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Deposition patterns on the Chukchi shelf using radionuclide inventories in relation to surface sediment characteristics

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ABSTRACT

Forty sediment cores collected on the Chukchi shelf and adjacent portions of the East Siberian Sea have been assayed for the sedimentation tracer ^{137}Cs and 34 were also assayed for ^{210}Pb. While both sedimentation and bioturbation influence how these tracers are distributed vertically in sediment cores, only about half of the cores had distinct, single mid-depth or subsurface maximum activity peaks associated with ^{137}Cs originating from bomb fallout. For the same reasons, only 14 of the 34 cores assayed showed a consistent decline in excess sedimentary ^{210}Pb with depth in the core. Furthermore, sedimentation rate estimates from ^{210}Pb assays were only consistent with estimated ^{137}Cs sedimentation rates in 4 of the 14 cores from north of Bering Strait. A high degree of bioturbation on the shelf is primarily responsible for these patterns, but the influence of sedimentation on vertical profiles is also important, particularly in areas of low accumulation where shallow burial of maximum burdens of ^{137}Cs in high current areas such as Herald Canyon can be observed. Shallow burial of radiocesium is also observed in comparatively low sedimentation areas such as Hanna Shoal, on the northeast Chukchi Shelf. By contrast, elsewhere on the northeast Chukchi Shelf and in productive benthic "hotspots," the stronger influence of bioturbation leads to radiocesium that is more evenly distributed vertically within sediments, i.e., no distinct mid- or subsurface depth maximum activity associated with bomb fallout. These sediment profiles of radiocesium reflect several other sediment characteristics that are affected by current flow. These sediment characteristics in turn impact biological activity, including grain size, carbon to nitrogen ratios of the organic fraction of surface sediments and total organic carbon content. The distribution patterns of the radionuclides, particularly the depth where ^{137}Cs reaches maximum activity, reflects sedimentation under both quiescent and strong currents. The activity of ^{137}Cs at that depth of maximum activity provide insights on how much the vertical distribution of the radionuclide has been impacted by bioturbation, as well as the characteristics of the sediments that play a role in influencing deposition and total inventories of radiocesium on continental shelves.

1. Introduction

Sedimentation rates and associated processes that control the accumulation of materials on the sea floor are critical to understanding linkages between pelagic and benthic systems (Hargrave, 1973; Grebmeier et al., 1988). Radionuclides such as ^{137}Cs and ^{210}Pb can be used in many circumstances to help improve our understanding of links to water column sedimentation and burial of potential contaminants [e.g. Koide et al. (1972); Robbins and Edgington (1975); Smith and Walton (1980)]. On shelves in the North American Arctic, recognition of strong pelagic-benthic coupling between seasonally productive water column and underlying shallow, broad shelves has led to several prior studies documenting sedimentation rates and accumulation patterns of specific radionuclides (e.g. Baskaran and Naidu, 1995; Cooper et al., 1998a; Cooper et al., 2005, Pirtle-Levy et al., 2009; Oguri et al., 2012; Trefry et al., 2014).

We expand on these earlier studies here by presenting radionuclide data from 40 cores collected at a wide variety of locations on the Chukchi and East Siberian shelves during programs supported by the US National Oceanic and Atmospheric Administration (the Russian-American Long-term Census of the Arctic—RUSALCA), and the US Bureau of Ocean Energy Management (Chukchi Sea Offshore Monitoring in Drilling Area —COMIDA Chemistry and Benthos and COMIDA Hanna Shoal). Each of these programs had different goals. For example, the COMIDA program, concerned about the fate of contaminants associated with oil and gas drilling on the Chukchi Shelf, required a better understanding of the dynamics and depth of bioturbation in shelf sediments to determine how long contaminants might

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persist near the sediment surface. The RUSALCA program was motivated by the need for better understanding of arctic biodiversity, so determining the relationship of overlying water production on the structuring of marine benthic communities and associated sediment characteristics was important. In the data presentations, a hyphen following the station name (e.g. UTX8-) precedes the station number (40 in UTX8-40) for the 2009 and 2013 cruises that were supported through the COMIDA program. RUSALCA stations are simply presented by name (e.g. HC22).

1.1. Radionuclide sources and distributions

We used the two widely used radioisotopes mentioned above, ^{137}Cs and ^{210}Pb, to meet these individual project objectives. ^{137}Cs is a bomb fallout product (30.2 year half-life) with a maximum deposition on the Earth's surface coinciding with the signing of the Limited Nuclear Test Ban Treaty in 1963, which ended most atmospheric nuclear weapons testing. Other secondary sources include the Chernobyl and Fukushima–Daiichi nuclear plant accidents, point pollution sources such as the La Hague (France) and Sellafield (UK) nuclear fuel cycle reprocessing plants, nuclear weapons manufacturing and waste generation facilities such as Hanford (Columbia River, USA) and Zheleznogorsk (Yenisei River, Russia). As an alkali metal, cesium is highly soluble in water and most radiocesium in the world ocean remains dissolved. It reaches the sediments through (1) sorption on clay particles in soils that are eroded into the ocean, (2) uptake or authigenesis at the sediment-water interface, and (3) biological uptake (Noshkin and Bowen, 1973; Livingston and Bowen, 1979; Ritchie and McHenry, 1990; Avery, 1996). The depth of penetration of the radionuclide and the distribution of the radioisotope in sediments reflects both sedimentation rates and bioturbation because no ^{137}Cs was present on Earth prior to development of nuclear weapons in the late 1940s. Given the stratospheric bomb fallout maximum in 1963–1964, a sedimentation rate can be estimated, where bioturbation has not obscured the maximum, by dividing the sediment depth where the radiocesium peak occurs by the number of years between core collection and 1964. We define sedimentation broadly here to include re-distribution of ^{137}Cs on fine clay particles during re-suspension events or transport by bottom boundary currents as well as the initial sedimentation of the isotope from bomb fallout. The available evidence from the Bering and Chukchi shelf and slope (e.g. Pirtle-Levy et al., 2009) suggests initial sedimentation is usually more important than re-suspension events because mid-depth or sub-surface maxima in radiocesium are preserved in many cores, and most cores outside of areas with known high bioturbation also show lower activities in recent years in the surface increments of the cores.

