Barium as a tracer of Arctic halocline and river waters

C. K. GUAY and K. KENISON FALKNER

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Abstract—Dissolved barium (Ba) concentrations are reported for water samples collected during six oceanographic cruises to the Arctic in 1993 and during the 1994 Arctic Ocean Section. Upper Arctic (<200 m) values ranged widely (19–168 nmol Ba l−1) in a manner geographically consistent with identified sources and sinks. Although surface waters in the eastern part of the Bering Strait and the southern Chukchi Sea were highly enriched in Ba (reflecting the influence of the Yukon River), surface waters over most of the Chukchi Sea were generally depleted in Ba due to the intense seasonal biological activity which occurs in the area. The highest Ba concentrations (≥75 nmol Ba l−1) observed in the surface mixed layer of the Arctic interior (i.e. beyond the 200 m isobath) occurred in the Canada Basin. As a result of the biological removal of Ba from surface waters of the Chukchi Sea and the tendency of the Bering inflow to enter the Arctic interior at depths below the relatively fresher mixed layer, we hypothesize that the Mackenzie River is the dominant source of the high Ba observed in the surface waters of the Canada Basin.

Features characterized by local salinity minima and Ba maxima in surface waters down to depths of 30–50 m were observed over the Arlis Plateau and Mendeleyev Ridge in both 1993 and 1994, and over the Makarov Basin and Lomonosov Ridge in 1994. The physical and chemical properties of these waters suggest that they have been significantly influenced by fluvial discharge. It could not be determined from available data whether these features arose from offshore transport of Eurasian river discharge from the Russian Arctic seas, meanders of the Mackenzie River-influenced Beaufort Gyre, or a branch of Bering inflow that crossed the Chukchi shelf and entrained river water from North American and/or Eurasian sources.

In both 1993 and 1994 Ba concentrations in the upper halocline layer (as defined by a core salinity of 33–1) ranged between 42 and 77 nmol Ba l−1, with highest values observed in the Canada Basin. The Ba maximum and the related nutrient maxima and oxygen minimum that characterize the upper halocline in the Canada Basin suggest sources in the Chukchi and Beaufort seas, and that the mechanism by which these waters are formed is linked with the influx of water through the Bering Strait. The Ba distributions for 1993 and 1994 delineate the lateral extent of upper halocline waters with Canada Basin character and show them to be chemically distinct from upper halocline waters in the Eurasian Basin. The front separating these water types ran roughly along the Mendeleyev and Alpha ridges, consistent with reports that the boundary between Atlantic and Pacific water mass assemblies in the Arctic has recently been displaced from its historical position over the Lomonosov Ridge. Lateral gradients in both Ba and the NO parameter were observed within the lower halocline layer (defined by an NO minimum and core salinity of 34.2–34.4) along the 1994 Arctic Ocean Section, indicating that lower halocline waters receive additional inputs as they transit to the Canadian Basin from their region of formation in the Eurasian sector of the Arctic. © 1998 Elsevier Science Ltd

INTRODUCTION

In this paper, we present dissolved Ba as a naturally occurring chemical tracer that provides new information pertinent to stratification in the upper (<200 m) Arctic Ocean (Fig. 1). Of

College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR, 97331-5503, USA.
particular interest is the utility of Ba for distinguishing between North American and Eurasian components of the total fluvial discharge to the Arctic. The potential of Ba as a tracer of oceanic circulation in the Arctic has been discussed previously, along with preliminary findings for the Bering Strait and the eastern Chukchi and southern Beaufort seas (Falkner et al., 1994). This paper presents the first widescale quasi-synoptic Ba distributions of the Arctic and implications for upper Arctic circulation.

BACKGROUND

Marine geochemical behavior of barium

The biogeochemical behavior of Ba in the marine environment is summarized below and has been reviewed elsewhere in more detail (Falkner et al., 1993, 1994). In general, dissolved Ba tends to be depleted in surface oceanic waters and enriched with depth and along advective flow lines, much like a hard-part nutrient such as alkalinity (which reflects CaCO₃ cycling) or Si (Chan et al., 1977; Lea, 1990; Falkner et al., 1993). This has been attributed to uptake of Ba at the surface as the mineral barite (BaSO₄), which is formed in association with biological particulate matter, and subsequently sinks and can be regenerated at depth or in the sediments (Dehairs et al., 1980; Collier and Edmond, 1984; Bishop, 1988; Dymond et al., 1992). The exact mechanism by which Ba is removed from surface oceanic waters remains the subject of ongoing research (e.g. Fresnel et al., 1979; Dehairs et al., 1987; Bishop, 1988; Bernstein et al., 1992).

Because Ba cycles in a manner similar to that of hard-part constituents, dissolved Ba tends to correlate linearly with dissolved Si and alkalinity in much of the world’s oceans (Bacon and Edmond, 1972; Chan et al., 1977). The slopes and intercepts of the correlation lines vary somewhat with location, in part because these constituents display diverse surface distributions; Si is a biolimiting element that can be depleted to essentially zero concentrations in surface waters, whereas alkalinity is only slightly altered by biological activities. Barium, being biointermediate, lies between the two in that it is measurably, but not fully, depleted. In addition, there exist areas of the oceans (the Arctic being one) where Ba, Si and alkalinity regeneration fluxes are probably decoupled, as barite, opal and carbonate arc subject to different dissolution controls. Being more like opal in this regard, elevated Ba concentrations are observed in sediments underlying the most highly productive areas of the oceans (Revelle, 1944; Revelle et al., 1955; Goldberg and Arrhenius, 1958; Turekian and Tausch, 1964).

The principal external sources of dissolved Ba to the world’s oceans are rivers (Martin and Meybeck, 1979) and hydrothermal venting at mid-ocean ridges (Edmond et al., 1979; Von Damm et al., 1985). Both sources tend to be elevated in Ba content over the seawater into which they arrive; this situation holds true for the major Arctic rivers (Guay and Falkner, 1998). Although the extent to which hydrothermal activity occurs along the extremely slow-spreading Nansen–Gakkel Ridge and in other areas of the Arctic is not well known, most hydrothermal Ba is generally thought to precipitate inorganically as barite in the vicinity of hot spring sources (Von Damm, 1990). Fluvial inputs, in contrast, are enhanced in estuaries where Ba adsorbed onto riverborne clays becomes desorbed in exchange for the more abundant cations of seawater (Hanor and Chan, 1977; Edmond et al., 1978; Li and Chan, 1979; Carroll et al., 1993).
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Physical and chemical tracers of Arctic circulation

Long-term surface circulation derived from modeling of ice buoy data shows two main features: the broad, anticyclonic Beaufort Gyre centered over the Canadian Basin; and a general transpolar drift towards the Fram Strait of waters originating from the region of the Siberian seas (Thorndike and Colony, 1982; Colony and Thorndike, 1985). Exactly how and where Siberian river waters enter the Arctic interior under the ice is unclear. Several chemical tracers, including oxygen isotopes, He–tritium and alkalinity, have been used to investigate the distribution and fate of freshwater in the Arctic surface layer; while measured values vary somewhat geographically, it does not appear to be feasible to distinguish between contributions from different fluvial sources to the Arctic on the basis of their oxygen isotope, tritium or alkalinity signatures.

