# Influence of a cyclonic eddy on microheterotroph biomass and carbon export in the lee of Hawaii

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[1] A multi-platform sampling strategy was used to investigate carbon cycling in a cold-core eddy that formed in the lee of Hawaii during September 2000. Microheterotroph biomass and $^{234}$Th-derived carbon export rates within the eddy were 2 to 3 times higher than those observed for adjacent waters. If this eddy is representative of other cyclonic eddies that are frequently formed in the lee of Hawaii, then eddy activity may significantly enhance the areal efficiency of the biological pump and facilitate the transfer of organic carbon to organisms inhabiting the mesopelagic and abyssal-benthic zones of this subtropical ecosystem. *INDEX TERMS:* 4520 Oceanography: Physical: Eddies and mesoscale processes; 4806 Oceanography: Biological and Chemical: Carbon cycling; 4855 Oceanography: Biological and Chemical: Plankton; 4866 Oceanography: Biological and Chemical: Sorptive scavenging; 4870 Oceanography: Biological and Chemical: Stable isotopes. **Citation:** Bidigare, R. R., C. Benitez-Nelson, C. L. Leonard, P. D. Quay, M. L. Parsons, D. G. Foley, and M. P. Seki, Influence of a cyclonic eddy on microheterotroph biomass and carbon export in the lee of Hawaii, *Geophys. Res. Lett.*, 30(6), 1318, doi:10.1029/2002GL016393, 2003.

## 1. Introduction

[2] Eddy activity generates significant mesoscale variability in plankton and plankton processes in surface waters of the World's ocean [*Lewis*, 2002]. At least three different eddy types contribute to this variability, and include first (cyclones and anticyclones) and second baroclinic mode eddies [*McGillicuddy et al.*, 1999]. Enhanced biological activities have been reported for each eddy type as evidenced by measurements of carbon fixation, nutrient uptake and oxygen production. Rates of carbon export within these features are generally thought to be stimulated by the input of growth-limiting nutrients that results from the upward displacement of nutrient-rich isopycnal surfaces, higher upwelling velocities, and/or larger vertical eddy diffusion coefficients. Unfortunately, there are only a limited number of studies that have documented eddy-stimulated increases in carbon export [*Honjo et al.*, 1999; *Sweeney*, 2001]. In the lee of the main Hawaiian Islands, local topography and prevailing northeasterly trade winds combine to generate a vigorous and continuous eddy field [*Seki et al.*, 2001]. Here we report the results of a multidisciplinary study undertaken to quantify the effects of a cyclonic eddy on microheterotroph biomass and carbon export in the lee of Hawaii.

## 2. Methods

[3] The satellite sea surface temperature (SST) data sets were derived from radiance data collected by the imager carried aboard one of the NOAA Geostationary Operational Environmental Satellites (GOES-10). The hourly data were screened for clouds, binned into 3-hour means, and distributed by the NOAA CoastWatch Program [*Wu et al.*, 1999].

[4] In situ measurements were performed during the NOAA ship *Townsend Cromwell* (TC) cruise 00–13 (17–20 November 2000) using techniques described in *Seki et al.* [2001]. A METOCEAN bio-optical drifter was deployed near the eddy core on 18 November 2000 to monitor temporal variations in SST. Seawater samples (500-mL each) for the determination of microheterotroph biomass (>3 μm heterotrophs) were collected from 9 depths in the upper 150 m at control (Sta. 11) and eddy (Sta. 3) sites, and fixed with 1% formalin. Samples (400-mL each) were stained with 0.03% proflavin hemisulfate and size-fractionated using 8.0 μm and 3.0 μm polycarbonate filters. Microscopy measurements were used to calculate microheterotroph biovolume and carbon biomass [*Berggreen et al.*, 1988; *Putt and Stoecker*, 1989; *Lessard*, 1991; *Verity et al.*, 1992; *Hillebrand et al.*, 1999].

[5] Seawater samples (2-L each) were collected for determining total $^{234}$Th activities [*Benitez-Nelson et al.*, 2001a]. Samples were collected from 6 depths in the upper 150 m at control (Sta. 11) and eddy (Sta. 3) sites. Samples for determining particulate carbon-to-$^{234}$Th ratios (C/$^{234}$Th) for sinking particles, defined here as the >53 μm size fraction, were collected with a Challenger Oceanic Mark II pump deployed at a depth of 150 m. Seawater (150–200 L) was pumped at a rate of 4–6 L min$^{-1}$ through a 53 μm Nitex screen followed by a 142 mm microquartz filter (~1 μm pore size) [*Benitez-Nelson et al.*, 2001b]. The

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detector was calibrated during the cruise with 1,375 m samples (assumed to be in radioactive equilibrium) that were collected from 5 different water bottles from the same cast. Replicate deep-water samples varied by <2% and averaged 2.37 dpm kg$^{-1}$.

