The Canada Basin 1989-1995: Upstream Events and Far-Field Effects of the Barents Sea Branch

by

Fiona Ann McLaughlin
B.Sc. University of Victoria, 1972
M.Sc., University of Victoria, 1996

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We accept this dissertation as conforming to the required standard

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Dr. A. J. Weaver, Supervisor (School of Earth and Ocean Sciences)

Dr. E. C. Carmack, Departmental Member (School of Earth and Ocean Sciences)

Dr. R. W. Macdonald, Departmental Member (School of Earth and Ocean Sciences)

Dr. N. Turner, Outside Member (Department of Environmental Sciences)

Dr. K. K. Falkner, External Examiner (Oregon State University)

Supervisor: Dr. Andrew J. Weaver

Abstract

Physical and geochemical tracer measurements were collected at one oceanographic station (Station A: 72 N 143 W) in the southern Canada Basin from 1989 to 1995, along sections from the Beaufort Shelf to this station in 1993 and 1995, and along a section westward of Banks Island in 1995. These measurements were examined to see how recent events in three upstream Arctic Ocean sub-basins impacted upon Canada Basin waters. Upstream events included Atlantic layer warming, relocation of the Atlantic/Pacific water mass boundary, and increased ventilation of boundary current waters. Early signals of change appeared first in the Canada Basin in 1993 along the continental margin and, by 1995, were evident at Station A in the basin interior and farther downstream. Differences in physical and geochemical properties (nutrients, oxygen, ^{129}I and CFCs) were observed throughout much of the water column to depths greater than 1600 m. In particular, the boundary distinguishing Pacific from Atlantic-origin water was found to be shallower and Atlantic-origin water occupied more of the Canada Basin water column. By 1995, Atlantic-origin water in the lower halocline at Station A was found to be colder and more ventilated. Likewise, within the Atlantic layer, Fram Strait Branch (FSB) water was colder, fresher, and more ventilated, and Barents Sea Branch (BSB) water was warmer, fresher, and more ventilated than during previous years. By comparing observations at Station A with eastern Nansen

Basin observations, the main source of these changes was traced to dense water outflow from the Barents Sea. Studies indicated that in early 1989 Barents Sea waters were 2 °C warmer and that, between 1988 and 1989, a large volume of dense water had left the shelf. These events coincided with an atmospheric shift to increased cyclonic circulation in 1989, a transition unprecedented in its magnitude, geographic reach, and apparent oceanographic impact. The effects of a large outflow of dense Barents Sea water were observed some 5000 km away downstream in the Canada Basin where the BSB component of the Atlantic layer had increased 20% by 1995.

Examiners:

Dr. A. J. Weaver, Supervisor (School of Earth and Ocean Sciences)

Dr. E. C. Carmack, Departmental Member (School of Earth and Ocean Sciences)

Dr. R. W. Macdonald, Departmental Member (School of Earth and Ocean Sciences)

Dr. N. Turner, Outside Member (Department of Environmental Sciences)

Dr. K. K. Falkner, External Examiner (Oregon State University)

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I have also been instructed in oceanography by the captains and crews of the Canadian Coast Guard icebreakers, especially Captains Gomes and Grandy, and the men and women who sailed with them. I have also learned much from my colleagues at the Institute of Ocean Sciences whose work in sampling and analysis contributed enormously to the data sets upon which this study of the Canada Basin is based. John Smith at the Bedford Institute was particularly helpful and supplied the iodine isotope data used here.

Last but not least, I would like to thank my partner, Thomas Fleming, who has taught me that the questions of research are universal, regardless of discipline, and that all researchers must first understand the "story" of their investigation in order to tell it to others, directly and simply. Together, all these people have taught me, as the novelist Laurence Sterne wrote in Tristram Shandy, " There is a North-west passage to the intellectual world."

1. Introduction

Over the past decade, the historical view of the Arctic Ocean as an ocean in a steady state (c.f. Coachman and Barnes, 1961; Treshnikov, 1959: Carmack, 1986) has given way to a newer view of the Arctic as an ocean in a state of transition. This new understanding is a product of several factors. Science-capable icebreakers and submarines provided new platforms for discovery and greatly expanded the geography of Arctic inquiry from basin-wide sampling in the 1980s to ocean-wide expeditions in the 1990s. Modern geochemical measurements also furnished more complete descriptions about the composition of arctic waters and how these waters are interconnected. Since the late 1970s, atmospheric, biological, and modelling studies have also expanded the scope of scientific research, making it possible to test the validity of old understandings and to consider new questions. A growing literature now sustains comparison among high-quality data sets assembled over time and over a larger domain. This enriched knowledge base has provided a portrait of the Arctic as a dynamic ocean, and one that is an integral part of the larger global ocean system.

