COMMENT

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Uncertainty versus variability in upper ocean carbon fluxes (Reply to comment by Benitez-Nelson and Charette)

The comment by Benitez-Nelson and Charette (2004), herein referred to as BNC2004, centers on their objections to the manner in which Moran et al. (2003) have chosen to assess the variability in the particulate organic carbon (POC) export flux estimated using the thorium-234 (^{234}Th) method. The study of Moran et al. (2003) was prompted by the marked increase in the use of the ^{234}Th technique during the past decade (Fig. 1) and the fact that the methods used for sample collection, analysis, and data reduction vary significantly for most of these studies. The main problem is that there is no clear standardization in the experimental parameters governing the application of the method. We sought to advance the discussion of the ^{234}Th technique and encourage the development of uniformity in its application by reviewing the variability in ^{234}Th-derived POC fluxes that can be calculated for a single data set using methods reported in the literature. However, the BNC2004 comment argues that our approach is misleading, even ''deceptive,'' to the rest of the oceanographic community.

POC fluxes, POC/^{234}Th ratios, and ^{234}Th/^{238}U disequilibria

The primary objection of the BNC2004 comment is that Moran et al. (2003) have compared ^{234}Th-derived POC fluxes over ''mismatched'' depth intervals (e.g., fluxes from 0 to 50 m compared to fluxes from 0 to 250 m) ''to imply that there is a large uncertainty in the POC export flux.'' A related objection is that Moran et al. (2003) incorrectly applied ''deeper POC/^{234}Th ratios with shallow ^{234}Th disequilibria in obtaining POC flux (*sic*).'' What Moran et al. (2003) have actually done is to use the range of data reduction methods *reported in the literature,* including the extreme cases noted above, to show that there are uncertainties in *reported* POC export fluxes owing to the absence of standardization in the experimental parameters and consequent inconsistencies in the methods of calculation. In no way have Moran et al. (2003) advocated the use of any one of these methods, many of which are indeed counterintuitive. The point of Moran et al. (2003) was not to dictate the choice of any one set of experimental variables, but to illustrate the range and uncertainty that characterize reported results in the absence of uniformity in the various approaches. Our intent was not to ''mislead'' the oceanographic community, as the BNC2004 comment states that we have done, but rather to educate and caution it with respect to the interpretation of published studies. While the authors of the BNC2004 comment apparently believe that ''the ^{234}Th community's understanding and application of the ^{234}Th method for deriving export'' has progressed beyond this point, that inferred progression is not necessarily clear to the uninitiated.

Specifically, Moran et al. (2003) deliberately apply the POC/^{234}Th ratios as described in table 2 of that article (e.g., as the BNC2004 comment notes, a 50-m integrated ^{234}Th flux with a POC/^{234}Th ratio from 250 m) to their data to illustrate the range in calculated POC fluxes that can be determined using data reduction methods from some of the studies listed in their table 1. This is done to replicate the operational procedures used in studies that have mismatched depths for the POC/^{234}Th ratio determination and ^{234}Th integration (Buesseler et al. 1992, 1995; Benitez-Nelson et al. 2000), either by applying measurements at different depths to the same calculation or by ''yo-yo'' sampling, which usually biases POC/^{234}Th ratios to the higher values characteristic of shallower depths. In most cases, these workers were careful about qualifying their results and noting the constraints imposed on the interpretation of the results. Nevertheless, calculations were made in these studies using mismatched depths out of necessity, and Moran et al. (2003) simply illustrate the range in POC export flux derived using these operationally different methods of calculation. Certainly, the rationale used for mismatched depths will vary from one study to another and will frequently be dictated by sampling constraints. Nevertheless, the implication is that a number of published ^{234}Th–POC export fluxes do in fact have an inherent uncertainty (not to be confused with analytical uncertainty or natural variability) as a result of these operational factors.

Moran et al. (2003) indicate that POC export fluxes are likely to vary by a factor of 2–3 under optimal conditions, such as in the equatorial Pacific (Buesseler et al. 1995; Bacon et al. 1996; Murray et al. 1996). The BNC2004 comment is in agreement with this point, noting that the total variability in POC flux decreases by almost 50% when using the same depth horizon for POC/^{234}Th ratios and ^{234}Th integration depths. However, the BNC2004 comment fails to consider the issue of ^{234}Th–POC export fluxes in shelf waters, where sediment resuspension and abiotic particle scavenging may increase this inherent uncertainty up to a factor of $\geq$10. As noted by Moran et al. (2003), shelf waters are where this technique may be prone to the greatest range and ambiguity in POC/^{234}Th ratios and ^{234}Th integration depths and hence POC export flux.

