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POC export fluxes in the Arabian Sea and the Bay of Bengal: A simultaneous $^{234}Th/^{238}U$ and $^{210}Po/^{210}Pb$ study

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ABSTRACT

Seasonal variation in POC export flux, from the upper ocean, was studied during post southwest monsoon (October–November 2013) and spring intermonsoon (May 2014) at selected locations in the central and southern Arabian Sea and during northeast monsoon (January 2014) and spring intermonsoon (March 2014) in the northern Bay of Bengal. POC fluxes estimated from two particle-reactive radionuclide flux proxies ($^{234}Th/^{238}U$ and $^{210}Po/^{210}Pb$) were compared. Spatial and temporal variations were observed in the POC/radionuclide ratios, net deficit flux of radionuclides and the estimated POC export fluxes in both the basins. During post southwest monsoon, the ^{234}Th flux (1346 ± 101 dpm $m^{-2} d^{-1}$), POC/^{234}Th ratio (5.96 ± 0.29 μmol dpm^{-1}) and associated POC flux (8.0 ± 0.6 mmol $m^{-2} d^{-1}$) were high in the southern Arabian Sea than those in the central Arabian Sea (450 ± 95 dpm $m^{-2} d^{-1}$, 1.76 ± 0.07 μmol dpm^{-1} and 0.8 ± 0.2 mmol $m^{-2} d^{-1}$, respectively). However, during spring intermonsoon these trends were similar in both the central and southern Arabian Sea with mean ^{234}Th fluxes, POC/^{234}Th ratios and ^{234}Th based POC export fluxes being 2762 ± 61 dpm $m^{-2} d^{-1}$, 1.45 ± 0.05 μmol dpm^{-1} and 4.0 ± 0.14 mmol $m^{-2} d^{-1}$, respectively. On the other hand, the ^{210}Po based POC export fluxes in the southern Arabian Sea (3.37 ± 0.32 and 6.73 ± 0.47 mmol $m^{-2} d^{-1}$) were higher by a factor of 2–3 than those in the central Arabian Sea (2.08 ± 0.16 and 2.12 ± 0.28 mmol $m^{-2} d^{-1}$) during post southwest monsoon and spring intermonsoon, respectively. In the northern Bay of Bengal, the ^{234}Th based POC export fluxes were similar and low (0.6–1.2 mmol $m^{-2} d^{-1}$) while the ^{210}Po based POC export fluxes were much higher (3.75–8.48 mmol $m^{-2} d^{-1}$) during both the northeast monsoon and spring intermonsoon seasons. One reason could be that more production and carbon export occurring in months prior to the period preceding sample collection due to weeks to several months difference in the mean-lives of the isotopes. The computed POC export fluxes and inferred efficiency of the biological carbon pump in the Arabian Sea and the northern Bay of Bengal are differentiated by this different span in half-lives of ^{234}Th and ^{210}Po (weeks to months, respectively). Also these values are distinct due to their biogeochemical behavior and preferred affinity for specific types of particles. This would require more joint application of each tracer in time and space for various biogeochemical regimes.

1. Introduction

The role of oceans in the global carbon cycle is to a large extent dependent on the biological carbon pump that continuously sequesters atmospheric CO_2 in the surface layer. About 5 Gt C is annually exported to the deep sea through the biological carbon pump (Falkowski et al., 1998; Henson et al., 2011). Most of the carbon fixed by the phytoplankton is recycled within the top 100 m of the water column. The organic matter sinking out of the euphotic layer is also largely remineralized and consumed by microbes and other biota (Giering et al., 2014) whereas particles sinking to deep sea sequester carbon for longer time scales (Villa-Alfageme et al., 2016). Carbon export occurs via diverse processes including the sinking of dead phytoplankton cells, aggregates and zooplankton pellets, with considerable spatial variability in the relative importance of these processes. The efficiency of the biological carbon pump (known as 'e-ratio') is determined by the amount of carbon exported from the ocean surface to its interior, to that produced (e-ratio = export flux/primary production) (Downs, 1989; Buesseler, 1998). Buesseler (1998) reported that global oceans export < 5–10% POC relative to primary production, except during

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bloom periods. Globally, time-series observations of carbon export have shown intra-annual (including seasonal) and inter-annual variations. Time-series stations at high latitudes showed high export flux during summer, while low latitude stations showed relatively constant flux throughout the year (Baumann et al., 2013; Kawakami and Honda, 2007; Buesseler et al., 1992; Brix et al., 2006; Benitez-Nelson et al., 2001).

