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# Inferring upwelling rates in the equatorial Atlantic using $^{7}$Be measurements in the upper ocean

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ABSTRACT

Ocean upwelling rates are difficult to measure because of the relatively small velocities involved, and therefore are typically inferred from indirect methods such as heat budget estimates or tracer observations. Here we present the first results using a novel technique, based on the isotope $^{7}$Be, to infer rates of upwelling along the equator. Beryllium-7 (half-life=53.3 d) is a cosmic-ray produced radioactive nuclide that is deposited by rainfall upon the ocean surface and subsequently enriched and homogenized within the mixed layer. Previous investigations have utilized the penetration of characteristically high mixed layer concentrations into the upper thermocline to trace ocean ventilation and subduction over seasonal timescales. Here, the tracer is used in a reverse sense; that is, the $^{7}$Be concentration in the usually $^{7}$Be-rich surface mixed layer will be diluted from penetration of $^{7}$Be "dead" water upwelled from below. This dilution provides a means to infer upwelling rates. Furthermore, with knowledge of upwelling rates, $^{7}$Be profiles can be used to constrain vertical diffusivity within the upper thermocline. These ideas were tested with samples collected during the Tropical Atlantic Climate Experiment (TACE) cruise (May 22–June 27, 2009). The observations indicated a nearly linear relationship between $^{7}$Be inventory and mixed layer temperature, as with increased upwelling, lower mixed layer temperatures correspond to greater $^{7}$Be dilution from depth. With this data, upwelling rates were estimated at a number of stations near the equator between 0°E and 30°W within and adjacent to the equatorial cold tongue. The derived upwelling rates ranged from 0 to 2.2 m/d, with maximum values found between the equator and 2°S. The corresponding $K_z$ values derived for the upper thermocline were in the range 1–4 $\times 10^{-4}$ m$^2$/s.



## 1. Introduction

Upwelling is an important component of the global ocean circulation, which affects biogeochemical cycling, climate dynamics, and sea-surface temperature. Determination of upwelling rates by direct measurement is difficult because of the relatively small velocities involved, and they must therefore be inferred by indirect methods such as those provided by tracer observations. Such tracers derive from the presence, in surface water, of properties characteristic of thermocline water, which have been emplaced by the upwelling process. Examples include surface anomalies in $^{14}$C, $\delta^{13}$C, AOU (apparent oxygen utilization), $\delta^{3}$He, $pCO_2$, $\Sigma CO_2$, and temperature (Broecker and Peng, 1982; Broecker et al., 1978; Quay et al., 1983; Wanninkhof et al., 1995; Klein and Rhein, 2004; Rhein et al., 2010). Several of these properties have been used to constrain rates of upwelling. For example, the maintenance of a $CO_2$ anomaly in the equatorial surface ocean in the presence of gas evasion and plant production demands that upwelling rates be at least tens of meters a year (Broecker and Peng, 1982). However, uncertainties with respect to gas exchange, primary production, and an air–sea equilibration time of ~1year limit the effectiveness of $CO_2$ for analyzing local and time-dependent upwelling rates. In another example, the helium isotopic disequilibrium (excess $\delta^{3}$He) in the mixed layer of upwelling regions can only be maintained by upward vertical motion, and was used to derive values of vertical velocity in the range of ~1–2 m/d for the equatorial Atlantic (Klein and Rhein, 2004; Rhein et al., 2010), comparable to calculations based on the Ekman divergence for that area (Xie and Hsieh, 1995). The timescale of gas transfer (days) allows this tracer to analyze local upwelling but relies on accurate assessment of the gas exchange rate and vertical diffusivity at the base of the mixed layer.

Here, a novel technique based on the isotope $^{7}$Be is used to infer rates of upwelling. Be-7 is a cosmic-ray produced isotope (half-life=53.3 d) that is deposited upon the ocean surface primarily by rainfall and subsequently homogenized within the surface mixed layer (e.g. Silker, 1972; Aaboe et al., 1981;

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Young and Silker, 1980; Kadko and Olson, 1996; Kadko, 2000, 2009). In the absence of physical removal processes other than radioactive decay the water column inventory of the isotope represents an integration of the atmospheric input flux over approximately the previous mean-life (77 d) of the isotope.

Typically, penetration of the characteristically high mixed layer concentrations of $^{7}$Be into the upper thermocline has been used to trace ocean ventilation and subduction (of water mass, heat, and chemical properties) over seasonal timescales within numerous ocean regimes (e.g. Kadko and Olson, 1996; Kadko, 2000; Kadko and Swart, 2004; Kadko and Johnson, 2008). In these works, the penetration of high $^{7}$Be below the mixed layer is used to infer ventilation rates of water that had previously been near the surface within the timescale of the isotopic mean life of 77 d, and derive mixing rates between the mixed layer and the upper thermocline. Here, a method is described how the tracer can be used in a reverse sense; that is, the $^{7}$Be concentration in the usually $^{7}$Be-rich surface mixed layer will be diluted from penetration of $^{7}$Be "dead" water upwelled from below. This dilution provides a means to infer upwelling rates. Furthermore, with knowledge of upwelling rates, $^{7}$Be profiles can be used to constrain vertical diffusivity within the upper thermocline. These ideas were tested during a cruise to the equatorial Atlantic in June 2009 as part of the Tropical Atlantic Climate Experiment (TACE).