Based on measurements of all of these tracers in the central Arctic, it has been speculated that Ob and Yenisey waters flow along the Nansen–Gakkel Ridge and/or transit along-shelf toward the Laptev Sea, where they merge with Lena-influenced waters and are then topographically steered along the Lomonosov Ridge into the interior (Jones et al., 1991; Anderson et al., 1994a,b; Schlosser et al., 1995). Unusually fresh, warm waters apparently emanating from the Laptev Sea were observed along the Amundsen flank of the Lomonosov Ridge in 1995 (when ice in the region had retreated farther north than had been observed in the previous 50 years), providing further evidence of the transport of Eurasian river waters in this region (R. Muench, personal communication). None of the data coverage is synoptic or extensive enough to determine whether a significant fraction of river-influenced waters continues further along the Laptev and East Siberian shelves and enters elsewhere into the broad transpolar drift indicated by ice studies. Presuming the Lomonosov Ridge pathway, interpretation of the tritium data (Schlosser et al., 1994) and overall freshwater budgets suggest river waters (Hanzlick and Aagaard, 1980) reside in the Kara Sea on the order of 2–3 years, and that an undetermined fraction of such waters require 5–8 years to transit the interior and exit at the Fram Strait.

Apart from a few ice-camp profiles in the Canadian Basin, the published surface tracer work has been conducted largely in the Eurasian sector of the Arctic (Schlosser et al., 1995 and references therein). In that sector, an oxygen isotope–salinity mass balance has been applied to quantitatively map river water, sea-ice melt and underlying Atlantic components. The situation becomes more complicated for the Canadian sector of the Arctic where waters of Pacific origin, which also bear a river water signal, are present in the upper 200 m. An attempt has been made to derive information about the composition of halocline waters from oxygen isotope data, using silicate as an index of the Bering Sea input; however, this required assumptions about the pathway of Bering Sea water that have yet to be directly observed (Bauch et al., 1995). The longer residence time of ice in the region renders calculations more sensitive to the assumption that the δ¹⁸O signature of sea-ice melt can be characterized by the surface seawater isotopic composition at the site of measurement. Additional tracer information is desirable to fully exploit circulation information in the oxygen isotopic compositions encountered in the Canadian Basin.

It has long been appreciated that the temperature and salinity characteristics of Arctic halocline waters do not reflect a simple mixing of surface water with underlying waters; a variety of processes have been implicated in the establishment and maintenance of a chemically defined structure within the Arctic halocline. A layer within the halocline marked by a distinct maximum in silicate at a salinity of approximately 33.1 is referred to in much
of the literature as the upper halocline (Jones and Anderson, 1986). The only source capable of supplying a signal of the observed magnitude is the Bering inflow (Coachman and Aagaard, 1974; Jones and Anderson, 1986). It has yet to be resolved whether the upper halocline derives directly from a winter Bering input that is moderately salinized by brine injection and/or involves diagenetic remobilization of Si temporarily deposited in association with high productivity in the Chukchi Sea. The limited observations up to 1991 suggested that this upper halocline feature could be found throughout the Canada and Makarov basins, extending across the Lomonosov Ridge to the East Greenland Current. Hydrographic measurements obtained during SCICEX-93 were used to examine the Arctic halocline on a basin-wide scale (Morison et al., 1998). Averaged temperature vs salinity curves, plotted separately for western Arctic and eastern Arctic data, were offset from each other in waters just above and below the upper halocline; but the two curves were indistinguishable (within analytical uncertainty) in the upper halocline itself (defined by Morison et al. (1998) as waters with a salinity of between 32.8 and 33.2, and a temperature of between $-1.3^\circ$C and the freezing line). Assuming that all waters with these temperature and salinity properties comprised one continuous mass, the upper halocline appeared as a relatively thick layer (75–100 m) throughout much of the Canada Basin, thinning and shoaling towards the eastern Arctic, and outcropping at the surface over parts of the Makarov and Amundsen basins in the vicinity of the Lomonosov Ridge.

A lower halocline layer with its core at salinity 34.2–34.4 has been identified on the basis of a minimum in the quasi-conservative NO parameter ($\text{NO} = \{\text{O}_2\} + 9 \times \{\text{NO}_3\}$; Broecker, 1974; Jones and Anderson, 1986). It was initially argued that the NO minimum associated with the lower halocline reflected its region of origin over the Barents and Kara shelves (Jones and Anderson, 1986). Subsequent examination of archived data for the shelves showed that values of NO vary considerably in the shelf seas around the Arctic perimeter. It was proposed that the ratio NO/PO (where $\text{PO} = \{\text{O}_2\} + 135 \times \{\text{PO}_4\}$; Broecker, 1974), which on the basis of available data appeared to be more geographically specific, might better serve as a determinant of the shelf regions from whence lower halocline waters originate (Wilson and Wallace, 1990).

Basin-wide budgets of freshwater, oxygen isotopes and tritium suggest average freshwater residence times in the halocline layer of approximately 10 years (Aagaard and Greisman, 1975; Östlund, 1982; Östlund and Hut, 1984). More detailed studies based on chlorofluorocarbons and oxygen isotopes/tritium/He to obtain ages produce residence times that tend to increase in the vertical in the upper 200 m and vary geographically within the Arctic (Wallace et al., 1987, 1992 and Schlosser et al., 1990, 1994). This work suggests surface waters may be renewed much faster (2–6 years) than halocline waters (up to 15 years).

**METHODS**

*Sampling procedure*

Water samples for Ba analyses were collected during six oceanographic cruises to the Arctic in 1993 and during the Arctic Ocean Section in 1994 (Table 1 and Fig. 2). On all of the cruises, except SCICEX-93 (which took place on-board the nuclear submarine U.S.S. *Pargo*) and Larsen-93, water samples were obtained from depths throughout the water column using standard Niskin bottles deployed on a rosette equipped with a CTD profiler.
Table 1. Oceanographic cruises to the Arctic in 1993 and 1994. At all of the stations occupied, a CTD profiler was deployed to obtain continuous profiles of salinity and temperature. Samples for Ba analyses were not collected at every station.

