

6-16-2005

# Interaction of sea ice sediments and surface sea water in the Arctic Ocean: Evidence from excess $^{210}\text{Pb}$

M. Baskaran

Wayne State University, baskaran@wayne.edu

---

## Recommended Citation

Baskaran, M. (2005), Interaction of sea ice sediments and surface sea water in the Arctic Ocean: Evidence from excess  $^{210}\text{Pb}$ , *Geophys. Res. Lett.*, 32, L12601, doi:10.1029/2004GL022191.

Available at: <http://digitalcommons.wayne.edu/geofrp/7>

This Article is brought to you for free and open access by the Geology at DigitalCommons@WayneState. It has been accepted for inclusion in Geology Faculty Research Publications by an authorized administrator of DigitalCommons@WayneState.

NOTICE IN COMPLIANCE WITH PUBLISHER POLICY: Copyright © 2005 American Geophysical Union. Available at <http://dx.doi.org/10.1029/2004GL022191>. Further reproduction or electronic distribution is not permitted.

# Interaction of sea ice sediments and surface sea water in the Arctic Ocean: Evidence from excess $^{210}\text{Pb}$

M. Baskaran

Department of Geology, Wayne State University, Detroit, Michigan, USA

Received 8 December 2004; revised 10 May 2005; accepted 13 May 2005; published 16 June 2005.

[1] We measured the activities of  $^{210}\text{Pb}$ ,  $^{226}\text{Ra}$ ,  $^{238}\text{U}$  and  $^{137}\text{Cs}$  in a suite of ice-rafted sediments (IRS) from the Arctic Ocean in an attempt to assess the interaction of sea ice sediments and surface water. The concentrations of these nuclides were compared to those of the benthic sediments in the coastal and shelf regions of the Arctic Ocean, which are believed to be the major source region for the IRS. The concentration factors (CF = activity of a nuclide in IRS/average activity in benthic sediments) are  $\sim 1$  and 4–92 for  $^{137}\text{Cs}$  and  $^{210}\text{Pb}$ , respectively. The CF values for  $^{137}\text{Cs}$  are comparable to the values that can be obtained from the previously published data while we report the first set of high CF values of  $^{210}\text{Pb}$ . A major portion of  $^{210}\text{Pb}$  in some IRS samples is likely derived from surface waters and thus, the concentrations of  $^{210}\text{Pb}$  combined with another particle-reactive radionuclide (such as  $^7\text{Be}$ ,  $^{234}\text{Th}$ ) in IRS might provide information on the residence time and transit time of sea ice-laden sediments. **Citation:** Baskaran, M. (2005), Interaction of sea ice sediments and surface sea water in the Arctic Ocean: Evidence from excess  $^{210}\text{Pb}$ , *Geophys. Res. Lett.*, 32, L12601, doi:10.1029/2004GL022191.

## 1. Introduction

[2] The extent, composition, thickness, and drift patterns of sea ice in the Arctic can influence the exchange of heat and gases between the ocean and the atmosphere, thus affecting the global energy balance and oceanic circulation [e.g., *Aagaard et al.*, 1985; *Nürnberg et al.*, 1994]. A major portion of the Arctic Ocean is covered by either perennial or seasonal sea ice. Large amounts of sediments have been reported to be entrained into the ice cover through several processes, including incorporation of suspended sedimentary particles into frazil-ice crystals, uplift of sediments by anchor ice, discharge of river-borne sediments into sea ice, and atmospheric deposition of dust particles [*Darby et al.*, 1974; *Reimnitz et al.*, 1987; *Eicken et al.*, 1997]. A major portion of the sediments are presumably incorporated in the coastal and shelf areas of the East Siberian Arctic region and subsequently transported to other regions in the Arctic [*Reimnitz et al.*, 1987]. This is consistent with the common occurrence of continental shelf foraminifera in the deep Arctic basins, which was attributed to incorporation of benthic sediments into the sea ice in the shallow shelf areas and transport by ice drift [*Wollenburg*, 1993]. The movement of sediments incorporated in the sea ice and glacial icebergs is controlled by the surface currents of the Arctic Ocean and is dominated by the clockwise Beaufort Gyre in