The BNC2004 comment has confused the above objectives of Moran et al. (2003) with that of determining the

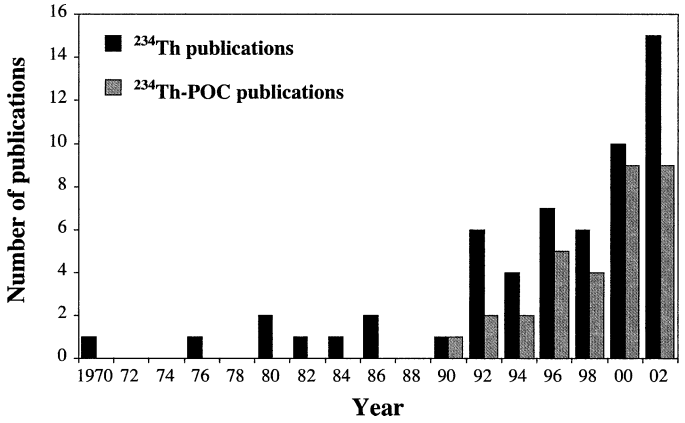

Fig. 1. Number of journal publications related to the application of $^{234}Th:^{238}U$ disequilibrium and POC/^{234}Th ratios to POC export flux in ocean waters as a function of year. Data are plotted in 2-yr bins. Since 1992, 64% of these publications have been on the application of ^{234}Th, a tracer of POC export flux. Note that these papers are considered most related to the application of ^{234}Th as a tracer of POC export flux; not included in the plot are those papers that simply report ^{234}Th data. Data are from Moran et al. (2003).

uncertainty in the POC export flux itself. The POC export flux is an operationally determined quantity whose value reflects the transport or ''export'' of POC from the euphotic zone. The accuracy of measurement of the POC export flux by the ^{234}Th method hinges on assumptions that require ^{234}Th and C to be transported by the same assemblage of particles and that also require this particle distribution to be replicated in samples collected by the chosen sampling technique (e.g., pumps, bottles, traps). Problems with these assumptions include the kinetics of Th and C association with particles and biases inherent in the sampling techniques. The authors of the BNC2004 comment profess disappointment at our ''narrow focus and interpretation,'' but the characterization of the fundamental uncertainties in the method itself is a separate task and one that is beyond the scope of the immediate objectives in Moran et al. (2003).

Moran et al. (2003) do not argue that the ^{234}Th method is deeply flawed. Rather, the key argument promoted in Moran et al. (2003) is that there is an inherent uncertainty in a number of published POC export fluxes owing to varying assumptions and operational differences in sample collection, measurements, and calculations. Because the calculations of Moran et al. (2003) are based entirely on methods used in previously published studies, the misapplication of POC/^{234}Th ratios is not an issue for us to decide, but one to be addressed by the entire ^{234}Th community. Logically, ^{234}Th depletion should be measured to the base of the euphotic zone and the POC/^{234}Th ratio determined at this depth in order to estimate POC export, but this is not always practically feasible. Moran et al. (2003) have simply assessed the range and variability in POC/^{234}Th ratios, measured at different water depths relative to those for the base of the euphotic zone, and discussed the consequent uncertainty implicit in calculations of the POC fluxes.

Contrary to the assertion of BNC2004, Moran et al. (2003) do focus on a number of factors in addition to mismatched sampling depths that contribute to uncertainty in the ^{234}Th technique: (1) POC/^{234}Th ratios, including a discussion of differences in sample collection techniques; (2) methods used to calculate depth-integrated ^{234}Th fluxes; (3) particle size considerations in evaluating POC export; and (4) differences in published methods used to calculate POC fluxes. Moran et al. (2003) also address the issue of ^{234}Th–POC export fluxes in shelf waters, where sediment resuspension and abiotic particle scavenging are responsible for ambiguities in the interpretation of POC/^{234}Th ratios and ^{234}Th integration depths in the context of biogenic POC export fluxes. Finally, Moran et al. (2003) provide guidance for future work by proposing recommendations intended to improve our understanding of this technique, including mechanistic studies of ^{234}Th–organic matter interactions; detailed comparisons of POC/^{234}Th ratios; increased spatial and temporal sampling of ^{234}Th data fields; and more standardized procedures to calculate the ^{234}Th export flux.