<table>
<thead>
<tr>
<th>Cruise</th>
<th>Vessel</th>
<th>Dates</th>
<th>Sampling areas</th>
<th>Total number of stations occupied</th>
<th>Stations with Ba samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>HX171</td>
<td>R/V Alpha Helix</td>
<td>11 June–1 July 1993</td>
<td>Bering and Chukchi seas</td>
<td>75</td>
<td>43</td>
</tr>
<tr>
<td>ARK IX/4</td>
<td>R/V Polarstern</td>
<td>10 August–20 September 1993</td>
<td>Barents and Laptev seas, Eurasian Basin</td>
<td>64</td>
<td>56</td>
</tr>
<tr>
<td>SCICEX-93</td>
<td>U.S.S. Pargo</td>
<td>26 August–11 September 1993</td>
<td>Canada, Makarov and Eurasian basins</td>
<td>20</td>
<td>17</td>
</tr>
<tr>
<td>Larsen-93</td>
<td>C.C.G.S. Henry Larsen</td>
<td>29 August–23 September 1993</td>
<td>Chukchi Sea, Canada Basin</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>HX174</td>
<td>R/V Alpha Helix</td>
<td>9 September–10 October 1993</td>
<td>Bering and Chukchi seas, Canada Basin</td>
<td>114</td>
<td>68</td>
</tr>
</tbody>
</table>

*The samples for Ba analyses were collected on the C.C.G.S. Louis S. St-Laurent.

Samples from SCICEX-93 were obtained by casting standard Niskin bottles on a hydrowire deployed from a gantry mounted on the hull of the surfaced submarine. Samples from Larsen-93 were obtained using 10-l BIO bottles deployed on a rosette. Unfiltered samples for Ba analyses were collected in high-density polyethylene (HDPE) bottles previously leached overnight with 1 N HCl at 50°C, rinsed in reverse osmosis-deionized water (RODW) and dried in a laminar flow bench.

Analytical procedure

Barium concentrations were determined for 3699 samples by isotope-dilution inductively coupled plasma quadrupole mass spectrometry (ID-ICPMS) at Oregon State University using a Fisons PlasmaQuad II equipped with an autosampler. The analytical method employed was similar to that described in more detail elsewhere (Klinkhammer and Chan, 1990; Falkner et al., 1993). Sample preparation was carried out entirely in a laminar flow hood. All pipette tips, test tubes and HDPE bottles used for preparing standard and spike solutions were leached overnight with 1 N HCl at 50°C and rinsed copiously with RODW. All HCl solutions used for leaching, sample preparation, instrument washout and blanks were diluted with RODW from 6 N HCl prepared by triple distillation in a quartz apparatus. Aliquots (250 µl) of samples were spiked with an equal volume of $^{135}$Ba-enriched solution (Oak Ridge National Laboratories) and diluted 20-fold with 0-2 N HCl in a polypropylene test tube. Samples were introduced into the instrument via a peristaltic pump ($\approx 1$ ml min$^{-1}$ flow rate) coupled to a Meinhard concentric nebulizer and Scott double bypass spray chamber. The instrument was operated in peak jump mode, monitoring masses...
135 and 138, and acquiring data in three 20-s intervals for each sample. A 4-min washout with 0.2 N HCl was performed after every sample to reduce memory effects. A gravimetric Ba standard (spiked and diluted in an identical manner to the samples) and a 0.2 N HCl blank were inserted between every five samples in the autosampler tray for instrumental offset, drift and blank corrections. The accuracy of the method was verified by frequent analyses of an independent gravimetric barium standard. Applying our analytical method to archived GEOSECS samples, that were spiked upon collection in the 1970s, reproduced GEOSECS values to within 1%. Based on replicate analyses of selected samples and a seawater consistency standard, the analytical uncertainty (2σ) ranges from better than 5% at 10 nmol Ba l⁻¹ to better than 3% at 100 nmol Ba l⁻¹.

RESULTS

1993 cruises: surface mixed layer

For each of the 344 stations occupied between June and October 1993, profiles of both continuous-sensor and bottle-derived temperature, salinity and depth records were examined to determine the depth of the surface mixed layer. At 246 stations a relatively fresh, homogenous, surface layer was observed, separated from underlying waters by a steep salinity gradient; a discontinuity and/or gradient in the temperature profile often coincided with the salinity gradient (Fig. 3a & b). Assigning a depth to the mixed layer at such stations was straightforward. At 98 stations a unique, distinct, homogenous surface layer was not observed and more than one depth could have been assigned to the mixed layer; the majority of such stations were located over the shelves of the marginal Arctic seas, and the structure observed in the surface layer reflects seasonal processes occurring in those areas. An example is HX174 Station 73, located between Wrangel Island and the Siberian coast (Fig. 3c); a depth of 28 m was assigned to the surface mixed layer at this station, but a depth of 8 m would have been another possible choice. Depths assigned to the surface mixed layer ranged from 5 to 46 m, with deeper mixed layers (> 20 m) generally observed in the basins of the Arctic interior, and shallower mixed layers (< 20 m) observed over the shelves and slopes. Exceptions include areas in the central Chukchi Sea and over parts of the slope north of the Laptev Sea where deeper surface mixed layers were observed.

At each station, a mean value of salinity for the surface mixed layer was calculated from all CTD measurements taken at depths within the surface mixed layer. The distribution of salinity in the surface mixed layer is shown in Fig. 4 (the false-color contour images appearing in this paper were generated from the data using the Barnes objective analysis technique (Barnes, 1973; Koch et al., 1983)). Mean surface mixed layer salinity ranged from 25.1 to 33.6. Highest values (32.3-33.6) were observed north of the Barents Sea and over the slope north of the Laptev Sea (adjacent to the region of high salinity north of the Laptev Sea were areas of low salinity (as low as 28) over the shelf near the Novosibirskie Islands and in Vilkitsky Strait). High values (32.8-33.2) also were observed in the Eurasian Basin and central Makarov Basin. Values between 28.5 and 30.0 were generally observed in the Canada Basin, with higher values (30.0-30.5) over the Chukchi Cap and Arlis Plateau, and lower values (26.8-28.5) near the southern edge of the Canada Basin. Mean surface mixed layer salinity in the central Chukchi Sea ranged between 31.0 and 32.0, with lower values (28.0-30.0) in the northern Chukchi Sea and western Chukchi Sea near Wrangel Island, and extremely low values (25.1-27.5) in the western Chukchi Sea along the Russian coast.
Fig. 1. Bathymetry and major rivers of the Arctic.
Fig. 2. Stations occupied during six oceanographic cruises to the Arctic in 1993 and during the 1994 Arctic Ocean Section.
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Fig. 3. Profiles of salinity, temperature and dissolved Ba at: (a) ARCRAD-93 Station 40 north of the Chukchi shelf break in the vicinity of the Chukchi Cap (74.50°N, 166.50°W), occupied on 10 August 1993; (b) ARK IX/4 Station 51 north of the Laptev shelf break (77.86°N, 125.59°E), occupied on 10 September 1993; and (c) HX174 Station 73 between Wrangel Island and the Siberian coast (69.90°N, 177.93°E), occupied on 4 October 1993.