Views of a changing Arctic Ocean were first outlined in several studies documenting temperature change in the water column of three of the ocean's four main sub-basins (see Figure 1). Warmer temperatures in the Atlantic layer of the water column were initially observed in 1990 in the Nansen Basin, geographically the first Arctic Ocean basin to receive Atlantic water inflow (Quadfasel et al., 1991; Quadfasel et al., 1993). Downstream of this inflow, Atlantic layer temperatures warmer than the climatological record were observed in 1993 over the Lomonosov Ridge in the Amundsen Basin (Morison et al., 1998) and, also, near the Mendeleyev Ridge in the southern Makarov Basin (Carmack et al., 1995). Warmer Atlantic layer temperatures were further confirmed by comparison of 1991 and 1994 temperatures on the eastern flank of the Lomonosov Ridge, which showed an increase of 0.5-0.6°C over this brief period (Swift et al., 1998).

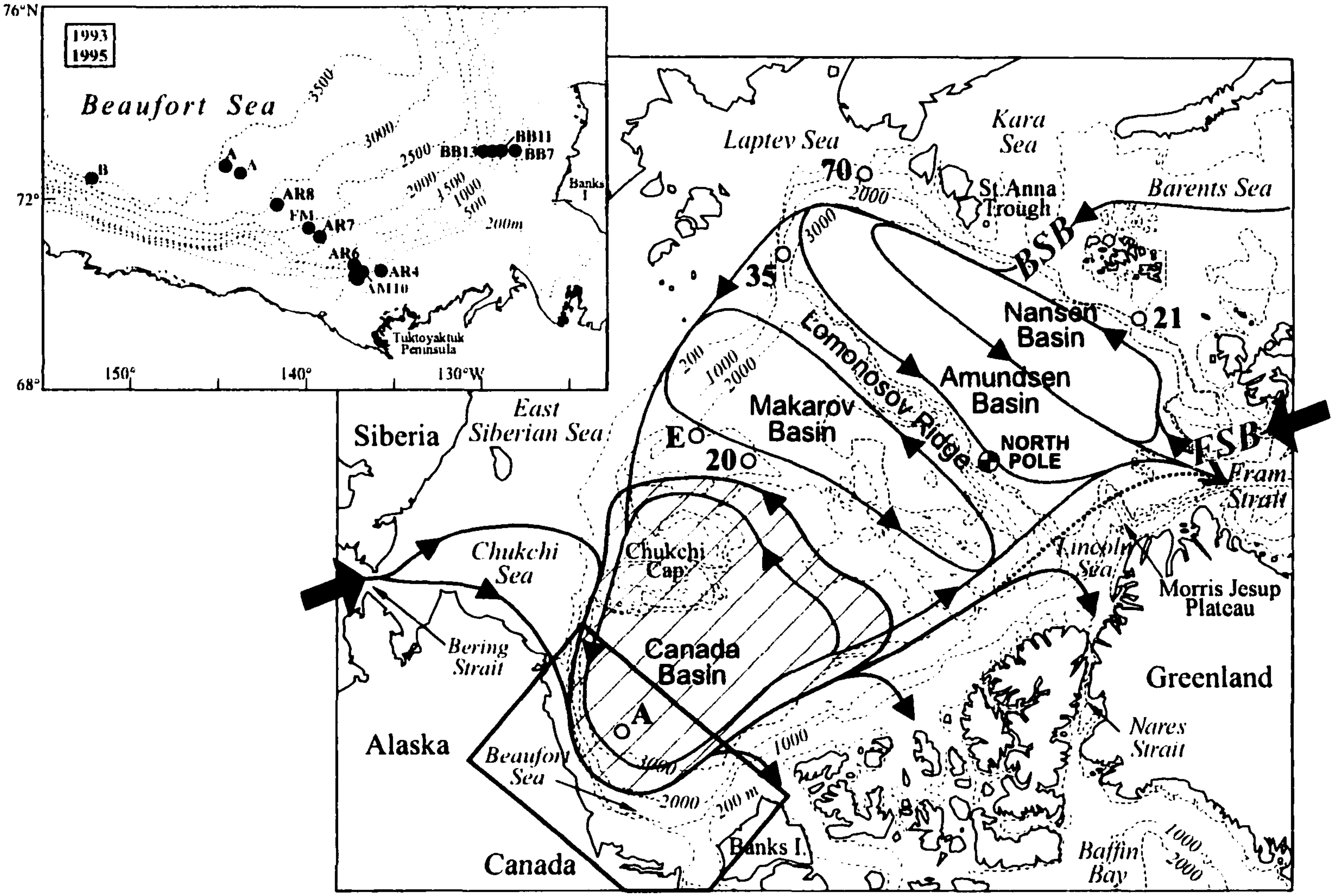

Figure 1. Arctic Ocean map illustrating bathymetric features and circulation of inflowing Atlantic (red) and Pacific (blue) waters. Map inset shows the Canada Basin study area.

Along with Atlantic layer warming, recent research has also documented a shift in water mass composition in the Makarov Basin, signalling an alteration in the circulation of the Arctic Ocean itself. The historical view of the Arctic Ocean (Gorshkov, 1983; Moore et al., 1983) held that the Eurasian Basin halocline consisted of Atlantic-origin water characterized by cold temperatures and low nutrients. Further, it held that the Canadian Basin halocline was comprised largely of Pacific-origin water, characterized by a local temperature maximum and minimum as well as a nutrient maximum (Kinney et al., 1970). Observations showed that these two haloclines were separated by a boundary located above the Lomonosov Ridge. This view was first questioned in 1991 when silicate concentrations in the upper layer of the Makarov Basin near the Lomonosov Ridge were found to be markedly lower than previously reported. This finding suggested the halocline front was variable (Anderson et al., 1994). The historical view was again challenged when low-nutrients were observed in the southern Makarov Basin halocline in 1993, a finding that signalled an eastward shift of the Atlantic/Pacific water mass boundary from a location over the Lomonosov Ridge to one over the Mendeleyev Ridge (McLaughlin et al., 1996). In addition to displacement of Pacific-origin water in the halocline, and the concomitant shallowing of the Atlantic layer, southern Makarov Basin waters were also found to be fresher and more ventilated between 400 m and 1600 