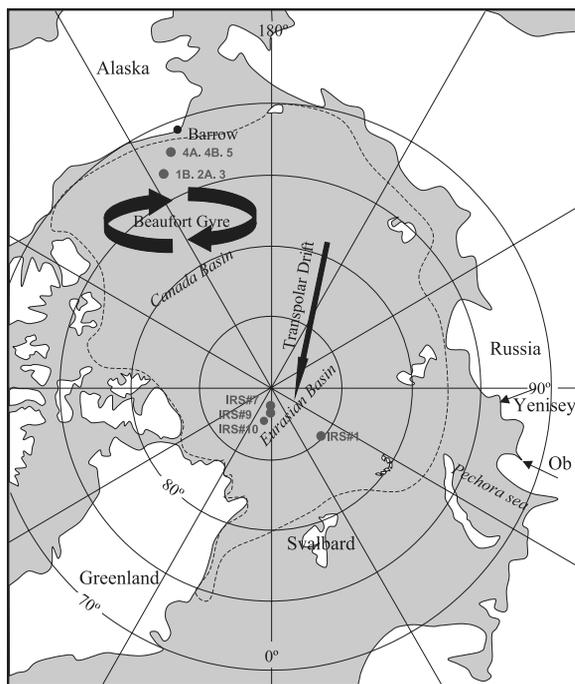
the Amerasian Basin and east flowing Transpolar Drift in the Eurasian Basin [e.g., *Pfirman et al.*, 1995; *Eicken et al.*, 1997; *Tucker et al.*, 1999]. In the limited studies conducted on IRS so far, no exact source areas for sea ice sediments have been located due to the complexity of the drift regime in the Arctic Ocean [e.g., *Nürnberg et al.*, 1994].

[3] The presence of sediments in sea ice affects the radiation balance of the Arctic Ocean. For example, *Tucker et al.* [1999] found an albedo of 0.48 for sea ice with sediments compared to 0.83 for fresh snow. A decreased albedo leads to melting of ice surrounding the sediment, forming pits (cryoconite holes) that ultimately could lead to the concentrated accumulation of sediments at the surface [*Pfirman et al.*, 1995]. Drifting sediment-laden sea ice also may play a key role in the long-range redistribution of contaminants in the Arctic [e.g., *Pfirman et al.*, 1995; *Cooper et al.*, 1998] as well as affect the particle flux to the deep sea [*Hebbeln and Wefer*, 1991]. Further, pollutants derived from the Atlantic and Pacific Ocean surface water currents and atmospheric deposition, mainly through Arctic haze during the winter-spring seasons, have led to increased pollution in sediments and the water column. The sea ice and IRS could potentially serve as atmospheric collectors where the surface ocean is ice-covered. The sediments in sea ice could also pick up additional particle-reactive contaminants during contact with surface waters.

[4] Particle-reactive radionuclides that are delivered to the ocean surface at a known rate, such as  $^{210}\text{Pb}$  (and  $^7\text{Be}$ ), could be used to investigate the accumulation of contaminants from surface waters in sea ice, as well as yield information on the time scale of interaction between IRS and surface water. A comparison of the concentrations of less-particle-reactive and particle-reactive nuclides provides information on the importance of scavenging of particle-reactive nuclides at the sea ice-water interface. We have measured the activities of excess  $^{210}\text{Pb}$  ( $^{210}\text{Pb}_{\text{xs}} = ^{210}\text{Pb}_{\text{total}} - ^{226}\text{Ra}$ ) from a suite of ice-rafted detritus from the Arctic Ocean along with  $^{226}\text{Ra}$ ,  $^{238}\text{U}$  and  $^{137}\text{Cs}$ . Here we report the first set of very high enrichment factors for  $^{210}\text{Pb}$  and discuss the factors and processes that could cause the one- to two orders of magnitude higher activities of excess  $^{210}\text{Pb}$  compared to those in source sediments in the coastal and continental shelves of the Arctic Ocean.