Values in the Bering Strait ranged between 26.9 and 32.6, while values in the Bering Sea ranged between 30.8 and 32.1.

Samples for Ba analysis were collected at 239 of the 344 stations occupied in 1993. There were 183 stations at which more than one sample for Ba analysis was collected from within
the surface mixed layer. For each of these stations a mean value of Ba concentration for the surface mixed layer was calculated based on all samples collected at depths within the surface mixed layer (lack of detailed sampling throughout the water column eliminated any advantage to depth-weighted averaging). At 129 of these stations Ba concentrations were fairly uniform throughout the surface mixed layer; at 54 of these stations Ba concentrations were not vertically uniform in the surface mixed layer. There were 42 stations at which only one sample for Ba analysis was collected from within the surface mixed layer. For each of these stations the Ba concentration of the single sample was assigned as the mean value of Ba concentration for the surface mixed layer. There were nine stations at which no samples for Ba analysis were collected from depths within the surface mixed layer; these stations were excluded from the discussion of Ba in the surface mixed layer. Results from an additional five stations (two from SCICEX-93 and three from ARK IX/4) were rejected due to ambiguities in depth assignments and other sample identification problems.

Mean surface mixed layer Ba concentrations in 1993 ranged from 19 to 168 nmol Ba$^{-1}$ (Fig. 5) and were not directly correlated to mixed layer depth. At 89% of the stations values fell in the range between 35 and 80 nmol Ba$^{-1}$; values below 35 nmol Ba$^{-1}$ were limited to areas in the western Chukchi Sea adjacent to the Russian coast and in the vicinity of Wrangel Island, while values above 80 nmol Ba$^{-1}$ were limited to the eastern half of the Bering Strait and the southern edge of the Canada Basin.

Mean surface mixed layer Ba concentrations between 42 and 45 nmol Ba$^{-1}$ were observed north of the Barents Sea, and slightly higher values (45–50 nmol Ba$^{-1}$) were observed in the Eurasian Basin, the central Makarov Basin, and the vicinity of the shelf break and slope north of the Laptev Sea (with the exception of one station northwest of the Novosibirskie Islands at which a value of 67 nmol Ba$^{-1}$ was observed). High values (>75 nmol Ba$^{-1}$) were observed over most of the Canada Basin, with one notably high value (93 nmol Ba$^{-1}$) observed at a station just beyond the slope north of the Beaufort Sea. A branch of water with values between 65 and 70 nmol Ba$^{-1}$ extended over the Arlis Plateau and Mendeleyev Ridge, merging with high Ba surface waters of the Canada Basin and low-Ba surface waters of the Eurasian Basin in a zone of intermediate values (60–70 nmol Ba$^{-1}$) over the northern Makarov Basin and the Lomonosov Ridge in the vicinity of the North Pole.

Over much of the Chukchi Sea, and the adjacent Chukchi Cap to the north, mean surface mixed layer Ba concentrations between 55 and 65 nmol Ba$^{-1}$ were observed, with areas of elevated values (70–75 nmol Ba$^{-1}$) in the central Chukchi Sea, areas of depleted values (40–50 nmol Ba$^{-1}$) in the northern Chukchi Sea, and areas of extremely depleted values (<30 nmol Ba$^{-1}$) in the western Chukchi Sea adjacent to the Russian coast and in the vicinity of Wrangel Island. In the Bering Strait, values ranged from 50 to 168 nmol Ba$^{-1}$, with lower values on the western side and higher values on the eastern side of the strait. Values between 50 and 60 nmol Ba$^{-1}$ were generally observed in the Bering Sea, with some elevated values (65–75 nmol Ba$^{-1}$) south of St. Lawrence Island.

**1993 cruises: upper halocline**

To examine the lateral distribution of Ba in the upper halocline layer, we considered only stations past the shelf break (i.e. stations with bottom depths greater than 200 m). At each of the 85 such stations occupied during 1993, the upper halocline was taken to be the layer of water with a salinity between 32.5 and 33.5. The depth range corresponding to this salinity
range was determined from CTD data at each station. At 50 stations the layer of water with salinity between 32.5 and 33.5 was located entirely below the surface (e.g. Fig. 3a). At 30 stations occupied during the ARK IX/4 cruise (all of which were located in the Eurasian sector of the Arctic), salinity at the surface fell to between 32.5 and 33.5 (e.g. Fig. 3b). At these stations the upper halocline layer was interpreted to extend from the surface to the depth at which a salinity of 33.5 was encountered, and the depth range of the upper halocline coincides with that of the surface mixed layer. Five stations north of the Barents and Laptev seas, at which salinity over the entire water column was greater than 33.5, were excluded from the discussion of the upper halocline. The thickness of the upper halocline layer assigned in this manner ranged from 0 to 144 m, covering depths in the water column between 0 and 226 m. The layer was thickest in the Canadian Basin, particularly in the southern Canada Basin, and gradually thinned towards the Eurasian Basin.

There were 47 stations at which more than one sample for Ba analysis was collected from within the upper halocline. For each of these stations a mean value of Ba concentration for the upper halocline was calculated based on all samples collected from depths within the upper halocline (as was the case for the surface mixed layer, lack of detailed coverage over this depth range eliminated any advantage to depth-weighted averaging). There were 22 stations at which only one sample for Ba analysis was collected from within the upper halocline. For each of these stations the Ba concentration of the single sample was assigned as the mean value of Ba concentration for the upper halocline. There were 11 stations at which no samples for Ba analysis were collected from depths within the upper halocline; these stations were excluded from the discussion of Ba in the upper halocline.