m than in the overlying Atlantic layer. Increased ventilation suggested that rapid transport of upstream shelf-water by topographically-steered boundary currents had occurred. Observations of Atlantic-origin water extending from the Mendeleyev Ridge to the Lomonosov Ridge across the Makarov Basin in 1994 confirmed the basin-wide extent of the Atlantic/Pacific water mass transition (Carmack et al., 1998). Presence of ventilated water at depths greater than 1500 m in basin slope locations likewise confirmed transport of water from shelf regions (Swift et al., 1998).

Arctic Ocean research has focused principally on investigations of physical and geochemical changes in the Nansen, Amundsen and Makarov basins. Investigation into these three basins (hereafter referred to as "upstream" because of their pre-eminent location with respect to Atlantic water inflow, illustrated in

Figure 1) has prompted enquiry into whether similar changes have taken place downstream in the Canada Basin—the fourth of the arctic basins, the largest, and the one which most directly influences outflow to the Canadian Archipelago and Labrador Sea. Time-series study of the Canada Basin to date has been limited to two investigations. Initial work was based on temperature and salinity measurements collected in the southern Canada Basin between 1979 and 1996 (Melling, 1998). Melling reported that changes were progressive during these 17 years. Compared to the early 1980s, the upper halocline was warmer, the lower halocline was colder, the Atlantic warm core was colder and fresher and, below this core, waters were warmer and fresher. He attributed the difference in the upper halocline to a decrease in strength of the Siberian High, and the difference in the lower halocline and increased thickness of the Atlantic layer's warm core to variation in flow via the Barents Sea.

The second investigation into the Canada Basin presented ^{18}O measurements collected in the Beaufort Sea between 1987 and 1997 (Macdonald et al., 1999). Resolving freshwater in the water column's top 250 m and comparing sea-ice melt and runoff components, this study reported that sea-ice melt increased by 4-6 m after 1989. Macdonald et al. (1999) noted that the timing of this increase coincided with three events—a shift in the Arctic Oscillation Index (Overland et al., 1999), reduced anti-cyclonic wind forcing (Proshutinsky and Johnson, 1997), and a record minimum in ice extent (Serreze et al., 1995). Because increase in sea-ice melt was unaccompanied by change in runoff, they proposed that sea-ice melt increase was a thermal and mechanical response to the 1989 atmospheric-circulation regime shift.