^{210}Pb is another independent tracer of sedimentation (Koide et al., 1972). It is a natural radioisotope (22.3 year half-life) that is a daughter product of the ^{238}U decay series. Some ^{210}Pb is present that falls to the Earth's surface because one of the immediate precursors to ^{210}Pb in the uranium decay series is the radioactive gas ^{222}Rn. Sedimentation studies of this radionuclide require determining the "supported" or background activities of ^{210}Pb in the sediments by determining an inventory of the radionuclide present naturally without considering the contributions of "excess" ^{210}Pb that is derived from atmospheric deposition (as radon decays). Once the supported ^{210}Pb inventory has been determined, a sedimentation rate can be estimated by plotting the logarithm of the excess ^{210}Pb activity against the mid-depth point of each core increment where ^{210}Pb declines steadily with depth. The decay constant for ^{210}Pb we use here is -0.01352 year^{-1} for convenience with plots of base 10 logarithms of excess activity (-0.031 yr^{-1} can be used alternatively for the natural log of excess activity that reflects the 22.3 year half-life). This activity coefficient is then divided by the calculated slope of this line relating sediment depth to the logarithm of the excess activity. Expressed as a formula, sedimentation is estimated from the best-fit equation,

$$sedimentation\ \ rate = \lambda/b$$

where λ is the ^{210}Pb decay constant (-0.01352; for data plotted logarithmically) and b is the slope of the best-fit equation relating log excess radioactivity to the mid-point of each depth increment in the regression. Activity in the surface mixed layer, and below the point at which ^{210}Pb activities decline to a background level supported by in-situ radioactive decay are excluded from the calculated slope.

1.2. Synthesis with other available data

In addition to the specific radionuclide data that we present here, large data sets documenting other sediment characteristics have become available on the Chukchi Shelf within the past decade, including distributions of grain size, organic content and elemental and isotopic ratios of that organic content, sediment chlorophyll inventories as a function of settling organic matter, benthic biomass, taxonomic distributions and other indicators (e.g. Grebmeier et al., 2006; Dunton et al., 2012; Grebmeier and Cooper, 2014; Grebmeier and Cooper, 2016; Cooper et al., 2015; Grebmeier et al., 2015). Many of these sediment characteristics vary in response to water masses that influence productivity and sedimentation, which can in turn impact bioturbation within the sediments by supporting benthic communities. In addition, the intensity of flow northward across the shelf also plays a key role in structuring benthic biological communities, which can be dominated by epibenthic filter feeders in areas of high current flow (Bluhm et al., 2009; Pisareva et al., 2015), or infaunal macrofaunal communities where deposition of organic materials sustains deposit feeding benthic organisms (Grebmeier et al., 2015).

In this study, we synthesize some of the available data sets from the Chukchi Shelf to determine whether the characteristics of surficial sediments and benthic communities are coupled closely to insights provided by direct sedimentation measurements provided by radionuclide profiles. The synthesis challenge that we sought to address in this study was whether the large and diverse data sets that have become available for the Chukchi Shelf sediment characteristics and benthic communities could be linked to the measurements of direct sedimentation provided by the radionuclides studied. Sedimentation is modulated by bioturbation, which is a function of benthic biological activity. Characteristics of flow and currents across the broad shelf also impact the sedimentation of materials to the sea floor, while also influencing the structure of benthic biological communities. We use these sediment data that were acquired on the same research cruises where the sedimentation cores were collected in order to explore these complexities.

The sediment characteristics that were evaluated in the context of the sedimentation studies undertaken with the radionuclides included sediment grain size, C/N ratios and total organic carbon (TOC) in surface sediments, and the inventories of sediment chlorophyll present in surface sediments. On the Chukchi Shelf, the predominance of fine sediment grain sizes is one of the single best key predictors for biomass of benthic biological community structure (Grebmeier et al., 2006), which would be expected to influence the depth and degree of bioturbation. TOC in surface sediments is interrelated with benthic productivity and is also a significant predictor of benthic biomass (Grebmeier et al., 2006). In addition, TOC is an indicator of current flow regimes, with higher TOC associated with slower current speeds (Pisareva et al., 2015). Significantly, on the Chukchi Shelf, activities of ^{137}Cs, which is preferentially bound to clay mineral surfaces, are also related to fine sediment content and TOC, (Cooper et al., 1998a) so it should be expected that regional variation in the total inventories of radiocesium in sediments will be related in part to current regimes through their influence on fine particle deposition. C/N ratios in the organic fraction of surface sediments provide an index of food quality reaching the sea floor with lower C/N ratios reflecting areas of enhanced marine deposition of pelagic marine production (Grebmeier and McRoy, 1989; Grebmeier et al., 2006). Finally, the inventory of active chlorophyll