# Global database of oceanic particulate organic carbon to [234]Th ratios: Improving estimates of the biological carbon pump

Viena Puigcorbé[1], Pere Masqué[1,2], Frédéric A. C. Le Moigne[3]

[1] School of Science, Centre for Marine Ecosystems Research, Edith Cowan University, Joondalup WA 6027, Australia.

[2] Institut de Ciència i Tecnologia Ambientals and Departament de Física, Universitat Autònoma de Barcelona, 08193 Cerdanyola del Vallès, Spain.

[3] Mediterranean Institute of Oceanography, UM110 CNRS, Aix-Marseille Université, IRD, 13288 Marseille, France.

*Correspondance to* : Viena Puigcorbé (viena.puigcorbe@outlook.com)

**Abstract**

The ocean's biological carbon pump (BCP) plays a major role in the global carbon cycle. A fraction of the photosynthetically fixed organic carbon produced in surface waters is exported below the sunlit layer as settling
5   particles (e.g. marine snow). Since the seminal works on the BCP, global estimates of the global strength of the BCP have improved but large uncertainties remain (from 5 to 20 GtC $yr^{-1}$ exported below the euphotic zone or mixed layer depth). The [234]Th technique is widely used to measure the downward export of particulate organic carbon (POC). This technique has the advantage to allow a downward flux to be determined by integrating the deficit of [234]Th in the upper water column and coupling it the POC/[234]Th ratio in sinking particles. However, the
10   factors controlling the regional, temporal and depth variations of POC/[234]Th ratios are poorly understood. We present a database of 9110 measurements of the POC/[234]Th ratio in the ocean, from the surface down to >5500 m, sampled on three size fractions (~>0.7 μm, ~1-50 μm, ~>50 μm), collected with *in situ* pumps and bottles, and also from bulk particles collected with sediment traps. The dataset is archived on the data repository PANGAEA® (www.pangaea.de) under https://doi.pangaea.de/10.1594/PANGAEA.911424 (Puigcorbé, 2019). The samples
15   presented in this dataset were collected between 1989 and 2016 and the data have been obtained from published papers and open datasets available online. Unpublished data has also been included. Multiple measurements can be found in most of the open ocean provinces. However, there is an uneven distribution of the data, with some areas highly sampled (e.g, China Sea, Bermuda Atlantic Time Series station) compared to some others that are not well represented, such as the southeastern Atlantic, the south Pacific and the south Indian oceans. Some coastal
20   areas, although in a much smaller number, are also included in this global compilation. Globally, based on different depths horizons and climate zones, the median POC/[234]Th ratios have a wide range, from 0.6 to 18 μmol $dpm^{-1}$.

## 1 Introduction

The ocean's biological carbon pump (Eppley and Peterson, 1979) plays a major role in the global carbon cycle.
25   A fraction of the photosynthetically produced organic carbon is exported from the surface waters below the sunlit layer as settling particles (e.g. marine snow). Through this process, the ocean stores carbon dioxide ($CO_2$) away from the atmosphere and buffers the global climate system (Kwon et al., 2009). Indeed, estimates suggest that

atmospheric $CO_2$ levels would be 200 ppm higher than current concentrations without the biological carbon pump (Parekh et al., 2006). However, quantifying the magnitude of the biological carbon pump at both the regional and

30 global scales is challenging and current assessments vary widely, with estimates ranging from 5 to 20 GtC $y^{-1}$ being exported below the euphotic zone or the mixed layer depth (Guidi et al., 2015; Henson et al., 2011; Laws et al., 2011).

Downward export fluxes of organic carbon can be estimated using: (i) indirect approaches derived from nutrient uptake (Le Moigne et al., 2013a; Pondaven et al., 2000; Sanders et al., 2005), radioisotopes (Cochran and Masqué,

35 2003; and references therein), satellite empirical algorithms (Dunne et al., 2007; Henson et al., 2011; Laws et al., 2011), underwater video systems (Guidi et al., 2008) or (ii) direct measurements using various designs of sediment traps (Buesseler et al., 2007; Engel et al., 2017; Lampitt et al., 2008; Owens et al., 2013) or marine snow catchers (Cavan et al., 2015; Riley et al., 2012).

Here we focus on the use of radioisotopes, specifically, $^{234}$Th. The $^{234}$Th approach allows to quantify an export

40 flux from i) a water profile of $^{234}$Th to obtain its deficit relative to $^{238}$U combined with ii) an estimate of the POC concentration to $^{234}$Th activity (POC/Th ratio) in sinking matter (Buesseler et al., 1992). In reviewing POC/Th ratios variability using the data available at the time, (Buesseler et al., 2006) found that the POC/Th ratios i) increase or remain constant with increasing particle size and ii) decrease with depth. Regionally, the POC/Th ratios vary largely between oceanic provinces and regimes (Puigcorbé et al., 2017a). The study of the

45 biogeochemical behavior of $^{234}$Th with regards to marine particles has received significant attention (Maiti et al., 2010; e.g., Le Moigne et al., 2013b; Puigcorbé et al., 2015; Rosengard et al., 2015; Santschi et al., 2006; and references therein), and the availability of $^{234}$Th related data has been enhanced thanks to international and national programs such as GEOTRACES (Mawji et al., 2015; Schlitzer et al., 2018) JGOFS (Joint Global Ocean Flux Study) (Buesseler et al., 1998, 1995, 2001) or VERTIGO (Buesseler et al., 2008b), yet the factors controlling the

50 variations of the POC/Th ratio as function of region, time, particle size/type and water column depth remain poorly understood. Assessing the influence of such factors on the POC/Th ratios will contribute to improve our modelling efforts and our capacity to predict the export and fate of the organic carbon produced in the surface layers. Indeed, the necessity to constrain the variability of the POC/Th was discussed and considered a priority at the technical meeting "The Application of Radionuclides in Studies of the Carbon Cycle and the Impact of Ocean Acidification"

55 held at the International Atomic Energy Agency (IAEA) Environment Laboratories in Monaco in October 2016 (Morris et al., 2017).

Therefore, we compiled a database that comprises 9110 POC/Th ratios collected between 1989 to 2016 covering most oceanic provinces at depths ranging from 0 to >5500 m deep. The particles were collected using collection bottles (i.e., Niskin), *in situ* pumps or sediment traps, and include bulk and size fractionated samples. This database

60 increases significantly the pool of POC/Th ratio data available at the time of (Buesseler et al., 2006) and enables to test the influence of various factors on the variability of POC/Th ratios. Among other information, the influence of biogeochemical characteristics of the area (e.g, nutrient concentrations) together with the surface productivity levels, phytoplankton compositions, zooplankton abundance could be examined through satellites products and/or global databases (e.g., Buitenhuis et al., 2013; Moriarty et al., 2013; Moriarty and O'Brien, 2013).

65

## 2 Data

### 2.1 The [234]Th approach

The short-lived radionuclide thorium-234 ([234]Th, $t_{1/2}$ = 24.1 d) is widely used to estimate the magnitude of the

70   POC that escapes the upper ocean layers (e.g., the euphotic zone) (Waples et al., 2006). [234]Th is the decay product
     of uranium-238 ([238]U, $t_{1/2}$ = 4.47·10$^9$ y). While uranium is conservative and proportional to salinity in well
     oxygenated seawater (Chen et al., 1986; Ku et al., 1977; Owens et al., 2011), thorium is not soluble in seawater it
     is scavenged by particles as they form and/or sink along the water column. As a consequence, a radioactive
     disequilibrium between [238]U and [234]Th can be observed, mainly in the upper layers of the water column, which in

75   first approximation, is proportional to the amount of particles exported and hence can be used to estimate particle
     and elemental export fluxes.

     One-box scavenging model (see review by Savoye et al. (2006) and references therein) is commonly applied to
     calculate [234]Th export rates. Steady state (SS) or non-steady state conditions (NSS) are assumed depending on the
     conditions at the sampling time and the possibility to reoccupy locations within an adequate timescale. Le Moigne

80   et al. (2013c) reported [234]Th fluxes from both types of models in their database with flux integration depths
     spanning from the surface down to 300 m, although the most common integration depths were between 100 and
     150 m. The choice of export depth when using the [234]Th technique is not trivial. Rosengard et al. (2015) provide
     recommendations to the various manners of choosing the export depth in order to integrate the [234]Th fluxes. Once
     the [234]Th export flux is estimated it is multiplied by the ratio of POC to particulate [234]Th activity in sinking particles

85   to obtain the POC flux. The sinking particles from which the ratio is measured should, ideally, be collected at the
     depth where the export has been estimated and represent the pool of particles that is driving the export of organic
     carbon.

### 2.2 The crux of the [234]Th approach: POC/Th ratios of sinking particles

The determination of the POC/Th ratio has been historically attained by assuming that sinking carbon is driven

90   by large particles, generally >50 µm in size (researchers also use 51, 53 or 70 µm, depending on the mesh supplier),
     whereas organic carbon within small particles is assumed to remain suspended and therefore not contribute to the
     export flux (Bishop et al., 1977; Fowler and Knauer, 1986), although recent studies have shown that small particles
     can be significant players in the particle export and should not be disregarded (Alonso-González et al., 2010;
     Durkin et al., 2015; Le Gland et al., 2019; Puigcorbé et al., 2015; Richardson, 2019), particularly in oligotrophic

95   regions. The most common methods to obtain the particulate fraction to measure the POC/Th ratio are i) *in situ*
     pumps (ISP), which can allow for sampling different particle sizes, ii) collection bottles (CB) such as Niskin
     bottles, providing bulk particles, i.e., >0.7 or 1 µm particles, iii) sediment traps (ST) and although less common
     iv) marine snow catchers. In some instance various methods have been used in combination (e.g., Cai et al., 2010;
     Maiti et al., 2016; Puigcorbé et al., 2015).

100  Different sampling devices have been shown to provide differences in POC/Th ratios, usually within a factor of 2
     to 4 (see review by Buesseler et al., 2006). The differences can be related to the collection of different particles
     pools and/or the enhanced presence of swimmers. ST collect sinking particles and may suffer from hydrodynamic
     discrimination and undersample slow sinking particles (Gustafsson et al., 2004), while CB sample both, sinking

and suspended particle, similar to ISP. ISP filter large volumes of water and have been suggested to potentially

105 undersample some of the fast sinking particles (Lepore et al., 2009) and sample neutrally buoyant C-rich aggregates (i.e., non-sinking but with high POC/Th ratios) (Lalande et al., 2008). Biases due to washout of large particles when using ISP (Bishop et al., 2012) or aggregates collapse induced by their high cross-filter pressure (Gardner et al., 2003) may further enhance these differences. The presence of swimmers can also be an important bias of POC/Th ratios when not thoroughly removed, since they skew measurements towards higher values

110 because of their high POC proportion compared to $^{234}$Th (Buesseler et al., 1994; Coale, 1990).

### 2.3 POC/$^{234}$Th ratio variability

Despite the significant body of literature available on POC/Th ratios, more than 10 years after the review by (Buesseler et al., 2006) we still cannot explain the variability of the POC/Th ratios with depth, time, particle type, size or sinking velocity easily nor at a global level. Changes with size and depth have been the most extensively

115 examined. The relation between POC/Th ratio and particle size have been assessed before with results suggesting that there is not a direct relationship. Previous studies have reported increasing ratios with increasing particle size (e.g., Benitez-Nelson et al., 2001; Buesseler et al., 1998; Cochran et al., 2000), which has been interpreted as an effect of the volume to surface area ratio of the particles, due to $^{234}$Th being surface bound whereas C would be contained within the particles (Buesseler et al., 2006). Yet, a number of studies have reported the opposite trend

120 (i.e., decreasing ratio with increasing particle size; (Bacon et al., 1996; Hung et al., 2010; Planchon et al., 2013; Puigcorbé et al., 2015) or no clear change with size (Hung and Gong, 2010; Lepore et al., 2009; Speicher et al., 2006). Depth is another factor that has been considered when assessing the variability of POC/Th, since particles are produced in the surface layer and are remineralized on their transit along the water column (Martin et al., 1987). POC/Th ratios have been found to be attenuated with depth (Jacquet et al., 2011; Planchon et al., 2015;

125 Puigcorbé et al., 2015). This is due to (in no order or importance) decreasing autotrophic production with increasing water depth, preferential C loss compared to $^{234}$Th through remineralization processes, changes in superficial binding ligands along the water column, and/or scavenging of $^{234}$Th during particle sinking resulting in enhanced particulate $^{234}$Th activities (Buesseler et al., 2006; Rutgers van der Loeff et al., 2002); leading to significant variability in the attenuation rates. Theoretically, high sinking velocities may limit the variations of

130 POC/Th ratios with depth, owing to shorter residence times limiting the impacts of biotic and abiotic processes. However, using specifically design ST that segregate particles according to their *in situ* sinking velocities, (Szlosek et al., 2009) observed no consistent trend between POC/Th ratios and sinking velocities.

The truth is that numerous processes can impact the POC/Th ratios apart from particle size or depth, such as particle composition or aggregation/disaggregation processes mediated by physical or biological activity

135 (Buesseler and Boyd, 2009; Burd et al., 2010; Maiti et al., 2010; Szlosek et al., 2009) which adds a level of complexity to the prediction of their variability in the ocean. Yet, due to the significance of the POC/Th ratios for the accuracy of the $^{234}$Th flux method, the effort should be made to constrain the factors that will impact its variability and a number of environmental and biogeochemical parameters can be assessed with that goal at a global scale. Among others, surface productivity, phytoplankton composition, zooplankton abundance, mixed

140 layer depth, dust inputs to the surface ocean and ice cover (Buitenhuis et al., 2013; Mahowald et al., 2009; Moriarty et al., 2013; Moriarty and O'Brien, 2013) are all potential candidates to test their global patterns against POC/Th ratios variability.

