

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 ²³⁴Th-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 [Lewiss, 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 ²³⁴Th 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-²³⁴Th ratios (C/²³⁴Th) 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 $\delta^{13}\text{C}$ 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 $\pm 4 \mu\text{mol kg}^{-1}$ 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 $\delta^{13}\text{C}$ measurement is $\pm 0.025\text{‰}$ 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 $\sim 3^\circ\text{C}$ 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* ($z_{\text{eu}} = 72 \pm 2 \text{ m}$) relative to control stations ($z_{\text{eu}} = 117 \pm 13 \text{ m}$). 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. $0.67 \pm 0.03 \text{ g m}^{-2} \text{ d}^{-1}$; 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 ($>3 \mu\text{m}$) eukaryotes. Notably, the abundances of prymnesiophytes, diatoms and dinoflagellates were 25-, 2.4- and 1.6-fold higher inside the eddy.

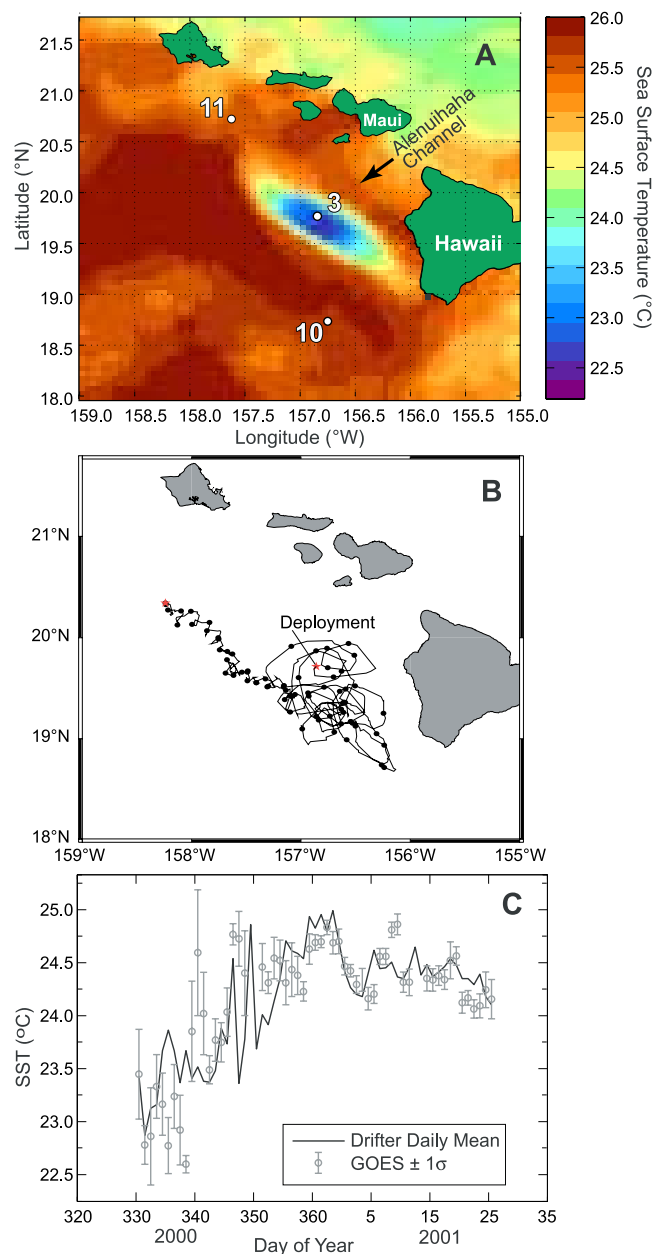


Figure 1. Remote sensing of SST in the lee of the main Hawaiian islands: (A) GOES-10 SST image (YD322 2000) showing station locations and position of cyclonic eddy *Haulani* (B) map showing the METOCEAN drifter trajectory during YD326 2000 to YD25 2001, and (C) comparison of drifter and GOES-10 (20 km 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
<i>Hydrographic Properties^a</i>			
Nitrate + nitrite (0–150 m)	40 ± 38 mmol m ⁻² (4)	364 ± 23 mmol m ⁻² (3)	9.0
Phosphate (0–150 m)	16 ± 3 mmol m ⁻² (4)	41 ± 3 mmol m ⁻² (3)	2.6
Silicate (0–150 m)	236 ± 33 mmol m ⁻² (4)	461 ± 24 mmol m ⁻² (3)	2.0
Euphotic zone depth (1% E ₀)	117 ± 13 m (4)	72 ± 2 m (2)	0.6
Mean K _{PAR} (euphotic zone)	0.040 ± 0.004 m ⁻¹ (4)	0.065 ± 0.002 m ⁻¹ (2)	1.6
TChl <i>a</i> (0–150 m)	26 ± 4 mg m ⁻² (4)	33 ± 1 mg m ⁻² (3)	1.3
Primary productivity (0–150 m)	0.67 ± 0.03 g m ⁻² d ⁻¹ (3)	0.87 ± 0.02 g m ⁻² d ⁻¹ (3)	1.3
<i>Microheterotroph Biomass (>3 μm, mg C m⁻², 0–150 m)</i>			
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
<i>Carbon Export Parameters</i>			
²³⁴ Th flux (dpm m ⁻² d ⁻¹)	643 ± 183	1096 ± 172	1.7
>53 μm C (μmol kg ⁻¹ , 150 m)	0.078 ± 0.004	0.150 ± 0.008	1.9
C/ ²³⁴ Th (μmol C dpm ⁻¹)	1.59 ± 0.12	2.37 ± 0.18	1.5
C Flux (mmol C m ⁻² d ⁻¹)	1.02 ± 0.30	2.60 ± 0.45	2.6
δ ¹³ C of DIC added (<300 m)	-12 ± 1‰	-19 ± 2‰	-