Lowest mean upper halocline Ba concentrations in 1993 (42–45 nmol Ba l⁻¹) were observed north of the Barents Sea, and slightly higher values (45–51 nmol Ba l⁻¹) were observed in the vicinity of the shelf break and slope north of the Laptev Sea, in the Eurasian Basin and central Makarov Basin, and over the Mendeleyev Ridge and Arlis Plateau (Fig. 6). Mean upper halocline Ba concentrations were highest (70–77 nmol Ba l⁻¹) in the central and southern Canada Basin and over the Chukchi Cap, and slightly lower (65–70 nmol Ba l⁻¹) in the northern Canada Basin and over the north of the Chukchi Sea. A front was observed separating the low-Ba waters characteristic of the eastern Arctic from the high-Ba waters characteristic of the western Arctic, running roughly between the Canada and Makarov basins and extending into a zone of intermediate values (55–65 nmol Ba l⁻¹) over the northern Makarov Basin and the Lomonosov Ridge in the vicinity of the North Pole.

1994 Arctic Ocean Section

The distribution of salinity in the upper 400 m along the cruise track of the C.C.G.S. *Louis S. St-Laurent* during the 1994 Arctic Ocean Section is shown in Fig. 7. Salinity was fairly uniform throughout the water column at station 1 over the southern Chukchi shelf, ranging between 32.6 and 32.7. Across the Arctic interior, a layer of relatively fresh surface water was observed above underlying waters of greater salinity. Surface salinity was lowest north of the Chukchi Sea and over the Arlis Plateau, generally increasing as the transect proceeded across the Makarov Basin and into the Eurasian Basin. Local minima in surface salinity were observed centered on stations 5, 15, 19, 26, 28, 35 and 38.

The distribution of Ba in the upper 400 m along the cruise track of the C.C.G.S. *Louis S. St-Laurent* during the 1994 Arctic Ocean Section is shown in Fig. 8. Much higher Ba concentrations (> 70 nmol Ba l⁻¹) were observed in the surface waters over the Chukchi
shelf (stations 1–6) than were observed in the same area in 1993 (Fig. 5). Previous investigators (Falkner et al., 1994) encountered surface Ba concentrations between 12 and 63 nmol Ba l⁻¹ in the surface waters of the central and eastern Chukchi Sea in September 1992. Between the Chukchi shelf break and the Arlis Plateau (stations 7–12), surface values dropped to 60–65 nmol Ba l⁻¹, while a prominent subsurface maximum (characterized by values between 65 and 75 nmol Ba l⁻¹) was observed centered at depths between 75 and 100 m. The extent of the subsurface maximum along the AOS94 transect coincides with the boundary between high-Ba and low-Ba waters in the upper halocline layer observed between the Canada and Makarov basins in 1993 (Fig. 6).

A Ba-enriched (65–70 nmol Ba l⁻¹) feature extending from the surface to depths as great as 55 m was observed over the Arlis Plateau and the Mendeleyev Ridge (stations 13–21). This feature was located in the same area as the branch of water with similar Ba concentrations observed over the Mendeleyev Ridge in 1993 (Fig. 5). As the transect crossed the Makarov Basin to the Lomonosov Ridge (stations 22–29), intermediate values (55–60 nmol Ba l⁻¹) were observed down to depths of about 50 m, with local maxima (60–65 nmol Ba l⁻¹) at stations 26 and 28. Values in the upper water column drop to 45–55 nmol Ba l⁻¹ over the Lomonosov Ridge (stations 30–34), rising back up to values above 60 nmol Ba l⁻¹ in the surface waters just across the ridge in the Amundsen Basin (station 35). The Ba-enriched features at stations 13–21, 26, 28 and 35 all coincided with local minima in salinity. Relatively low Ba concentrations (< 45 nmol Ba l⁻¹) were observed throughout the water column in the Nansen Basin (stations 36–38) and below depths of 100–200 m over the entire transect. Results for stations 22–38 are consistent with observations made in the same areas of the Makarov and Eurasian basins in 1993 (Figs 5 and 6).

Measurements of NO (Swift et al., 1997) provided a basis for examining the lower halocline along the AOS94 transect. The lower halocline was taken to be the layer of water with a salinity between 34.0 and 34.5, and containing a NO minimum. Lowest Ba (< 46 nmol Ba l⁻¹) and highest NO ( > 400 µmol l⁻¹) in the lower halocline were observed in the Eurasian Basin, with Ba concentrations increasing steadily and NO levels decreasing steadily towards the Canadian sector of the Arctic (Fig. 9). Highest Ba concentrations (50–77 nmol Ba l⁻¹) and lowest NO (223–380 µmol l⁻¹) in the lower halocline were observed over the Chukchi shelf break.

DISCUSSION

While the combined data set for the six cruises in 1993 has the advantage of covering a large geographic area (thereby allowing examination of tracer fields in the Arctic on a basin-wide scale), a drawback is that the data are distributed very irregularly within the sampling area. The data from the 1994 Arctic Ocean Section are much more uniformly spaced. The resolution and smoothing scales used for gridding and contouring both sets of data represent a compromise between not obscuring legitimate small-scale features in areas of dense sample coverage and not creating unwarranted detail in areas of sparse sample coverage. The data were examined thoroughly to verify that the salinity and Ba distributions generated by means of the Barnes objective analysis technique (i.e. Figs 4–8) were consistent with the actual values observed at individual stations; but as holds true for any method of gridding and contouring data, the values in spaces between sampling locations are interpolated estimates and cannot be treated as exact.

Because the data were collected over a period of months during the summer and fall
Fig. 4. Distribution of salinity in the surface mixed layer in 1993 (the following parameter values were used for the Barnes objective analysis: horizontal and vertical grid spacing ($G_x$ and $G_y$) = 10 nautical miles, numerical convergence parameter ($\gamma$) = 0.2, number of iterations ($i$) = 2, horizontal data spacing ($\Delta n_x$) = 100 nautical miles, vertical data spacing ($\Delta n_z$) = 70 nautical miles). Black dots show the locations of all 1993 stations included in the surface mixed layer salinity data. The 1994 AOS cruise track and stations are superimposed in magenta on this figure for reference when comparing 1993 and 1994 results.
Fig. 5. Distribution of Ba in the surface mixed layer in 1993 ($G_x$ and $G_y = 10$ nautical miles, $\gamma = 0.2$, $i = 2$, $\Delta n_x = 100$ nautical miles, $\Delta n_y = 70$ nautical miles) (see caption to Fig. 4 for the meaning of abbreviations). Black dots show the locations of all 1993 stations included in the surface mixed layer Ba data. The 1994 AOS cruise track and stations are superimposed in magenta on this figure for reference when comparing 1993 and 1994 results.
Fig. 6. Distribution of Ba in the upper halocline (i.e. the layer of water with a salinity of between 32.3 and 33.5) in 1993 ($G_x$ and $G_y$ = 10 nautical miles, $\gamma = 0.2$, $i = 2$, $\Delta n_x = 70$ nautical miles, $\Delta n_y = 100$ nautical miles) (see caption to Fig. 4 for the meaning of abbreviations). Black dots show the locations of all 1993 stations included in the upper halocline Ba data. The 1994 AOS cruise track and stations are superimposed in magenta on this figure for reference when comparing 1993 and 1994 results.
Fig. 7. Distribution of salinity along the 1994 Arctic Ocean Section ($G_r = 25$ nautical miles, $G_s = 5$ m, $\gamma = 0.2, i = 2, \Delta n_r = 25$ nautical miles, $\Delta n_s = 10$ m) (see caption to Fig. 4 for the meaning of abbreviations). Black dots show the locations of samples included in the salinity data.
Stations

