Marine Chemistry 168 (2015) 140–150

Contents lists available at ScienceDirect

Marine Chemistry

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

Upwelling velocity and eddy diffusivity from ^{7}Be measurements used to compare vertical nutrient flux to export POC flux in the Eastern Tropical South Pacific

William Z. Haskell II [a],*, David Kadko [b], Douglas E. Hammond [a], Angela N. Knapp [c], Maria G. Prokopenko [a], William M. Berelson [a], Douglas G. Capone [d]

[a] Dept. of Earth Sciences, University of Southern California, 3651 Trousdale Pkwy, Los Angeles, CA, 90089, United States
[b] RSMAS, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149, United States
[c] Earth, Ocean and Atmospheric Science Dept., Florida State University, Tallahassee, FL 32306, United States
[d] Dept. of Biological Sciences, University of Southern California, 3616 Trousdale Pkwy, Los Angeles, CA 90089, United States

ARTICLE INFO

Article history:
Received 2 June 2014
Received in revised form 1 October 2014
Accepted 1 October 2014
Available online 22 October 2014

Keywords:
Upwelling
Eddy diffusivity
New production
Export
Nutrient cycling

ABSTRACT

Five ^{7}Be profiles, measured in an area bounded by 10°S–20°S and 80°W–100°W, were used to determine upwelling velocity (w_H) and vertical diffusivity (K_z). A positive correlation between w_H and ^{14}C primary production rate and a negative correlation between the inventories of ^{7}Be and phosphate were observed. We interpret this as the influence of deeper, nutrient-rich, ^{7}Be-poor water brought up by upwelling. Excluding two stations that appear to be influenced by non-steady state dynamics or horizontal transport, upwelling velocities were estimated to be 0 to 1.0 m d^{-1} and K_z values ranged from 0.4 to 2.6 cm^2 s^{-1}. From these parameters, NO_3^- fluxes into the euphotic zone were assessed and ranged from 0.15 to 2.9 mmol m^{-2} d^{-1}. Using these values, we estimate 1.0 to 19 mmol C m^{-2} d^{-1} of new production in the ETSP. New production based on ^{7}Be-derived transport parameters agree with carbon export estimates using a ^{234}Th balance, sediment traps and O_2/Ar supersaturation for stations along 20°S, but are higher than export estimates at 10°S, 100°W.

1. Introduction

The vertical transport of nutrients in the upper ocean is vital to biogeochemical cycling and the ocean's ability to sequester atmospheric carbon dioxide via the supply of particulate organic carbon to deep-sea ecosystems. The uncertainty involved in estimating eddy diffusivity, an important mechanism for transporting subsurface nutrients into surface waters, is substantial, and direct measurement of upwelling velocity is difficult, in part because of the small velocities involved. Previously employed approaches typically utilize surface anomalies in tracers found in thermocline waters, including ^{14}C, δ^{13}C, Apparent Oxygen Utilization (AOU), δ^3He, pCO$_2$, and temperature (Broecker and Peng, 1982; Broecker et al., 1978; Klein and Rhein, 2004; Quay et al., 1983; Rhein et al., 2010; Wanninkhof et al., 1995). Uncertainties in gas exchange, primary production, and the air-sea equilibration rate of CO$_2$ (~1 yr) limit the effectiveness of many of these tracers. In order to determine local and time-dependent upwelling velocities, a tracer with a time-scale of weeks is desirable. While the tritiugenic ^{3}He-based approach does integrate over the time scale of gas exchange in the mixed layer, accurate knowledge of the gas exchange velocity and vertical diffusivity at the base of the mixed layer must be known to effectively utilize this method for estimating upwelling velocity.

