Mesoscale Cyclonic Eddies and Pelagic Fisheries in Hawaiian Waters

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Abstract-**The combination of prevailing northeasterly tradewinds and island topography result 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 islands of Maui and the Big Island of Hawaii. Like other open-ocean eddies, their biological impact can be significant, although Hawaii's open-ocean, wind driven features dynamically contrast 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.**

Cyclonic eddies in subtropical waters such as around Hawaii vertically displace the underlying nutricline into the overlying, nutrient-deplete euphotic zone creating localized biologically enhanced patches. Recent direct high-resolution horizontal and vertical observations of these vortices made from satellite and shipboard platforms provide new perspectives on biological enhancement within open-ocean cyclonic eddies and are presented here. These localized regions of high productivity may lead to aggregation and development of a forage base for higher trophic levels.

How eddies may directly influence pelagic fish distribution are examined from recreational and commercial fish catch data coinciding with the presence of eddies. We highlight the 1995 Hawaii International Billfish Tournament in which a cyclonic eddy dominated the ocean conditions during the weeklong event and appeared to be the principle factor influencing fish availability. On the tournament 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 direct (e.g., physiological limitations) and/or indirect (e.g., prey availability) biological responses of blue marlin to the prevailing environment.

I. INTRODUCTION

Regional oceanography has long been recognized to play a key role in the distribution, migration, availability, and catchability of pelagic fishes, particularly tunas and billfishes [1]. Oceanic fronts and eddies in particular have been shown to attract and sustain these large, rapidly swimming animals [2, 3, 4].

In Hawaiian waters, the combination of prevailing northeasterly tradewinds and island topography encourages the generation of vigorous eddies on the leeward side of the archipelago [5, 6], creating the potential for very productive fishing areas. These physical features are nowhere more conspicuous and occur more frequently than in the Alenuihaha Channel, adjacent to the Kona coast of the Big Island of Hawaii, site of Hawaiian International Billfish Tournament (HIBT).

These cyclonic, mesoscale features (~10^2 km) can be observed at all times during the year. They are typically generated in the lee of Hawaii on time scales of 50-70 days with diameters of 50 - 100 km and surface currents up to 100 cm sec^{-1} [6]. Like other open-ocean eddies, their biological impact can be significant. Eddies have been postulated to play a key role in recruitment processes, mechanically both limiting and aiding dispersal of littoral and pelagic young through entrainment and transport of organisms [2, 7]. From a trophic standpoint, localized regions of higher productivity created by eddies may lead to aggregation and development of a forage base; physical gradients in water properties may provide cues for predators to locate prey or, more directly, may aggregate or concentrate food items. As a result, these same cues are used by fishermen to locate fish. Recently, much interest has focused on the role of eddies in nutrient transport, as divergent surface flows result in uplifting of the thermal structure and localized upwelling of nutrients into the euphotic zone [8]. This eddy pumping is believed to increase primary and new production and is thus a key mechanism for the development of plankton communities in oligotrophic seas, which otherwise are severely nutrient-limited [9, 10]. The annual vertical nutrient flux resulting from eddy upwelling in the Sargasso Sea was found sufficient to reconcile the apparent discrepancy in the nutrient budget [11].

Although regularly occurring features, obtaining detailed information on open-ocean eddies have proved difficult in the past principally due to the inability to identify and track them on time- and space-scales that adequately accommodate shipboard sampling. The recent development of sea surface temperature (SST) estimates using Geostationary Operational Environmental Satellites (GOES) radiance measurements facilitates detection and sampling of dynamically active open-ocean eddies [12]. GOES observations may be acquired up to 48 times a day as compared to the twice per day sampling provided by Advanced Very High Resolution Radiometers (AVHRR) carried aboard polar orbiting satellites. In areas that are often in-

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fluenced by cloud cover, GOES significantly increases the possibility of measuring SST [12]. In waters around Hawaii, where cloud cover is abundant, hourly images enable frequent composites that are timely in guiding *in situ* sampling.

In this paper we present observations from a number of cyclonic eddies with recent sampling made possible by this new technology. High-resolution horizontal and vertical observations from ship and satellite platforms refine our characterization of these oceanographic features and provide new perspectives on the coupling of the physics and biology in association with open-ocean cyclonic eddies.

