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Glimpses of Arctic Ocean shelf–basin interaction from submarine-borne radium sampling

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ABSTRACT

Evidence of shelf-water transfer from temperature, salinity, and $^{228}Ra/^{226}Ra$ sampling from the nuclear submarine *USS L. Mendel Rivers* SCICEX cruise in October, 2000 demonstrates the heterogeneity of the Arctic Ocean with respect to halocline ventilation. This likely reflects both time-dependent events on the shelves and the variety of dispersal mechanisms within the ocean, including boundary currents and eddies, at least one of which was sampled in this work. Halocline waters at the 132 m sampling depth in the interior Eurasian Basin are generally not well connected to the shelves, consonant with their ventilation within the deep basins, rather than on the shelves. In the western Arctic, steep gradients in $^{228}Ra/^{226}Ra$ ratio and age since shelf contact are consistent with very slow exchange between the Chukchi shelf and the interior Beaufort Gyre. These are the first radium measurements from a nuclear submarine.

1. Introduction

It is now over a century ago that Nansen (1902) recognized the extensive influence on the upper Arctic Ocean of the surrounding shelf seas. Sixty years later, seminal discussions by Coachman and Barnes (1961, 1962) of both the Pacific and Eurasian shelf influences on the Arctic Ocean, including summaries of Russian work during the intervening years, renewed widespread interest in the topic. The focus was subsequently sharpened by Aagaard et al. (1981), who argued the particular importance to the Arctic Ocean of its pronounced halocline and proposed shelf connections to that feature. Since then, numerous studies, and indeed whole research programs, have been dedicated to interactions between the Arctic Ocean and the adjacent shelves (for examples cf., Killworth and Smith, 1984; Jones and Anderson, 1986; Wallace et al., 1987; Rudels et al., 1996; Schauer et al., 1997; Steele and Boyd, 1998; Grebmeier and Harvey, 2005; Woodgate et al., 2005a).

Initially, attention was concentrated on the role of plumes in moving shelf waters offshore (Melling and Lewis, 1982), but later the interest shifted to other processes, including transfer along the continental margins and ridges by topographically constrained boundary currents (Aagaard, 1989), offshore fluxes forced by double-diffusive mechanisms (Carmack et al., 1997) or resulting from partial breakdown of the boundary currents (Smith et al., 1999), and eddies propagating into the interior from a baroclinically unstable boundary current (Pickart et al., 2005).

Here, we discuss such shelf-water transfer processes, using temperature, salinity, and radium isotope ratio ($^{228}Ra/^{226}Ra$) measurements from the nuclear submarine *USS L. Mendel Rivers* SCICEX accommodation cruise in October, 2000. The ^{228}Ra is derived from shelf sediments and is therefore a specific marker for waters that have resided on the shelves, and the use of the isotopic ratio

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precludes complications arising from possible biological or particle uptake of radium. Moreover, the half-life of ^{228}Ra (5.77 yr) is comparable to advective time scales within the Arctic Ocean, but much shorter than the half-life of ^{226}Ra (1620 yr), so that the isotopic ratio provides a useful estimate of the time elapsed since the waters left the shelf (e.g., Rutgers van de Loeff et al., 1995, 2003; Kadko and Muench, 2005; Kadko et al., 2008).

2. Methods

Unlike the earlier dedicated SCICEX scientific submarine cruises that included civilian scientists, accommodation cruises allow scientific sampling, but without civilian participation at sea (Arctic Ocean Science, SCICEX 2000 workshop report, 1999). Onboard biological and chemical analyses of water samples are therefore not possible, and water must be stored for later analysis ashore. Determination of dissolved oxygen, for example, is effectively eliminated.

To sample radium, approximately 130 l of seawater were collected from a hull intake port and filtered at ~0.7 l min^{-1} through a manganese-coated acrylic fiber which adsorbs radium isotopes efficiently and without fractionation (Moore et al., 1985). The fibers were subsequently sealed in plastic petrie dishes and then counted ashore by gamma-spectrometry using established procedures (e.g., Michel et al., 1981; Rutgers van de Loeff et al., 1995, 2003; Kadko and Muench, 2005). The water draw and filtration occurred at a depth of 132 m while the submarine was underway, and typically each sample required ~3 h and up to ~90 km of cruise track.