^{7}Be (half-life: 53 d) is a cosmic-ray produced radionuclide deposited on the ocean surface mainly by rainfall and reaches a uniform activity within the mixed layer (Aaboe et al., 1981; Kadko, 2000, 2009; Kadko and Olson, 1996; Silker, 1972a,b; Young and Silker, 1980). It has been demonstrated that ^{7}Be is quite soluble in the relatively low particle density environments of the open ocean (<10% loss to particle adsorption; Silker, 1972; Aaboe et al., 1981; Andrews et al., 2008; Kadko and Prospero, 2011; Kadko and Johns, 2011). Therefore, if radioactive decay is the only removal process, then the inventory in the water column is equal to the integrated input flux over approximately the mean life of the isotope (~77 d). Previous studies have used the penetration of ^{7}Be-rich mixed layer water to trace subduction and ventilation of the upper thermocline over a seasonal timescale and to estimate mixing rates (Kadko, 2000; Kadko and Johnson, 2008; Kadko and Olson, 1996; Kadko and Swart, 2004). In this study, we used ^{7}Be to evaluate upwelling, following the approach of Kadko and Johns (2011) in the Equatorial Atlantic: The dilution of the ^{7}Be-rich mixed layer by ^{7}Be-depleted waters from below is used to estimate upwelling velocities by mass balance calculations. Furthermore, with knowledge of upwelling rates, vertical eddy diffusivities may then be calculated from ^{7}Be profiles. This technique was used during a cruise to the Eastern

---

* Corresponding author. Tel.: +1 240 687 0772; fax: +1 213 740 8801.
E-mail address: whaskell@usc.edu (W.Z. Haskell).

http://dx.doi.org/10.1016/j.marchem.2014.10.004
0304-4203/© 2014 Elsevier B.V. All rights reserved.

Tropical South Pacific (ETSP) from March 23 to April 28, 2011 to investigate surface ocean nutrient budgets, in order to complement a larger effort of characterizing the nitrogen cycle surrounding the intense Oxygen Minimum Zone (OMZ) found in this region.

2. Methods

2.1. Beryllium-7

Five stations were sampled for ^{7}Be at three depths between 10°S–20°S and 80°W–100°W (Fig. 1). Sampling depths were chosen based on the strength of the temperature gradient observed during CTD descent, which should reflect the extent of vertical mixing, and thus the depth of ^{7}Be penetration into the water column. Samples from the mixed layer (200 L), about 20 m below the mixed layer (400 L), and about 20 m below that (600 L), were taken with a CTD equipped with twelve, 30 L Niskin bottles, on multiple casts. Water from each depth was transferred into 208 L drums via 10 L buckets, and then pumped twice through a cartridge containing FeOH-impregnated acrylic fibers for ^{7}Be extraction (Krishnaswami et al., 1972; Lal et al., 1988; Lee et al., 1991). The efficiency of the fiber for extraction of ^{7}Be from seawater has previously been determined by adding a stable Be atomic absorption standard to a drum containing seawater. As described in Kadko and Johns (2011), seawater was pumped through an iron fiber cartridge and at every 100 L the Be content of the cartridge effluent was measured by atomic absorption. From this data, the integrated Be extraction efficiencies were calculated. For sample volumes in the range 400–700 L, based on several trials, the extraction efficiencies were respectively, 82 ± 3% to 76 ± 2%. In this study, the drums and buckets used for transfer from the CTD were rinsed thoroughly with fresh water prior to processing each sample. Fibers were then removed from the cartridges and placed into bags for transport to the University of Miami, where they were subsequently dried, ashed, pressed into 5.8 cm diameter ‘pucks’ and counted on an Ortec low-background, High Purity Germanium (HPGe) gamma detector. The analysis is described in detail elsewhere (Kadko, 2009). ^{7}Be has a readily identifiable gamma peak at 478 keV. The detector was calibrated for puck geometry by adding a commercially prepared solution of known mono-energetic gamma activities (thus avoiding summation corrections) to an ashed fiber; these were treated identically to a sample. From these data, a calibration curve based on puck thickness (in the range 7–13 mm) was derived. The uncertainty of extraction efficiency (4%) and the detector efficiency (2%) was in all cases smaller than the statistical counting error and the uncertainty in the blank.