## 2. Materials and Methods

[5] One set of sea-ice rafted detritus (1B, 2A, 3, 4A-B, and 5) was collected from the Canada Basin during summer 2000 and the second set was collected during 2001 from the Eurasian Basin (IRS-1, 7, 9, and 10), from Svalbard to the North Pole (Figure 1). Sea ice samples (10–50 L, yielding



**Figure 1.** Sample location map in the Arctic Ocean. See color version of this figure in the HTML.

10–40 g of dry sediments in Canada Basin and 4–50 g in the Eurasian Basin) were collected and thawed inside the ship. The sediments were separated by decanting the supernatant, after a few days of sediment settling and brought to the laboratory for further analysis. The activities of excess  $^{210}\text{Pb}$ ,  $^{226}\text{Ra}$ ,  $^{238}\text{U}$  and  $^{137}\text{Cs}$  in IRS from the Canada Basin were measured using gamma-ray spectrometry while  $^{210}\text{Pb}$  from the Eurasian Basin were measured using alpha spectrometry [Baskaran and Naidu, 1995]. The activities of  $^{210}\text{Pb}_{\text{xs}}$  and  $^{137}\text{Cs}$  were decay corrected to the date of collection.

### 3. Results and Discussion

[6] The activities of  $^{226}\text{Ra}$ ,  $^{137}\text{Cs}$  and  $^{238}\text{U}$  in IRS (Table 1) are comparable to the values reported for the benthic sedi-

ments in the coastal and continental shelf regions of the Arctic region [Baskaran and Naidu, 1995; Baskaran et al., 1996, 2000; Meese et al., 1997; Landa et al., 1998; Cooper et al., 1998]. In contrast, the activities of excess  $^{210}\text{Pb}$  in IRS are about 1–2 orders of magnitude higher, up to 175 dpm/g. These high values cannot be derived from surface water suspended particulate matter (SPM), which have been found to range from 6.9 to 45.7 dpm/g (mean = 25 dpm/g, 3 data points from 5–10 m in surface waters off Barrow, Alaska; unpublished data). Also, most of the SPM are of biogenic origin while the IRS are of primarily benthic origin. Roberts et al. [1997] reported 330 dpm/g  $^{210}\text{Pb}_{\text{xs}}$  in one particulate matter in sea ice in the Northeast Polynya. Masque et al. [2002] reported  $^7\text{Be}$  and  $^{210}\text{Pb}$  data for a suite of IRS from the western Fram Strait and suggested that the source of  $^7\text{Be}$  and  $^{210}\text{Pb}$  was atmospheric input to the sea ice.

[7] The activities of  $^{137}\text{Cs}$  and  $^{210}\text{Pb}$  in IRS can be compared to possible source sediments in the coastal/shelf areas of the Arctic Ocean. There are no significant variations on the surficial activities of  $^{210}\text{Pb}$  or  $^{137}\text{Cs}$  from different regions of the Arctic Ocean (such as coastal Alaskan waters and Russian marginal seas [Weiss and Naidu, 1986; Baskaran and Naidu, 1995; Baskaran et al., 1996, 2000]). For comparison, the extensive database (for  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$ ) for the surficial sediments in the Ob and Yenisey Rivers, the Kara Sea, and the continental shelf sediments from the Pechora Sea, that have  $^{210}\text{Pb}_{\text{xs}}$  activities ranging up to 6.56 dpm/g (mean = 1.90 dpm/g;  $n = 134$  [Baskaran et al., 1996, 2000]) were utilized. The  $^{137}\text{Cs}$  activities varied from below detection limit to 4.28 dpm/g (mean = 0.75 dpm/g). Using these mean values, the concentration factors (CF = activity in IRS/mean activity in bottom sediments) are  $\sim 1$  for  $^{137}\text{Cs}$  (Table 1), similar to the values calculated from the published data reported for the Arctic Ocean [Cooper et al., 1998; Landa et al., 1998; Meese et al., 1997]. Cesium is not strongly particle-reactive in the marine environment ( $K_d$  (= activity (dpm/g) in the solid/activity in water (dpm/cm<sup>3</sup>))  $\sim 500$  cm<sup>3</sup>/g, IAEA, 1985) and hence the adsorption of  $^{137}\text{Cs}$  from seawater on to IRS is expected to be minimal.

