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Biological enhancement at cyclonic eddies tracked with GOES thermal imagery in Hawaiian waters

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Abstract. In November 1999, ship and satellite platforms were used to track, target and map the vertical and horizontal structure of two cyclonic eddies in the lee of Hawaii. Depth-integrated nitrate+nitrite levels within the photic zone of the eddy cores were 3- to 15- fold higher than those observed for control stations. The depth and magnitude of the deep chlorophyll maximum were significantly elevated in the more mature of the two eddies. HPLC analyses revealed that the enhanced chlorophyll was largely contributed by chromophyte microalgae. Modeled primary productivity rates were up to twofold higher at the stations within the eddies.

Introduction

The combination of prevailing northeasterly tradewinds and island topography encourages the generation of vigorous eddies on the leeward side of the Hawaiian Islands on time scales of 50 to 70 days (Fig. 1A) [*Patzert*, 1969; *Lumpkin*, 1998].

Recently, much interest has focused on the role of eddies in localized upwelling of nutrients into the euphotic zone [*McGillicuddy and Robinson*, 1997]. 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 [*Falkowski et al.*, 1991].

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 [*Wu et al.*, 1999]. GOES observations may be acquired up to 48 times a day as compared to the twice per day sampling provided by radiometers carried aboard polar orbiting satellites. In areas that are often influenced by cloud cover, such as around Hawaii, GOES significantly increases the possibility of measuring SST; abundant hourly images enable frequent composites that are timely in guiding *in situ* sampling. We present high-resolution horizontal and vertical observations from ship and satellite platforms from a pair of cyclonic eddies made possible by this new technology.

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Methods

GOES-10 SST data were processed into three day composites. NASA's SeaWiFS Project provided 8-day composites of ocean color.

Two transects about 185 km (100 nmi) long and stations spaced 18.6 km (10 nmi) apart were conducted by the NOAA ship *Townsend Cromwell* (TC) through two eddies designated as "*Mikalele*" (November 16-18, 1999) and "*Loretta*" (November 22-23, 1999) (Fig. 1C, D). Hydrographic data and *in situ* water samples for nutrient and HPLC pigment analyses were acquired with a SeaBird SBE 9/11+ CTD system plus rosette sampler [*Lukas and Karl*, 1999; *Fargion and Mueller*, 2000]. Chloropigment fluorescence was measured *in situ* with CTD-mounted fluorometers and calibrated with extracted pigments determined with a Turner 10-AU fluorometer [*Fargion and Mueller*, 2000]. Along track currents were measured with a 153 kHz RDI acoustic Doppler current profiler (ADCP).

Primary production rates were estimated with a bio-optical production algorithm [*Ondrusek et al.*, 2001], and knowledge of *in situ* TChl *a* distributions and surface irradiance. Maximum quantum yield (Φ_{max}) values of 0.03 and 0.05 mol C mol photons^{-1} were used in model calculations performed for outside and inside stations, respectively, to account for eddy enhanced photosynthetic efficiencies [*Falkowski et al.*, 1991; *Ondrusek and Bidigare*, 1997].

Results

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 *a* (Fig. 1A,B). In comparison, *Mikalele* was short-lived, existing from late October 1999 to mid-January 2000.

At the time of sampling, both eddies were ~100 km in diameter. *Mikalele* was approximately one month old and centered near 19°45′N 157°12′W; *Loretta* was six months old and centered near 20°25′N 160°W. Surface thermal gradients were stronger for *Mikalele* (Fig. 1C, D), however subsurface vertical structure was more developed in the older eddy (Fig. 2). Upper ocean doming of isotherms were most

