Deep-Sea Research II 55 (2008) 1445–1460

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

The influence of a mature cyclonic eddy on particle export in the lee of Hawaii

Kanchan Maiti [a,*], Claudia R. Benitez-Nelson [a], Yoshimi Rii [b], Robert Bidigare [b]

[a] Department of Geological Sciences, University of South Carolina, Columbia, SC 29208, USA
[b] Department of Oceanography, University of Hawaii, Honolulu, HI 92822, USA

ARTICLE INFO

Article history:
Accepted 3 February 2008

Keywords:
Carbon export
Biogenic silica
Remineralization
Eddies
Thorium-234
North Pacific Subtropical Gyre

ABSTRACT

Mesoscale eddies may enhance primary production (PP) in the open ocean by bringing nutrient-rich deep waters into the euphotic zone, potentially leading to increased transport of particles to depth. This hypothesis remains controversial, however, due to a paucity of direct particle export measurements. In this study, we investigated particle dynamics using ^{234}Th–^{238}U disequilibria within a mesoscale cold-core eddy, Cyclone *Opal*, which formed in the lee of the Hawaiian Islands. ^{234}Th samples were collected along two transects across Cyclone *Opal* as well as during a time-series within the eddy core during a decaying diatom bloom. Particulate carbon (PC), particulate nitrogen (PN) and biogenic silica ($bSiO_2$) fluxes at 150 m varied spatially and temporally within the eddy and strongly depended on the ^{234}Th model formulation used (e.g., steady state versus non-steady state, inclusion of upwelling, etc.). Particle fluxes estimated from a steady state model assuming an upwelling rate of 2 m day^{-1} yielded the best fit to sediment-trap data. These ^{234}Th-derived particle fluxes ranged from 332 ± 14 to 1719 ± 53 μmol C m^{-2} day^{-1}, 27 ± 3 to 114 ± 12 μmol N m^{-2} day^{-1}, and 33 ± 20 to 309 ± 73 μmol Si m^{-2} day^{-1}. Although PP rates within Cyclone *Opal* were elevated by a factor of 2–3, PC and PN fluxes were the same, within error, inside and outside of Cyclone *Opal*. The ratio of PC export to PP remained surprisingly low at <0.03 and similar to those measured in surrounding waters. In contrast, $bSiO_2$ fluxes within the eddy core were three times higher. Detailed analyses of ^{234}Th depth profiles consistently showed excess ^{234}Th at 100–175 m, associated with the remineralization and possible accumulation of suspended and dissolved organic matter from the surface. We suggest that strong microzooplankton grazing facilitated particulate organic matter recycling and resulted in the export of empty diatom frustules. Thus, while eddies may increase PP, they do not necessarily increase PC and PN export to deep waters. This may be a general characteristic of wind-driven cyclonic eddies of the North Pacific Subtropical Gyre and suggests that eddies may preferentially act as a silica pump, thereby playing an important role in promoting silicic-acid limitation in the region.

1. Introduction

Mesoscale eddies are dynamic and ubiquitous features within marine systems (Cheney and Richardson, 1976; Olson, 1980; Falkowski et al., 1991; Allen et al., 1996; McGillicuddy and Robinson, 1997; Dickey et al., 1998; van Haren et al., 2006). Recent evidence suggests that in the open-ocean, these episodic phenomena enhance the upwelling of cold, nutrient-rich deep waters into the euphotic zone, thereby increasing primary production (PP), potentially altering plankton community structure, and facilitating carbon export in otherwise nutrient-deficient waters (Garcon et al., 2001; Sweeney et al., 2003; McGillicuddy et al., 2007). Current estimates suggest that 10–50% of global new PP is caused by eddy-induced nutrient fluxes (Falkowski et al., 1991; McGillicuddy et al., 1998; Oschlies and Garcon 1998; Siegel et al., 1999; Letelier et al., 2000). Such a wide range in estimates is due to the paucity of direct field observations of eddy biogeochemistry (Savidge and Williams, 2001; Bidigare et al., 2003). The ephemeral nature of most eddies, coupled with their spatial and temporal variability, makes them difficult to predict and study. Eddy dynamics constitute a further confounding factor, particularly with regard to biological community structure and resulting particle formation and export, which likely vary with eddy age (e.g., Flierl and McGillicuddy, 2002; Haury et al., 1978; Haury, 1984; Woods 1988; Dower and Denman, 2001; Sweeney et al., 2003).