[8] The CF values for  $^{210}\text{Pb}$  vary between 4 and 92, and there are no published data for comparison. As discussed above, benthic sediments in the shelf and suspended sedi-

**Table 1.** Location and Concentrations of  $^{210}\text{Pb}$ ,  $^{226}\text{Ra}$  and  $^{137}\text{Cs}$  in Sea Ice Sediments From the Arctic Ocean

Sample	Latitude, N	Longitude, E/W	$^{210}\text{Pb}_{\text{total}}$ , dpm/g	$^{238}\text{U}$ , dpm/g	$^{226}\text{Ra}$ , <sup>a</sup> dpm/g	$^{137}\text{Cs}$ , <sup>b</sup> dpm/g	$^{210}\text{Pb}_{\text{xs}}$ , <sup>b</sup> dpm/g
IRS-1	85°32'	40°04'E	32.4 ± 1.5	NM	(1.95 ± 0.15)	NM	32.9 ± 1.6 (17.3)
IRS-7	88°44.58'	1°37.73'W	16.8 ± 2.6	NM	(1.95 ± 0.15)	NM	16.0 ± 2.8 (8.4)
IRS-9	88°35.97'	0°43.73'E	102.2 ± 6.4	NM	(1.95 ± 0.15)	NM	108.3 ± 6.9 (57.0)
IRS-10	88°25.3'	6°37.8'W	26.5 ± 1.4	NM	(1.95 ± 0.15)	NM	26.5 ± 1.5 (13.9)
1B	73°15'	153°35.5'W	20.9 ± 0.2	2.88 ± 0.13	2.04 ± 0.09	0.34 ± 0.04 (0.47)	21.0 ± 0.2 (11.1)
2A	73°15'	153°35.5'W	30.7 ± 0.3	2.50 ± 0.66	1.80 ± 0.52	BD	32.2 ± 0.7 (16.9)
3	73°15'	153°35.5'W	20.4 ± 0.2	3.40 ± 0.19	2.17 ± 0.13	0.21 ± 0.38 (0.28)	20.3 ± 0.3 (10.7)
4A	72°40.7'	154°33.5'W	159.0 ± 1.8	3.68 ± 0.33	2.00 ± 0.19	0.75 ± 0.08 (1.0)	175.0 ± 2.0 (92.1)
4B	72°40.7'	154°33.5'W	114.3 ± 1.1	2.19 ± 0.16	1.76 ± 0.13	0.76 ± 0.02 (1.0)	125.5 ± 1.2 (66.1)
5	72°40.7'	154°33.5'W	8.60 ± 0.09	1.93 ± 0.15	1.95 ± 0.14	0.16 ± 0.08 (0.23)	7.4 ± 0.2 (3.9)

<sup>a</sup> $^{226}\text{Ra}$  concentration in IRS-1, 7, 9 and 10 was assumed to be the average of the remaining 6 samples.