[6] Seawater samples for measuring the concentration and $\delta^{13}C$ of the dissolved inorganic carbon (DIC) were collected in the upper 1,375 m at control (Stas. 10 and 11) and eddy (Sta. 3) sites. The DIC concentration was determined manometrically by measuring the amount of $CO_2$ extracted for isotopic analysis and weighing the seawater sample [*Quay et al.*, 2003]. The accuracy and precision of the measurement is ± 4 μmol kg$^{-1}$ based on replicate analysis and measurements of DIC reference materials prepared by A. Dickson (Scripps Institution of Oceanography, San Diego, CA). The accuracy of the $\delta^{13}C$ measurement is ± 0.025‰ based on replicate measurements of seawater samples and DIC standards (*Quay et al.*, submitted).

## 3. Eddy Dynamics and Planktonic Biomass

[7] GOES-10 SST imagery revealed that cyclonic eddy *Haulani* was generated between the islands of Maui and Hawaii on 26 September 2000. Sequential GOES-10 images were used to track the movement of *Haulani* as it first traveled to the southwest, and then remained in the lee of Hawaii for several weeks where it was sampled during TC 00–13. *Haulani* was approximately 2 months old at this time, and SST values near its center were ~3°C cooler than surrounding waters (Figure 1A). Following the shipboard observations, *Haulani* migrated to the southeast, and then changed its trajectory to the northwest (Figure 1B). The 1.5°C increase in SST during YD330–360 2000 is suggestive of a relaxation in eddy pumping during this period (Figure 1C). *Haulani*'s lifespan was ~5 months based on discernable SST gradients detected with GOES-10 imagery. In a companion study, *Vaillancourt et al.* [in press, 2003] provides detailed comparisons of hydrographic, floristic, and photosynthetic parameters for stations occupied inside and outside of *Haulani*. In order to place the observations reported here in context, the primary findings of *Vaillancourt et al.* are summarized below and in Table 1.

[8] The pronounced doming of isopycnal surfaces within *Haulani* increased the availability of inorganic nutrients to resident phytoplankton populations. Vertically integrated nitrate + nitrite, phosphate, and silicate concentrations were 9.0-, 2.6-, and 2.0-fold higher, respectively, in the upper 150 m of inside vs. outside stations (Table 1). The depth of the euphotic zone (1% light level) was 45 m shallower within *Haulani* ($z_{eu}$ = 72 ± 2 m) relative to control stations ($z_{eu}$ = 117 ± 13 m). The latter was a consequence of the elevated TChl $a$ levels in *Haulani*, which increased the diffuse attenuation coefficient for photosynthetically available radiation. Modeled rates of primary productivity were 1.3-fold higher in *Haulani* relative to control stations (0.87 ± 0.02 vs. 0.67 ± 0.03 g m$^{-2}$ d$^{-1}$; Table 1). Complimentary floristic and accessory pigment measurements reported by *Vaillancourt et al.* [in press, 2003] document that the enhancement in phytoplankton biomass in *Haulani* was attributable to larger (>3 μm) eukaryotes. Notably, the abundances of prymnesiophytes, diatoms and dinoflagellates were 25-, 2.4- and 1.6-fold higher inside the eddy.
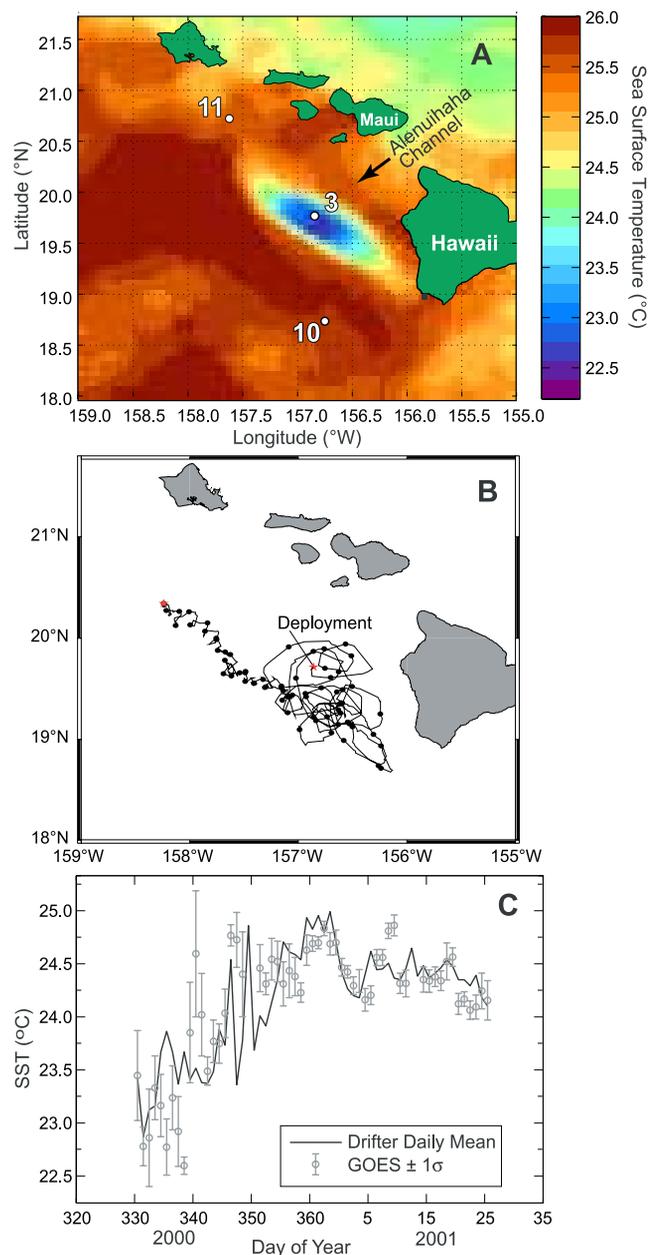