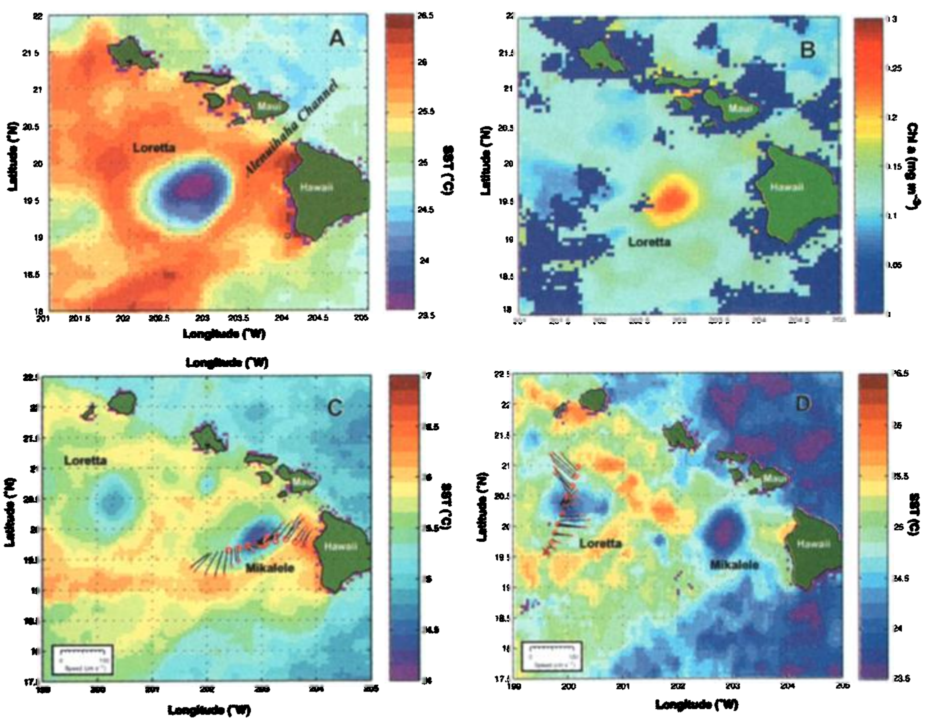

Figure 1. Satellite remote sensing of cyclonic eddies "*Loretta*" and "*Mikalele*": 2-day composites of GOES-SST (°C) for (A) 3-4 September 1999, (C) 16-18 November 1999, and (D) 22-24 November 1999; and (B) 8-day composite of SeaWiFS TChl *a* (mg m^{-3}), 29 August-5 September 1999. Overlying (C) *Mikalele* and (D) *Loretta* are CTD stations (red circles), control stations (red "X"s), and estimated current velocities (averaged over the upper 21-100 m) along survey track.

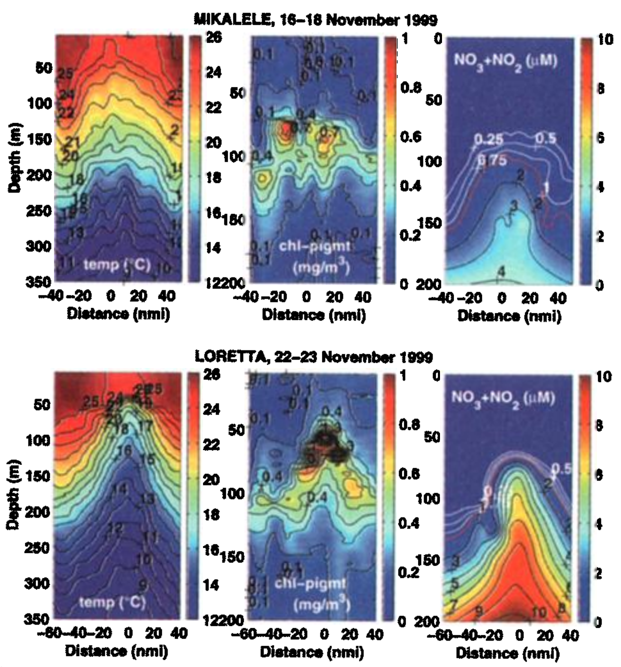

Figure 2. Vertical section of temperature (°C) (left), total *in situ* chloropigment (mg m^{-3}) (center), and nitrate+nitrite (N+N, μM) (right) for eddies *Mikalele*, 16-18 November 1999 (top) and *Loretta* 22-23 November 1999 (bottom). Red contour in N+N-sections depicts the 1 μM N+N isopleth. Station locations spaced ca. 18.6 km (10 nmi) apart from eddy center; macronutrients collected at 500 m, 300 m, 200 m, 150 m, 125 m, 100 m, 80 m, 65 m, 50 m, 35 m, 20 m, and the surface on the CTD upcasts.

intense in the upper 200 m and eddy influence was generally confined to the upper 300-400 m. 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.

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 μM N+N isopleth), and shallowed to about 80 m and 65 m for *Mikalele* and *Loretta*, respectively (Fig. 2, Table 1.) Nitrate+nitrite concentrations at the base of the thermocline increased from 0.02 μM to >1 μM for *Mikalele* and >6 μM 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 (Table 1). Phytoplankton pigment biomass was 1.5 times higher in *Loretta* than in *Mikalele* or the control stations (Table 1).

From HPLC pigment analysis, depth-integrated concentrations of divinyl chl *a* and zeaxanthin show little or no change within the eddies, suggesting that cyanobacteria in the lee of Hawaii are not nutrient limited (Table 1). For *Mikalele*, most accessory pigment levels were similar to those measured at control stations with two exceptions: 19′-but-fucoxanthin (pelagophytes) and prasinoxanthin (prasinophytes) were twofold higher. For *Loretta*, >twofold enhancements were measured for peridinin (dinoflagellates), fucoxanthin (diatoms), and 19′-hex-fucoxanthin (haptophytes), in addition to 19′-but-fucoxanthin and prasinoxanthin. Most of the elevated TChl *a* observed for *Loretta* was therefore contributed by chromophyte microalgae, a trend also apparent in the accessory pigment-to-TChl *a* ratios.