The Indian Ocean is a tropical, low latitude ocean surrounded by continents in the north. Unlike other tropical oceans, the northward heat export in the Indian Ocean is prevented by its low latitude northern boundary. A discontinuity in hydrochemical characteristics around 10°S, called Hydrochemical Front, is maintained throughout the year by westward flow of the South Equatorial Current. This is best manifested by steep subsurface gradients in salinity, oxygen and nutrients with the waters north of the Front being more saline, oxygen-depleted and nutrient-enriched than to its south (Wyrtki, 1973). The entire region north of the Hydrochemical Front is influenced by the semi-annual reversal of wind regimes caused by the monsoons. These reversals have significant impact on the upper ocean circulation and biological productivity of the region (Madhupratap et al., 1996). The North Indian Ocean with its two contrasting basins (the Arabian Sea and the Bay of Bengal) is distinguished by its seasonally reversing winds and surface circulation, high precipitation in the northeast and excessive evaporation in the northwest, seasonal upwelling along the northwestern boundary, high primary production and pronounced permanent oxygen minimum zones (OMZs). These basins act as both sources and sinks of atmospheric CO_2 (Kumar et al., 1996).

The high biological productivity coupled with restricted ventilation contribute to the formation of OMZs at intermediate depths that are among the thickest (100–1200 m) and most intense in the oceans. While the OMZ of the Arabian Sea experiences intense denitrification (Naqvi, 1994), that in the Bay of Bengal is on the threshold of being reducing with microorganisms having nitrogen-metabolizing capabilities typical of active N_2 producing systems (Bristow et al., 2017). Despite several major programmes conducted in the past, the information available on the spatial and temporal variability of and the factors controlling carbon export in this region is still severely inadequate.

Measurement of particle export can be done following direct (sediment traps) and indirect (particle-reactive radionuclides) techniques (Bacon et al., 1976; Friedrich and van der Loeff, 2002). Direct methods like sediment traps generally underestimate particle fluxes due to particle solubilization, zooplankton swimmers and hydrodynamics (Lee et al., 1988; Knauer et al., 1990; Honjo et al., 2008; Buesseler et al., 2006 and Buesseler et al., 2007). From the continuous, high-resolution O_2/Ar measurements by equilibrator inlet mass spectrometry (EIMS), Net Community Production, that is equal to carbon export production from the mixed layer at steady state conditions, can be resolved at high spatial resolution (Cassar et al., 2009).

Particle-reactive radionuclides (^{234}Th-^{238}U, ^{210}Po-^{210}Pb) present in the ocean facilitate in-situ estimation of organic carbon export from surface to deeper layers as they have well known production and decay rates, half-lives and well-studied adsorption behavior (Cochran et al., 1983; Coale and Bruland, 1985; Chung and Finkel, 1988; Sarin et al., 1994a, 1994b). ^{234}Th (half-life: 24.1 d) is highly suitable for tracing short time scale (weeks) particle flux events like those following phytoplankton blooms (Buesseler et al., 1995). Murray et al. (1989) and Shimmield et al. (1995) have explained ^{234}Th as a mass flux proxy. To characterize the nature of the material settling out of the euphotic zone, ^{210}Po-^{210}Pb pair produced in the ^{238}U decay chain is used as a tracer. ^{210}Po-^{210}Pb disequilibrium determines POC export on a longer timescale (around 6 months) while ^{234}Th/^{238}U disequilibrium integrates particle export for five weeks (Friedrich and van der Loeff, 2002). Enrichment of ^{210}Po in cell protoplasm, by biological uptake (Stewart and Fisher, 2003a, 2003b) and non-specific surface adsorption of ^{234}Th and ^{210}Pb make them better tracers for organic matter flux and mass flux, respectively (Fisher et al., 1983). From a study on the partitioning of ^{210}Po and ^{210}Pb activity between particles and solution in the upper 500 m water column across the North Atlantic basin, Tang et al. (2017) have shown that ^{210}Po consistently exhibited a higher affinity for POC than ^{210}Pb, especially in the open ocean away from the margins, supporting the use of ^{210}Po fractionation and disequilibrium from ^{210}Pb as a tracer of carbon export in the surface ocean. Differences in these two radioisotope pairs with regard to their half-lives, particle reactivity and scavenging affinity in seawater should provide complementary information concerning the processes occurring in the water column.