^aHydrographic 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 Φ_{max} of 0.03 mol C Ein⁻¹) and utilized SeaWiFS-measured mean daily PAR.

microheterotroph biomass maximum (1.5 ± 0.3 mg C m⁻³) was observed in the upper 65 m.

4. Carbon Export Parameters

[10] ²³⁴Th activities ranged from 1.81 ± 0.08 to 2.48 ± 0.10 dpm kg⁻¹. The largest ²³⁴Th deficits, relative to its parent ²³⁸U, 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% E₀) and lower (0.2–7% E₀) 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 ²³⁴Th 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 ²³⁴Th 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 ²³⁴Th from the upper ocean, and hence the extent of carbon export, the following ²³⁴Th activity equation was used: $P = (A_U - A_{Th})/\lambda$, where *P* is the net removal flux of ²³⁴Th on particles, *A_U* is the salinity-estimated ²³⁸U activity [Chen *et al.*, 1986], *A_{Th}* is the total measured ²³⁴Th activity, and λ is the decay constant for ²³⁴Th (0.0288 d⁻¹). This simple, steady-state mass balance approach yielded a ²³⁴Th flux (0–150 m) of 1096 ± 172 dpm m⁻² d⁻¹ within the eddy and 643 ± 183 dpm m⁻² d⁻¹ outside the eddy (Table 1). These ²³⁴Th 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

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

[12] The δ¹³C 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 δ¹³C was higher inside vs. outside the eddy at σ_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 δ¹³C enrichment within *Haulani* is an increased export of biological organic carbon, which has a δ¹³C 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 δ¹³C and DIC. Outside the eddy, the measured δ¹³C decrease and DIC increase down to 300 m requires the addition of DIC with a δ¹³C of -12 ± 1‰ (Table 1). This value is similar to the value of -12 ± 3‰ observed at Sta. ALOHA (P. D. Quay and J. Stutsman, Surface layer carbon budget for the subtropical N. Pacific: δ¹³C constraints at Station ALOHA, submitted to *Deep-Sea Research, Part I*, 2003), and suggests that the δ¹³C 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 δ¹³C decrease and DIC increase with depth to 300 m requires the addition of DIC with a δ¹³C of -19 ± 2‰ (Table 1). This value is close to the δ¹³C of

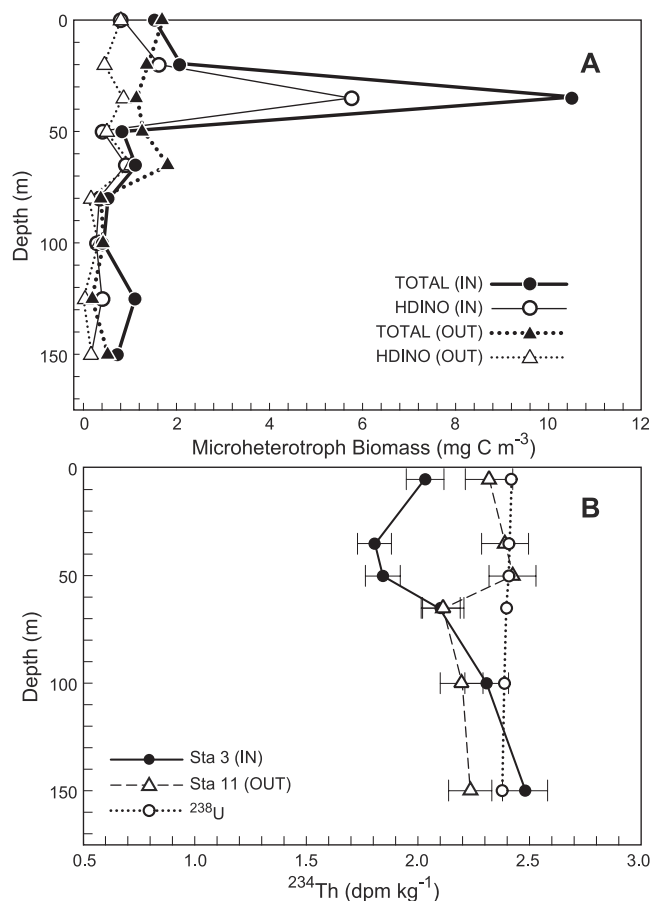


Figure 2. Vertical profiles of biological and geochemical parameters measured at stations occupied outside and inside of cyclonic eddy *Haulani*: (A) microheterotroph biomass (HDINO = heterotrophic dinoflagellates) and (B) ²³⁴Th and ²³⁸U activities.

–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 $\delta^{13}\text{C}$ 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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