Temperature and salinity were obtained from SeaBird SBE-19 CTDs mounted external to the hull near the top of the sail, 15 m above the keel. (Note that the seawater intake for the radium draw was approximately 14 m below the CTD.) The two SeaBirds were calibrated both pre- and post-cruise, and on that basis we judge them accurate to better than 0.01 °C and 0.01 in salinity. In addition, expendable CTDs (XCTDs) were launched from the submarine approximately every 30–45 km, depending on the location. These probes sampled from near-surface to ~1000 m. The linear regression of a 20% sub-sample of the XCTD profiles, sampled at 118 m, with the corresponding SeaBird values yields an expected difference of ~0.3 °C and 0.1 in salinity, with the XCTD sample being colder and fresher. The discrepancies are, respectively, about 10 and 5 times greater than the XCTD manufacturer's published accuracy. In contrast, comparison of ship-based SeaBird 911 data with XCTD casts in the same environment (Kadko et al., 2008) has shown agreement close to the published XCTD accuracy (~0.02 °C and ~0.03 in salinity). Examination of individual CTD/XCTD data pairs, i.e., from the same time and location, suggests that the discrepancy is most pronounced in areas of large vertical gradients along the SCICEX track. Very likely, this reflects the inability of the sail-mounted CTDs to sample an undisturbed environment, but rather bias the measurements toward the deeper values intercepted by the hull, in this case warmer and more saline. In contrast, the XCTDs do not distort the temperature and salinity fields, but their accuracy is less. Faced with this dilemma, we have chosen to accept the XCTD profiles as correct, with accuracy limits approximately as specified by the manufacturer, consonant with the findings of Kadko et al. (2008). This does not have serious consequences for our analysis, since we primarily use the XCTD sections to examine features of the density field and the temperature and salinity of the water sampled for radium over approximately 90 km track segments (Table 1).

Although additional sensors (dissolved oxygen, transmissometer, and fluorometer) were mounted on the sail, all of these sensors failed before the start of data recording.

The sampling began in the northern Nansen Basin, extended across the Amundsen Basin and the Lomonosov Ridge, the northern Makarov and Canada basins, and the eastern Chukchi Borderland (CBL), thence westward over the Chukchi continental slope (Fig. 1). The trans-Arctic portion follows the 1998 and 1999 SCICEX tracks between 85°N, 46°E and 72.5°N, 155.75°W. This track segment was conducted as a straight, continuous transect, and the radium samples reported here were from 132 m depth. The track segment midpoint for each radium filtration is shown in Fig. 1 along with the measured ^{228}Ra/^{226}Ra ratio.

3. Results

The results are listed in Table 1. The salinity distribution in the upper 300 m (Fig. 2) reflects the relatively saline upper waters on the Eurasian side of the Arctic Ocean (Schauer et al., 2002) grading into the large freshwater storage of the upper Canada Basin (Aagaard and Carmack, 1989), with the isohalines rising again over the Beaufort slope (Aagaard, 1984; Pickart, 2004), indicative of the Pacific water influence upon flows along the basin boundary.

3.1. Rapid eddy transfer

By far the highest ^{228}Ra/^{226}Ra ratio observed in the section is the value 1.60 found near the southeast flank of the Northwind Ridge in the Canada Basin (Fig. 1; sample 26, Table 1), representing water that has been in recent contact with shelf sediments. The density distribution along this portion of the section (Fig. 3) shows that a portion of the radium sample was taken within the upper half of an anti-cyclonic eddy that extended downward from the bottom of the mixed layer to almost 400 m. The eddy radius was no larger than the separation of the XCTD casts, about 44 km, and probably considerably less, since halocline eddies typically have a diameter of 30 km or less (e.g., Muench et al., 2000). The thermal wind velocity maximum was near 200 m, where the isopycnal slope changes sign with depth. Water properties at 200 m in the eddy core were near −1.8 °C and 33.65 in salinity, corresponding to a potential density of 1027.08 kg m^{-3}. The observed eddy core is identical in temperature to those found by Muench et al. 2000 and Pickart et al. 2005 for cold-core halocline eddies, but more saline by ~0.4