<sup>b</sup> $^{210}\text{Pb}_{\text{xs}} = ^{210}\text{Pb}_{\text{total}} - ^{226}\text{Ra}$ ; the error from  $^{222}\text{Rn}$  loss [Imboden and Stiller, 1982] is expected to be very small, as  $^{210}\text{Pb}_{\text{total}} \gg ^{226}\text{Ra}$ ;  $^{210}\text{Pb}_{\text{xs}}$  activities were decay corrected to the time of collection; numbers in parenthesis denote concentration factor, CF. CF = concentration/mean concentration in surficial sediments in Ob, Yenisey Rivers, Kara and Laptev Sea; the mean  $^{210}\text{Pb}_{\text{xs}}$  and  $^{137}\text{Cs}$  activities in 134 samples was found to be 1.90 (range: below detection limit (BD) to 6.56 dpm/g) and 0.75 dpm/g (range: BD to 4.28 dpm/g), respectively [Baskaran et al., 1996, 2000]; NM; Not measured.

ments do not have such high concentrations of  $^{210}\text{Pb}_{\text{xs}}$ . This is true even if finer sediments with potentially greater adsorptive surface areas were selectively incorporated, since studies have shown that there is no significant correlation between the bulk radioactivity and grain size of the IRS [Cooper *et al.*, 1998]. Other sources include direct atmospheric deposition onto sea ice followed by incorporation into sea ice-bound sediments during melting/refreezing cycles; or scavenging by IRS from the underlying water during contact over an extended period immediately after entrainment or by exposure during subsequent reworking of the ice. Of these sources, as discussed before, the benthic sediments do not have sufficiently high  $^{210}\text{Pb}$  to account for the highest IRS values reported here. A comparison can also be made with Pu, another particle-reactive nuclide measured in IRS. The distribution coefficient of Pu (both in the oxidized and reduced form) is comparable to Pb [Sholkovitz, 1983; International Atomic Energy Agency (IAEA), 1985] and hence the concentration factors for Pu and  $^{210}\text{Pb}$  should be comparable. Earlier studies have shown that there is no significant enrichment of Pu in IRS [Landa *et al.*, 1998; Cooper *et al.*, 1998]. However, while  $^{210}\text{Pb}$  is constantly supplied through the atmosphere,  $^{239,240}\text{Pu}$  is a transient tracer with virtually no atmospheric depositional flux since early 1970s. Since Pu is efficiently removed by particle scavenging, most of the Pu in the surface waters derived from the atmospheric fallout in early 1970s has been quantitatively removed.

[9] An estimate on the amount of  $^{210}\text{Pb}_{\text{xs}}$  in IRS contributed by direct atmospheric deposition can be made by assuming that all  $^{210}\text{Pb}$  deposited onto the ice is eventually collected in melt water and scavenged onto IRS. The IRS concentration in dirty sea ice is highly variable, and values ranging between 8 and  $>250 \text{ g m}^{-2}$  have been reported for the Arctic [Nürnberg *et al.*, 1994; Eicken *et al.*, 1997; Tucker *et al.*, 1999]. Assuming a typical IRS concentration of  $100 \text{ g m}^{-2}$ , a residence time of IRS in seasonal ice cover of 3 yrs [Nürnberg *et al.*, 1994], atmospheric depositional flux of  $^{210}\text{Pb}$  of  $0.06 \text{ dpm cm}^{-2} \text{ y}^{-1}$  [Weiss and Naidu, 1986; Baskaran and Naidu, 1995; Huh *et al.*, 1997], then a value for the sediments of  $\sim 18 \text{ dpm/g}$  is obtained, under the assumption that all the atmospherically-delivered  $^{210}\text{Pb}$  is eventually collected onto IRS. This is significantly lower than the three highest values reported in Table 1. Further, it is unlikely that the processes involved are completely efficient, so that only a fraction of  $^{210}\text{Pb}$  is likely to be collected by IRS. However, due to the extremely heterogeneous distribution of sediments and the possible range of the area from which  $^{210}\text{Pb}$  might be scavenged, it is not known how great a range of IRS concentrations can be generated, although reaching values as high as those measured here may be unlikely.