Earlier studies on carbon export flux in the North Indian Ocean are limited to sediment trap measurements (Nair et al., 1989; Ittekkot et al., 1991; Ramaswamy and Nair, 1994; Ramaswamy et al., 1997; Ramaswamy et al., 2005; Honjo et al., 1999; Honjo et al., 2008) and ^{15}N isotope addition techniques (Kumar et al., 2004) with the exception of a few studies by Sarin et al. (1994a, 1994b, 1996), Buesseler et al. (1998) and Ramaswamy et al. (2005) in the Arabian Sea using ^{234}Th as a flux proxy. Sarin et al. (1996) studied the particle export fluxes and scavenging rates using ^{234}Th and showed that the sediment trap fluxes were systematically low and ^{234}Th based carbon export were significantly higher than column primary production. Seasonal variability of POC export flux using ^{234}Th in the Arabian Sea was described in detail by Buesseler et al. (1998). These investigators showed that the carbon export was high during the late-southwest monsoon period (September–October) and to some extent during spring intermonsoon period (March–May). Ramaswamy et al. (2005) reported that the seasonally occurring salp swarms in the northern Arabian Sea form a significant pathway for carbon export from the euphotic zone. The above studies showed that the carbon export in the Arabian Sea varied from intra- to inter-seasonal time scales. Anand et al. (2017) reported that remineralization of organic carbon in the surface and subsurface waters considerably reduced POC export in the Bay of Bengal owing to organic carbon consumption and heterotrophy enhanced by anticyclonic eddies.

Several authors have recommended the simultaneous use of ^{234}Th/^{238}U and ^{210}Po/^{210}Pb since they cover different time scales, from weeks to months, respectively, and ^{234}Th and ^{210}Po have different biogeochemical behaviors, providing complementary information on POC export fluxes (Friedrich and van der Loeff, 2002; Verdeny et al., 2009; Stewart et al., 2011; Wei et al., 2011; Le Moigne et al., 2013; Roca-Mart et al., 2016). Under the Sustained Indian Ocean Biogeochemical and Ecosystem Research (SIBER) programme, a few stations have been selected for long-term monitoring of carbon export in the Arabian Sea and the Bay of Bengal, two tropical, bio-geochemically important, but quite contrasting basins of the North Indian Ocean. As a part of this effort, simultaneous measurements of particle-reactive radionuclides (^{234}Th, ^{210}Po, ^{210}Pb) were carried out at a few stations in the Arabian Sea and the Bay of Bengal during different seasons from 2013 to 2014. Here we report the first results of POC export fluxes from 4 cruises in these basins from the distributions of the three particle-reactive radionuclides in the upper Indian Ocean. The goals of this study are (1) to investigate the temporal variability of particle scavenging and removal processes, (2) to compare the geochemical behavior of ^{234}Th, ^{210}Pb, and ^{210}Po, and (3) to estimate the export flux of POC, by ^{234}Th/^{238}U and ^{210}Po/^{210}Pb disequilibria in the euphotic layer of the Arabian Sea and the Bay of Bengal.

2. Sampling and methods

2.1. Sample collection

Seawater samples were collected from surface to 800 m depth using a standard CTD rosette system (Sea-Bird Electronics, USA) fitted with 10 L Niskin bottles onboard RV *Sindhu Sankalp* (Cruise SSK56) in the Arabian Sea during post southwest monsoon (October–November 2013) and onboard ORV *Sagar Kanya* (Cruise SK312) during spring