Increased atmospheric cyclonicity and the resulting adjustment of ice distribution and thickness also serves to explain observations of anomalously thin multi-year ice in the Beaufort Sea in 1997 by McPhee et al. (1998) and Welch (1998). Comparison of sea-ice draft measurements from the larger Arctic Ocean between 1958-1976 and 1993-1997 substantiated that sea-ice thickness in the Beaufort and Chukchi seas decreased, and also identified that the decrease was greatest in the central and eastern Arctic (Rothrock et al., 1999). A reduction in the areal extent of multiyear ice between 1978 and 1998 was also observed (Johannessen et al., 1999). Comparison of areal trends with model simulations led Vinnikkov et al. (1999) to conclude that observed decreases in sea-ice extent were far greater than could be expected from natural climate variations and were related to anthropogenic global warming.

The following paper attempts to record differences in Canada Basin waters from 1989 to 1995 and to connect such developments to the broader Arctic Ocean which is, in turn, part of a complex global oceanic and atmospheric system. It will do so, first, by examining physical and geochemical measurements for evidence of change at one deep basin station in the southern Canada Basin. It will then compare these measurements to physical and geochemical measurements collected in upstream basins during three expeditions—the 1993 southern Makarov Basin expedition, the 1993 southeastern Eurasian Basin ARK IX/4 expedition, and the 1994 Arctic Ocean section expedition. Finally, measurements from sections extending from the Canada Basin shelf to the basin interior will be compared by time and location. Variation in water mass composition will be determined by geochemical tracers. For example: nutrients and ^{129}I will be used to define the intersection of Pacific and Atlantic waters within the water column; and, oxygen and CFC-11 will be used to distinguish between shelf and non-shelf sources of Atlantic layer water.

In summary, the following discussion will attempt to answer three questions: What changes have taken place in the Canada Basin since 1989? Can they be attributed to a source? And, how can they be explained?

2. Methods

Station A was located at 72 °N 143 °W in the southern Canada Basin at a water column depth of 3300 m. Oceanographic samples were first collected in the summer of 1989 and, subsequently, collected every autumn with the exception of 1991 and 1994. In addition, oceanographic samples were collected along two sections in the Beaufort Sea, one northward from the Tuktoyatuk Peninsula to

Station A in 1993 and 1995, and one westward from Banks Island toward the basin interior to a depth of 1200 m in 1995 (Figure 1).

CTD data were collected from 1989 to 1992 with a Guildline conductivity-temperature-depth (CTD) profiler and, in 1993 and 1995, using a Falmouth Scientific Instruments ICTD. Measurements of temperature, pressure, and conductivity were recorded during downcasts. Instruments were calibrated before and after each cruise. Potential temperatures (θ) and densities (σ) were calculated using UNESCO (1983) algorithms.

Water samples were collected between 1989 and 1992 with 5 and 10 L Niskin bottles deployed from a wire and, in 1993 and 1995, collected in 10 L Niskin-type bottles mounted on a General Oceanics rosette together with the FSI ICTD and tripped on the upcast. Subsamples drawn for salinity (S), oxygen and nutrients were analyzed onboard. Halocarbon samples, collected in 1992, 1993, and 1995, were also analyzed onboard. Samples for ^{129}I measurements were collected in 1993 and 1995 for later analysis. A complete discussion of methods was reported in the *Canadian Data Report Hydrography and Ocean Sciences* data report series 1990-1996. Each year, the same analytical methods were used and the precision reported below, based on 1995 measurements, typified the entire time period.