Variability versus uncertainty

Regarding BNC2004's concern about natural variability versus uncertainty, Moran et al. (2003) explicitly state on page 1019 that the POC/^{234}Th ratio of marine particles varies significantly with ''. . . location and time in association with changes in primary and secondary productivity, plankton community structure, export production, particle size-distribution, particle aggregation-disaggregation, and food web dynamics.'' Furthermore, it is the authors of BNC2004 who have confused the approach used by Moran et al. (2003) to evaluate the inherent uncertainty in published POC fluxes (due in large part to operational differences in calculation, as discussed above) with the separate issue of POC export flux from the euphotic zone and of natural variability versus uncertainty in POC/^{234}Th ratios and $^{234}Th:^{238}U$ disequilibrium.

Specifically, BNC2004 states: ''That POC/^{234}Th ratios may vary within an individual study does not imply that the POC fluxes are uncertain by a similar magnitude as stated on page 1025 in M2003.'' In fact, the calculated POC flux does vary with the POC/^{234}Th ratio within an individual study area due primarily to the depth dependence of the POC/^{234}Th ratio. That is, the POC flux calculated using matched depths for the ^{234}Th integration and POC/^{234}Th ratio above the base of the euphotic zone will typically be higher, due to higher POC/^{234}Th ratios. Below the base of the euphotic zone, the calculated POC flux will typically be lower, due to lower POC/^{234}Th ratios that result from remineralization of POC with depth. The outstanding question that remains is, how representative are these published POC fluxes across particular depth horizons of the ''true'' POC export flux?

BNC2004 also states that Moran et al. (2003) erroneously attribute natural variability in POC fluxes among stations to variability implicit in the use of different data reduction methods. However, the comparisons of range in POC fluxes calculated by Moran et al. (2003) and plotted in fig. 4 of that article are performed on an individual station basis—not averaged or compared across all stations, as stated by

BNC2004. Figure 4c in Moran et al. (2003) clearly indicates calculated POC fluxes compared for individual stations: Sta. 9 POC flux = 3.7–30 mmol C m^{-2} d^{-1}; Sta. 18 POC flux = 4.7–38 mmol C m^{-2} d^{-1}; and Sta. 25 POC flux = 3.7–47 mmol C m^{-2} d^{-1}. These results are also tabulated in the same manner in table 2 of that study. The only space-saving measure in Moran et al. (2003) is in the lines plotted in fig. 3 (a–d, f–h, and j–l) that represent average values for these parameters in order to facilitate a qualitative comparison in their respective distributions between stations. Clearly, the lines representing average values are not used in a quantitative manner.

We concur with the authors of BNC2004 that the methods used to collect particulate matter for the determination of POC/^{234}Th ratios introduce yet another measure of uncertainty in calculating POC export fluxes. Although this is discussed in Moran et al. (2003), the focus of their study was not to evaluate differences in POC/^{234}Th ratios due to differences in collection methods using in situ pumps, water bottles, and sediment traps. While this separate issue is certainly worth pursuing, a thorough and comprehensive study of this kind has yet to be conducted. It would be premature of Moran et al. (2003), whose samples were all collected by a single method, to conclude that the difference in POC/^{234}Th ratios measured by these various sampling techniques ''. . . drives the largest uncertainties associated with determining upper ocean POC/^{234}Th ratios and hence ^{234}Th-derived POC fluxes,'' as stated in BNC2004.

The key question that emerges from the analysis of Moran et al. (2003) is, How representative are the published estimates of ^{234}Th-derived POC export flux of ''true'' export production at the base of the euphotic zone? In attempting to answer this question, they provide (1) a critical discussion of published studies of POC export flux using ^{234}Th as a tracer; and (2) an assessment of the inherent uncertainty of this technique. The ^{234}Th technique, like sediment traps and other techniques, has both advantages and disadvantages—no method is perfect—and these are discussed in detail in Moran et al. (2003). One can and should dispute the relative merits of these techniques, which is what Moran et al. (2003) have focused on. Perhaps the most important aspect of the Moran et al. (2003) study is that careful attention needs to be paid to past and future studies using ^{234}Th as a tracer of POC export flux, particularly the operational differences that have characterized its use during the past decade.

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