Fig. 8. Distribution of Ba along the 1994 Arctic Ocean Section ($G_x = 25$ nautical miles, $G_y = 5$ m, $\gamma = 0.2$, $i = 2$, $\Delta n_x = 25$ nautical miles, $\Delta n_y = 10$ m) (see caption to Fig. 4 for the meaning of abbreviations). Black dots show the locations of samples included in the Ba data.
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Fig. 9. NO vs dissolved Ba for 117 samples taken within the lower halocline (i.e. the layer of water with a salinity of between 34.0 and 34.5) during the 1994 Arctic Ocean Section. One sample from station 4 (NO = 223 \(\mu\)mol l\(^{-1}\), [Ba] = 77 nmol l\(^{-1}\)) does not appear within the boundaries of this plot.

(June–October for the 1993 cruises and July–August for AOS94), caution must be exercised when interpreting Figs 4–8 as quasi-synoptic snapshots of basin-wide tracer fields. Although this may not be very realistic for the dynamic areas over the shelves of the marginal seas, it is reasonable for areas in the Arctic interior where waters have longer residence times, are completely ice-covered most or all of the year, and experience less extreme seasonal fluctuations in biological activity and fluvial input than Arctic nearshore environments.

**Surface mixed layer**

In both 1993 and 1994 Ba concentrations between 40 and 50 nmol Ba l\(^{-1}\) and high salinity characterized surface waters of the Eurasian Basin, reflecting their North Atlantic origin (Chan *et al.*, 1977). The 1993 distributions of salinity and Ba show surface waters of Eurasian character extending across the Lomonosov Ridge and into the Makarov Basin (Figs 4 and 5). These results are consonant with recent studies (Carmack *et al.*, 1995; McLaughlin *et al.*, 1996; Morison *et al.*, 1998) that document subsurface waters of Eurasian character penetrating the Makarov Basin, in contrast with historical data which show the boundary between Atlantic and Pacific subsurface water mass assemblies lying along the Lomonosov Ridge (Kinney *et al.*, 1970; Gorshkov, 1983; Moore *et al.*, 1983; Jones and Anderson, 1986; Anderson *et al.*, 1994a).

Relative to surface waters in the North Atlantic, surface waters in the North Pacific are fresher (due to greater runoff and net precipitation over evaporation in the North Pacific) and enriched in Ba (reflecting both runoff and the upwelling of regenerated biogenic material in the Gulf of Anadyr (Falkner *et al.*, 1994). North Pacific waters entering the
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Arctic through the Bering Strait become further freshened and enriched in Ba by fluvial discharge. The extremely high Ba concentrations observed in the eastern side of the Bering Strait in 1993 are associated with the Alaskan Coastal Current, which receives large amounts of fluvial discharge (primarily from the Yukon River) as it flows northward into the Arctic along the coast of Alaska (Coachman and Shigaev, 1992).

Falkner et al. (1994) showed that biological activity is capable of severely depleting Ba in the surface waters of the Chukchi Sea (Ba concentrations as low as 12 nmol Ba l⁻¹ were observed in September 1992), resulting in the transport of Ba to deeper waters. In 1993 the high Ba concentrations observed in the surface waters in the Bering Strait and the southern Chukchi Sea did not extend continuously along the advective flow path northward over the shelf; this further demonstrates that Ba can be stripped from the surface waters of the Chukchi Sea by the intense biological activity known to occur in the area during the summer (Coachman and Shigaev, 1992 and references therein). The area of extreme surface Ba depletion in the vicinity of Wrangel Island and the Siberian coast was associated with very low surface salinity and elevated Ba concentrations in deeper waters (Fig. 3c), suggesting the occurrence of a large plankton bloom in conjunction with seasonal increases in solar radiation and melting ice. Both the 1992 and 1993 Ba data suggest that removal of Ba from surface waters in association with the extremely high productivity over the Chukchi shelf outpaces advective delivery when the ice has retreated in the summer. The extent of removal is not as pronounced as it is for silicate, which approaches analytically undetectable levels over the Chukchi shelf.

Special attention must be given to the area north of the Alaskan coast in the vicinity of Barrow Canyon. Stations were occupied in this region on two different cruises in 1993: 12 stations were occupied between 13 and 14 August during the ARCRAD-93 cruise, and seven stations were occupied between 24 and 26 September during the HXI74 cruise. At all stations from both cruises located north of the Chukchi shelf break and the mouth of Barrow Canyon, the surface mixed layer was characterized by high Ba concentrations (mean values above 75 nmol Ba l⁻¹). But over Barrow Canyon itself, Ba concentrations in the surface mixed layer were quite different during the two cruises: mean values between 55 and 66 nmol Ba l⁻¹ were observed at the ARCRAD-93 stations, and mean values between 71 and 87 nmol Ba l⁻¹ were observed at the HXI74 stations (note that the data collected at different times from the same area during these two cruises are averaged during the Barnes objective analysis, resulting in the appearance of intermediate values around 65 nmol Ba l⁻¹ over Barrow Canyon in Fig. 5). While the values at the ARCRAD-93 stations are similar to those seen in other areas over the northern and central Chukchi shelf, the values observed at the HXI74 stations are comparable to those seen in the Bering Strait and the southern Chukchi Sea; this suggests that during the time in which the HXI74 stations were occupied, the Alaska Coastal Current transported Ba-enriched surface waters directly into the Arctic interior in the vicinity of Barrow Canyon. Thus, the observation of Ba-depleted surface waters over most of the Chukchi shelf in 1992 and 1993 does not rule out direct delivery of Ba associated with Bering inflow to the surface waters of the Arctic interior during certain times of the year.