Salinities were determined from conductivity measurements using a Guildline Autosal salinometer and referenced to Standard Sea Water, IAPSO Batch P118 (pooled variance S_p=0.0012, n=33). Oxygen was analyzed by the Carpenter-Winkler method (S_p=1.57 mmol m^{-3}, n=85); silicate and nitrate by standard AutoAnalyzer Technicon methods, and phosphate by a modified method ($Si(OH)_4$: S_p=0.16 mmol m^{-3}, n=496; NO_3: S_p=0.15 mmol m^{-3}, n=493; PO_4: S_p=0.06 mmol m^{-3}, n=502). Halocarbons were analyzed by an automated purge and trap system combined with a Hewlett-Packard gas chromatograph electron capture detector (CFC-12: S_p=0.07 nmol m^{-3}, n=26; CFC-11: S_p=0.07 nmol m^{-3}, n=26; CFC-113: S_p=0.06 nmol m^{-3}, n=27; and CCl_4: S_p=0.24 nmol m^{-3}, n=26). Only CFC-11 and CFC-12 were analyzed in 1992 whereas, in 1993 and in 1994, all four halocarbons were analyzed. All concentrations were reported using the SIO93 scale (Cunnold et al., 1994). ^{129}I analyses were performed on 1 liter seawater samples by accelerator mass spectrometry (Kilius et al., 1992; Kilius et al., 1994; Smith et al., 1998) at the IsoTrace Laboratory at the University of Toronto. Sample data were normalized to IsoTrace Reference Material #2 ($^{129}I/^{127}I = 1.174 \times 10^{-11}$ atom ratio). The blank for this procedure is $0.75 \pm 0.10 \times 10^{8}$ atoms/liter and the standard deviation (one sigma) ranged from 5-10% (Edmonds et al., 1998).

To remove inter-year offsets, all deep casts (below 1700 m) were internally calibrated. This was undertaken with the assumption that modification occurs extremely slowly in the 450-500 year-old deep layer (Macdonald et al., 1993; Schlosser et al., 1997) and would be undetectable over periods as short as six years. Accordingly, the deep theta minimum (2500 m) and maximum (2950 m) were assumed to occur at the same temperature and salinity given the comparatively short time-scale of this study. The magnitude of correction applied was S=<0.001 and θ =<0.005 °C, except for 1992 when the correction was 0.01 °C. Geochemical data were internally calibrated using the same approach. The magnitude of these corrections, which were similar in size to the standard error for each measurement, was NO_3=<0.4 mmol m^{-3}, PO_4=<0.04 mmol m^{-3}, $Si(OH)_4$=<0.3 mmol m^{-3}, and O_2=<1 mmol m^{-3}. These corrections were approximately an order of magnitude smaller than differences identified in the discussion below (i.e. $\Delta\theta$=0.03 °C, ΔS=0.01, ΔNO_3=2 mmol m^{-3}, ΔPO_4 =0.1 mmol m^{-3}, $\Delta Si(OH)_4$=2-4 mmol m^{-3}, ΔO_2=20 mmol m^{-3}).

3. Observations

3.1 Water column description

The Arctic Ocean water column consists of three main layers: a cold, low-salinity upper layer; a warm Atlantic-origin layer; and a cold, saline deep layer separated by transition zones. A strong inverse thermocline, where temperature increases rapidly with depth, is found between the upper and Atlantic layers, and a weak thermocline is found between the Atlantic and deep layers. Within this simple salt-stratified ocean, two distinct water mass assemblies are found—the Western Arctic assembly (WAA) and the Eastern Arctic assembly (EAA). These two assemblies constitute the geochemical composition of Arctic Ocean waters which are distinguished, in the upper layer, by the presence or absence of Pacific-origin water (McLaughlin et al., 1996).

Water mass properties of the WAA in the Arctic Ocean are characterized by Pacific-origin water and, since 1993, are found only in the Canada Basin. The WAA upper layer contains polar mixed water to a depth of about 50 m, and a halocline layer which extends to about 200 m. Upper layer waters overlie the Atlantic layer whose warm core is found near 500 m. In contrast, EAA waters are characterized by an absence of Pacific-origin water in the upper layer and, since 1993, are found in Nansen, Amundsen, and Makarov basins. The EAA upper layer is comprised of a polar mixed layer that extends to 50 m, and a halocline layer which extends to 120 m. The EAA upper layer overlies the Atlantic layer with a warm core found near 275 m.