**Figure 1.** Remote sensing of SST in the lee of the main Hawaiian islands: (A) GOES-10 SST image (YD322 2000) showing station locations and position of cyclonic eddy *Haulani* (B) map showing the METOCEAN drifter trajectory during YD326 2000 to YD25 2001, and (C) comparison of drifter and GOES-10 (20 km box around drifter) SST measurements made near the center of *Haulani*.

[9] The microzooplankton sampled at our study site were dominated by heterotrophic dinoflagellates and ciliates, with smaller contributions by other taxa (nanoflagellates, crustacean larvae, radiolarians, forams, and silicoflagellates) (Table 1). Depth-integrated microheterotroph biomass was ~2-fold higher within *Haulani* (295 mg C m$^{-2}$) relative to the control station (131 mg C m$^{-2}$). Total microheterotroph biomass inside the eddy peaked at a depth of 35 m (10.5 mg C m$^{-3}$) and was dominated by heterotrophic dinoflagellates (Figure 2A). Outside the eddy, a considerably weaker

**Table 1.** Water Column Properties of Control and Eddy Stations Occupied During November 2000

| Parameter | Outside Haulani | Inside Haulani | In/Out |
|---|---|---|---|
| *Hydrographic Properties*[a] | | | |
| Nitrate + nitrite (0–150 m) | $40 \pm 38$ mmol m$^{-2}$ (4) | $364 \pm 23$ mmol m$^{-2}$ (3) | 9.0 |
| Phosphate (0–150 m) | $16 \pm 3$ mmol m$^{-2}$ (4) | $41 \pm 3$ mmol m$^{-2}$ (3) | 2.6 |
| Silicate (0–150 m) | $236 \pm 33$ mmol m$^{-2}$ (4) | $461 \pm 24$ mmol m$^{-2}$ (3) | 2.0 |
| Euphotic zone depth (1% $E_o$) | $117 \pm 13$ m (4) | $72 \pm 2$ m (2) | 0.6 |
| Mean $K_{PAR}$ (euphotic zone) | $0.040 \pm 0.004$ m$^{-1}$ (4) | $0.065 \pm 0.002$ m$^{-1}$ (2) | 1.6 |
| TChl $a$ (0–150 m) | $26 \pm 4$ mg m$^{-2}$ (4) | $33 \pm 1$ mg m$^{-2}$ (3) | 1.3 |
| Primary productivity (0–150 m) | $0.67 \pm 0.03$ g m$^{-2}$ d$^{-1}$ (3) | $0.87 \pm 0.02$ g m$^{-2}$ d$^{-1}$ (3) | 1.3 |
| *Microheterotroph Biomass (>3 $\mu m$, mg C m$^{-2}$, 0–150 m)* | | | |
| Heterotrophic dinoflagellates | 64.4 | 167.0 | 2.6 |
| Ciliates | 55.3 | 109.9 | 2.0 |
| Other | 11.4 | 18.0 | 1.6 |
| Total biomass | 131.1 | 294.9 | 2.2 |
| *Carbon Export Parameters* | | | |
| $^{234}$Th flux (dpm m$^{-2}$ d$^{-1}$) | $643 \pm 183$ | $1096 \pm 172$ | 1.7 |
| >53 $\mu$m C ($\mu$mol kg$^{-1}$, 150 m) | $0.078 \pm 0.004$ | $0.150 + 0.008$ | 1.9 |
| C/$^{234}$Th ($\mu$mol C dpm$^{-1}$) | $1.59 \pm 0.12$ | $2.37 \pm 0.18$ | 1.5 |
| C Flux (mmol C m$^{-2}$ d$^{-1}$) | $1.02 \pm 0.30$ | $2.60 \pm 0.45$ | 2.6 |
| $\delta^{13}$C of DIC added (<300 m) | $-12 \pm 1$‰ | $-19 \pm 2$‰ | - |