[10] In most oceans, the highest  $^{210}\text{Pb}$  activity in the water column is found in the surface waters due to atmospheric deposition. Surface waters are an obvious source of  $^{210}\text{Pb}$ . Direct scavenging may occur during a prolonged period after entrainment while IRS are at the ice/water interface or at subsequent times when collisions or melting move sediment within the ice back in contact with the water. It may also be possible that ice around sediments becomes porous through processes such as melting due to solar heating of the sediments at the surface, and ice reworking

may submerge these regions and locate them where seawater may pass through. When sea ice melts as a result of solar heating, sediments can be moved by snowmelt and can concentrate in patches. The transfer of  $^{210}\text{Pb}$  from snow or sea ice on to IRS must involve water and hence during this process additional  $^{210}\text{Pb}$  could be picked-up by IRS from water. Overall, each sediment sample may have experienced an involved and different history. The amount of water that must have been scavenged to generate the highest  $^{210}\text{Pb}$  activity ( $175 \text{ dpm/g}$ ) can be obtained using the average concentration of dissolved  $^{210}\text{Pb}$  of  $5.7 \text{ dpm/100L}$  (particulate  $^{210}\text{Pb}$  is  $\sim 10\%$  of this) in the upper 5 m from two stations where 1B and 4A (Table 1) were collected (M. Baskaran, unpublished data). Assuming the  $^{210}\text{Pb}$  was quantitatively scavenged, each gram of the IRS was in contact with  $\sim 3 \text{ m}^3$ , corresponding to a  $K_d$  of  $3 \times 10^6 \text{ cm}^3/\text{g}$ . This  $K_d$  value is comparable to the values reported for  $^{210}\text{Pb}$  in marine setting [IAEA, 1985; Baskaran and Santschi, 2002]. If some of the atmospherically delivered  $^{210}\text{Pb}$  is added to IRS through melting/freezing of sea ice, then, each gram of the IRS need to be in contact with  $<3 \text{ m}^3$  water.

[11] From the discussion above, it appears that a major portion of excess  $^{210}\text{Pb}$  is derived from surface waters by effective sorption onto ice-rafted sediments. Sea ice could undergo considerable recycling during alternating melting/refreezing cycles, leading to varying amounts of contact time with the seawater, and thus affecting the amount of  $^{210}\text{Pb}$  sorbed from seawater. The variations in the activities of  $^{210}\text{Pb}$  clearly indicate that there are differences in the life history of IRS and their extent of interaction with seawater. Recent supplemental data indicate that there are significant differences in Sr- and Nd-isotopic compositions, and so different IRS source regions [Andersson *et al.*, 2004]. In addition, combining  $^{210}\text{Pb}_{\text{xs}}$  activities with those of other short-lived particle-reactive radionuclides, such as  $^7\text{Be}$  and/or  $^{210}\text{Po}$ , could be utilized to determine the residence/transit time of IRS [Masque *et al.*, 2002].

[12] The implication of our observation is that other atmospherically-delivered contaminants such as Hg and other heavy metals and PCBs to the seasonally covered Arctic Ocean surface could significantly concentrate on IRS and be redistributed to farther distances from the source region. Some recent studies suggest the importance of IRS in redistributing particle-reactive nuclides in the upper water column. Recently, Baskaran *et al.* [2003] proposed that particulate matter trapped in porous sea-ice could serve as a sieve, by picking-up additional particle-reactive radionuclides when surface water freely flows through the porous particle-laden sea ice. In addition, the activity ratios of  $^{230}\text{Th}/^{232}\text{Th}$  in particulate matter from the upper 5–10 m in the deep Canada Basin were significantly higher than the crustal average and these were attributed to recycling of sedimentary particles by ice rafting, from ice resulting in additional removal of  $^{230}\text{Th}$  from the water column [Trimble *et al.*, 2004].