The Canada Basin halocline has three distinct components. Two of these components are dominated by Pacific-origin water which enters via Bering Strait and crosses the wide Chukchi Shelf where it is seasonally modified by productivity and ice formation. Inflowing Pacific-origin waters include nutrient-rich water from the Gulf of Anadyr and fresher Alaskan Coastal Water characterized by low nutrients (Walsh et al., 1989). Seasonal modification on the Chukchi Shelf produces two forms of Pacific-origin water, referred to as Bering Sea summer and winter waters (Coachman and Barnes, 1961). Summer inflow, augmented by riverine and ice-melt waters, is fresher and characterized by a local temperature maximum between S=31 and S=32, low nutrient concentrations and high oxygen concentrations. Winter inflow, augmented by ice formation, is more saline than summer inflow and characterized by a temperature minimum near S=33.1, high nutrient concentrations, and low oxygen concentrations. Dense water produced by ice formation on the Mackenzie Shelf, from water sufficiently preconditioned by storm-induced upwelling, also contributes to the maintenance of the temperature minimum (Melling and Moore, 1995).

The third component of the Canada Basin halocline is water of Atlantic-origin. It is formed either on the Barents Sea shelf (Jones and Anderson, 1986;

Steele et al., 1995; Melling, 1998), or north of the Barents Sea (Rudels et al., 1996), and modified further by shelf input from Eurasian or Chukchi Sea shelves (Salmon and McRoy, 1994; McLaughlin et al., 1996; Guay and Falkner, 1997)). In the Canada Basin, this third component of the halocline is characterized by both low nutrient and low oxygen concentrations, resulting in a local minimum in NO (defined by Broecker (1974) as NO= $9NO_3 + O_2$) at S=34.4 (Jones and Anderson, 1986). Although these waters have been labelled in the literature as upper, middle and lower halocline, these terms do not identify whether they are of Pacific (i.e. WAA) or Atlantic (i.e. EAA) origin.

Below the Canada Basin halocline lies the Atlantic layer, identified by a temperature maximum at its core. To reach the Canada Basin, Atlantic layer waters pass through three upstream basins, during which time this water becomes colder and fresher. Because Pacific-origin water adds to the thickness of the halocline in the WAA, Atlantic layer water lies deeper in the Canada Basin water column than in the upstream basins. Recent temperature and salinity measurements in the eastern Nansen Basin (Schauer et al., 1997) identified two distinct branches of Atlantic water in the Arctic Ocean; one entering through Fram Strait (FSB), and one seasonally modified during transit across the Barents Sea shelf and entering primarily through St. Anna Trough (BSB). These observations confirmed the two-branch hypothesis proposed by Anderson et al. (1994) and Rudels et al. (1994). Schauer et al. (1997) demonstrated that BSB inflow water, when compared to FSB water, was colder and fresher in the top 700 m and warmer and fresher below 800 m (their Figure 8). Downstream of the confluence zone, and north of the Laptev Sea, evidence of vigorous mixing between these two branches was manifested in temperature-salinity properties. Composition of the Atlantic layer, exiting eastward from the Amundsen Basin in 1993, was estimated by Schauer et al. (1997) to be 60% FSB near 275 m (EAA Atlantic layer core depth) and 80% BSB between 800 m and 1000 m.

The term "Atlantic layer" is used throughout this discussion to denote origin and to signify that this layer is comprised of two components that vary in relative amounts—the FSB, whose presence is identified by its θ_{max} and found higher in the water column, and the BSB, whose presence is identified by its freshness and found lower in the water column. The Atlantic layer so-defined extends to about 2000 m in the Canada Basin and encompasses much of the weak thermocline. This definition expands the classical description of Coachman and Aagaard (1974) who characterized Atlantic Water as water warmer than 0.0 °C. Physical characteristics of FSB and BSB water, as well as their rates of inflow into the Arctic Ocean's Atlantic layer, will vary from year to year according to seasonal and atmospheric conditions.

3.2 Temperature and salinity observations

Potential temperature and salinity CTD measurements, collected between 1989 and 1995 at Station A in the Canada Basin, were examined for evidence of change using the basic water mass layer approach described above (Figures 2a, 2b, and 2c). In the water column's upper layer, the mixed layer was found to exhibit significant variability between years, without a temporal trend (Figure 2a). Surface salinity varied from less than S=25, when temperatures were 0.5 °C to -1.3 °C, to greater than S=28 when temperatures were near -1.5 °C. These measurements reflected annual freshwater variation from both local (Mackenzie River outflow) and upstream (Alaska Coastal Current, Bering Sea and Pacific Ocean) sources, as well as annual variations in atmospheric conditions affecting ice cover and surface drift.