### 3 Results and discussion

#### 3.1 Data classification

145    Our dataset is archived on the data repository PANGAEA® (www.pangaea.de), https://doi.pangaea.de/10.1594/PANGAEA.911424 (Puigcorbé, 2019). Latitude, longitude and sampling dates are reported. When dates of the individual stations were not reported in the original publications, we allocated the midpoint of the sampling period as the sampling date. The same was done when the specific sampling coordinates were not available. The database consists of 9110 measurements of POC/Th ratios in the ocean. Particles were

150    collected using *in situ* pumps (ISP), water collection bottles (CB) and sediment traps (ST). We refer to "bulk" (BU) for particles sampled using CB and ISP with a pore size filter of 0.2-1 µm. For this group of samples, particles >0.7 µm were collected using GFF filters and >1 µm using QMA filters. In some particular cases other types of filters, with a different pore size (e.g., 0.2 µm, 0.45 µm or 0.6 µm) might have been used (see database for details). Hereafter, we use >1 µm for the bulk particles. We refer to "small particles" (SP) for particles usually

155    collected using ISP on a 1-50 µm mesh size and "large particles" (LP) for particles usually collected using ISP on mesh size >50 µm (see details on other size ranges also used in the database). Finally, some POC/Th ratios were measured in sinking particles sampled using sediment traps (ST). Figure 1 shows the global distribution of POC/Th ratios grouped by these four categories: BU, LP, SP and ST. The POC/Th ratios were obtained from particles collected at various depths from surface to >5500 m deep (Figure 2). All the information on locations,

160    dates, depth, size fractions/device (BU, SP, LP and ST) and references are included as metadata in the online database and presented in Table 1.

   Our database covers POC/Th measurements sampled between 1989 and 2016, including unpublished data from our laboratories or graciously made available to us by colleagues and data available in online databases. Figure 3 shows the number of POC/Th measurements available per year. In years 1997, 2004, 2005, 2008, 2010, 2011 and

165    2013, the number of POC/Th measurements was >500. This highlights dedicated carbon export programs such as the Joint Global Ocean Flux Study (JGOFS) (Buesseler et al., 1992, 1998, 1995, 2001; Murray et al., 1996, 2005), the VERTIGO (Vertical Transport in the Global Ocean) voyages in the Pacific Ocean (Buesseler et al., 2008b), and the GEOTRACES program (Mawji et al., 2015; Schlitzer et al., 2018), as well as the maintained effort of the Time Series Stations (Kawakami et al., 2004, 2010, e.g., 2015; Kawakami and Honda, 2007). Sampling effort

170    also varied depending on the month of the year (Fig. 3B), with late spring-summer months being the most highly sampled in both hemispheres. The northern hemisphere has been largely sampled in September, May and June (49, 10 and 5 times more data than in the southern hemisphere, respectively), whereas the southern hemisphere has been more sampled in December and February (5 and 4 times more data than the northern hemisphere, respectively), with no data available for the months of July and August and only 5 data points in September

175    (austral winter). For the rest of the months, the northern hemisphere presents 1.4-1.8 times more data than the southern hemisphere. In the equatorial region (taken as the latitudes between -10° and 10° N) major sampling efforts took place in May, with no data collected in January and just 8 data points available from December. The monthly distribution is, therefore, globally biased towards the warmer and more productive seasons, leaving the winter months largely undersampled, particularly in the southern hemisphere.

180

### 3.2 Global variability: climate zones and depth horizons

The global variability of POC/Th ratios looking at six different depths horizons (50, 100, 200, 500, 1000 and >1000 m) and grouped by climatic zones (Polar >66.5°, Subpolar 66.5°-50°, Temperate 50°-35°, Subtropical 35°-23.5° and Tropical 23.5°N-23.5°S) is presented in Figure 4. A PERMANOVA analysis was conducted to examine the data and the results indicate that all the depths horizons defined here were significantly different ($p<0.05$). Significant differences were also found between climatic zones, except between the Temperate and Subtropical zones and between the Subtropical and the Tropical zones, when considering all the data together. Statistical differences between zones within a certain depth range are shown in Figure 4.

In general, we observe a reduction in POC/Th ratios with depth, previously reported by others (e.g., Buesseler et al., 2006 and references therein), and likely mainly due to the remineralization of carbon along the water column. The decrease is particularly marked in the upper 200 m, where biological processes affecting the ratios are more intense, and then it smoothes below that depth horizon as the strength of these processes is more limited below the euphotic zone. It is worth noticing that some studies, particularly in coastal areas, presented extremely large POC/Th ratios (> 100 μmol dpm$^{-1}$, not included in Figure 4). These high ratios are not always discussed in the publications but the presence of live zooplankton (Buessler et al., 2009; Savoye et al., 2008; Trull et al., 2008) especially in BU, ST and LP fractions when not picked out can be the cause for those high values and should be considered with caution.

Regarding the climate zones, there is significant variability but, in general, large POC/Th ratios occur more often in productive and high latitude regions relative to low latitude tropical areas, particularly in the upper 200 m (Figure 4). When looking at the different types of sampling method, the link between latitude and magnitude of the ratio seems to be clear for ST and BU but quite variable for LP and SP (Figure 5). High POC/Th ratios are usually associated to the presence of large phytoplankton groups, such as diatoms, which are dominant in high latitude areas with no nutrient limitations, or where zooplankton populations are large and there is a significant input of fecal pellets, which should have also high POC/Th ratios. Low ratios, on the other hand, are commonly observed in warm oligotrophic areas where productivity is limited and the main phytoplanktonic groups are picoplankton (see Buessler et al., 2006 and references therein). Exceptions do exist but they are usually found in coastal areas where other factors could be influencing the planktonic community (e.g., seasonal upwelling, continental influence, river inputs).

### 3.3 Contributing to global POC export estimates

The $^{234}$Th approach has been used to derive an export model at global scale that uses sea surface temperatures and net primary productivity from satellite products (Henson et al., 2011). The parametrization for this model has large uncertainties in the cold regions (low sea surface temperature), which lead to a reduced estimate of the global biological carbon pump (~5 GtC y$^{-1}$) compared to other satellite-derived export models (9-13 GtC y$^{-1}$; (Dunne et al., 2007; Laws et al., 2011). A recent study by (Puigcorbé et al., 2017a) estimated POC export fluxes in the North Atlantic using *in situ* data for the $^{234}$Th method and compared it to three different satellite-derived export, (Dunne et al., 2007; Henson et al., 2011; Laws et al., 2011). The conclusion was that, overall, the geographical trends were captured by all the approaches but the absolute values between them could reach important discrepancies. In that study, the authors advised for a revision of the parametrization of the models going beyond sea surface

Open Access Earth System Science Data Discussions

220   temperatures in order to adjust to specific ocean bioregions. This database sets a strong background to develop that parametrization and contribute to similar modeling efforts to constrain the global carbon export fluxes as done by (Henson et al., 2011).

**3.4 Significant gaps and recommendations.**

This database provides the global POC/Th ratios sampled from all the oceans up until 2016. The sampling coverage is significant but it is not evenly distributed. Areas such as the China Sea, Arabian Sea, North Western

225   Mediterranean Sea, Central Pacific and high latitudes of the Atlantic Ocean are well represented, whereas other areas, such as the oligotrophic gyres, West Pacific or the Southern Ocean, present important gaps. The data is not evenly distributed between seasons either, with most of the sampling taking place during spring and summer in both hemispheres, which is also when the export fluxes are expected to be larger. High seasonality in under sampled areas could potentially bias our global view of the POC/Th ratios and have an impact on the Th-derived

230   carbon export fluxes estimates.

It would be recommended to obtain data for those undersampled areas with high seasonality to better characterize the expected variability in the ratios within those areas and to cover a larger span of seasons in order to better understand the seasonality of POC/Th and thus be able to translate it more accurately to the global POC export estimates.

235   **4 Conclusion**

Here we provide a global database of 9110 estimates of POC/Th ratios obtained between 1989 and 2016. POC/Th ratios were sampled on three size fractions (~>0.7 μm, ~0.7-50 μm, ~>50 μm) or on the bulk of particles at various depths from below the surface to >5500 m deep using *in situ* pumps, Niskin® bottles and sediment traps. The observed pattern of POC/Th ratios reflects a decrease with depth and a link with the latitude, with higher ratios

240   usually observed in high latitudes areas. Some noteworthy gaps in the dataset are the Benguela system, the Mauritanian upwelling, the western and south Pacific, and the Southern Indian Ocean. The fall-winter months in both hemispheres are also underrepresented. The temporal and spatial undersampling of some areas could bias the global view of the POC/Th ratios. Despite the gaps, this database is the largest compilation POC/Th ratios up to date and could be used to better understand the factors controlling the variation of ratios on a global scale. This

245   will help revising and providing improved estimates of the ocean's biological carbon pump.

**Data availability**

Our dataset is archived on the data repository PANGAEA® (www.pangaea.de), under the following doi:
https://doi.pangaea.de/10.1594/PANGAEA.911424 (Puigcorbé, 2019).

**Authors contribution**

VP and FACLM compiled the dataset and prepared and reviewed the manuscript. PM contributed to the review
of the manuscript.

**Competing interests**

The authors declare that they have no conflict of interest

**References**

Alonso-González, I. J., Arístegui, J., Lee, C., Sanchez-Vidal, A., Calafat, A., Fabrés, J., Sangrá, P., Masqué, P., Hernández-Guerra, A. and Benítez-Barrios, V.: Role of slowly settling particles in the ocean carbon cycle, Geophys. Res. Lett., 37(13), L13608, doi:10.1029/2010GL043827, 2010.

Amiel, D. and Cochran, J. K.: Terrestrial and marine POC fluxes derived from $^{234}$Th distributions and $\delta^{13}$C measurements on the Mackenzie Shelf, J. Geophys. Res. Ocean., 113(C3), doi:10.1029/2007JC004260, 2008.

Amiel, D., Cochran, J. K. and Hirschberg, D. J.: $^{234}$Th/$^{238}$U disequilibrium as an indicator of the seasonal export flux of particulate organic carbon in the North Water, Deep Sea Res. Part II Top. Stud. Oceanogr., 49(22), 5191–5209, 2002.

Anand, S. S., Rengarajan, R., Sarma, V. V. S. S., Sudheer, A. K., Bhushan, R. and Singh, S. K.: Spatial variability of upper ocean POC export in the Bay of Bengal and the Indian Ocean determined using particle-reactive $^{234}$Th, J. Geophys. Res. Ocean., 122(5), 3753–3770, doi:10.1002/2016JC012639, 2017.

Anand, S. S., Rengarajan, R. and Sarma, V. V. S. S.: 234Th-Based Carbon Export Flux Along the Indian GEOTRACES GI02 Section in the Arabian Sea and the Indian Ocean, Global Biogeochem. Cycles, doi:10.1002/2017GB005847, 2018a.

Anand, S. S., Rengarajan, R., Shenoy, D., Gauns, M. and Naqvi, S. W. A.: POC export fluxes in the Arabian Sea and the Bay of Bengal: A simultaneous $^{234}$Th/$^{238}$U and $^{210}$Po/$^{210}$Pb study, Mar. Chem., 198, 70–87, doi:10.1016/j.marchem.2017.11.005, 2018b.

Aono, T., Yamada, M., Kudo, I., Imai, K., Nojiri, Y. and Tsuda, A.: Export fluxes of particulate organic carbon estimated from $^{234}$Th/$^{238}$U disequilibrium during the Subarctic Pacific Iron Experiment for Ecosystem

Dynamics Study (SEEDS 2001), Prog. Oceanogr., 64(2–4), 263–282, doi: 10.1016/j.pocean.2005.02.013, 2005.

Bacon, M. P., Cochran, J. K., Hirschberg, D., Hammar, T. R. and Fleer, A. P.: Export flux of carbon at the equator during the EqPac time-series cruises estimated from $^{234}$Th measurements, Deep Sea Res. Part II Top. Stud. Oceanogr., 43(4–6), 1133–1153, doi:10.1016/0967-0645(96)00016-1, 1996.

Baskaran, M., Swarzenski, P. W. and Porcelli, D.: Role of colloidal material in the removal of $^{234}$Th in the Canada basin of the Arctic Ocean, Deep Sea Res. Part I Oceanogr. Res. Pap., 50(10–11), 1353–1373, doi:10.1016/S0967-0637(03)00140-7, 2003.

Baumann, M. S., Moran, S. B., Lomas, M. W., Kelly, R. P. and Bell, D. W.: Seasonal decoupling of particulate organic carbon export and net primary production in relation to sea-ice at the shelf break of the eastern Bering Sea: Implications for off-shelf carbon export, J. Geophys. Res. Ocean., 118, 1–19, doi:10.1002/jgrc.20366, 2013.

Benitez-Nelson, C., Buesseler, K. O., Karl, D. M. and Andrews, J.: A time-series study of particulate matter export in the North Pacific Subtropical Gyre based on $^{234}$Th:$^{238}$U disequilibrium, Deep Sea Res. Part I Oceanogr. Res. Pap., 48(12), 2595–2611, doi:10.1016/S0967-0637(01)00032-2, 2001.

Benitez-Nelson, C. R., Buesseler, K. O. and Crossin, G.: Upper ocean carbon export, horizontal transport, and vertical eddy diffusivity in the southwestern Gulf of Maine, Cont. Shelf Res., 20(6), 707–736, doi:10.1016/S0278-4343(99)00093-X, 2000.

Bishop, J. K. B., Edmond, J. M., Ketten, D. R., Bacon, M. P. and Silker, W. B.: The chemistry, biology, and vertical flux of particulate matter from the upper 400 m of the equatorial Atlantic Ocean, Deep Sea Res., 24(6), 511–548, doi:10.1016/0146-6291(77)90526-4, 1977.

Bishop, J. K. B., Lam, P. J. and Wood, T. J.: Getting good particles: Accurate sampling of particles by large volume in-situ filtration, Limnol. Oceanogr. Methods, 10, 681–710, doi:/10.4319/lom.2012.10.681, 2012.

Black, E. E., Buesseler, K. O., Pike, S. M. and Lam, P. J.: $^{234}$Th as a tracer of particulate export and remineralization in the southeastern tropical Pacific, Mar. Chem., 201, 35–50, doi:10.1016/J.MARCHEM.2017.06.009, 2018.

Brew, H. S., Moran, S. B., Lomas, M. W. and Burd, A. B.: Plankton community composition, organic carbon and thorium-234 particle size distributions, and particle export in the Sargasso Sea, J. Mar. Res., 67(6), 845–868, doi:10.1357/002224009792006124, 2009.

Buesseler, K., Bacon, M., Cochran, J. and Livingston, H.: Carbon and nitrogen export during the JGOFS North Atlantic Bloom Experiment estimated from $^{234}$Th:$^{238}$U disequilibria, Deep Sea Res. Part A.Oceanographic Res. Pap., 39(7–8), 1115–1137, doi:10.1016/0198-0149(92)90060-7, 1992.

Buesseler, K., Ball, L., Andrews, J., Benitez-Nelson, C., Belastock, R., Chai, F. and Chao, Y.: Upper ocean export of particulate organic carbon in the Arabian Sea derived from thorium-234, Deep. Res. Part II, 45(10–11), 2461–2487, doi:10.1016/S0967-0645(98)80022-2, 1998.