Table 1. Water Column Properties of Control and Eddy Stations Occupied During November 1999

Parameter (units)	Control Stations (Casts 1 & 24)	*Mikalele* (Cast 6)	*Loretta* (Casts 29 & 30)
DCML depth (m)	100	80	65
1% E_{PAR} depth (m)	104 ± 3	99	75 ± 5
$[TChl\ a]_{DCML}$ (mg m^{-3})	0.36 ± 0.03	0.42	0.89 ± 0.15
Nitrate+Nitrite (mmol m^{-2})	35.3 ± 5.7	119.7	486.9 ± 36.4
Phosphate (mmol m^{-2})	15.6 ± 1.0	21.4	44.8 ± 3.0
Silicate (mmol m^{-2})	190.3 ± 7.3	265.6	578.2 ± 37.6
TChl *a* (mg m^{-2})	24.58 ± 2.76	24.96	37.62 ± 3.73
DV Chl *a* (mg m^{-2})	10.11 ± 2.57	6.76	11.48 ± 0.12
Peridinin (mg m^{-2})	0.31 ± 0.11	0.29	0.91 ± 0.11
Fucoxanthin (mg m^{-2})	0.77 ± 0.13	0.96	1.84 ± 0.28
19′-but-fucoxanthin (mg m^{-2})	2.62 ± 0.44	4.72	7.01 ± 0.55
19′-hex-fucoxanthin (mg m^{-2})	6.34 ± 0.22	9.74	12.25 ± 1.74
Prasinoxanthin (mg m^{-2})	0.51 ± 0.43	1.05	1.15 ± 0.26
Zeaxanthin (mg m^{-2})	10.48 ± 2.87	7.15	10.92 ± 0.82
Chl *b*:TChl *a* (w:w)	0.29	0.29	0.33
Chl *c*:TChl *a* (w:w)	0.15	0.22	0.24
DVChl *a*:TChl *a* (w:w)	0.41	0.27	0.31
Primary productivity (mg C m^{-2} d^{-1})	593 ± 11[a]	980[b]	1230 ± 27[b]

Water column nutrient concentrations and pigment/productivity parameters have been depth-integrated to 150 m and uncertainties are expressed as ± range. The depth of the 1% light level (1% E_{PAR}) was calculated according to *Morel* [1988]. The HPLC-determined total chlorophyll *a* (TChl *a*) values represent the sum of monovinyl and divinyl (DV) chlorophyll *a*. DCML = deep chlorophyll maximum layer.

[a]Calculated using a Φ_{max} value of 0.03 mol C mol photons^{-1}[*Falkowski et al.,1991; Ondrusek and Bidigare,1997*]

[b]Calculated using a Φ_{max} value of 0.05 mol C mol photons^{-1} *Falkowski et al.,1991; Ondrusek and Bidigare,1997*]

Model-derived, daily primary production rates were enhanced within *Mikalele* and *Loretta*, a result of the higher pigment biomass and elevated photosynthetic quantum yield within the eddies (Table 1).

Discussion

Our understanding of biogeochemical processes occurring within Hawaiian eddies has up to now been based in sampling conducted at a single eddy [*Falkowski et al.*, 1991; *Olaizola et al.*, 1993; *Allen et al.*, 1996] and inferred from studies on eddies in other oligotrophic oceans [*McGillicuddy and Robinson*, 1997; *McGillicuddy et al.*, 1998; *McNeil et al.*, 1999]. The GOES-SST guided transects and navigated sampling through two well defined eddies. Surface thermal gradients measured both by satellite and *in situ* sampling 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*. Consequently, increases in all parameters including TChl *a*, accessory pigments, and macronutrient concentrations were substantially magnified with *Loretta*, resulting in higher modeled production rates. These observations are consistent with a system that has matured with the protracted life of the eddy field. Interestingly, *Olaizola et al.* [1993] also noted a weakening of SST gradients accompanied by a stronger subsurface signature in the eddy that they investigated.

Outside of the eddies, our observations were consistent with biological values typically reported for the Hawaiian region [*Ondrusek et al.*, 2001; *Lukas and Karl*, 1999]. Primary productivity rates of 399 and 662 mg C m^{-2} d^{-1} were reported at control and eddy stations, respectively, for an eddy located in a similar position as *Mikalele* which had a model-estimated production rate of 980 mg C m^{-2} d^{-1} [*Allen et al.*, 1996]. This higher production rate may be a consequence of higher TChl *a* biomass observed for *Mikalele* (25 vs. 20 mg m^{-2}).

Finally, our results reveal substantially greater biological enhancement associated with Hawaiian eddies than previously observed, yet we realize that particularly in the case of *Loretta*, our *in situ* assessment was conducted while the eddy was spinning down. Based on archived satellite imagery (GOES and SeaWiFS), it is likely that the eddy pumping and biological responses were greatest during the late August-early September interval when surface manifestation of enhanced TChl *a* was detected by SeaWiFS.

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