II. METHODS

Satellite SST data were obtained principally from the National Oceanic and Atmospheric Administration's (NOAA) geostationary west meteorological satellite GOES-10. Hourly GOES-SST images were processed into 3-h composites, and distributed by the NOAA CoastWatch program. The three-hour images were then combined to yield three day composites. Earlier (i.e., 1995) SST information was acquired from the AVHRR aboard the NOAA-12 polar orbiting satellite. Surface chlorophyll responses were monitored with 8-day composites of ocean color from NASA's Sea-viewing Wide Field-of-View Sensor (SeaWiFS).

Shipboard measurements were made on the NOAA ship *Townsend Cromwell* (TC) over a survey area about 93 km (50 nmi) longitude by 111 km (60 nmi) latitude off the southwest Kona coast of Hawaii during July-August 1995 and along two transects about 185 km (100 nmi) long and stations spaced about 18.6 km (10 nmi) apart that traversed two eddies designated "*Mikalele*" and "*Loretta*" during November 1999 (Fig. 1). Hydrographic data (pressure, temperature, salinity, *in situ* Chl fluorescence, and dissolved oxygen) and seawater samples were acquired with a SeaBird 9/11+ CTD/rosette sampler system. Seawater samples were analyzed for chlorophyll and phaeopigments onboard ship [13], and frozen samples were collected for shore-based determinations of photosynthetic pigments by HPLC [14], and inorganic nutrients using standard autoanalyzer techniques [15]. Local-scale, along track currents were measured underway with a 153 kHz hull-mounted RDI acoustic Doppler current profiler (ADCP).

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.

III. RESULTS AND DISCUSSION

A. Biologically Enhanced Hawaiian Eddies

The high frequency of eddy formation in Hawaiian waters provides an ideal opportunity to study these mesoscale ecosystems. Although the physical dynamics associated with the evolution, maintenance, and decay of Hawaiian eddies have been well documented [5,6], quantifying the associated biological

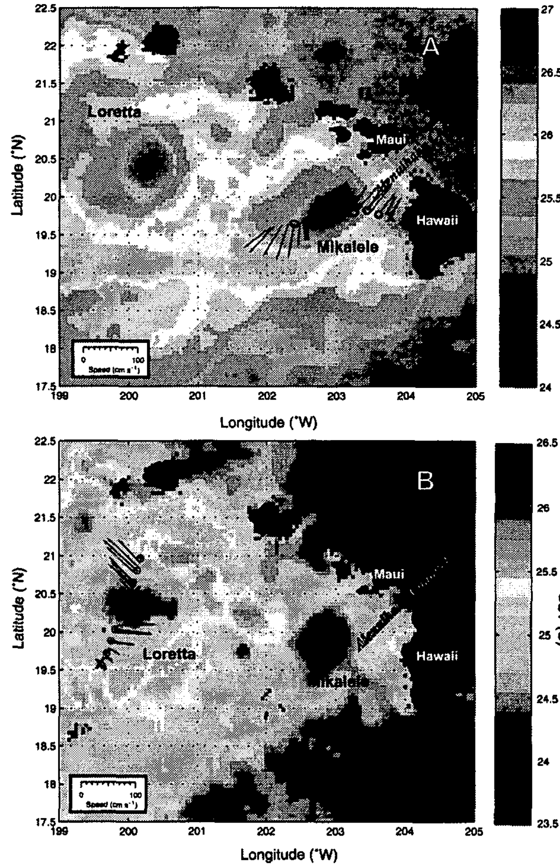

Fig. 1. False color, 2-day composite GOES SST (°C) image of cyclonic eddies "Loretta" and "Mikalele"for (A) 16-18 November and (B) 22-24 November 1999. Overlying the temperature expressions are CTD stations (red circles), control stations (red "X"s), and estimated ADCP current velocities (averaged over the upper 21-100 m) along the survey tracks.