Below the mixed layer in the upper halocline, annual variability in temperature and salinity of the local θ_{max} was observed without trend. Salinities ranged between S=31.35 and S=32.35 where the local temperature maximum was between -1.10°C and -1.40°C at depths from 55 m to 80 m (Figures 2b and 3). The range in physical properties, like observations made by Coachman and Barnes (1961), showed that temperature and salinity in the upper halocline are seasonally conditioned. Winter ice production and export, which vary annually, influence the depth of the polar mixed layer and, in turn, impact on temperature and salinity. Summer import of Alaska Coastal Current and Bering Sea waters, whose temperatures and salinities vary from year to year, likewise influences characteristics of the upper halocline.

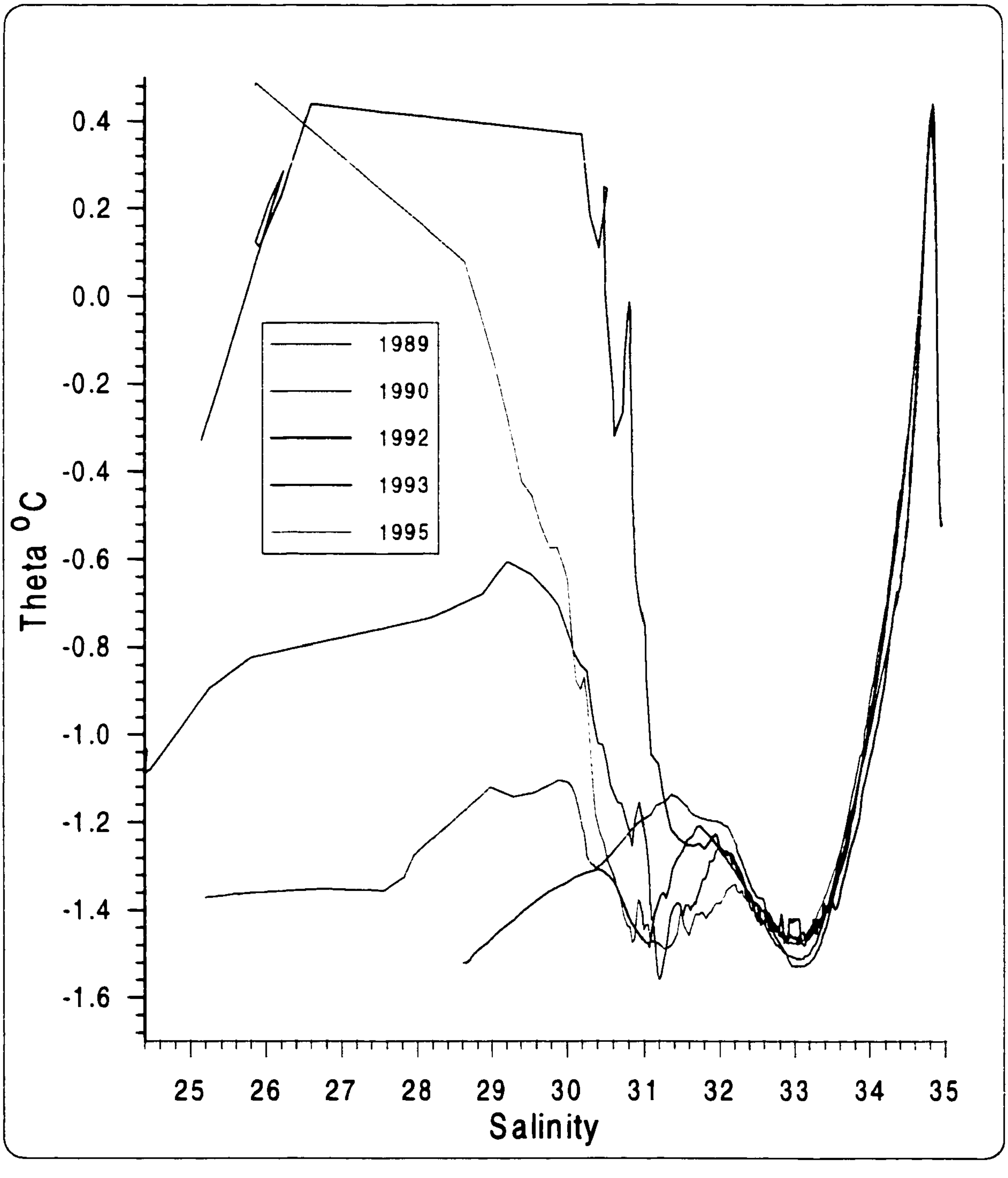

Figure 2a. CTD potential temperature versus salinity from Canada Basin Station A, 1989-1995: S=25 to S=35.