[a]Hydrographic data are means (±SD or range) of the station data given in *Vaillancourt et al.* [in press, 2003]. Values in parentheses = number of stations and TChl $a$ = total chlorophyll a (monovinyl plus divinyl chlorophyll *a*) concentration. Primary production rates were estimated using the bio-optical model of *Ondrusek et al.* [2001]. The model was run in the "default" mode (measured TChl $a$ profiles and a $\Phi_{max}$ of 0.03 mol C Ein$^{-1}$) and utilized SeaWiFS-measured mean daily PAR.

microheterotroph biomass maximum ($1.5 \pm 0.3$ mg C m$^{-3}$) was observed in the upper 65 m.

## 4. Carbon Export Parameters

[10] $^{234}$Th activities ranged from $1.81 \pm 0.08$ to $2.48 \pm 0.10$ dpm kg$^{-1}$. The largest $^{234}$Th deficits, relative to its parent $^{238}$U, were measured above 50 m inside the eddy and below 65 m outside the eddy (Figure 2B). These regions of the water column correspond to zones of active particle export, and imply that particle removal rates were highest in the upper (4–100% $E_o$) and lower (0.2–7% $E_o$) photic zones of the inside and outside stations, respectively. It is interesting to note that the depth of the microheterotroph biomass maximum in *Haulani* overlaps with that of the largest $^{234}$Th deficit (Figure 2A and 2B). This observation suggests that microheterotroph grazing within *Haulani* may be partially responsible for the elevated particle removal rates observed there. It should be noted, however, that the correlation between $^{234}$Th removal and microheterotroph biomass is not expected to be perfect since the former integrates over a much longer timescale (~1 month) than the latter (days) and the biomass estimates reported here do not include contributions by larger grazers.

[11] In order to determine the flux of $^{234}$Th from the upper ocean, and hence the extent of carbon export, the following $^{234}$Th activity equation was used: $P = (A_U - A_{Th}) \lambda$, where P is the net removal flux of $^{234}$Th on particles, $A_U$ is the salinity-estimated $^{238}$U activity [*Chen et al.*, 1986], $A_{Th}$ is the total measured $^{234}$Th activity, and $\lambda$ is the decay constant for $^{234}$Th (0.0288 d$^{-1}$). This simple, steady-state mass balance approach yielded a $^{234}$Th flux (0–150 m) of $1096 \pm 172$ dpm m$^{-2}$ d$^{-1}$ within the eddy and $643 \pm 183$ dpm m$^{-2}$ d$^{-1}$ outside the eddy (Table 1). These $^{234}$Th fluxes are within the range of steady-state values (313 to 2311 dpm m$^{-2}$ d$^{-1}$) determined for the Hawaii Ocean Time-series study at Sta. ALOHA (22.75°N, 158°W) [*Benitez-Nelson et al.*, 2001b]. It is highly likely that the estimated flux of

$^{234}$Th inside the eddy is an underestimate since it does not take into account the upwelling of high $^{234}$Th activity deepwater [*Buesseler et al.*, 1998]. In order to estimate the flux of carbon, it is first necessary to measure the particulate C/$^{234}$Th ratio for sinking particles. Sinking particles are operationally defined here as those particles that are retained on a 53 $\mu$m filter. Using a >53 $\mu$m C/$^{234}$Th ratio of $2.37 \pm 0.18$ $\mu$mol C dpm$^{-1}$ inside the eddy, and a C/$^{234}$Th ratio of $1.59 \pm 0.12$ $\mu$mol C dpm$^{-1}$ outside the eddy, results in a carbon export of $2.60 \pm 0.45$ and $1.02 \pm 0.30$ mmol C m$^{-2}$ d$^{-1}$, respectively (Table 1).