and geochemical processes has been hampered (until recently) by the inability to detect eddy presence and the logistical difficulties in sampling once eddies are detected. Much of our prior understanding of biogeochemical processes occurring within Hawaiian eddies was rooted in sampling conducted at a single eddy [10, 16, 17] and inferred from works on eddies in other oligotrophic oceans [8, 11,18]. The advent of satellite AVHRR SST data facilitated detection of these features, although the obstacle of matching the sampling scales between satellites and ships remained. Modest deviations in eddy position and intensity observed in SST composite images from shore to ship may be quite substantial when operating on local time- and space-scales such as those encountered during research surveys. The predictive capability offered by the near real-time GOES-SST product has significantly enhanced our abilities to optimize sampling strategy and target dynamic features such as eddies with greater precision than previously available. In the present study, eddy evolution was initially established, eddy positions and strength monitored, and the shipboard sampling track was dynamically adjusted using the GOES-SST images.

In November 1999, the GOES-SST guided transects navigated sampling through two well defined eddies, *Loretta* and

Mikalele (Fig. 1). At the time of the survey, both eddies were ~100 km in diameter. *Mikalele* was approximately one month old and centered near19°45'N 157°12'W; *Loretta* was six months old and centered near 20°25'N 160°W. Upper ocean doming of isotherms were most intense in the upper 200 m and eddy influence was generally confined to the upper 300-400 m. Thermocline depth shoaled to within 40 m of the surface in both eddies, but the magnitude of vertical displacement and compression of isotherms were substantially more pronounced in *Loretta* where a vertical temperature change of 6°C over 20 m was observed in the eddy core. Maximum ADCP current velocities exceeded 70 cm s^{-1} (1.3 knots) and 85 cm s^{-1} (1.65 knots) at *Mikalele* and *Loretta*, respectively. Surface thermal gradients measured both by satellite and *in situ* were stronger at the more recently formed (ca. one month) *Mikalele*, but maximum current velocities were higher and subsurface vertical structure (doming) considerably more developed at the older (~6 months) *Loretta*. Historical GOES-10 thermal imagery revealed that *Loretta* began spinning up during mid-May 1999 and maintained a presence in the lee of the Hawaiian Islands until January 2000. The strongest temperature gradients in *Loretta* occurred during late August-early September 1999 when core SSTs measured 23.5°C concurrent with a twofold increase in surface TChl. In comparison, *Mikalele* was short-lived, existing from late October 1999 to mid-January 2000.

The vertical distribution of chloropigments and macronutrients (nitrate+nitrite (N+N), phosphate, and silicate) closely tracked the isotherms. The deep chlorophyll maximum layer was coincident with the nitracline depth (defined as the 1 uM N+N isopleth), and shallowed to about 80 m and 65 m for *Mikalele* and *Loretta*, respectively). Nitrate+nitrite concentrations at the base of the thermocline increased from 0.02 uM to 1 uM for *Mikalele* and 6 uM for *Loretta*. Depth-integrated N+N levels measured near the centers of *Mikalele* and *Loretta* were 3- to 15-fold higher than observed for control stations. Concentrations of phosphate and silicate were also elevated within the eddies. Phytoplankton pigment biomass was 1.5 times higher in *Loretta* than in *Mikalele* or the control stations. See [19] for additional details and results.

B. The 1995 HIBT: An Oceanographic Perspective

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 higher trophic levels (Fig. 2). The eddy formed in early July and at the time of the survey (30 July-4 August), was asymmetrically centered about 20 nmi off Kailua-Kona and was pressed tightly against the island [6]. On the tournament grounds, well-mixed surface layers (to about 75 m)and strong current flows at the eddy periphery characterized inshore waters surveyed south of Keahole Point. Offshore, localized fronts formed at the interface of the eddy periphery and core. Regions with well-defined surface layers coincided with the areas of highest current velocities, which were strongest in the upper 75 m of the surface with measured speeds exceeding 60 cm/sec (1.2 knts) towards the periphery of the eddy field. These current speeds diminished rapidly (approaching zero horizontal velocity) towards the eddy center. The water column of the eddy interior, in contrast, was well stratified with thermohaline parameters changing gradually and continuously with depth and no evidence of mixing. Since mixed layers normally tend to be the product of wind-generated turbulence, the existence of the inshore surface mixed layers off Kona in the absence of much wind stress were ascribed directly to the eddy energy and the water mass present in the tournament region, composed largely of recirculated or well-mixed water advected in from offshore. Diurnal warming in Hawaii's wind shadow created a thin layer of warm water overlying the upwelled cold water in the eddy and thus a warm core surface expression in both in situ measurements and AVHRR SST satellite imagery was observed.