#### 4. Conclusions

[13] Combining all the recent evidences, it appears that the scavenging of particle-reactive nuclides is a dynamic and ongoing process, and the time-scale of interaction

between sea ice-laden sediments and surface water at the sea-ice interface can be investigated using a suite of particle-reactive radionuclides (such as  $^{234}\text{Th}$ ,  $^7\text{Be}$ ). Our results indicate that the enrichment factor for  $^{210}\text{Pb}$  in IRS can be very high and the source of this  $^{210}\text{Pb}$  appears to be mainly derived from the interaction of IRS with upper surface waters. We propose that the sea ice and the sediments therein can interact with surface waters, leading to high enrichments of particle-reactive contaminants, both organic and inorganic species.

[14] **Acknowledgments.** The work was supported in part by a grant from the National Science Foundation (NSF-OPP-9996337). The IRS sampling in 2001 was supported by The Swedish Polar Research Secretariat (AO-01). We thank the crews and captains of the POLAR STAR (AWS-2000) and ODEN for their assistance with the sample collection. Constructive reviews from Don Porcelli, Per Andersson, and two anonymous reviewers are deeply appreciated.

## References

- Aagaard, K., J. H. Swift, and E. C. Carmack (1985), Thermohaline circulation in the Arctic Mediterranean seas, *J. Geophys. Res.*, **90**, 4833–4846.
- Andersson, P., M. Baskaran, D. Porcelli, M. Frank, J. Ingri, and O. Gustafsson (2004), The isotopic composition of Sr and Nd in Arctic Ocean ice rafted sediments: Implications for provenance and transport, *Geochim. Cosmochim. Acta*, **68**(11), suppl. S, A338.
- Baskaran, M., and A. S. Naidu (1995),  $^{210}\text{Pb}$ -derived chronology and the fluxes of  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$  isotopes into continental shelf sediments, East Chukchi Sea, Alaskan Arctic, *Geochim. Cosmochim. Acta*, **59**, 4435–4448.
- Baskaran, M., and P. H. Santschi (2002), Particulate and dissolved  $^{210}\text{Pb}$  activities in the shelf and slope regions of the Gulf of Mexico waters, *Cont. Shelf Res.*, **22**, 1493–1510.
- Baskaran, M., S. Asbill, P. H. Santschi, J. M. Brooks, M. A. Champ, D. Adkinson, M. R. Colmer, and V. Makeyev (1996), Pu,  $^{137}\text{Cs}$  and excess  $^{210}\text{Pb}$  in Russian Arctic sediments, *Earth Planet. Sci. Lett.*, **140**, 243–257.
- Baskaran, M., S. Asbill, J. Schwantes, P. H. Santschi, M. A. Champ, J. M. Brooks, D. Adkinson, and V. Makeyev (2000), Concentrations of  $^{137}\text{Cs}$ ,  $^{239,240}\text{Pu}$  and  $^{210}\text{Pb}$  in sediment samples from the Pechora Sea and biological samples from the Ob, Yenisey rivers and Kara Sea, *Mar. Pollut. Bull.*, **40**, 830–838.
- Baskaran, M., P. W. Swarzenski, and D. Porcelli (2003), Role of colloidal material in the removal of  $^{234}\text{Th}$  in the Canada Basin of the Arctic Ocean, *Deep Sea Res., Part I*, **50**, 1353–1373.
- Cooper, L. W., I. L. Larsen, T. M. Beasley, S. S. Dolvin, J. M. Grebmeier, J. M. Kelley, M. R. Scott, and A. Johnson-Pyrtle (1998), The distribution of radiocesium and plutonium in sea ice-entrained Arctic sediments in relation to potential sources and sinks, *J. Environ. Radioact.*, **39**, 279–303.