Data collected along the AOS94 transect in the summer of 1994 further illustrate this point. In contrast to summer/fall conditions in 1992 and 1993, Ba-enriched surface waters were observed at all stations occupied over the Chukchi shelf and slope. This may be a direct result of the 50-year high in transport through Bering Strait (1.1 Sv) observed in the first 9 months of 1994 (Roach et al., 1995). The seasonal differences between sampling periods in
the different years also must be taken into account. While most of the 1992 and 1993 stations in the Chukchi Sea were occupied between August and October, stations in the Chukchi Sea along the AOS94 transect were occupied in late July. In general, it must be remembered that the shelves of the Arctic’s marginal seas are very complex, dynamic regions subject to significant temporal variability, and that observations made during one particular interval of time do not necessarily represent conditions prevailing throughout the entire year.

We hypothesize that although waters entering the Arctic through the Bering Strait (which includes the discharge from the Yukon River) may contribute to the Ba inventory of surface waters in the Canada Basin during certain times of the year, much of the Ba contained in the Bering inflow is not delivered directly to the surface waters of the Arctic interior. In addition to the biologically mediated transfer of Ba from surface to deeper waters in the Chukchi and Bering seas described above, waters of Pacific origin flowing northward through the Bering Strait in winter are generally more saline than surface waters covering the Canadian Basin and thus tend to enter the Arctic interior below the surface mixed layer (Coachman and Shigaev, 1992; Weingartner et al., 1998). We therefore hypothesize that the Mackenzie River is the dominant source of the high Ba levels observed in the surface waters of the Canada Basin. The Mackenzie River is the fourth largest Arctic river in terms of discharge and the largest entering from North America (average annual discharge of the Yukon River is only about 60% that of the Mackenzie River). The Mackenzie River is highly enriched in Ba; during a survey of Arctic rivers carried out between 1993 and 1996, Ba concentrations observed in the Mackenzie River were 5–20 times greater than those observed in any of the major Eurasian Arctic rivers (Guay and Falkner, 1998). The notably high surface Ba concentrations and low surface salinity observed at the station north of the Beaufort slope in 1993 probably reflect the influence of the Mackenzie River.

A simplified mass balance provides a first-order confirmation of this hypothesis. The surface area of the Canada Basin (not including the area over the Chukchi Cap and Arlis Plateau, where surface Ba concentrations were significantly lower than values over the rest of the Canada Basin) is estimated to be $1.36 \times 10^6 \text{ km}^2$. Assuming $25 \pm 5 \text{ m}$ and $75 \pm 5 \text{ nmol Ba} \text{ l}^{-1}$ for the depth and mean Ba concentration, respectively, of the surface mixed layer results in an estimate of $2.6 \times 10^8 \pm 0.7 \text{ mol}$ for the Ba inventory of the surface mixed layer in the Canada Basin. A value of $520 \pm 20 \text{ nmol Ba} \text{ l}^{-1}$ is taken for the effective end-member Ba concentration (i.e. accounting for estuarine desorption of Ba from riverborne clay particles; Edmond et al., 1978) of the Mackenzie River (Guay and Falkner, 1998). Multiplying this value by the average annual discharge of the Mackenzie River ($340 \text{ km}^3 \text{ year}^{-1}$) results in an estimate of $1.8 \times 10^8 \pm 0.07 \text{ mol Ba year}^{-1}$ for its annual delivery of Ba to the Arctic Ocean. Thus, over a period of 10 years (the estimated residence time of surface waters in the Beaufort Gyre), the Mackenzie River can supply approximately 52–97% (with a best estimate of 68%) of the total Ba inventory of the surface mixed layer in the Canada Basin. The remainder of the Ba inventory can be supplied by a combination of North Pacific waters, discharge from other rivers (the Yukon River in particular), and vertical mixing.

Various combinations of source waters could have produced the surface features observed in 1993 and 1994 over the Arlis Plateau and Mendeleyev Ridge, and at AOS94 stations 26, 28 and 35. The local salinity minima and Ba maxima associated with these features suggest the influence of discharge from North American and/or Eurasian Arctic rivers (although Eurasian Arctic rivers are low in Ba compared to the Mackenzie River, they are highly elevated in Ba relative to oceanic surface waters entering the Arctic from the
North Atlantic and North Pacific; Guay and Falkner, 1998). The features also coincided with local maxima in vertically integrated dissolved C/N ratios (14-6–25-1) and normalized alkalinity (2.43–2.50 meq l⁻¹) during the AOS94 transect; in addition, the most extreme maximum in vertically integrated DOC (121.6 g m⁻²) observed during the AOS94 transect was observed at station 28 (C/N and DOC data from Wheeler et al., 1997; alkalinity data from Swift et al., 1997). These chemical signatures provide further evidence that the salinity minima resulted primarily from fluvial discharge. The features may indicate areas where shelf waters containing discharge from Eurasian rivers flow into the Arctic interior. Alternatively, the features may have occurred in areas where the Beaufort Gyre merges with the transpolar drift flowing towards the Fram Strait, thus reflecting contributions from both the Mackenzie and Eurasian Arctic rivers. In addition, the Arlis Plateau–Mendeleyev Ridge feature could have resulted from a branch of Bering influx that flowed across the Chukchi shelf and entrained river water of North American and/or Eurasian origin; while this explanation seems unlikely in light of the biological activity in the Chukchi Sea and the presumed path of Bering inflow previously discussed, it cannot be ruled out based solely on the data presented in this paper.

Ignoring ice-melt, we examined linear combinations of end-members representing Atlantic inflow, Pacific inflow and fluvial discharge capable of reproducing the salinity and Ba concentrations of the surface features (Tables 2 and 3). Waters with the physical and chemical properties of the surface features could result from a mixture containing 86–92% of the Atlantic end-member and 8–14% of a fluvial end-member with a Ba concentration of between 179 and 319 nmol Ba l⁻¹; or from a mixture containing 91–98% of the Pacific end-

| Table 2. Salinity and Ba concentrations of source waters to the upper Arctic |
|-----------------------------|-----------------------------|
| Source                     | Salinity        | Ba concentration (nmol Ba l⁻¹) |
| Atlantic                   | 34.9*           | 42–45                         |
| Pacific                    | 32.5–33.0      | 50–60                         |
| Mackenzie River            | 0              | 520                         |
| Eurasian rivers            | 0              | 100–200                      |
| Sea-ice melt               | 3              | ≤5                           |

*From Schlosser et al. (1994).
† From Coachman and Shigaev (1992).
‡ From Guay and Falkner (1998).
§ From Wagner and Falkner (unpublished data).