Buesseler, K. O. and Boyd, P. .: Shedding light on processes that control particle export and flux attenuation in the twilight zone of the open ocean, Limnol. Oceanogr., 54(4), 1210–1232, doi:10.4319/lo.2009.54.4.1210, 2009.

Buesseler, K. O., Michaels, A. F., Siegel, D. A. and Knap, A. H.: A three dimensional time-dependent approach to calibrating sediment trap fluxes, Global Biogeochem. Cycles, 8(2), 179–193, doi:10.1029/94GB00207, 1994.

Buesseler, K. O., Andrews, J. A., Hartman, M. C., Belastock, R. and Chai, F.: Regional estimates of the export flux of particulate organic carbon derived from thorium-234 during the JGOFS EqPac program, Deep Sea Res. Part II Top. Stud. Oceanogr., 42(2–3), 777–791, doi:10.1016/0967-0645(95)00043-P, 1995.

Buesseler, K. O., Steinberg, D. K., Michaels, A. F., Johnson, R. J., Andrews, J. E., Valdes, J. R. and Price, J. F.: A comparison of the quantity and composition of material caught in a neutrally buoyant versus surface-tethered sediment trap, Deep Sea Res. Part I Oceanogr. Res. Pap., 47(2), 277–294, doi:10.1016/S0967-0637(99)00056-4, 2000.

Buesseler, K. O., Ball, L., Andrews, J., Cochran, J. K., Hirschberg, D. J., Bacon, M. P., Fleer, A. and Brzezinski, M.: Upper ocean export of particulate organic carbon and biogenic silica in the Southern Ocean along 170°W, Deep Sea Res. Part II Top. Stud. Oceanogr., 48(19–20), 4275–4297, doi:10.1016/S0967-0645(01)00089-3, 2001.

Buesseler, K. O., Andrews, J. E., Pike, S. M., Charette, M. A., Goldson, L. E., Brzezinski, M. A. and Lance, V. P.: Particle export during the Southern Ocean Iron Experiment (SOFeX), Limnol. Oceanogr., 50, 311–327, 2005.

Buesseler, K. O., Benitez-Nelson, C. R., Moran, S. B., Burd, A., Charette, M., Cochran, J. K., Coppola, L., Fisher, N. S., Fowler, S. W. and Gardner, W. D.: An assessment of particulate organic carbon to thorium-234 ratios in

the ocean and their impact on the application of [234]Th as a POC flux proxy, Mar. Chem., 100(3–4), 213–233, doi:10.1016/j.marchem.2005.10.013, 2006.

Buesseler, K. O., Antia, A. N., Chen, M., Fowler, S. W., Gardner, W. D., Gustafsson, O., Harada, K., Michaels, A. F., Rutgers van der Loeff, M. and Sarin, M.: An assessment of the use of sediment traps for estimating upper ocean particle fuxes, J. Mar. Res., 65, 345–416, 2007.

Buesseler, K. O., Lamborg, C., Cai, P., Escoube, R., Johnson, R., Pike, S., Masque, P., McGillicuddy, D. and Verdeny, E.: Particle fluxes associated with mesoscale eddies in the Sargasso Sea, Deep Sea Res. Part II Top. Stud. Oceanogr., 55(10–13), 1426–1444, doi:10.1016/j.dsr2.2008.02.007, 2008a.

Buesseler, K. O., Trull, T. W., Steinberg, D. K., Silver, M. W., Siegel, D. A., Saitoh, S.-I., Lamborg, C. H., Lam, P. J., Karl, D. M., Jiao, N. Z., Honda, M. C., Elskens, M., Dehairs, F., Brown, S. L., Boyd, P. W., Bishop, J. K. B. and Bidigare, R. R.: VERTIGO (VERtical Transport In the Global Ocean): A study of particle sources and flux attenuation in the North Pacific, Deep Sea Res. Part II Top. Stud. Oceanogr., 55(14–15), 1522–1539, doi: 10.1016/j.dsr2.2008.04.024, 2008b.

Buesseler, K. O., Pike, S., Maiti, K., Lamborg, C. H., Siegel, D. A. and Trull, T. W.: Thorium-234 as a tracer of spatial, temporal and vertical variability in particle flux in the North Pacific, Deep Sea Res. Part I Oceanogr. Res. Pap., 56(7), 1143–1167, doi: 10.1016/j.dsr.2009.04.001, 2009.

Buesseler, K. O., McDonnell, A. M. P., Schofield, O. M. E., Steinberg, D. K. and Ducklow, H. W.: High particle export over the continental shelf of the west Antarctic Peninsula, Geophys. Res. Lett., 37(22), doi:10.1029/2010GL045448, 2010.

Buitenhuis, E., Vogt, M., Moriarty, R., Bednarsek, N., Doney, S. C., Leblanc, K., Le Quéré, C., Luo, Y.-W., O'Brien, C., O'Brien, T., Peloquin, J., Schiebel, R. and Swan, C.: MAREDAT: towards a world atlas of MARine Ecosystem DATa, Earth Syst. Sci. Data, 5, 227–239, doi:10.1594/PANGAEA.779970, 2013.

Burd, A. B., Hansell, D. a., Steinberg, D. K., Anderson, T. R., Arístegui, J., Baltar, F., Beaupré, S. R., Buesseler, K. O., DeHairs, F., Jackson, G. a., Kadko, D. C., Koppelmann, R., Lampitt, R. S., Nagata, T., Reinthaler, T., Robinson, C., Robison, B. H., Tamburini, C. and Tanaka, T.: Assessing the apparent imbalance between geochemical and biochemical indicators of meso- and bathypelagic biological activity: What the @$#! is wrong with present calculations of carbon budgets?, Deep Sea Res. Part II Top. Stud. Oceanogr., 57(16), 1557–1571, doi:10.1016/j.dsr2.2010.02.022, 2010.

Cai, P., Huang, Y., Chen, M., Liu, G. and Qiu, Y.: Export of particulate organic carbon estimated from [234]Th-[238]U disequilibria and its temporal variation in the South China Sea, Chinese Sci. Bull., 46(20), 1722–1726, doi:10.1007/BF02900660, 2001.

Cai, P., Dai, M., Chen, W., Tang, T. and Zhou, K.: On the importance of the decay of 234Th in determining size-fractionated C/[234]Th ratio on marine particles, Geophys. Res. Lett., 33(23), L23602, doi:10.1029/2006GL027792, 2006.

Cai, P., Chen, W., Dai, M., Wan, Z., Wang, D., Li, Q., Tang, T. and Lv, D.: A high-resolution study of particle export in the southern South China Sea based on [234]Th:[238]U disequilibrium, J. Geophys. Res. Ocean., 113(C4), doi:10.1029/2007JC004268, 2008.

Cai, P., Rutgers van der Loeff, M., Stimac, I., Nöthig, E. M., Lepore, K. and Moran, S. B.: Low export flux of particulate organic carbon in the central Arctic Ocean as revealed by [234]Th:[238]U disequilibrium, J. Geophys. Res., 115(C10), C10037, doi:10.1029/2009JC005595, 2010.

Cai, P., Zhao, D., Wang, L., Huang, B. and Dai, M.: Role of particle stock and phytoplankton community structure in regulating particulate organic carbon export in a large marginal sea, J. Geophys. Res. Ocean., 120(3), 2063–2095, doi:10.1002/2014JC010432, 2015.

Cavan, E. L., Le Moigne, F. A. C., Poulton, A. J., Tarling, G. A., Ward, P., Daniels, C. J., Fragoso, G. and Sanders, R. J.: Attenuation of particulate organic carbon flux in the Scotia Sea, Southern Ocean, is controlled by zooplankton fecal pellets, Geophys. Res. Lett., 42, 821–830, doi:10.1002/2014GL062744, 2015.

Ceballos-Romero, E., Le Moigne, F. A. C., Henson, S., Marsay, C. M., Sanders, R. J., García-Tenorio, R. and Villa-Alfageme, M.: Influence of bloom dynamics on Particle Export Efficiency in the North Atlantic: a comparative study of radioanalytical techniques and sediment traps, Mar. Chem., 186, 198–210, doi: 10.1016/j.marchem.2016.10.001, 2016.

Charette, M. A. and Moran, S. B.: Rates of particle scavenging and particulate organic carbon export estimated using [234]Th as a tracer in the subtropical and equatorial Atlantic Ocean, Deep. Res. Part II, 46(5), 885–906, doi:10.1016/S0967-0645(99)00006-5, 1999.

Charette, M. A., Moran, S. B. and Bishop, J. K. B.: [234]Th as a tracer of particulate organic carbon export in the subarctic northeast Pacific Ocean, Deep. Res. Part II, 46, 2833–2861, doi: 10.1016/S0967-0645(99)00085-5, 1999.

Charette, M. A., Moran, S. B., Pike, S. M. and Smith, J. N.: Investigating the carbon cycle in the Gulf of Maine using the natural tracer thorium-234, J. Geophys. Res. Ocean., 106(C6), 11553–11579, doi: 10.1029/1999JC000277, 2001.

Chen, J. H., Lawrence Edwards, R. and Wasserburg, G. J.: $^{238}$U, $^{234}$U and $^{232}$Th in seawater, Earth Planet. Sci. Lett., 80, 241–251, doi: 10.1016/0012-821X(86)90108-1, 1986.

Chen, M., Huang, Y., Cai, P. and Guo, L.: Particulate organic carbon export fluxes in the Canada Basin and Bering Sea as derived from $^{234}$Th/$^{238}$U disequilibria, Arctic, 56(1), 32, 2003.

Chen, W., Cai, P., Dai, M. and Wei, J.: $^{234}$Th/$^{238}$U disequilibrium and particulate organic carbon export in the northern South China Sea, J. Oceanogr., 64(3), 417–428, doi:10.1007/s10872-008-0035-z, 2008.

Coale, K. H.: Labyrinth of doom: A device to minimize the" swimmer" component in sediment trap collections, Limnol. Oceanogr., 35, 1376–1381, doi:10.4319/lo.1990.35.6.1376, 1990.

Cochran, J. K. and Masqué, P.: Short-lived U/Th series radionuclides in the ocean: tracers for scavenging rates, export fluxes and particle dynamics, Rev. Mineral. Geochemistry, 52(1), 461–492, doi:10.2113/0520461, 2003.

Cochran, J. K., Barnes, C., Achman, D. and Hirschberg, D. J.: Thorium-234/uranium-238 disequilibrium as an indicator of scavenging rates and participate organic carbon fluxes in the Northeast Water Polynya, Greenland, J. Geophys. Res. Ocean., 100(C3), 4399–4410, doi: 10.1029/94JC01954, 1995.

Cochran, J. K., Buesseler, K. O., Bacon, M. P., Wang, H. W., Hirschberg, D. J., Ball, L., Andrews, J., Crossin, G. and Fleer, A.: Short-lived thorium isotopes ($^{234}$Th, $^{228}$Th) as indicators of POC export and particle cycling in the Ross Sea, Southern Ocean, Deep Sea Res. Part II Top. Stud. Oceanogr., 47(15–16), 3451–3490, doi:10.1016/S0967-0645(00)00075-8, 2000.

Coppola, L., Roy-Barman, M., Wassmann, P., Mulsow, S. and Jeandel, C.: Calibration of sediment traps and particulate organic carbon export using $^{234}$Th in the Barents Sea, Mar. Chem., 80(1), 11–26, doi: 10.1016/S0304-4203(02)00071-3, 2002.

Coppola, L., Roy-Barman, M., Mulsow, S., Povinec, P. and Jeandel, C.: Low particulate organic carbon export in the frontal zone of the Southern Ocean (Indian sector) revealed by $^{234}$Th, Deep Sea Res. Part I Oceanogr. Res. Pap., 52(1), 51–68, doi: 10.1016/j.dsr.2004.07.020, 2005.

Dai, M. H. and Benitez-Nelson, C. R.: Colloidal organic carbon and $^{234}$Th in the Gulf of Maine, Mar. Chem., 74(2–3), 181–196, doi:http://dx.doi.org/10.1016/S0304-4203(01)00012-3, 2001.

Dunne, J. P., Sarmiento, J. L. and Gnanadesikan, A.: A synthesis of global particle export from the surface ocean and cycling through the ocean interior and on the seafloor, Glob. Biogeochem.Cycles, 21(4), doi:10.1029/2006GB002907, 2007.

Durkin, C. A., Estapa, M. L. and Buesseler, K. O.: Observations of carbon export by small sinking particles in the upper mesopelagic, Mar. Chem., 175, 72–81, doi:10.1016/j.marchem.2015.02.011, 2015.

Engel, A., Wagner, H., Le Moigne, F. A. C. and Wilson, S. T.: Particle export fluxes to the oxygen minimum zone of the eastern tropical North Atlantic, Biogeosciences, 14(7), 1825–1838, doi:10.5194/bg-14-1825-2017, 2017.

Eppley, R. W. and Peterson, B. J.: Particulate organic matter flux and planktonic new production in the deep ocean, Nature, 282, 677–680, doi: 10.1038/282677a0, 1979.

Evangeliou, N., Florou, H. and Psomiadou, C.: Size-fractionated particulate organic carbon (POC) export fluxes estimated using $^{234}$Th-$^{238}$U disequilibria in the Saronikos Gulf (Greece) during winter bloom, Fresenius Environ. Bull., 22(7a), 1951–1961, 2013.

Foster, J. M. and Shimmield, G. B.: $^{234}$Th as a tracer of particle flux and POC export in the northern North Sea during a coccolithophore bloom, Deep Sea Res. Part II Top. Stud. Oceanogr., 49(15), 2965–2977, doi: 10.1016/S0967-0645(02)00066-8, 2002.

Fowler, S. W. and Knauer, G. A.: Role of large particles in the transport of elements and organic compounds through the oceanic water column, Prog. Oceanogr., 16(3), 147–194, doi:0.1016/0079-6611(86)90032-7, 1986.

Friedrich, J. and Rutgers van der Loeff, M.: A two-tracer ($^{210}$Po-$^{234}$Th) approach to distinguish organic carbon and biogenic silica export flux in the Antarctic Circumpolar Current, Deep Sea Res. Part I Oceanogr. Res. Pap., 49(1), 101–120, doi:10.1016/S0967-0637(01)00045-0, 2002.

Gardner, W. D., Richardson, M. J., Carlson, C. A., Hansell, D. and Mishonov, A. V: Determining true particulate organic carbon: bottles, pumps and methodologies, Deep Sea Res. Part II Top. Stud. Oceanogr., 50(3), 655–674, doi:10.1016/S0967-0645(02)00589-1, 2003.