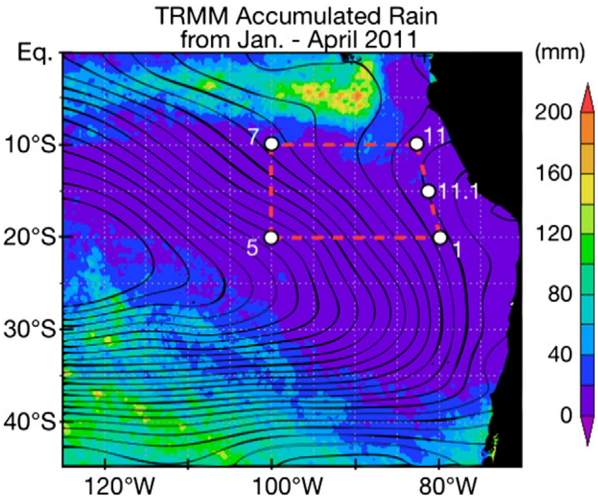

Fig. 1. ETSP cruise track and rainfall estimates. Map of the cruise track (red dashed lines) showing the location of each station sampled for ^{7}Be (Stations shown with white circles and numbered) overlaid on TRMM accumulated rainfall estimates from January to April, 2011 over the study region (colors; NASA, 2014). Black lines are spring dynamic height isopleths relative to 1000 m acquired from World Ocean Atlas 2009 (Schlitzer, 2014; World Ocean Atlas, 2009).

2.2. Nutrients

Nutrients were collected from 24 depths at each station via a CTD equipped with 24 10 L Niskin bottles. Samples collected in the upper 400 m were filtered through a 0.2 μm syringe filter before collection in acid-washed 60 mL HDPE Nalgene bottles that were rinsed with sample water three times before filling. The concentration of nitrate plus nitrite ($NO_3^- + NO_2^-$) was determined on samples frozen at −20 °C at sea and analyzed on land using the chemiluminescent method of Braman and Hendrix (1989) in a configuration with a detection limit of ~0.05 μM. The average standard deviation for replicate [$NO_3^- + NO_2^-$] analysis from an individual sample was ±0.1 μM. The concentrations of NO_2^- and phosphate (PO_4^{3-}) were measured at sea using colorimetric methods described by Strickland and Parsons (1968) with a detection limit of 50 nM and standard deviation of ±20 nM for both NO_2^- and PO_4^{3-} analyses. Measurements of dissolved silica were made on refrigerated samples transported back to USC and analyzed colorimetrically with a Hitachi UV/vis-spectrophotometer at 810 nm (Parsons et al., 1984).

2.3. Floating sediment traps

Two strings of floating Particle Interceptor Sediment Traps (PITs) were deployed at both 100 m and 200 m for an average of ~35 h at Stations 1, 11, 11.1, and for ~65 h at Stations 5 and 7. All traps had 12 collection tubes with an aspect ratio of 6.4 and 5 cm thick baffles (1 cm × 1 cm) fitted into the top opening of the tubes. Funnels with centrifuge tubes (Falcon, 50 mL) were attached into the base of each trap tube. Each centrifuge tube contained a brine solution of NaCl and $NaBO_4$ (in excess of sea water by 5 ppt) poisoned with 2% Formaldehyde. After retrieval, swimmers were picked from each trap sample under a microscope, the remaining material was combined onto two Whatman GF/F (0.7 μm poresize) filters and one Whatman polycarbonate membrane filter (0.4 μm), and then each was weighed. One GF/F filter was used for gamma spectroscopy at USC, the polycarbonate membrane filter was used for bSi analysis at USC, and the other GF/F was sent to UC Davis Stable Isotope Facility (SIF) for C and N analysis. The measured values were then scaled up by mass to the entire trap catch. A detailed description of this method can be found in Haskell et al. (2013).

2.4. Thorium-234

Ten depths from the surface to 300 m were chosen based on fluorescence measured with a SeaBird sensor during the CTD's descent. An isotope dilution method using a ^{229}Th spike of known activity and coprecipitation with MnO_2 was used to measure ^{234}Th (Rutgers van der Loeff and Moore, 1999). The ^{234}Th deficit relative to its parent isotope, ^{238}U, was calculated by trapezoidal integration of the profile. The POC:^{234}Th and bSi:^{234}Th ratios measured in trap material were used to estimate organic carbon and bSi fluxes on sinking particles. A detailed description of these calculations can be found in Haskell et al. (2013).

3. Results and discussion

3.1. Box model

To investigate the vertical transport of nutrients and tracers in the upper thermocline, we used a simple, one-dimensional box model of the upper ocean consisting of a surface mixed layer of uniform concentration underlain by a gradient with depth, adopting the convention that depth (z) is positive downward. We assume that upwelled water