[12] The $\delta^{13}$C and DIC depth distributions inside and outside *Haulani* are compared at similar densities since isopycnal surfaces were domed within this cyclonic eddy [*Vaillancourt et al.*, in press, 2003]. At equal densities, the $\delta^{13}$C was higher inside vs. outside the eddy at $\sigma_t < 25$ (~80 m) whereas the DIC concentrations inside were equal to (Sta. 11) or less than (Sta. 10) those outside the eddy (data not shown). One mechanism to explain the observed $\delta^{13}$C enrichment within *Haulani* is an increased export of biological organic carbon, which has a $\delta^{13}$C of ~−21‰ in this region [*Goericke and Fry*, 1994]. Further evidence for the enhanced role of biological carbon cycling inside vs. outside the eddy is seen in the measured relationship between the $\delta^{13}$C and DIC. Outside the eddy, the measured $\delta^{13}$C decrease and DIC increase down to 300 m requires the addition of DIC with a $\delta^{13}$C of $-12 \pm 1$‰ (Table 1). This value is similar to the value of $-12 \pm 3$‰ observed at Sta. ALOHA (P. D. Quay and J. Stutsman, Surface layer carbon budget for the subtropical N. Pacific: $\delta^{13}$C constraints at Station ALOHA, submitted to *Deep-Sea Research, Part I*, 2003), and suggests that the $\delta^{13}$C of DIC added at depth was influenced by "horizontal" processes (including advection and air-sea gas exchange at the isopycnal outcrop) as well as by in situ remineralization of organic carbon. In contrast, within the eddy the $\delta^{13}$C decrease and DIC increase with depth to 300 m requires the addition of DIC with a $\delta^{13}$C of $-19 \pm 2$‰ (Table 1). This value is close to the $\delta^{13}$C of
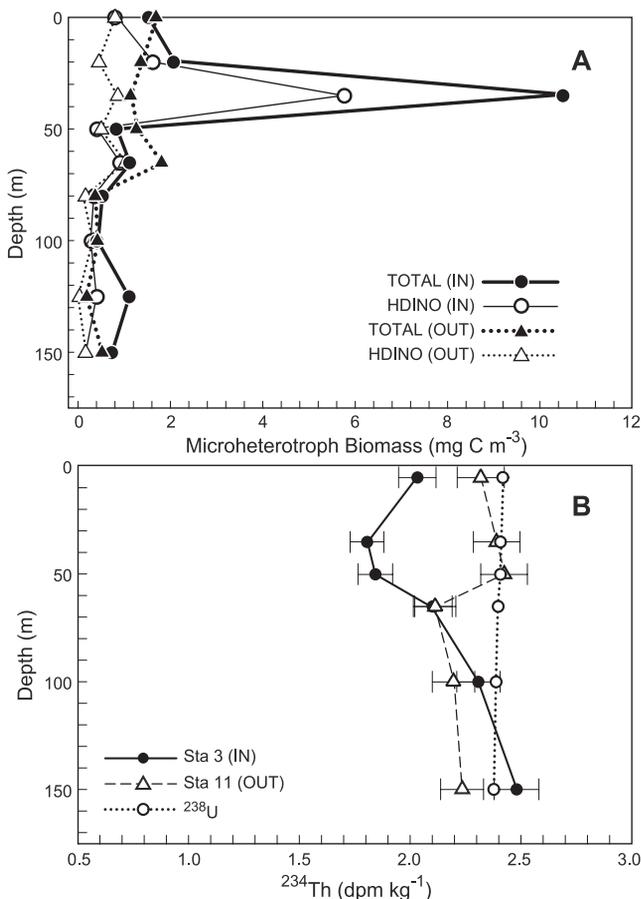
**Figure 2.** Vertical profiles of biological and geochemical parameters measured at stations occupied outside and inside of cyclonic eddy *Haulani*: (A) microheterotroph biomass (HDINO = heterotrophic dinoflagellates) and (B) $^{234}$Th and $^{238}$U activities.

$-21‰$ for the biological material itself and implies that remineralization of organic carbon was the dominant source of the DIC increase with depth inside the eddy. If this explanation is correct, then the carbon cycling within *Haulani* had time to "reset" the $\delta^{13}$C and DIC depth profiles during the eddy's 54-day age.

[13] In a recent review of plankton processes on the mesoscale, *Lewis* [2002] points out that if there is insufficient supply of organic material to the isopycnal, and there is not sufficient time for its remineralization, then the eddy pumping mechanism only 'works' once, and serves to push the nitracline to a deeper isopycnal surface. The results presented above indicate that the supply of organic material was indeed higher within cyclone *Haulani* and that a portion of the exported organic matter was remineralized within the upper 300 m of this mesoscale feature. The latter would serve to partially restore nutrient inventories for future eddy-pumping events.

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