Giuliani, S., Radakovitch, O., Frignani, M. and Bellucci, L. G.: Short time scale variations of $^{234}$Th/$^{238}$U disequilibrium related to mesoscale variability on the continental slope of the Gulf of Lions (France), Mar. Chem., 106(3), 403–418, doi:10.1016/j.marchem.2007.03.007, 2007.

Le Gland, G., Aumont, O. and Mémery, L.: An Estimate of Thorium-234 Partition Coefficients Through Global

Inverse Modeling, J. Geophys. Res. Ocean., 124(6), 3575–3606, doi:10.1029/2018JC014668, 2019.

Guidi, L., Jackson, G. A., Stemmann, L., Miquel, J. C., Picheral, M. and Gorsky, G.: Relationship between particle size distribution and flux in the mesopelagic zone, Deep Sea Res. Part I Oceanogr. Res. Pap., 55(10), 1364–1374, doi:10.1016/j.dsr.2008.05.014, 2008.

Guidi, L., Legendre, L., Reygondeau, G., Uitz, J., Stemmann, L. and Henson, S. A.: A new look at ocean carbon remineralization for estimating deepwater sequestration, Global Biogeochem. Cycles, 29(7), 1044–1059, doi:10.1002/2014GB005063, 2015.

Guo, L., Hung, C. C., Santschi, P. H. and Walsh, I. D.: $^{234}$Th scavenging and its relationship to acid polysaccharide abundance in the Gulf of Mexico, Mar. Chem., 78(2), 103–119, doi:10.1016/S0304-4203(02)00012-9, 2002.

Gustafsson, Ö. and Andersson, P. S.: $^{234}$Th-derived surface export fluxes of POC from the Northern Barents Sea and the Eurasian sector of the Central Arctic Ocean, Deep Sea Res. Part I Oceanogr. Res. Pap., doi: 10.1016/j.dsr.2012.05.014, 2012.

Gustafsson, Ö., Gschwend, P. M. and Buesseler, K. O.: Using $^{234}$Th disequilibria to estimate the vertical removal rates of polycyclic aromatic hydrocarbons from the surface ocean, Mar. Chem., 57(1–2), 11–23, doi:10.1016/S0304-4203(97)00011-X, 1997.

Gustafsson, Ö., Andersson, P., Roos, P., Kukulska, Z., Broman, D., Larsson, U., Hajdu, S. and Ingri, J.: Evaluation of the collection efficiency of upper ocean sub-photic-layer sediment traps: a 24-month in situ calibration in the open Baltic Sea using $^{234}$Th, Limnol.Oceanogr.Methods, 2, 62–74, doi: 10.4319/lom.2004.2.62, 2004.

Gustafsson, Ö., Larsson, J., Andersson, P. and Ingri, J.: The POC/$^{234}$Th ratio of settling particles isolated using split flow-thin cell fractionation (SPLITT), Mar. Chem., 100(3), 314–322, doi:10.1016/j.marchem.2005.10.018, 2006.

Hall, I. R., Schmidt, S., McCave, I. N. and Reyss, J. L.: Particulate matter distribution and disequilibrium along the Northern Iberian Margin: implications for particulate organic carbon export, Deep Sea Res. Part I Oceanogr. Res. Pap., 47(4), 557–582, doi:10.1016/S0967-0637(99)00065-5, 2000.

Haskell II, W. Z., Berelson, W. M., Hammond, D. E. and Capone, D. G.: Particle sinking dynamics and POC fluxes in the Eastern Tropical South Pacific based on $^{234}$Th budgets and sediment trap deployments, Deep Sea Res. Part I Oceanogr. Res. Pap., doi: 10.1016/j.dsr.2013.07.001, 2013.

Henson, S. A., Sanders, R., Madsen, E., Morris, P. J., Le Moigne, F. and Quartly, G. D.: A reduced estimate of the strength of the ocean's biological carbon pump, Geophys. Res. Lett., 38(4), L04606, doi:10.1029/2011GL046735, 2011.

Hung, C.-C. and Gong, G.-C.: Export flux of POC in the main stream of the Kuroshio, Geophys. Res. Lett., 34(18), L18606, doi:10.1029/2007GL030236, 2007.

Hung, C. C. and Gong, G. C.: POC/$^{234}$Th ratios in particles collected in sediment traps in the northern South China Sea, Estuar. Coast. Shelf Sci., 88(3), 303–310, doi:10.1016/j.ecss.2010.04.008, 2010.

Hung, C. C., Guo, L., Roberts, K. A. and Santschi, P. H.: Upper ocean carbon flux determined by the 234Th approach and sediment traps using size-fractionated POC and $^{234}$Th data from the Gulf of Mexico, Geochem. J., 38(6), 601–611, doi:10.2343/geochemj.38.601, 2004.

Hung, C. C., Xu, C., Santschi, P. H., Zhang, S. J., Schwehr, K. A., Quigg, A., Guo, L., Gong, G. C., Pinckney, J. L. and Long, R. A.: Comparative evaluation of sediment trap and $^{234}$Th-derived POC fluxes from the upper oligotrophic waters of the Gulf of Mexico and the subtropical northwestern Pacific Ocean, Mar. Chem., 121(1), 132–144, doi:10.1016/j.marchem.2010.03.011, 2010.

Hung, C. C., Gong, G. C. and Santschi, P. H.: $^{234}$Th in different size classes of sediment trap collected particles from the Northwestern Pacific Ocean, Geochim. Cosmochim. Acta, 91, 60–74, doi:10.1016/j.gca.2012.05.017, 2012.

Jacquet, S. H. M., Lam, P. J., Trull, T. W. and Dehairs, F.: Carbon export production in the subantarctic zone and polar front zone south of Tasmania, Deep Sea Res. Part II Top. Stud. Oceanogr., 58(21–22), 2277–2292, doi:/10.1016/j.dsr2.2011.05.035, 2011.

Kawakami, H.: Scanvenging of $^{210}$Po and $^{234}$Th by particulate organic carbon in the surfaca layer of the northwestern North Pacific Ocean, Far East Journal of Ocean Research, 2(2), 67-82, 2009.

Kawakami, H. and Honda, M. C.: Time-series observation of POC fluxes estimated from $^{234}$Th in the northwestern North Pacific, Deep Sea Res. Part I Oceanogr. Res. Pap., 54(7), 1070–1090, doi: 10.1016/j.dsr.2007.04.005, 2007.

Kawakami, H., Yang, Y.-L., Honda, M. C. and Kusakabe, M.: Particulate organic carbon fluxes estimated from $^{234}$Th deficiency in winters and springs in the northwestern North Pacific, Geochem. J., 38(6), 581–592, doi:10.2343/geochemj.38.581, 2004.

Kawakami, H., Honda, M. C., Matsumoto, K., Fujiki, T. and Watanabe, S.: East-west distribution of POC fluxes estimated from $^{234}$Th in the northern North Pacific in autumn, J. Oceanogr., 66(1), 71–83, doi:10.1007/s10872-010-0006-z, 2010.

Kawakami, H., Honda, M. C., Matsumoto, K., Wakita, M., Kitamura, M., Fujiki, T. and Watanabe, S.: POC fluxes estimated from $^{234}$Th in late spring–early summer in the western subarctic North Pacific, J. Oceanogr., 71(3), 311–324, doi:10.1007/s10872-015-0290-8, 2015.

Kim, D., Choi, M.-S., Oh, H.-Y., Song, Y.-H., Noh, J.-H. and Kim, K. H.: Seasonal export fluxes of particulate organic carbon from $^{234}$Th/$^{238}$U disequilibrium measurements in the Ulleung Basin1 (Tsushima Basin) of the East Sea1 (Sea of Japan), J. Oceanogr., 67(5), 577, doi:10.1007/s10872-011-0058-8, 2011.

Kim, G. and Church, T. M.: Seasonal biogeochemical fluxes of $^{234}$Th and $^{210}$Po in the upper Sargasso Sea: Influence from atmospheric iron deposition, Glob. Biogeochem.Cycles, 15(3), 651–661, doi: 10.1029/2000GB001313, 2001.

Ku, T.-L., Knauss, K. G. and Mathieu, G. G.: Uranium in open ocean: concentration and isotopic composition, Deep Sea Res., 24(11), 1005–1017, doi: 10.1016/0146-6291(77)90571-9, 1977.

Kwon, E. Y., Primeau, F. and Sarmiento, J. L.: The impact of remineralization depth on the air–sea carbon balance, Nat. Geosci., 2, 630, doi:10.1038/ngeo612, 2009.

Lalande, C., Lepore, K., Cooper, L. W., Grebmeier, J. M. and Moran, S. B.: Export fluxes of particulate organic carbon in the Chukchi Sea: A comparative study using $^{234}$Th/$^{238}$U disequilibria and drifting sediment traps, Mar. Chem., 103(1), 185–196, doi: 10.1016/j.marchem.2006.07.004, 2007.

Lalande, C., Moran, S. B., Wassmann, P., Grebmeier, J. M. and Cooper, L. W.: $^{234}$Th-derived particulate organic carbon fluxes in the northern Barents Sea with comparison to drifting sediment trap fluxes, J. Mar. Syst., 73(1), 103–113, doi:10.1016/j.jmarsys.2007.09.004, 2008.

Lamborg, C. H., Buesseler, K. O., Valdes, J., Bertrand, C. H., Bidigare, R., Manganini, S., Pike, S., Steinberg, D., Trull, T. and Wilson, S.: The flux of bio- and lithogenic material associated with sinking particles in the mesopelagic "twilight zone" of the northwest and North Central Pacific Ocean, Deep Sea Res. Part II Top. Stud. Oceanogr., 55(14–15), 1540–1563, doi: 10.1016/j.dsr2.2008.04.011, 2008.

Lampitt, R. S., Boorman, B., Brown, L., Lucas, M., Salter, I., Sanders, R., Saw, K., Seeyave, S., Thomalla, S. J. and Turnewitsch, R.: Particle export from the euphotic zone: Estimates using a novel drifting sediment trap, $^{234}$Th and new production, Deep Sea Res. Part I Oceanogr. Res. Pap., 55(11), 1484–1502, doi:10.1016/j.dsr.2008.07.002, 2008.

Laws, E. A., D'Sa, E. and Naik, P.: Simple equations to estimate ratios of new or export production to total production from satellite-derived estimates of sea surface temperature and primary production, Limnol. Oceanogr. Methods, 9(12), 593–601, doi:10.4319/lom.2011.9.593, 2011.

Lemaitre, N., Planchon, F., Planquette, H., Dehairs, F., Fonseca-Batista, D., Roukaerts, A., Deman, F., Tang, Y., Mariez, C. and Sarthou, G.: High variability of particulate organic carbon export along the North Atlantic GEOTRACES section GA01 as deduced from $^{234}$Th fluxes, Biogeosciences, 15(21), 6417–6437, doi:10.5194/bg-15-6417-2018, 2018.

Lepore, K., Moran, S. B., Grebmeier, J. M., Cooper, L. W., Lalande, C., Maslowski, W., Hill, V., Bates, N. R., Hansell, D. A., Mathis, J. T. and Kelly, R. P.: Seasonal and interannual changes in particulate organic carbon export and deposition in the Chukchi Sea, J. Geophys. Res. Ocean., 112(C10), doi:10.1029/2006JC003555, 2007.

Lepore, K., Moran, S. B., Burd, A. B., Jackson, G. A., Smith, J. N., Kelly, R. P., Kaberi, H., Stavrakakis, S. and Assimakopoulou, G.: Sediment trap and in-situ pump size-fractionated POC/$^{234}$Th ratios in the Mediterranean Sea and Northwest Atlantic: Implications for POC export, Deep Sea Res. Part I Oceanogr. Res. Pap., 56(4), 599–613, doi:10.1016/j.dsr.2008.11.004, 2009.

Luo, Y., Miller, L. A., Baere, B. De, Soon, M. and Francois, R.: POC fluxes measured by sediment traps and $^{234}$Th:$^{238}$U disequilibrium in Saanich Inlet, British Columbia, Mar. Chem., 162, 19–29, doi:10.1016/j.marchem.2014.03.001, 2014.

Ma, Q., Chen, M., Qiu, Y. and Li, Y.: Regional estimates of POC export flux derived from thorium-234 in the western Arctic Ocean, Acta Oceanol. Sin., 24(6), 97–108, 2005.

Mahowald, N. M., Engelstaedter, S., Luo, C., Sealy, A., Artaxo, P., Benitez-Nelson, C., Bonnet, S., Chen, Y., Chuang, P. Y., Cohen, D. D., Dulac, F., Herut, B., Johansen, A. M., Kubilay, N., Losno, R., Maenhaut, W., Paytan, A., Prospero, J. M., Shank, L. M. and Siefert, R. L.: Atmospheric Iron Deposition: Global Distribution, Variability, and Human Perturbations, Ann. Rev. Mar. Sci., 1(1), 245–278, doi:10.1146/annurev.marine.010908.163727, 2009.

Maiti, K., Benitez-Nelson, C. R., Rii, Y. and Bidigare, R.: The influence of a mature cyclonic eddy on particle

export in the lee of Hawaii, Deep Sea Res. Part II Top. Stud. Oceanogr., 55(10), 1445–1460, 2008.

Maiti, K., Benitez-Nelson, C. R., Lomas, M. W. and Krause, J. W.: Biogeochemical responses to late-winter storms in the Sargasso Sea, III--Estimates of export production using $^{234}$Th: $^{238}$U disequilibria and sediment traps, Deep Sea Res. Part I Oceanogr. Res. Pap., 56(6), 875–891, doi: 10.1016/j.dsr.2009.01.008, 2009.

Maiti, K., Benitez-Nelson, C. R. and Buesseler, K. O.: Insights into particle formation and remineralization using the short-lived radionuclide, Thoruim-234, Geophys. Res. Lett., 37(15), L15608, doi:10.1029/2010GL044063, 2010.

Maiti, K., Bosu, S., D'Sa, E. J., Adhikari, P. L., Sutor, M. and Longnecker, K.: Export fluxes in northern Gulf of Mexico - Comparative evaluation of direct, indirect and satellite-based estimates, Mar. Chem., 184, 60–77, doi:10.1016/j.marchem.2016.06.001, 2016.

Martin, J. H., Knauer, G. A., Karl, D. M. and Broenkow, W. W.: VERTEX: carbon cycling in the northeast Pacific, Deep Sea Res. Part A. Oceanogr. Res. Pap., 34(2), 267–285, doi: 10.1016/0198-0149(87)90086-0, 1987.

Martin, P., Lampitt, R. S., Jane Perry, M., Sanders, R., Lee, C. and D'Asaro, E.: Export and mesopelagic particle flux during a North Atlantic spring diatom bloom, Deep Sea Res. Part I Oceanogr. Res. Pap., 58, 338–349, doi:10.1016/j.dsr.2011.01.006, 2011.