Fish catches were extracted directly from the HIBT daily catch record for the tournament week 31 July to 4 August 1995. A total of 89 fishes were caught: 80 Pacific blue marlin, *Makaira mazara*; 6 yellowfin, *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. 2); a pattern shifted farther south than historically observed. Areas of highest blue marlin catches coincided with (1) regions over which the strongest fronts and surface gradients of temperature, salinity, etc. were observed ("**L**" and "**K**") and (2) regions of strong coastwise current and deep surface mixed layers ("**S**", "**T**", and

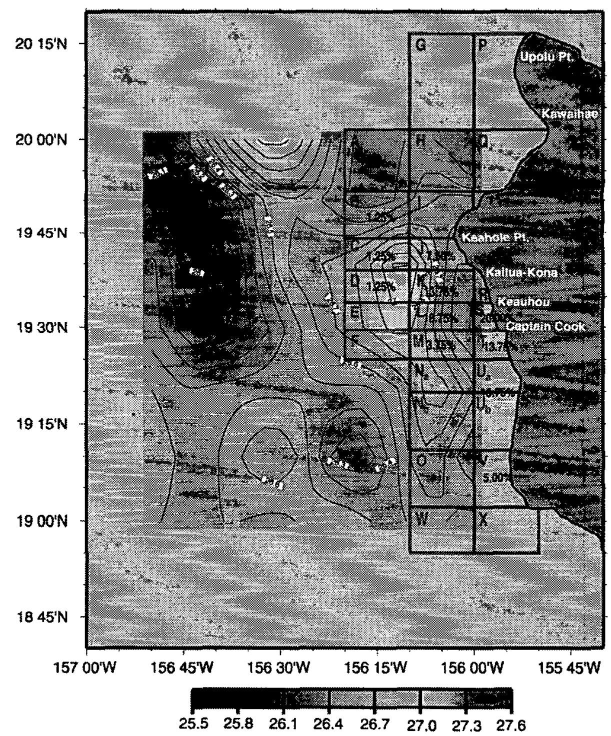

Fig. 2. *In situ* sea surface temperature (SST) for 30 July - 4 August 1995. Catch, as proportion of total catch, of Pacific blue marlin by statistical fishing area at the 1995 HIBT is overlaid to help illustrate the relationship between fishing and eddy position.

"U") suggesting direct (e.g. physiological limitations) and/or indirect (e.g. prey availability) biological responses of blue marlin to the environment.

IV. SUMMARY AND CONCLUSIONS

In conclusion, our results reveal substantially greater biological enhancement associated with Hawaiian eddies than previously observed. In stratified, oligotrophic waters such as those found around Hawaii, recycling of nutrients between the grazers and the phytoplankton typically maintains primary production at uniformly low levels. Transient episodes of upwelled nutrient-rich water by strong cyclonic eddies have been shown to induce "new" production, thus providing a mechanism to shorten the trophic pathway and facilitate energy transfer. Accompanying the injection of nitrogeneous nutrient enrichment at these features are not only increases in the biomass of phytoplankton but also the contribution of larger eukaryotic phytoplankton, notably diatoms and dinoflagellates over recycled-nutrient based picophytoplankton (e.g., photosynthesizing cyanobacteria species) to the phytoplankton community structure that normally typifies the system.

Relationships between the physical environment and higher trophic levels are considerably more difficult to ascertain, primarily due to the difficulty in acquiring the necessary biological information for such an assessment. The presence of the eddy field during the 1995 HIBT offered a unique opportunity to examine potential relationships between fish and their environment. On the fishing grounds (i.e., the 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. This resulted in well-mixed surface layers inshore south of Keahole Point and localized fronts at the interface of the eddy periphery and core. Areas of high tournament fish catches coincided with these ocean features, suggesting direct (e.g. physiological limitations) and/or indirect (e.g. prey availability) biological responses of blue marlin to the environment. All considered, there was compelling evidence supporting the notion that the prevailing ocean conditions was the principle factor influencing fish availability during the 1995 HIBT.

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