- Darby, D. L., L. H. Burckle, and D. L. Clark (1974), Airborne dust on the Arctic pack ice, its composition and fallout rate, *Earth Planet. Sci. Lett.*, **24**, 166–172.
- Eicken, H., E. Reimnitz, V. Alexandrov, T. Martin, H. Kassens, and T. Viehoff (1997), Sea-ice processes in the Laptev Sea and their importance for sediment export, *Cont. Shelf Res.*, **17**, 205–223.
- Hebbeln, D., and G. Wefer (1991), Effects of ice coverage and ice-rafted material on sedimentation in the Fram Strait, *Nature*, **350**, 409–411.
- Huh, C.-A., N. G. Piasis, J. M. Kelley, T. C. Maiti, and A. Grantz (1997), Natural radionuclides and plutonium in sediments from the western Arctic Ocean: Sedimentation rates and pathways of radionuclides, *Deep Sea Res., Part II*, **44**, 1725–1743.
- Imboden, D. M., and M. Stiller (1982), The influence of radon diffusion on the  $^{210}\text{Pb}$  distribution in sediments, *J. Geophys. Res.*, **87**, 557–565.
- International Atomic Energy Agency (IAEA) (1985), Sediment  $K_d$ s and concentration factors for radionuclides in the marine environment, *Tech. Rep. 247*, Vienna.
- Landa, E. R., E. Reimnitz, D. M. Beals, J. M. Pochkowski, W. G. Winn, and I. Rigor (1998), Transport of  $^{137}\text{Cs}$  and  $^{239,240}\text{Pu}$  with ice-rafted debris in the Arctic Ocean, *Arctic*, **51**, 27–39.
- Masque, P., J. K. Cochran, D. J. Hirschberg, A. Winkler, D. Dethleff, D. Hebbeln, and S. L. Pfirman (2002), Radionuclides as tracers of transport and sedimentation processes in the Arctic Ocean, extended abstract, paper presented at IAEA Meeting, Vienna.
- Meese, D. A., E. Reimnitz, W. B. Tucker, A. J. Gow, J. Bischoff, and D. Darby (1997), Evidence for radionuclide transport by sea ice, *Sci. Total Environ.*, **202**, 267–278.
- Nürnberg, D., I. Wollenburg, D. Dethleff, H. Eicken, H. Kassens, T. Letzig, E. Reimnitz, and J. Thiede (1994), Sediments in Arctic sea ice—Implications for entrainment, transport and release, *Mar. Geol.*, **119**, 185–214.
- Pfirman, S. L., H. Eicken, D. Bauch, and W. F. Weeks (1995), The potential transport of pollutants by Arctic sea ice, *Sci. Total Environ.*, **159**, 129–146.
- Reimnitz, E., E. W. Kempema, and P. W. Barnes (1987), Anchor ice, seabed freezing, and sediment dynamics in shallow arctic seas, *J. Geophys. Res.*, **92**, 14,671–14,678.
- Roberts, K. A., J. K. Cochran, and C. Barnes (1997),  $^{210}\text{Pb}$ ,  $^{239,240}\text{Pu}$  in the Northeast Water Polynya, Greenland: Particle dynamics and sediment mixing rates, *J. Mar. Syst.*, **10**, 401–413.
- Sholkovitz, E. R. (1983), The geochemistry of plutonium in fresh and marine water environments, *Earth Sci. Rev.*, **19**, 95–161.
- Trimble, S. M., M. Baskaran, and D. Porcelli (2004), Scavenging of thorium isotopes in the Canada Basin of the Arctic Ocean, *Earth Planet. Sci. Lett.*, **222**, 915–932.
- Tucker, W. B., A. J. Gow, D. A. Meese, and H. W. Bosworth (1999), Physical characteristics of summer sea ice across the Arctic Ocean, *J. Geophys. Res.*, **104**, 1489–1504.
- Weiss, R. F., and A. S. Naidu (1986),  $^{210}\text{Pb}$  flux in an Arctic region, *Arctic*, **39**, 59–64.
- Wollenburg, I. (1993), Sediment transport by Arctic sea ice: The recent sediment load of lithogenic and biogenic material, *Ber. Polarforsch.*, **1**–159.

M. Baskaran, Department of Geology, Wayne State University, Detroit, MI 48202, USA. (baskaran@wayne.edu)