Martin, P., van der Loeff, M. R., Cassar, N., Vandromme, P., d'Ovidio, F., Stemmann, L., Rengarajan, R., Soares, M., González, H. E., Ebersbach, F., Lampitt, R. S., Sanders, R., Barnett, B. A., Smetacek, V. and Naqvi, S. W. A.: Iron fertilization enhanced net community production but not downward particle flux during the Southern Ocean iron fertilization experiment LOHAFEX, Global Biogeochem. Cycles, 27(3), 871–881, doi:10.1002/gbc.20077, 2013.

Mawji, E., Schlitzer, R., Masferrer, E., Abadie, C., Abouchami, W., Anderson, R. F., Baars, O., Bakker, K., Baskaran, M., Bates, N. R., Bluhm, K., Bowie, A., Bown, J., Boye, M., Boyle, E. A., Branekkec, P., Bruland, K. W., Brzezinski, M. A., Bucciarelli, E., Buesseler, K., Butler, E., Cai, P., Cardinal, D., Casciotti, K., Chaves, J., Cheng, H., Chever, F., Church, T. M., Colman, A. S., Conway, T. M., Croot, P. L., Cutter, G. A., de Baar, H. J. W., de Souza, G. F., Dehairs, F., Deng, F., Thi Dieu, H., Dulaquais, G., Echegoyen-Sanz, Y., Edwards, R. L., Fahrbach, E., Fitzsimmons, J., Fleisher, M., Frank, M., Friedrich, J., Fripiat, F., Galer, S. J. G., Gamo, T., Garcia-Solsona, E., Gerringa, L. J. A., Godoy, J. M., Gonzalez, S., Grossteffan, E., Hatta, M., Hayes, C. T., Heller, M. I., Henderson, G., Huang, K.-F., Jeandel, C., Jenkins, W. J., John, S., Kenna, T. C., Klunder, M., Kretschmer, S., Kumamoto, Y., Laan, P., Labatut, M., Lacan, F., Lam, P. J., Lannuzel, D., Le Moigne, F., Lechtenfeld, O., Lohan, M. C., Lu, Y., Masqué, P., McClain, C. R., Measures, C., Middag, R., Moffett, J., Navidad, A., Nishioka, J., Noble, A., Obata, H., Ohnemus, D. C., Owens, S., Planchon, F., Pradoux, C., Puigcorbé, V., Quay, P., Radic, A., Rehkämper, M., Remenyi, T., Rijkenberg, M. J. A., Rintoul, S., Robinson, L. F., Roeske, T., Rosenberg, M., Rutgers van der Loeff, M., Ryabenko, E., et al.: The GEOTRACES Intermediate Data Product 2014, Mar. Chem., (177), 1–8, doi:10.1016/j.marchem.2015.04.005, 2015.

Le Moigne, F. A. C., Sanders, R. J., Villa-Alfageme, M., Martin, A. P., Pabortsava, K., Planquette, H., Morris, P. J. and Thomalla, S. J.: On the proportion of ballast versus non-ballast associated carbon export in the surface ocean, Geophys. Res. Lett., 39(15), L15610, doi:10.1029/2012GL052980, 2012.

Le Moigne, F. A. C., Boye, M., Masson, A., Corvaisier, R., Grossteffan, E., Guéneugues, A. and Pondaven, P.: Description of the biogeochemical features of the subtropical southeastern Atlantic and the Southern Ocean south of South Africa during the austral summer of the International Polar Year, Biogeosciences, 10(1), 281–295, doi:10.5194/bg-10-281-2013, 2013a.

Le Moigne, F. A. C., Villa-Alfageme, M., Sanders, R. J., Marsay, C., Henson, S. and García-Tenorio, R.: Export of organic carbon and biominerals derived from $^{234}$Th and $^{210}$Po at the Porcupine Abyssal Plain, Deep Sea Res. Part I Oceanogr. Res. Pap., 72, 88–101, doi:10.1016/j.dsr.2012.10.010, 2013b.

Le Moigne, F. A. C., Henson, S. A., Sanders, R. J. and Madsen, E.: Global database of surface ocean particulate organic carbon export fluxes diagnosed from the $^{234}$Th technique, Earth Syst. Sci. Data, 5(2), 295–304, doi:10.5194/essd-5-295-2013, 2013c.

Le Moigne, F. A. C., Poulton, A. J., Henson, S. A., Daniels, C. J., Fragoso, G. M., Mitchell, E., Richier, S., Russell, B. C., Smith, H. E. K., Tarling, G. A. and Zubkov, M.: Carbon export efficiency and phytoplankton community composition in the Atlantic sector of the Arctic Ocean, J. Geophys. Res. Ocean., doi:10.1002/2015JC010700, 2015.

Le Moigne, F. A. C., Henson, S. A., Cavan, E., Georges, C., Pabortsava, K., Achterberg, E. P., Ceballos-Romero, E., Zubkov, M. and Sanders, R. J.: What causes the inverse relationship between primary production and export efficiency in the Southern Ocean?, Geophys. Res. Lett., 43(9), 4457–4466, doi:10.1002/2016GL068480, 2016.

Moran, S. B. and Buesseler, K. O.: Size-fractionated $^{234}$Th in continental shelf waters off New England: Implications for the role of colloids in oceanic trace metal scavenging, J. Mar. Res., 51(4), 893–922, doi:10.1357/0022240933223936, 1993.

Moran, S. B. and Smith, J. N.: $^{234}$Th as a tracer of scavenging and particle export in the Beaufort Sea, Cont. Shelf Res., 20(2), 153–167, doi:10.1016/S0278-4343(99)00065-5, 2000.

Moran, S. B., Ellis, K. M. and Smith, J. N.: $^{234}$Th/$^{238}$U disequilibrium in the central Arctic Ocean: implications for particulate organic carbon export, Deep Sea Res. Part II Top. Stud. Oceanogr., 44(8), 1593–1606, doi:10.1016/S0967-0645(97)00049-0, 1997.

Moran, S. B., Weinstein, S. E., Edmonds, H. N., Smith, J. N., Kelly, R. P., Pilson, M. E. Q. and Harrison, W. G.: Does $^{234}$Th/$^{238}$U disequilibrium provide an accurate record of the export flux of particulate organic carbon from the upper ocean?, Limnol. Oceanogr., 48(3), 1018–1029, doi:10.4319/lo.2003.48.3.1018, 2003.

Moran, S. B., Kelly, R. P., Hagstrom, K., Smith, J. N., Grebmeier, J. M., Cooper, L. W., Cota, G. F., Walsh, J. J., Bates, N. R. and Hansell, D. A.: Seasonal changes in POC export flux in the Chukchi Sea and implications for water column-benthic coupling in Arctic shelves, Deep Sea Res. Part II Top. Stud. Oceanogr., 52(24–26), 3427–3451, doi:10.1016/j.dsr2.2005.09.011, 2005.

Moran, S. B., Lomas, M. W., Kelly, R. P., Gradinger, R., Iken, K. and Mathis, J. T.: Seasonal succession of net primary productivity, particulate organic carbon export, and autotrophic community composition in the eastern Bering Sea, Deep Sea Res. Part II Top. Stud. Oceanogr., doi:10.1016/j.dsr2.2012.02.011, 2012.

Moriarty, R. and O'Brien, T. D.: Distribution of mesozooplankton biomass in the global ocean, Earth Syst. Sci. Data, 5(1), 45–55, doi:10.5194/essd-5-45-2013, 2013.

Moriarty, R., Buitenhuis, E. T., Le Quéré, C. and Gosselin, M.-P.: Distribution of known macrozooplankton abundance and biomass in the global ocean, Earth Syst. Sci. Data, 5(2), 241–257, doi:10.5194/essd-5-241-2013, 2013.

Morris, P. J., Sanders, R., Turnewitsch, R. and Thomalla, S.: 234Th-derived particulate organic carbon export from an island-induced phytoplankton bloom in the Southern Ocean, Deep Sea Res. Part II Top. Stud. Oceanogr., 54(18–20), 2208–2232, doi:10.1016/j.dsr2.2007.06.002, 2007.

Morris, S. A., Hansman, R. L. and Miquel, J.-C.: Tracing carbon's fate in the ocean, Eos (Washington. DC)., 98, doi:10.1029/2017EO076681, 2017.

Murray, J. W., Young, J., Newton, J., Dunne, J., Chapin, T., Paul, B. and McCarthy, J. J.: Export flux of particulate organic carbon from the central equatorial Pacific determined using a combined drifting trap-$^{234}$Th approach, Deep Sea Res. Part II Top. Stud. Oceanogr., 43(4–6), 1095–1132, doi:10.1016/0967-0645(96)00036-7, 1996.

Murray, J. W., Paul, B., Dunne, J. P. and Chapin, T.: $^{234}$Th, $^{210}$Pb, $^{210}$Po and stable Pb in the central equatorial Pacific: Tracers for particle cycling, Deep Sea Res. Part I Oceanogr. Res. Pap., 52(11), 2109–2139, doi:10.1016/j.dsr.2005.06.016, 2005.

Owens, S. A., Buesseler, K. O. and Sims, K. W. W.: Re-evaluating the 238U-salinity relationship in seawater: Implications for the $^{238}$U-$^{234}$Th disequilibrium method, Mar. Chem., 127, 31–39, doi:10.1016/j.marchem.2011.07.005, 2011.

Owens, S. A., Buesseler, K. O., Lamborg, C. H., Valdes, J., Lomas, M. W., Johnson, R. J., Steinberg, D. K. and D.A, S.: A new time series of particle export from neutrally buoyant sediments traps at the Bermuda Atlantic Time-series Study site, Deep Sea Res. Part I Oceanogr. Res. Pap., 72(0), 34–47, doi:10.1016/j.dsr.2012.10.011, 2013.

Owens, S. A., Pike, S. and Buesseler, K. O.: Thorium-234 as a tracer of particle dynamics and upper ocean export in the Atlantic Ocean, Deep Sea Res. Part II Top. Stud. Oceanogr., 116, 42–59, doi:10.1016/j.dsr2.2014.11.010, 2015.

Pabortsava, K.: Downward particle export and sequestration fluxes in the oligotrophic Atlantic Ocean, University of Southampton. [online] Available from: https://eprints.soton.ac.uk/id/eprint/372493, 2014.

Parekh, P., Dutkiewicz, S., Follows, M. J. and Ito, T.: Atmospheric carbon dioxide in a less dusty world, Geophys. Res. Lett., 33(3), L03610, doi:10.1029/2005GL025098, 2006.

Planchon, F., Cavagna, A.-J., Cardinal, D., André, L. and Dehairs, F.: Late summer particulate organic carbon export and twilight zone remineralisation in the Atlantic sector of the Southern Ocean, Biogeosciences, 10(2), 803–820, doi:10.5194/bg-10-803-2013, 2013.

Planchon, F., Ballas, D., Cavagna, A.-J., Bowie, A. R., Davies, D., Trull, T., Laurenceau-Cornec, E. C., Van Der Merwe, P. and Dehairs, F.: Carbon export in the naturally iron-fertilized Kerguelen area of the Southern Ocean based on the $^{234}$Th approach, Biogeosciences, 12(12), 3831–3848, doi:10.5194/bg-12-3831-2015, 2015.

Pondaven, P., Ragueneau, O., Tréguer, P., Hauvespre, A., Dezileau, L. and Reyss, J. L.: Resolving the 'opal paradox' in the Southern Ocean, Nature, 405(6783), 168–172, doi: 10.1038/35012046, 2000.

Puigcorbé, V., Benitez-Nelson, C. R., Masqué, P., Verdeny, E., White, A. E., Popp, B. N., Prahl, F. G. and Lam, P. J.: Small phytoplankton drive high summertime carbon and nutrient export in the Gulf of California and

Eastern Tropical North Pacific, Global Biogeochem. Cycles, 29(8), 1309–1332, doi:10.1002/2015GB005134, 2015.

Puigcorbé, V., Roca-Martí, M., Masqué, P., Benitez-Nelson, C., Rutgers van der Loeff, M., Bracher, A. and Moreau, S.: Latitudinal distributions of particulate carbon export across the North Western Atlantic Ocean, Deep. Res. Part I Oceanogr. Res. Pap., 129, 116–130, doi:10.1016/j.dsr.2017.08.016, 2017a.

Puigcorbé, V., Roca-Martí, M., Masqué, P., Benitez-Nelson, C. R., Rutgers v. d. Loeff, M., Laglera, L. M., Bracher, A., Cheah, W., Strass, V. H., Hoppema, M., Santos-Echeandía, J., Hunt, B. P. V., Pakhomov, E. A. and Klaas, C.: Particulate organic carbon export across the Antarctic Circumpolar Current at 10°E: Differences between north and south of the Antarctic Polar Front, Deep Sea Res. Part II Top. Stud. Oceanogr., 138, 86–101, doi:10.1016/j.dsr2.2016.05.016, 2017b.

Puigcorbé, V.: Global database of oceanic particulate organic carbon to particulate [234]Th ratios. PANGAEA, https://doi.pangaea.de/10.1594/PANGAEA.911424, 2019.

Radakovitch, O., Frignani, M., Giuliani, S. and Montanari, R.: Temporal variations of dissolved and particulate [234]Th at a coastal station of the northern Adriatic Sea, Estuar. Coast. Shelf Sci., 58(4), 813–824, doi:10.1016/S0272-7714(03)00187-2, 2003.

Richardson, T. L.: Mechanisms and Pathways of Small-Phytoplankton Export from the Surface Ocean, Ann. Rev. Mar. Sci., 11(1), 57–74, doi:10.1146/annurev-marine-121916-063627, 2019.

Riley, J. S., Sanders, R., Marsay, C., Le Moigne, F. A. C., Achterberg, E. P. and Poulton, A. J.: The relative contribution of fast and slow sinking particles to ocean carbon export, Global Biogeochem. Cycles, 26(1), doi:10.1029/2011GB004085, 2012.

Roca-Martí, M., Puigcorbé, V., Rutgers van der Loeff, M. M., Katlein, C., Fernández-Méndez, M., Peeken, I. and Masqué, P.: Carbon export fluxes and export efficiency in the central Arctic during the record sea-ice minimum in 2012: a joint [234]Th/ [238]U and [210]Po/ [210]Pb study, J. Geophys. Res. Ocean., 121(7), 5030–5049, doi:10.1002/2016JC011816, 2016.