## 2. Methods

Samples were collected during the *R/V Endeavor* (cruise EN463, May 22–June 27, 2009) at a total of 19 stations along the cruise track (Fig. 1), mostly along three cross-equatorial sections at 23°W, 10°W, and 0°E. The subsequent analysis followed procedures described in detail elsewhere (Kadko, 2009). Briefly, $^{7}$Be was collected at selected depths by pumping 400–700 L of seawater via a 1.5 inch hose into large plastic barrels on deck. From these barrels, the seawater was then pumped through iron-impregnated acrylic fibers at ~10 L/min (Lal et al., 1988; Krishnaswami et al., 1972; Lee et al., 1991). The efficiency of the fiber for extraction of Be from seawater was determined by adding 500 ml of a 1000 ppm Be atomic absorption standard to a drum containing seawater. The 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, the extraction efficiencies were respectively 82–76%. On land, the fibers were dried and then ashed. The ash was subsequently pressed into a pellet (5.8 cm diameter) and placed on a low background germanium gamma detector.

The $^{7}$Be has a readily identifiable gamma peak at 478 keV. The detector was calibrated for the pellet geometry by adding a commercially prepared mixed solution of known gamma activities to an ashed fiber, pressing the ash into a pellet, and counting the activities to derive a calibration curve. The uncertainty of the extraction efficiency (4%) and the detector efficiency (2%) was in all cases smaller than the statistical counting error and the uncertainty in the blank.

Th-234 samples were collected by pumping seawater into 10 L plastic jugs. The samples were then acidified with HCl and spiked with a yield tracer (Th-230) and an iron chloride solution. After equilibrating overnight, thorium was co-precipitated with $FeOH_3$ by adding a sodium hydroxide solution. The precipitate was filtered and then passed through ion exchange columns to remove uranium (Bhat et al., 1969). The Th was electroplated on stainless steel planchets (Anderson and Fleer, 1982) and counted on calibrated alpha and beta detectors.

Particle samples were collected by passing 200 L seawater samples through 142 mm GF/F filters by vacuum filtration. The filters were leached with boiling HCl and $HNO_3$ in the presence of stable Be and $^{230}$Th spikes. The leachate was precipitated with iron hydroxide, dried in a petri dish, and placed on the gamma detector for $^{7}$Be analysis. Subsequently, the dried precipitate was dissolved in 1 N HCL. An aliquot of this was used for analysis of stable Be, by AA, to determine the $^{7}$Be recovery. The remainder was treated for $^{234}$Th analysis as described above.

## 3. Results and discussion

The $^{7}$Be data are presented in Table 1. At each station, a full depth CTD cast was also performed, so that the corresponding temperature profile and mixed layer depth are known. Surface mixed layer $^{7}$Be samples were collected at all 19 stations, and at 9 of the stations (which we refer to as "profile" stations), $^{7}$Be samples were collected at 4 additional depths within the upper thermocline. The purpose of these profile stations was to estimate the total water column inventory of $^{7}$Be at a number of sites where strong upwelling was anticipated to be taking place, as well as at a few locations where upwelling was expected to be weak or zero.

The $^{7}$Be activity in the mixed layer (Tables 1 and 2) exhibits a total variation of about a factor of four, between low values of ~200 dpm/m$^3$ found in areas with cooler sea surface temperatures (SSTs) and high values of ~800 dpm/m$^3$, which are

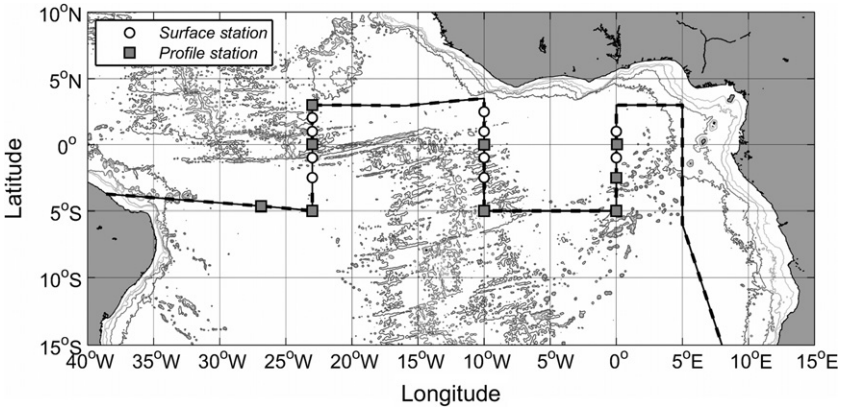


**Fig. 1.** Cruise track for the *R/V Endeavor* (cruise EN463, May 22–June 27, 2009) indicating location of the $^{7}$Be samples (mixed layer samples only, circles; full profiles, squares).