns. The physical environment may be providing cues for marlin to locate prey even as it aggregates or concentrates 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,

More Data Required to Resolve Role of Environment in Behavior

In summary, a cyclonic eddy physically occupying some 8500 km^2 of surface area dominated the oceanography off the Kona coast of Hawai‘i during the 1995 HIBT. On the tournament grounds, well-mixed surface layers and strong current flows induced by the eddy 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

[4]Equivocal diagnostic characters keep the larvae identification to blue marlin tentative; IDs courtesy of Bruce C. Mundy.

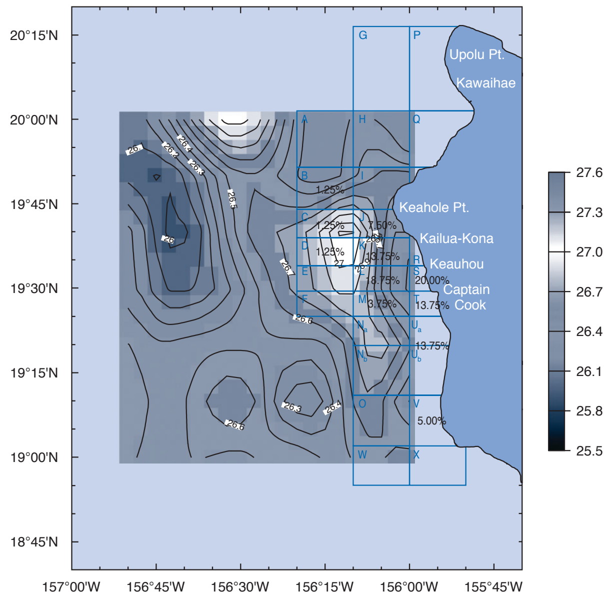

Figure 5. Eddy structure mapped by horizontal sea surface temperature distribution and proportion of total blue marlin catch per area at the 1995 HIBT.

direct (e.g., physiological limitations) or indirect (e.g., prey availability) biological responses of blue marlin to the environment. Unfortunately, lack of information about fishing effort precludes a full investigation of whether these catch patterns are a response to changes in physical environment or simply a chance outcome of effort allocation.

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