Roca-Martí, M., Puigcorbé, V., Iversen, M. H., van der Loeff, M. R., Klaas, C., Cheah, W., Bracher, A. and Masqué, P.: High particulate organic carbon export during the decline of a vast diatom bloom in the Atlantic sector of the Southern Ocean, Deep Sea Res. Part II Top. Stud. Oceanogr., 138, 102–115, doi:10.1016/j.dsr2.2015.12.007, 2017.

Rodriguez-Baena, Y., Alessia, M., Boudjenoun, R., Fowler, S. W., Miquel, J. C., Masqué, P., Sanchez-Cabeza, J. A. and Warnau, M.: [234]Th-based carbon export during an ice-edge bloom: Sea-ice algae as a likely bias in data interpretation, Earth Planet. Sci. Lett., 269, 596–604, doi: 10.1016/j.epsl.2008.03.020, 2008.

Rosengard, S. Z., Lam, P. J., Balch, W. M., Auro, M. E., Pike, S., Drapeau, D. and Bowler, B.: Carbon export and transfer to depth across the Southern Ocean Great Calcite Belt, Biogeosciences, 12(13), 3953–3971, doi:10.5194/bg-12-3953-2015, 2015.

Rutgers van der Loeff, M., Cai, P., Stimac, I., Bracher, A., Middag, R., Klunder, M. and van Heuven, S.: [234]Th in surface waters: distribution of particle export flux across the Antarctic Circumpolar Current and in the Weddell Sea during the GEOTRACES expedition ZERO and DRAKE, Deep Sea Res. Part II Top. Stud. Oceanogr., 58, 2749–2766, doi:10.1016/j.dsr2.2011.02.004, 2011.

Rutgers van der Loeff, M. M., Friedrich, J. and Bathmann, U. V: Carbon export during the spring bloom at the Antarctic Polar Front, determined with the natural tracer [234]Th, Deep Sea Res. Part II Top. Stud. Oceanogr., 44(1–2), 457–478, doi:10.1016/S0967-0645(96)00067-7, 1997.

Rutgers van der Loeff, M. M., Buesseler, K., Bathmann, U., Hense, I. and Andrews, J.: Comparison of carbon and opal export rates between summer and spring bloom periods in the region of the Antarctic Polar Front, SE Atlantic, Deep Sea Res. Part II Top. Stud. Oceanogr., 49(18), 3849–3869, doi:10.1016/S0967-0645(02)00114-5, 2002.

Sanders, R., Brown, L., Henson, S. and Lucas, M.: New production in the Irminger Basin during 2002, J. Mar. Syst., 55(3–4), 291–310, doi: 10.1016/j.jmarsys.2004.09.002, 2005.

Sanders, R., Morris, P. J., Poulton, A. J., Stinchcombe, M. C., Charalampopoulou, A., Lucas, M. I. and Thomalla, S. J.: Does a ballast effect occur in the surface ocean?, Geophys. Res. Lett., 37(8), L08602, doi:10.1029/2010GL042574, 2010.

Santschi, P. H., Guo, L., Walsh, I. D., Quigley, M. S. and Baskaran, M.: Boundary exchange and scavenging of radionuclides in continental margin waters of the Middle Atlantic Bight: implications for organic carbon fluxes, Cont. Shelf Res., 19(5), 609–636, doi:10.1016/S0278-4343(98)00103-4, 1999.

Santschi, P. H., Murray, J. W., Baskaran, M., Benitez-Nelson, C. R., Guo, L. D., Hung, C. C., Lamborg, C., Moran, S. B., Passow, U. and Roy-Barman, M.: Thorium speciation in seawater, Mar. Chem., 100(3), 250–268, doi:10.1016/j.marchem.2005.10.024, 2006.

Savoye, N., Benitez-Nelson, C., Burd, A. B., Cochran, J. K., Charette, M., Buesseler, K. O., Jackson, G. A., Roy-

Earth System
**Science**
**Data**

Open Access    Discussions

Barman, M., Schmidt, S. and Elskens, M.: [234]Th sorption and export models in the water column: a review, Mar. Chem., 100(3–4), 234–249, doi:10.1016/j.marchem.2005.10.014, 2006.

Savoye, N., Trull, T. W., Jacquet, S. H. M., Navez, J. and Dehairs, F.: [234]Th-based export fluxes during a natural iron fertilization experiment in the Southern Ocean (KEOPS), Deep Sea Res. Part II Top. Stud. Oceanogr., 55(5–7), 841–855, doi:10.1016/j.dsr2.2007.12.036, 2008.

Schlitzer, R., Anderson, R. F., Dodas, E. M., Lohan, M., Geibert, W., Tagliabue, A., Bowie, A., Jeandel, C., Maldonado, M. T., Landing, W. M., Cockwell, D., Abadie, C., Abouchami, W., Achterberg, E. P., Agather, A., Aguliar-Islas, A., van Aken, H. M., Andersen, M., Archer, C., Auro, M., de Baar, H. J., Baars, O., Baker, A. R., Bakker, K., Basak, C., Baskaran, M., Bates, N. R., Bauch, D., van Beek, P., Behrens, M. K., Black, E., Bluhm, K., Bopp, L., Bouman, H., Bowman, K., Bown, J., Boyd, P., Boye, M., Boyle, E. A., Branellec, P., Bridgestock, L., Brissebrat, G., Browning, T., Bruland, K. W., Brumsack, H.-J., Brzezinski, M., Buck, C. S., Buck, K. N., Buesseler, K., Bull, A., Butler, E., Cai, P., Mor, P. C., Cardinal, D., Carlson, C., Carrasco, G., Casacuberta, N., Casciotti, K. L., Castrillejo, M., Chamizo, E., Chance, R., Charette, M. A., Chaves, J. E., Cheng, H., Chever, F., Christl, M., Church, T. M., Closset, I., Colman, A., Conway, T. M., Cossa, D., Croot, P., Cullen, J. T., Cutter, G. A., Daniels, C., Dehairs, F., Deng, F., Dieu, H. T., Duggan, B., Dulaquais, G., Dumousseaud, C., Echegoyen-Sanz, Y., Edwards, R. L., Ellwood, M., Fahrbach, E., Fitzsimmons, J. N., Russell Flegal, A., Fleisher, M. Q., van de Flierdt, T., Frank, M., Friedrich, J., Fripiat, F., Fröllje, H., Galer, S. J. G., Gamo, T., Ganeshram, R. S., Garcia-Orellana, J., Garcia-Solsona, E., Gault-Ringold, M., et al.: The GEOTRACES Intermediate Data Product 2017, Chem. Geol., doi:10.1016/j.chemgeo.2018.05.040, 2018.

Schmidt, S., Chou, L. and Hall, I. R.: Particle residence times in surface waters over the north-western Iberian Margin: comparison of pre-upwelling and winter periods, J. Mar. Syst., 32(1), 3–11, doi: 10.1016/S0924-7963(02)00027-1, 2002a.

Schmidt, S., Andersen, V., Belviso, S. and Marty, J.-C.: Strong seasonality in particle dynamics of north-western Mediterranean surface waters as revealed by [234]Th/[238]U, Deep Sea Res. Part I Oceanogr. Res. Pap., 49(8), 1507–1518, doi:10.1016/S0967-0637(02)00039-0, 2002b.

Schmidt, S., Goutx, M., Raimbault, P., Garcia, N., Guibert, P. and Andersen, V.: [234]Th measured particle export from surface waters in north-western Mediterranean: comparison of spring and autumn periods, Biogeoscience Discuss., 6, 143-161, 2009.

Schmidt, S., Harlay, J., Borges, A. V, Groom, S., Delille, B., Roevros, N., Christodoulou, S. and Chou, L.: Particle export during a bloom of Emiliania huxleyi in the North-West European continental margin, J. Mar. Syst., 109–110, S182–S190, doi:10.1016/j.jmarsys.2011.12.005, 2013.

Shaw, T. J., Smith, K. L., Hexel, C. R., Dudgeon, R., Sherman, A. D., Vernet, M. and Kaufmann, R. S.: [234]Th-Based Carbon Export around Free-Drifting Icebergs in the Southern Ocean, Deep Sea Res. Part II Top. Stud. Oceanogr., 58(11), 1384–1391, doi:10.1016/j.dsr2.2010.11.019, 2011.

Shimmield, G. B., Ritchie, G. D. and Fileman, T. W.: The impact of marginal ice zone processes on the distribution of ^{210}Pb, [210]Po and [234]Th and implications for new production in the Bellingshausen Sea, Antarctica, Deep Sea Res. Part II Top. Stud. Oceanogr., 42(4–5), 1313–1335, doi: 10.1016/0967-0645(95)00071-W, 1995.

Smetacek, V., Klaas, C., Strass, V. H., Assmy, P., Montresor, M., Cisewski, B., Savoye, N., Webb, A., D'Ovidio, F., Arrieta, J. M. and others: Deep carbon export from a Southern Ocean iron-fertilized diatom bloom, Nature, 487(7407), 313–319, doi:10.1038/nature11229, 2012.

Smoak, J. M., Moore, W. S., Thunell, R. C. and Shaw, T. J.: Comparison of [234]Th, [228]Th, and ^{210}Pb fluxes with fluxes of major sediment components in the Guaymas Basin, Gulf of California, Mar. Chem., 65(3), 177–194, doi:10.1016/S0304-4203(98)00095-4, 1999.

Speicher, E. A., Moran, S. B., Burd, A. B., Delfanti, R., Kaberi, H., Kelly, R. P., Papucci, C., Smith, J. N., Stavrakakis, S. and Torricelli, L.: Particulate organic carbon export fluxes and size-fractionated POC/[234]Th ratios in the Ligurian, Tyrrhenian and Aegean Seas, Deep Sea Res. Part I Oceanogr. Res. Pap., 53(11), 1810–1830, doi:10.1016/j.dsr.2006.08.005, 2006.

Stewart, G., Cochran, J. K., Miquel, J. C., Masqué, P., Szlosek, J., Rodriguez y Baena, A. M., Fowler, S. W., Gasser, B. and Hirschberg, D. J.: Comparing POC export from [234]Th/[238]U and [210]Po/^{210}Pb disequilibria with estimates from sediment traps in the northwest Mediterranean, Deep Sea Res. Part I Oceanogr. Res. Pap., 54(9), 1549–1570, doi:10.1016/j.dsr.2007.06.005, 2007.

Stewart, G., Moran, S. B., Lomas, M. W. and Kelly, R. P.: Direct comparison of [210]Po, [234]Th and POC particle-size distributions and export fluxes at the Bermuda Atlantic Time-series Study (BATS) site, J. Environ. Radioact., 102(5), 479–489, doi:10.1016/j.jenvrad.2010.09.011, 2011.

Stukel, M. R., Landry, M. R., Benitez-Nelson, C. R. and Goerickea, R.: Trophic cycling and carbon export relationships in the California Current Ecosystem, Limnol.Oceanogr, 56(5), 1866–1878, doi:10.4319/lo.2011.56.5.1866, 2011.

Stukel, M. R., Kahru, M., Benitez-Nelson, C. R., Décima, M., Goericke, R., Landry, M. R. and Ohman, M. D.: Using Lagrangian-based process studies to test satellite algorithms of vertical carbon flux in the eastern North Pacific Ocean, J. Geophys. Res. Ocean., 120(11), 7208–7222, doi:10.1002/2015JC011264, 2015.

Stukel, M. R., Benitez-Nelson, C. R., Décima, M., Taylor, A. G., Buchwald, C. and Landry, M. R.: The biological pump in the Costa Rica Dome: an open-ocean upwelling system with high new production and low export, J. Plankton Res., 38(2), 348–365, doi:10.1093/plankt/fbv097, 2016.

Stukel, M. R., Aluwihare, L. I., Barbeau, K. A., Chekalyuk, A. M., Goericke, R., Miller, A. J., Ohman, M. D., Ruacho, A., Song, H., Stephens, B. M. and Landry, M. R.: Mesoscale ocean fronts enhance carbon export due to gravitational sinking and subduction, Proc. Natl. Acad. Sci. , 114(6), 1252–1257, doi:10.1073/pnas.1609435114, 2017.

Stukel, M. R., Kelly, T. B., Aluwihare, L. I., Barbeau, K. A., Goericke, R., Krause, J. W., Landry, M. R. and Ohman, M. D.: The Carbon:$^{234}$Thorium ratios of sinking particles in the California current ecosystem 1: relationships with plankton ecosystem dynamics, Mar. Chem., doi:10.1016/j.marchem.2019.01.003, 2019.

Szlosek, J., Cochran, J. K., Miquel, J. C., Masqué, P., Armstrong, R. A., Fowler, S. W., Gasser, B. and Hirschberg, D. J.: Particulate organic carbon–$^{234}$Th relationships in particles separated by settling velocity in the northwest Mediterranean Sea, Deep Sea Res. Part II Top. Stud. Oceanogr., 56(18), 1519–1532, doi:10.1016/j.dsr2.2008.12.017, 2009.

Thomalla, S. J., Turnewitsch, R., Lucas, M. and Poulton, A.: Particulate organic carbon export from the North and South Atlantic gyres: The $^{234}$Th/$^{238}$U disequilibrium approach, Deep Sea Res. Part II Top. Stud. Oceanogr., 53(14–16), 1629–1648, doi:10.1016/j.dsr2.2006.05.018, 2006.

Trimble, S. M. and Baskaran, M.: The role of suspended particulate matter in $^{234}$Th scavenging and $^{234}$Th-derived export fluxes of POC in the Canada Basin of the Arctic Ocean, Mar. Chem., 96(1–2), 1–19, doi:10.1016/j.marchem.2004.10.003, 2005.

Trull, T. W., Bray, S. G., Buesseler, K. O., Lamborg, C. H., Manganini, S., Moy, C. and Valdes, J.: In situ measurement of mesopelagic particle sinking rates and the control of carbon transfer to the ocean interior during the Vertical Flux in the Global Ocean (VERTIGO) voyages in the North Pacific, Deep Sea Res. Part II Top. Stud. Oceanogr., 55(14), 1684–1695, doi:10.1016/j.dsr2.2008.04.021, 2008.

Turnewitsch, R., Dumont, M., Kiriakoulakis, K., Legg, S., Mohn, C., Peine, F. and Wolff, G.: Tidal influence on particulate organic carbon export fluxes around a tall seamount, Prog. Oceanogr., 149, 189–213, doi:10.1016/j.pocean.2016.10.009, 2016.

Waples, J. T., Benitez-Nelson, C., Savoye, N., Rutgers van der Loeff, M., Baskaran, M. and Gustafsson, Ö.: An introduction to the application and future use of $^{234}$Th in aquatic systems, Mar. Chem., 100(3–4), 166–189, doi:10.1016/j.marchem.2005.10.011, 2006.