| Table 3. Salinity and Ba concentrations in the surface features observed in 1993 and 1994 |
|-----------------------------|-----------------------------|
| Feature over the Arlis Plateau and Mendeleyev Ridge (1993 and 1994) | Salinity        | Ba concentration (nmol Ba l⁻¹) |
| Features at AOS94 stations 26, 28 and 35 | 30.0–31.0            | 65–70                          |
|                              | 31.0–32.0            | 60–65                          |
member and 2–9% of a fluvial end-member with a Ba concentration of between 60 and 1025 nmol Ba l$^{-1}$. For most of these combinations, the required fluvial end-members had Ba concentrations of between 100 and 520 nmol Ba l$^{-1}$ and can, therefore, represent mixtures of discharge from both the Mackenzie and Eurasian Arctic rivers. While this exercise demonstrated that combinations of Pacific and Atlantic inflow and fluvial discharge could have given rise to the surface features observed in 1993 and 1994, the limitations of a mixing model based solely on salinity and Ba are readily apparent. Additional oceanographic tracers must be incorporated to simultaneously account for Atlantic and Pacific inflow, ice-melt, and discharge from North American and Eurasian Arctic rivers, and to explicitly determine their relative contributions to Arctic circulation. In particular, adding Ba to mass balances based on salinity, $\delta^{18}$O and silicate (Schlosser et al., 1994; Bauch et al., 1995) would allow the fluvial component of Arctic circulation to be resolved into separate contributions from the North American and Eurasian Arctic rivers.

Upper halocline

In 1993 upper halocline waters with high mean Ba concentrations ($> 65$ nmol Ba l$^{-1}$) were separated from upper halocline waters with low mean Ba concentrations ($< 50$ nmol Ba l$^{-1}$) by a front lying roughly between the Canada and Makarov basins (Fig. 6). Along the AOS94 transect, the upper halocline between the Chukchi shelf and the Arlis Plateau is marked by high Ba concentrations (65–75 nmol Ba l$^{-1}$) and a subsurface Ba maximum occurring at depths between 50 and 200 m; beyond the Arlis Plateau, waters with upper halocline temperature and salinity characteristics had Ba concentrations $< 60$ nmol Ba l$^{-1}$ (Fig. 8). These observations demonstrate that upper halocline waters characterized by elevated Ba concentrations are confined to the Canadian Basin, and are chemically distinct from waters with similar temperature and salinity properties in the Eurasian Basin, suggesting that different mechanisms lead to the formation of halocline waters in the different sectors of the Arctic. The limit of the Ba-enriched upper halocline waters along the AOS94 transect approximately coincided with the location of the boundary between high-Ba and low-Ba upper halocline waters observed in the same area in 1993. The position of the front between the two types of upper halocline waters observed in both 1993 and 1994 provides further evidence that the boundary between subsurface water masses of Atlantic and Pacific character has shifted from its historically defined position along the Lomonosov Ridge to a position aligned with the Mendeleyev and Alpha ridges (Carmack et al., 1995; McLaughlin et al., 1996; Morison et al., 1998).

The Ba maximum and the related nutrient maxima and oxygen minimum (Jones and Anderson, 1990; Jones et al., 1991; Falkner et al., 1994) that characterize the upper halocline in the Canada Basin suggest sources in the Chukchi and Beaufort seas, and that the mechanism by which these waters are formed is linked with the influx of water through the Bering Strait. As was demonstrated in the previous discussion of the surface mixed layer, salinity and Ba data alone are not sufficient for quantitatively determining contributions to the Arctic halocline from different source waters.

Lower halocline

Data from the Eurasian Arctic suggest that the lower halocline achieves its NO levels in the Barents Sea and adjoining Nansen Basin over several seasons (Rudels et al., 1996).
Under the proposed scenario, biological productivity depletes nutrients in surface waters and much of the oxygen produced during photosynthesis becomes lost to the atmosphere. Deep convection occurring in the winter drives the surface NO signature to the depth of the lower halocline. As these waters advect under the ice and toward the Siberian seas, further deep convection is inhibited by capping with fresher waters influenced by the large Eurasian Arctic rivers (Rudels et al., 1996). It has been noted that the NO minimum in the Canadian sector of the Arctic is accompanied by higher temperatures and silicate concentrations than in the Eurasian sector (Salmon and McRoy, 1994). Because the NO parameter appeared to remain roughly constant at the few stations occupied in the Canadian Arctic, it was presumed that only small volumes of renewal waters were responsible for the altered temperature and salinity characteristics (Salmon and McRoy, 1994; Rudels et al., 1996). In at least one instance, altered lower halocline waters have been found to have a somewhat lower NO signal than unaltered lower halocline water, suggesting that the lower halocline layer can be the recipient of significant additional input as it advects from its supposed region of origin in the Barents toward the Arctic interior (McLaughlin et al., 1996).

The general trends of increasing NO and decreasing Ba concentration observed in the lower halocline along the AOS94 transect (Fig. 9) provide further evidence that lower halocline waters are influenced by contributions from additional sources (such as dense shelf waters formed in association with freezing and brine rejection) as they transit from Eurasian to Canadian sectors of the Arctic. Analogous to the situation in the upper halocline, elevated Ba in the lower halocline in the Canada Basin suggests contributions from sources in the Chukchi and Beaufort seas. The low NO in the lower halocline in the Canada Basin may result from denitrification thought to be occurring in association with biological activity over the highly productive Bering, Chukchi and East Siberian shelf regions (Codispoti et al., 1991).

CONCLUSIONS

Quasi-synoptic Ba distributions in the Arctic in 1993 and 1994 show that the surface mixed layer reflects the pronounced differences that exist between Ba concentrations in various source waters. Below the surface layer, Ba distributions delineate the present lateral extent of the nutrient-enriched upper halocline layer in the Canadian sector of the Arctic, confirm its general source region in the Chukchi and Beaufort seas, and show it to be discontinuous with waters of similar temperature and salinity properties that outcrop in the Eurasian Basin. Data from the 1994 Arctic Ocean Section suggest that lower halocline waters, which are established in the Eurasian sector of the Arctic, continue to be imprinted by shelf processes as they transit to the Canadian sector. In future work, application of multivariate analysis techniques to combined tracer data sets (salinity, $\delta^{18}$O, alkalinity, Si, Ba, etc.) will allow more quantitative mapping of components contributing to stratification of the upper Arctic and thus reveal circulation patterns in its sublayers. In particular, Ba shows unique promise for distinguishing between North American and Eurasian riverine components of oceanic circulation within the Arctic.

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