Wind-induced cold-core cyclonic eddies are conspicuous oceanographic features that occur off the leeward shores of the Hawaiian Islands throughout the year, but most frequently during periods of high trade wind intensity (October–March) (Patzel, 1969; Lumpkin, 1998; Chavanne et al., 2002; Dickey et al., 2008). These features are characterized by divergent flow at the surface

* Corresponding author. Present address: Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, 266 Woods Hole Road, Woods Hole, MA 02543, USA. Tel.: +1 508 289 3916.
E-mail address: kmaiti@whoi.edu (K. Maiti).

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doi:10.1016/j.dsr2.2008.02.008

that produces localized upwelling of cooler, nutrient-rich deep waters (Olaizola et al., 1993). Hawaiian lee eddies tend to be of significant size (~180 km in diameter) and have a typical life-span of 3–8 months (Patzel, 1969; Lumpkin, 1998). Their regular formation provides a natural laboratory for investigating eddy-enhanced biological production and carbon export in an accessible subtropical oligotrophic setting.

Although few in number, several previous studies suggest that Hawaiian lee eddies are highly productive features. For example, Falkowski et al. (1991) sampled a 1-month-old cyclonic eddy off the coast of Hawaii in August 1989 and found a ~3.5-fold increase in PP relative to the adjacent ocean. Most of the PP increase was attributed to the influx of 'new' nitrate into the system from depth, with the ratio of nitrate-based to total production (*f*-ratio), increasing from 0.2 in surrounding waters to 0.8 within the eddy (Allen et al., 1996). Subsequent studies of other cold-core Hawaiian lee eddies have also found significant increases in PP, plankton biomass, and larger organisms, such as the Pacific blue marlin (Seki et al., 2001; Bidigare et al., 2003).

In this study, the disequilibrium between ^{234}Th and its parent, ^{238}U was used to quantify the export of particles derived from a biologically mature eddy, Cyclone *Opal*. ^{234}Th is produced by the radioactive decay of ^{238}U ($t_{1/2} = 4.47 \times 10^9$ years). Since ^{234}Th is highly particle reactive and has a half-life of 24.1 days, the disequilibrium between its soluble parent, ^{238}U, and the measured ^{234}Th activity provides an estimate of the net rate of particle export from the upper ocean on time scales of days to weeks (Buesseler, 1998). Thus ^{234}Th enables one to examine particle export over the preceding 4–6 weeks, allowing us to examine particle fluxes that have taken place since eddy formation.

2. Methods

2.1. Study site and sample collection

Cyclone *Opal* was sampled from March 10–28, 2005 (E-Flux III) on board the R/V *Wecoma* in the lee of the island of Hawaii (Fig. 1A, also see Dickey et al., 2008). Cyclone *Opal* appeared in moderate resolution imaging spectroradiometer (MODIS) and geostationary operational environmental satellites (GOES) imagery between February 18 and 25, 2005 at approximately 20.30°N, 156.30°W, southwest of the 'Alenuihaha Channel (Nencioli et al., 2008). Spanning ~220 km, Cyclone *Opal* moved rapidly southward by ~165 km during the sampling period with an overall average displacement speed of ~8 km d^{-1}. This fast movement, coupled with the small ~40 km size of the eddy core (characterized by enhanced biomass, and shallow mixed-layer depth (MLD)) made sampling difficult (Fig. 1A). Samples across Cyclone *Opal* from E-Flux III Transect 3 (herein referred to as ^{234}Th sampling Transect 1) were collected on March 13, 2005, when the approximate location of the eddy-center was between stations EF-18 and EF-21 (Fig. 1B). The shoaling of the isopycnal lines is used here as a direct reflection of upwelling intensity (Fig. 2). The gradual deepening of isopycnal lines is indicative of the decrease in upwelling intensity from the center towards the eddy edge. Sampling during E-Flux III Transect 6 (herein referred to as ^{234}Th sampling Transect 2) was conducted on March 22, 2005 from within the center of the eddy towards the surrounding waters (Fig. 1B). Time-series ^{234}Th sampling within the eddy core was conducted over a 6-day period from March 16–21, 2005 (IN stations). Both *in situ* measurements (ADCP, SST, MLD) and satellite imagery suggested that sampling was maintained within the eddy core during the course of the time-series measurements (Dickey et al., 2008). Control or OUT stations were sampled to the west of the island of Maui, in a region well removed from the eddy flow field (Fig. 1B).