Wei, C. L., Chou, L. H., Tsai, J. R., Wen, L. S. and Pai, S. C.: Comparative geochemistry of $^{234}$Th, $^{210}$Pb, and $^{210}$Po: A case study in the Hung-Tsai Trough off southwestern Taiwan, Terr. Atmos. Ocean. Sci., 20(2), 411–423, doi:10.3319/TAO.2008.01.09.01(Oc), 2009.

Wei, C. L., Lin, S. Y., Sheu, D. D. D., Chou, W. C., Yi, M. C., Santschi, P. H. and Wen, L. S.: Particle-reactive radionuclides ($^{234}$Th, $^{210}$Pb, $^{210}$Po) as tracers for the estimation of export production in the South China Sea, Biogeosciences, 8(12), 3793–3808, doi:10.5194/bg-8-3793-2011, 2011.

Yang, Y., Han, X. and Kusakabe, M.: POC fluxes from euphotic zone estimated from $^{234}$Th deficiency in winter in the northwestern North Pacific Ocean.pdf, Acta Oceanol. Sin., 23(1), 135–148, 2004.

Yu, W., Chen, L., Cheng, J., He, J., Yin, M. and Zeng, Z.: $^{234}$Th-derived particulate organic carbon export flux in the western Arctic Ocean· Chinese J. Oceanol. Limnol., 28(6), 1146–1151, doi:10.1007/s00343-010-9933-1, 2010.

Yu, W., He, J., Li, Y., Lin, W. and Chen, L.: Particulate organic carbon export fluxes and validation of steady state model of $^{234}$Th export in the Chukchi Sea, Deep Sea Res. Part II Top. Stud. Oceanogr., doi:10.1016/j.dsr2.2012.03.003, 2012.

Zhou, K., Nodder, S. D., Dai, M. and Hall, J. A.: Insignificant enhancement of export flux in the highly productive subtropical front, east of New Zealand: a high resolution study of particle export fluxes based on $^{234}$Th:$^{238}$U disequilibria, Biogeosciences, 9(3), 973–992, doi:10.5194/bg-9-973-2012, 2012.

Zhou, K., Dai, M., Kao, S.-J., Wang, L., Xiu, P., Chai, F., Tian, J. and Liu, Y.: Apparent enhancement of $^{234}$Th-based particle export associated with anticyclonic eddies, Earth Planet. Sci. Lett., 381, 198–209, doi:10.1016/j.epsl.2013.07.039, 2013.

Zhou, K., Maiti, K., Dai, M., Kao, S.-J. and Buesseler, K.: Does adsorption of dissolved organic carbon and thorium onto membrane filters affect the carbon to thorium ratios, a primary parameter in estimating export carbon flux?, Mar. Chem., 184, 1–10, doi:10.1016/j.marchem.2016.06.004, 2016.
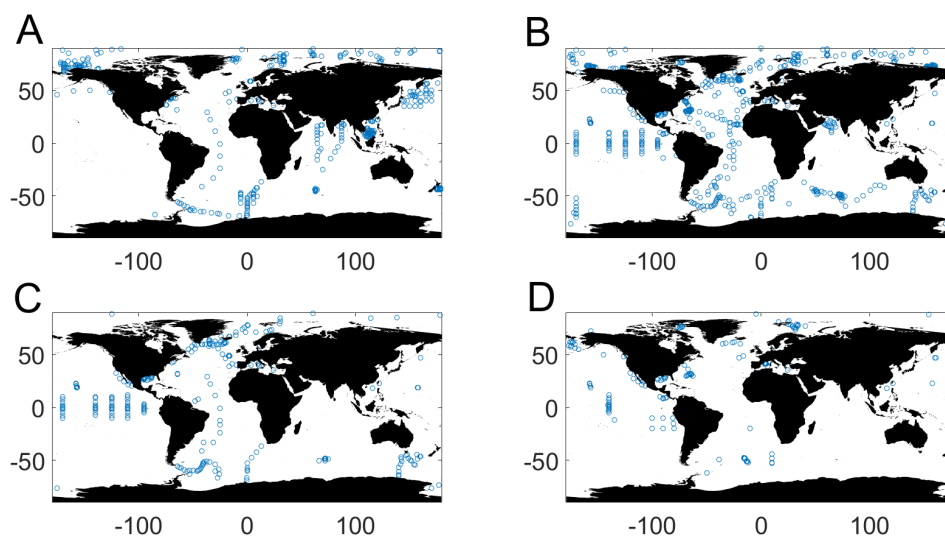
**Figure 1: Maps showing the distribution of POC/Th ratios measured on (A) bulk particles, (B) large particles, (C) small particles, and (D) particles from sediment traps. See main text for details.**
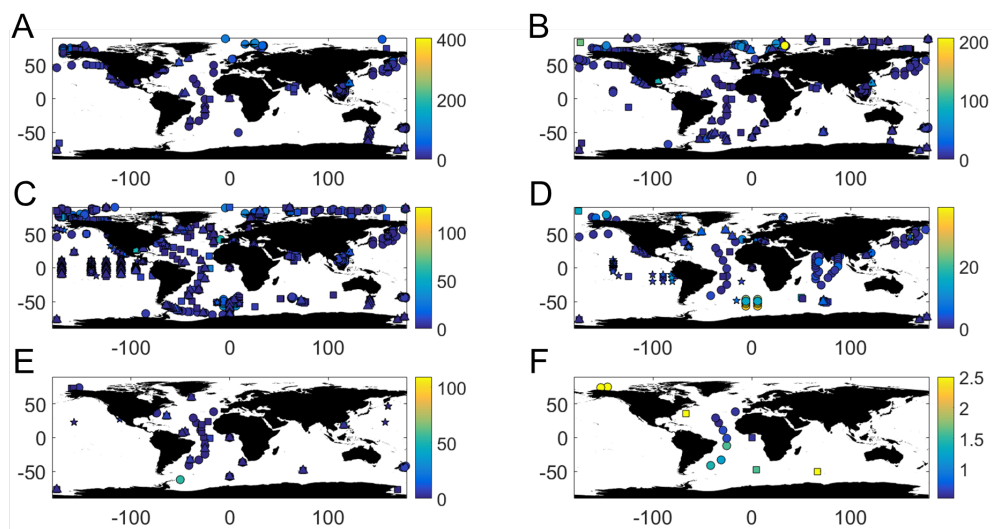


**Figure 2: Global distribution of the POC/Th ratios (A) in surface, (B) at 50 m, (C) at 100 m, (D) at 200 m, (E) at 500 m and (F) at 1000 m. Circles represent BU, squares represent LP, triangles represent SP and stars represent ST (see main text for details). Data corresponds to samples collected at depths at +/- 5 meters the nominal depth for all cases, except for panel F (+/- 50 meters).**
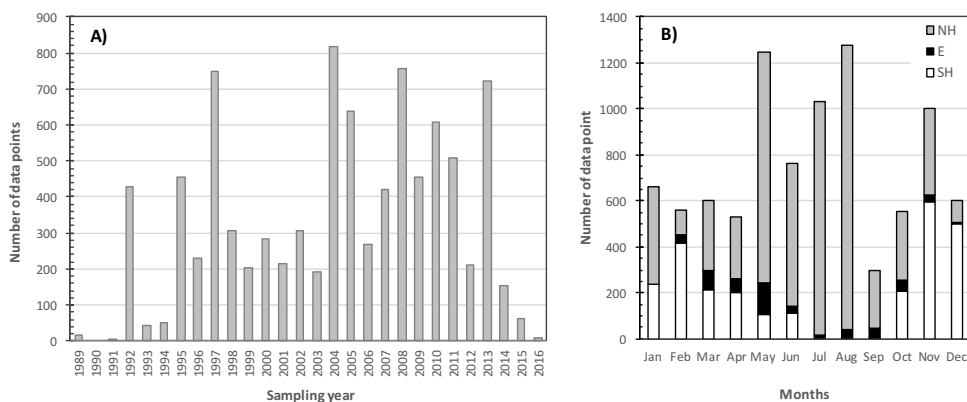
**Figure 3: A) Histogram of data sampled between 1989 and 2016. See Table 1 for details. B) Number of samples per month of the year grouped as per samples collected in the Northern Hemisphere (NH; grey), Southern Hemisphere (SH; white) or Equator (E; -10° to 10°N; black).**
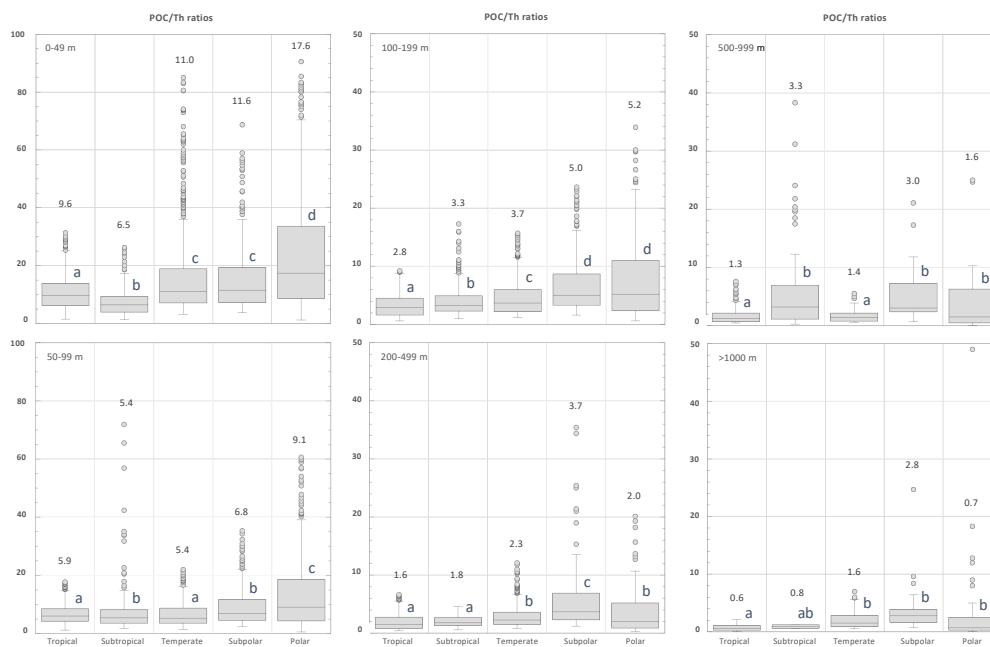


**Figure 4: POC/Th ratios variability (box whisker plots) of 90% of the data sorted by climate zones and depth. The values shown on top of each box represent their median. Box plots within the same depth range (e.g, 0-49 m) sharing a letter are not significantly different. Note the different scale used between the 0 to 99 m and the 100 to >1000 m plots.**
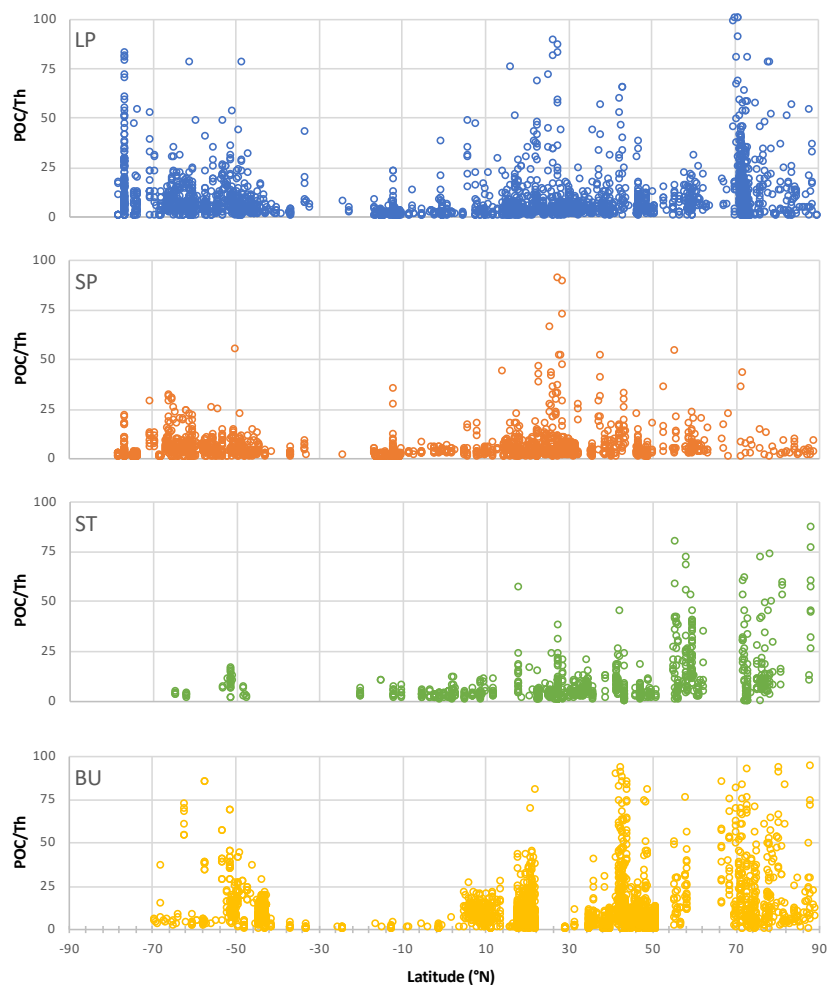
**Figure 5: Latitudinal variability of the POC/Th ratios (<100 μm/dpm) grouped by large particles (LP), small particles (SP), sediment trap particles (ST) and bulk particles (BU).**

