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Editorial: Natural and artificial radionuclides as tracers of ocean processes

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Editorial on the Research Topic
Natural and artificial radionuclides as tracers of ocean processes

Introduction

The global oceans are a repository of radionuclides, both naturally occurring and anthropogenic, the latter originating predominantly from fallout from past atmospheric nuclear weapons tests, discharges from nuclear reprocessing plants and releases following accidents at nuclear facilities. The sources and physical and geochemical properties (e.g., radioactive half-life, solubility, particle reactivity and bioavailability) of these radionuclides vary broadly, giving rise to their use as radiotracers and providing a rich collection of tools for improving our understanding of ocean dynamics and processes. This Research Topic demonstrates how physical oceanographers and marine biogeochemists are currently moving beyond the state-of-the-art in the application of these radiotracers for increasing our knowledge of water circulation, particle cycling and fluxes, sedimentation processes, paleoceanography and more.

Even so, more comprehensive use of radionuclides as tracers in ocean science can be hindered by various factors, including instrumental limitations, complex and laborious analytical procedures, sparse observation data and methodological uncertainty. Looking forward, we also consider below ways in which these are already being overcome.

Tracing water mass movement

Conservative radionuclides with known historical inputs in seawater can be used to track the movement of water masses, both at surface and abyssal layers, thus unraveling pathways, mixing regimes, transit times and ventilation rates. Point-source discharges of radionuclides from nuclear facilities, e.g., ^{129}I and ^{236}U and other radionuclides from the two European reprocessing plants (La Hague and Sellafield), provide a valuable means for tracking Atlantic water transport pathways (Castrillejo et al.), and for finger-printing water mass compositions and determining circulation timescales (Wefing et al.) in the North Atlantic and Arctic Ocean. Anthropogenic radionuclides (e.g., ^{137}Cs) distributed at global or regional scales are useful tracers for validating and refining ocean-earth system models (Maderich et al.), thus facilitating improved projections of future changes in ocean circulation and the fate of contaminants in the marine environment under a changing climate. In addition, radioisotopic signatures can be exploited for estimating deep-water residence times, revealing mechanisms leading to deep-water formation [e.g., $\Delta^{14}C$ in dissolved organic carbon (Zeidan et al.)], and for deriving vertical mixing patterns in the water columns and providing holistic insights into geochemical cycles of carbon and nutrients in the ocean [e.g., ^{226}Ra-^{228}Ra (Tazoe et al.; Cho et al)].

Tracing particle dynamics

Combinations of radionuclides with different half-lives and geochemical properties can be used to estimate the rates of particulate organic carbon (POC) export to the deep ocean. The naturally occurring ^{234}Th-^{238}U radionuclide pair has been widely used to quantify the sinking flux of POC. The effects of horizontal advection and vertical diffusion (Yang et al.) can be taken into account for improved evaluation of uncertainties in the POC flux estimation using ^{234}Th-model. Coupling of signals from both radioisotopes and stable isotopes enhances the tracer approach in biogeochemical studies for understanding changes in ecosystems, e.g., by using a $\delta^{13}C$-$\delta^{15}N$-$\Delta^{14}C$ multi-isotope approach for discerning the sources and cycling of particulate organic matter (POM) in the deep ocean basin (Fox and Walker), and by studying the fractionation of stable Ba and radioactive ^{226}Ra for verifying uncertainty in the use of ^{226}Ra for marine carbonates dating (Beek et al.).

Constructing sediment chronology

Construction of sediment chronologies has been widely carried out based on dating methodologies using other naturally occurring radionuclides, e.g., ^{210}Pb and ^{14}C (Li et al.), which facilitate insights into paleoclimate records and understanding of past climatic and oceanographic variabilities. For probing more recent changes, anthropogenic radionuclides, especially those resulting from global fallout from atmospheric nuclear weapon tests (e.g., ^{14}C, ^{137}Cs, $^{239,240}Pu$, ^{241}Am), provide additional benchmarks to the sediment age-depth models.

The way forward

Advancements in analytical techniques have paved the way for the application of novel radiotracers. Continuing enhancement of techniques such as Accelerator Mass Spectrometry (AMS) is key for the future development of new tracers in the oceans. In the last decade, this has led to the emergence of long-lived radionuclides such as ^{236}U and ^{233}U as novel ocean tracers. Applied both individually and in combination with other AMS-measured radionuclides such as ^{129}I and ^{14}C, these have been proven invaluable for understanding ocean physical processes (Wefing et al.). Other recent developments in measurement techniques, such as Ion-Laser Interaction Mass Spectrometry (ILIAMS) (Hain et al.), enable the determination of radionuclide concentrations in seawater samples at ultra-low levels and have facilitated the development of novel radiotracers (e.g., ^{135}Cs).

There are many other radiotracer applications which are not covered in depth by this Research Topic but which also have the potential to revolutionize the field of tracer oceanography. New measurement techniques such as Atom Trap Trace Analysis, (a laser-based atom counting method that can reach atomic ratios as low as 10^{-16}) are emerging as powerful alternatives to the decay counting techniques that will complement the ones mentioned above and expand the suit of radionuclides (e.g., ^{81}Kr, ^{85}Kr and ^{39}Ar) available to understand oceanic processes and timescales.

Sparse observation data coverage is a major obstacle hindering broader and more comprehensive research of ocean processes utilizing radiotracers. Marine sampling campaigns and sophisticated laboratory analyses are both expensive and time-consuming. A means of mitigating this is for researchers to share their measurement results openly and accessibly, thus enabling re-use of existing data for a range of activities, such as comparison with new observations, background research for new projects, and conducting reanalysis to address new research questions.

The Marine Radioactivity Information System (MARIS), managed and developed by the IAEA Marine Environment Laboratory in Monaco, is a data portal that provides open access to a broad range of radionuclides measurements in coastal and open ocean seawater, marine sediment and biota. Currently, more than 800,000 measurements are available, sourced mainly from scientific articles and national and regional databases, covering all areas of the global oceans and from 1957 up to the present day. MARIS is currently being developed to offer improved means of identifying and accessing data, higher quality and richer metadata and support to data management principles such as FAIR and GEO. The IAEA welcomes all submissions of relevant datasets and suggestions for further enhancement.

In summary, to continue to broaden the use of radionuclides in oceanographic research, we foresee the need for further development of novel and emerging radiotracers for oceanographic studies, itself directly related to further advances in cutting-edge measuring techniques, and of open-source data platforms.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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