Profiles of total ^{234}Th were collected from 21 separate casts using a CTD rosette with 10-L Niskin-like bottles. Sample depths ranged from 0 to 400 m during the transects, and from 0 to 1000 m at each IN and OUT station. Samples for particulate ^{234}Th, particulate carbon (PC), particulate nitrogen (PN), and biogenic silica ($bSiO_2$) were collected with a large-volume, *in situ* pump deployed below the mixed layer at 150 m. Pump samples consisted of ~300 L of seawater passed at 7 L min^{-1} sequentially through 142-mm-diameter 53- and 10-μm mesh nitex screens, followed by a 1-μm pore size micro-quartz filter (QMA). Nitex screens were rinsed onto 25-mm-diameter silver filters and the entire sample was analyzed for PC, PN, and $bSiO_2$ after ^{234}Th analysis. Additional samples were collected using particle interceptor sediment traps (PITs) deployed for a minimum of 3 days inside and outside of the eddy at 150 m following the methods described by Karl et al. (1991) and Rii et al. (2008). The majority (~1.75 L) of three separate sediment-trap sample tubes were filtered onto 25-mm GF/F pre-combusted filters for PC and PN analyses. A portion of the remaining three sediment-trap tubes (250 mL) were combined and filtered onto 25-mm 0.8-μm polycarbonate membranes for $bSiO_2$. Three blanks (2 L of the unused brine fill solution) were filtered using the exact same method.

2.2. ^{234}Th analyses

All sediment-trap samples used for PC and PN analysis were directly counted for ^{234}Th activity using the methods described by Buesseler et al. (1995). All water-column total ^{234}Th samples were processed using the 4-L manganese oxide co-precipitation technique described in detail by Pike et al. (2005) and Rutgers van der Loeff et al. (2006). *In situ* pump samples were collected and processed according to the techniques described by Buesseler et al. (1998, 2001, 2005). All particulate and total ^{234}Th samples were counted directly on a five sample gas-flow proportional low-level RISØ beta counter for at least 12 h or until counting errors were <3%. Samples were then recounted after >150 days (~6 half lives) since collection to precisely determine background count rates, which averaged 0.51 ± 0.05 cpm. The detector was calibrated for each cruise with >3000 m deep-water samples (assumed to be in radioactive equilibrium), collected from five different bottles within a cast ($n = 3$). Replicate deep-water samples varied by less than 5% between casts and other E-Flux cruises. Detector calibration for the stacked QMA and particulate samples was determined by using known ^{234}Th activities in the same sample geometries (Buesseler et al., 1998, 2001). After recounting samples for background activities, total ^{234}Th samples were purified using ion exchange chemistry. Recovery of the added ^{230}Th yield monitor was quantified by inductively coupled plasma-mass spectroscopy with addition of a ^{229}Th internal standard (Pike et al., 2005; Rutgers van der Loeff et al., 2006). Corrections were applied to ^{234}Th activities based on the ^{230}Th recovery for each sample, which averaged 0.89 ± 0.06. All data are decay corrected to the time of collection and reported with a propagated error that includes uncertainties associated with sampling, counting, and other calibration errors.

2.3. PC, PN and $bSiO_2$ analyses

Following ^{234}Th analysis, sediment-trap and pump sample filters were analyzed for PC and PN using a Perkin-Elmer CHN analyzer according to the Hawaii Ocean Time-series (HOT) protocol, which does not include fuming with HCl or distilled water rinsing pretreatments (Karl et al., 1991). The 25-mm silver filter samples were weighed, cut in half, and reweighed, with half