| Sampling year | Area | LP n | SP n | ST n | BU n | Reference/Investigator |
|---|---|---|---|---|---|---|
| 1989 | North Atlantic | - | - | 6 | 12 | Buesseler et al. (1992) |
| 1991-1992 | Buzzards Bay | - | - | - | 7 | Moran and Buesseler (1993) |
| 1992 | Equatorial Pacific | 80 | - | - | - | Bacon et al. (1996) |
| 1992 | Sargasso Sea | - | - | 2 | - | Buesseler et al. (1994) |
| 1992 | Equatorial Pacific | 71 | 78 | - | - | Buesseler et al. (1995) |
| 1992 | Atlantic sector of the Southern Ocean | - | - | - | 31 | Friedrich and Rutgers van der Loeff (2002) |
| 1992 | Central Equatorial Pacific | - | - | 124 | - | Murray US JGOFS EqPac (Murray et al., 1996 and Murray et al., 2005) |
| 1992 | Atlantic Sector Southern Ocean | - | - | - | 32 | Rutgers van der Loeff et al. (1997) |
| 1992 | Bellingshausen Sea, Antarctica | - | - | - | 3 | Shimmield et al. (1995) |
| 1992-1993 | Northeast Water Polynya Greenland | - | - | - | 11 | Cochran et al. (1995) |
| 1993 | Middle Atlantic Bight | - | - | - | 30 | Santschi et al. (1999) |
| 1993-1994 | Station BATS, North Atlantic, and Gulf of Maine | - | - | - | 4 | Gustafsson et al. (1997) |
| 1993-1996 | Guaymas Basin | - | - | 58 | - | Smoak et al. (1999) |
| 1994 | Central Arctic Ocean | 28 | - | - | - | Moran et al. (1997) |
| 1995 | Arabian Sea | 123 | 148 | - | - | Buesseler JGOFS dataset Arabian Sea |
| 1995 | Wilkinson Basin and Jordan Basin | 20 | 20 | - | - | Charette et al. (2001) |
| 1995 | Beaufort Sea | - | - | - | 22 | Moran and Smith (2000) |
| 1995 | Atlantic Sector Southern Ocean | - | - | - | 80 | Rutgers van der Loeff et al. (2002) |
| 1995 | NW Mediterranean Sea | - | - | 3 | 15 | Schmidt et al. (2002a) |
| 1996 | Subtropical and ropical Atlantic Ocean | 25 | 22 | - | - | Charette and Moran (1999) |
| 1996-1997 | Northeast Pacific Ocean | - | - | 4 | 144 | Charette et al. (1999) |
| 1996-1997 | Ross Sea | 82 | 79 | - | - | Cochran et al. (2000) |
| 1996-1997 | Gulf of Maine | - | - | - | 7 | Dai and Benitez-Nelson (2001) |
| 1996-1997 | Sargasso Sea | - | - | - | 6 | Kim and Church (2001) |
| 1996-1998 | Ross-Sea | 291 | 271 | - | - | Buesseler JGOFS dataset Southern Ocean |
| 1997 | Southwestern Gulf of Maine | - | - | - | 64 | Benitez-Nelson et al. (2000) |
| 1997 | Sargasso Sea | - | - | 3 | - | Buesseler et al. (2000) |
| 1997 | Gulf of Lions | - | - | - | 33 | Giuliani et al. (2007) |
| 1997 | Northern Iberian Margin | - | - | - | 22 | Hall et al. (2000) |
| 1997 | Northern Adriatic Sea | - | - | - | 23 | Radakovitch et al. (2003) |
| 1997-2000, 2002-2008 | NW North Pacific | 92 | - | 48 | 664 | Kawakami North Pacific Time Series |
| 1998 | Arctic Ocean | - | - | - | 19 | Baskaran et al. (2003) |
| 1998 | Western Iberian Margin | - | - | - | 12 | Schmidt et al. (2002b) |
| 1998-1999 | Polynya North Water | 15 | - | 45 | - | Amiel et al. (2002) |
| 1999 | South China Sea | - | - | - | 20 | Cai et al. (2001) |
| 1999 | Canada Basin, Bering Sea | - | - | - | 27 | Chen et al. (2003) |
| 1999 | Barents Sea | - | - | 5 | 25 | Coppola et al. (2002) |
| 1999 | Crozet Basin | - | - | - | 8 | Coppola et al. (2005) |
| 1999 | Northern North Sea | - | - | - | 24 | Foster and Shimmield (2002) |
| 1999 | Labrador Sea | 8 | 3 | - | - | Moran et al. (2003) |
| 1999-2000 | North Pacific Subtropical Gyre | 5 | 5 | 9 | - | Benitez-Nelson et al. (2001) |
| 2000 | Gulf of Mexico | 15 | 15 | - | - | Guo et al. (2002) |
| 2000 | Canada Basin Arctic Ocean | - | - | - | 25 | Trimble and Baskaran (2005) |
| 2000-2001 | Gulf of Mexico | 21 | 21 | 4 | - | Hung et al. (2004) |
| 2000-2002 | Northern South China Sea | - | - | - | 44 | Chen et al. (2008) |
| 2001 | Subarctic Pacific | - | - | 6 | 19 | Aono et al. (2005) |
| 2001 | Gullmar fjord, Sweden | - | - | 7 | 8 | Gustafsson et al. (2006) |
| 2001 | Arctic Ocean (Marginal Ice Zone) | - | - | 17 | 46 | Gustafsson and Andersson (2012) |
| 2001 | Southern Ocean | 38 | 36 | - | - | Trull and Buesseler (unpublished) |

| Year | Location | | | | | Reference |
|------|----------|---|---|---|---|-----------|
| 2002 | Southern Ocean/ South of the ACCF | 39 | 40 | - | - | Buesseler et al. (2005) |
| 2002 | Chukchi Sea | 171 | - | - | - | Moran et al. (2005) |
| 2002 | Bay of Biscay to Celtic Sea | - | - | - | 24 | Schmidt et al. (2013) |
| 2003 | Western Arctic Ocean | - | - | - | 18 | Ma et al. (2005) |
| 2003 | Southern Ocean | 6 | - | - | - | Rodriguez-Baena et al. (2008) |
| 2003 | NW Mediterranean Sea | 4 | - | 20 | - | Stewart et al. (2007) |
| 2003 | Western Arctic Ocean | - | - | - | 32 | Yu et al. (2010) |
| 2003, 2005 | Northern Barents Sea | 24 | - | 24 | - | Lalande et al. (2008) |
| 2003-2006 | Porcupine Abyssal Plain | 7 | - | 5 | - | Lampitt et al. (2008) |
| 2004 | Canadian Arctic Shelf | 24 | - | - | - | Amiel and Cochran (2008) |
| 2004 | South China Sea | - | - | - | 169 | Cai et al. (2008) |
| 2004 | Western Arctic Shelf-Basin | 38 | - | 45 | - | Lalande et al. (2007) |
| 2004 | Western Arctic Ocean | 206 | - | - | - | Lepore et al. (2007) |
| 2004 | Sargasso Sea | - | - | 2 | - | Maiti et al. (2009) |
| 2004 | NW Mediterranean Sea | - | - | 3 | - | Schmidt et al. (2009) |
| 2004 | Southern Ocean | - | - | - | 1 | Smetacek et al. (2012) |
| 2004 | Eastern Mediterranean Sea | 26 | 26 | - | - | Speicher et al. (2006) |
| 2004-2005 | Tropical North Pacific (Hawaii) | 103 | 115 | 8 | - | Buesseler et al. (2008a) |
| 2004-2005 | North Pacific (ALOHA and K2) | 35 | 97 | - | - | Buesseler et al. (2009) |
| 2004-2005 | North Pacific Ocean | - | - | 36 | - | Lamborg et al. (2008) |
| 2004-2005 | Southern Ocean | 20 | - | - | - | Morris et al. (2007) |
| 2005 | South China Sea | 16 | 15 | - | - | Cai et al. (2006) |
| 2005 | Mediterranean Sea and NW Atlantic | 37 | 32 | 15 | - | Lepore et al. (2009) |
| 2005 | Tropical North Pacific (Hawaii) | 13 | 13 | 2 | - | Maiti et al. (2008) |
| 2005 | Kerguelen Plateau, Southern Ocean | 26 | - | - | - | Savoye et al. (2008) |
| 2005 | Ligurian Sea, NW Mediterranean Sea | - | - | 22 | - | Szlosek et al. (2009) |
| 2005 | Falkland Island and Great Britain | 10 | 10 | - | 82 | Thomalla et al. (2006) |
| 2005-2006, 2009 | NW Gulf of Mexico and NW Pacific | 35 | 34 | 25 | - | Hung et al. (2010) |
| 2006 | Kuroshio Current | 6 | 6 | 4 | - | Hung and Gong (2007) |
| 2006 | Hung-Tsai Trough, southwestern Taiwan | - | - | - | 30 | Wei et al. (2009) |
| 2006-2007 | Sargasso Sea | 20 | 20 | 12 | - | Brew et al. (2009) |
| 2006-2007 | Sargasso Sea | 9 | 9 | 9 | - | Stewart et al. (2011) |
| 2006-2008 | Tsushima Basin, East Japan Sea | - | - | - | 12 | Kim et al. (2011) |
| 2006-2008 | South China Sea | - | - | 17 | - | Wei et al. (2011) |
| 2006-09, 2011-12, 2014, 2016 | California Current | 47 | - | 60 | - | Stukel et al. CCE |
| 2007 | Arctic Ocean | 14 | 14 | - | 36 | Cai et al. (2010) |
| 2007 | Southern Ocean | 77 | 75 | - | 2 | Jacquet et al. (2011) |
| 2007 | North Atlantic Ocean | 20 | - | - | - | Sanders et al. (2010) |
| 2007 | South China Sea | - | - | - | 85 | Zhou et al. (2013) |
| 2008 | Northwest Pacific | - | - | 13 | - | Hung et al. (2012) |
| 2008 | South China Sea | - | - | 9 | - | Hung and Gong (2010) |
| 2008 | Iceland Basin | - | - | 9 | - | Martin et al. (2011) |
| 2008 | Eastern Bering Sea | - | - | 35 | - | Moran et al. (2012) |
| 2008 | Southern Ocean | 46 | 49 | - | 45 | Planchon et al. (2013) |
| 2008 | Gulf of California and Easter Tropical Pacific | 83 | 83 | 8 | - | Puigcorbé et al. (2015) |
| 2008 | Atlantic Sector Southern Ocean | 12 | 12 | - | 27 | Rutgers van der Loeff et al. (2011) |
| 2008 | Chukchi Sea | - | - | - | 79 | Yu et al. (2012) |
| 2008 | Southern Ocean | - | - | - | 146 | Zhou et al. (2012) |
| 2008-2009 | West Antarctic Peninsula | 1 | 1 | 4 | - | Buesseler et al. (2010) |
| 2008-2009 | Southern Ocean and Sargasso Sea | - | 26 | - | - | Zhou et al. (2016) |
| 2009 | Porcupine Abyssal Plain | 20 | 13 | - | - | Le Moigne et al. (2013b) |
| 2009 | Southern Ocean | - | - | 6 | - | Martin et al. (2013) |

| Year | Area | LP | SP | BU | ST | Reference |
|---|---|---|---|---|---|---|
| 2009 | NW Mediterranean Sea | - | - | 42 | - | Puigcorbé et al (unpublished)-FAMOSO |
| 2009 | Powell Basin of the Weddell Sea | - | - | 5 | 6 | Shaw et al. (2011) |
| 2009 | Cape Verde Archipelago | 14 | - | - | - | Turnewitsch et al. (2016) |
| 2009-2010 | Eastern Bering Sea | - | - | 89 | - | Baumann et al. (2013) |
| 2009-2011 | South China Sea | - | - | - | 777 | Cai et al. (2015) |
| 2009-2011 | Saanich Inlet | - | - | - | 76 | Luo et al. (2014) |
| 2010 | Irminger Basin and Iceland Basin | - | - | 8 | - | Ceballos-Romero et al. (2016) |
| 2010 | Saronikos Gulf | 10 | 10 | - | - | Evangeliou et al. (2013) |
| 2010 | North Atlantic Ocean | 39 | 39 | - | - | Le Moigne et al. (2012) |
| 2010 | NW Atlantic | 11 | - | - | - | Puigcorbé et al. (2017a) |
| 2010 | Costa Rica upwelling Dome | 13 | - | 10 | - | Stukel et al. CRD |
| 2010-2011 | Southeastern Pacific | - | - | 16 | - | Haskell II et al. (2013) |
| 2010-2011 | Atlantic Ocean | 189 | - | - | - | Owens et al. (2015) |
| 2011 | Tropical Atlantic | 15 | - | - | - | Pabortsava (2014) |
| 2011 | Kerguelen Plateau, Southern Ocean | 48 | 52 | - | - | Planchon et al. (2015) |
| 2011-2012 | Southern Ocean (Atlantic and Indian Sectors) | 27 | - | - | - | Rosengard et al. (2015) |
| 2012 | Arctic Ocean | 13 | 10 | - | - | Le Moigne et al. (2015) |
| 2012 | Southeast of the Mississippi delta | 39 | 38 | 11 | - | Maiti et al. (2016) |
| 2012 | Atlantic Sector Southern Ocean | 8 | - | 2 | - | Puigcorbé et al. (2017b) |
| 2012 | Eurasian Basin of the central Arctic | 25 | - | - | - | Roca-Martí et al. (2016) |
| 2012 | Atlantic Sector Southern Ocean | 19 | - | 22 | - | Roca-Martí et al. (2017) |
| 2013 | Southeastern Tropical Pacific | 339 | 339 | - | - | Black et al. (2018) |
| 2013 | Southern Ocean (South Georgia) | 10 | 9 | - | - | Ceballos-Romero et al. unpublished |
| 2013 | Southern Ocean | 12 | 8 | - | - | Le Moigne et al. (2016) |
| 2013-2014 | Arabian Sea and Bay of Bengal | - | - | - | 4 | Anand et al. (2018b) |
| 2014 | Bay of Bengal | - | - | - | 13 | Anand et al. (2017) |
| 2014 | Southern Indian Ocean to Arabian Sea | - | - | - | 11 | Anand et al. (2018a) |
| 2014 | North Atlantic Ocean | 56 | 58 | - | - | Lemaitre et al. (2018) |
| 2015 | Arctic Ocean | 17 | 17 | - | 28 | Puigcorbé et al. (unpublished)-PS94 |
| | **Totals** | **3013** | **1968** | **939** | **3190** | **9110** |

Table 1: Sampling year, area, the number of samples for large particles (LP), small particles (SP), bulk particles (BU) and particles collected with sediment trap (ST) and reference of studies used in the database. Note the following reference refer to data published in several papers: Stukel et al. CCE refers to data published in Stukel et al. (2011, 2015, 2017, 2019); Stukel et al. CRD refers to data from Stukel et al. (2015, 2016). Buesseler JGOFS dataset Arabian Sea refers to data published in (Buesseler et al., 1998) and also available at https://www.bco-dmo.org/project/2043. Buesseler JGOFS dataset Southern Ocean refers to data published in (Buesseler et al., 2001) and also available at https://www.bco-dmo.org/project/2044. Kawakami North Pacific Time Series data is available at http://www.jamstec.go.jp/res/ress/kawakami/234Th.html and has also been published in Kawakami (2009), Kawakami et al. (2004, 2010, 2015), Kawakami and Honda (2007) and Yang et al. (2004). Further details regarding particle size specifications or sampling device can be found in the database file https://doi.pangaea.de/10.1594/PANGAEA.902103