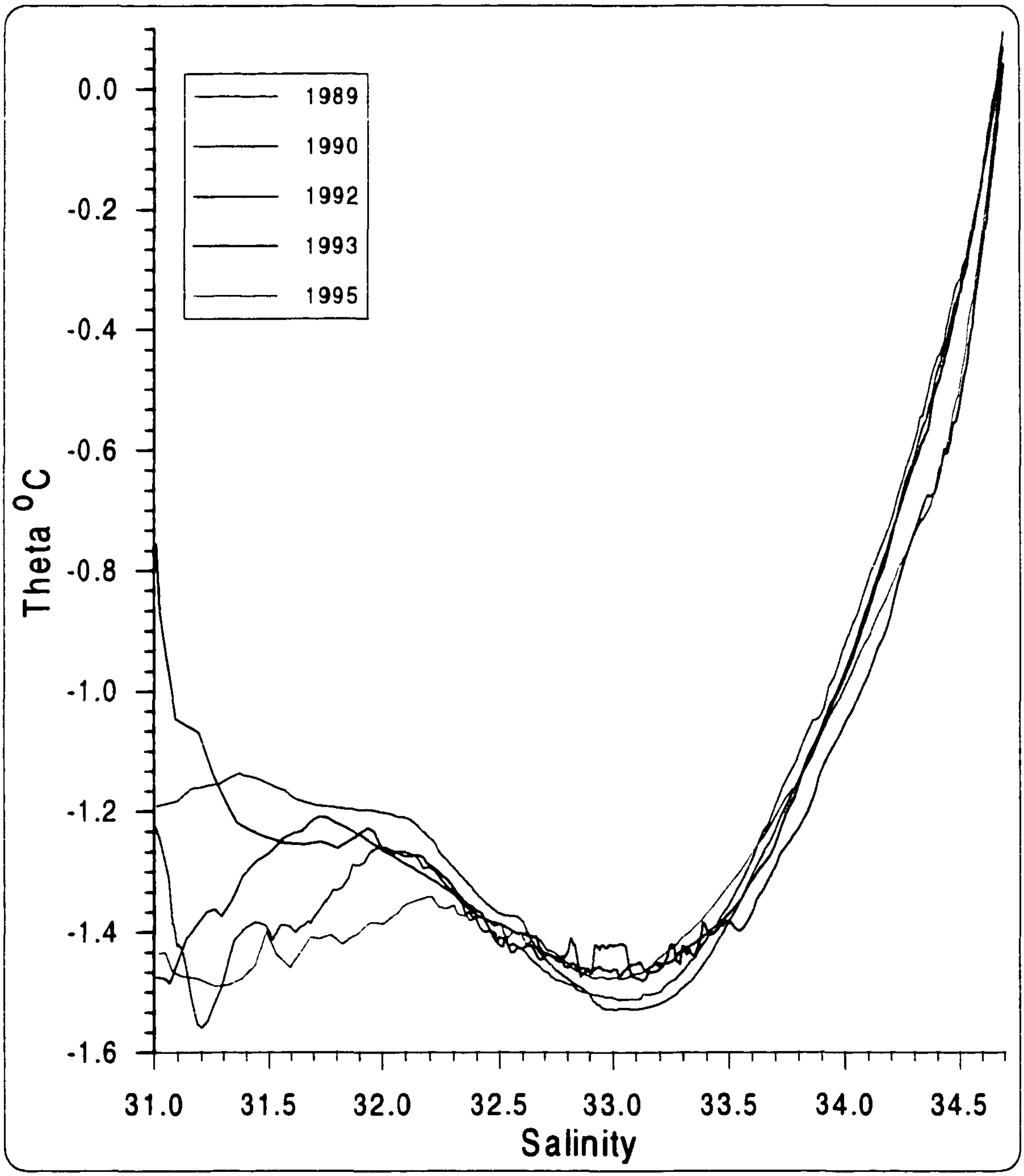

Figure 2b. CTD potential temperature versus salinity from Canada Basin Station A, 1989-1995: S=31.0 to S=34.7.

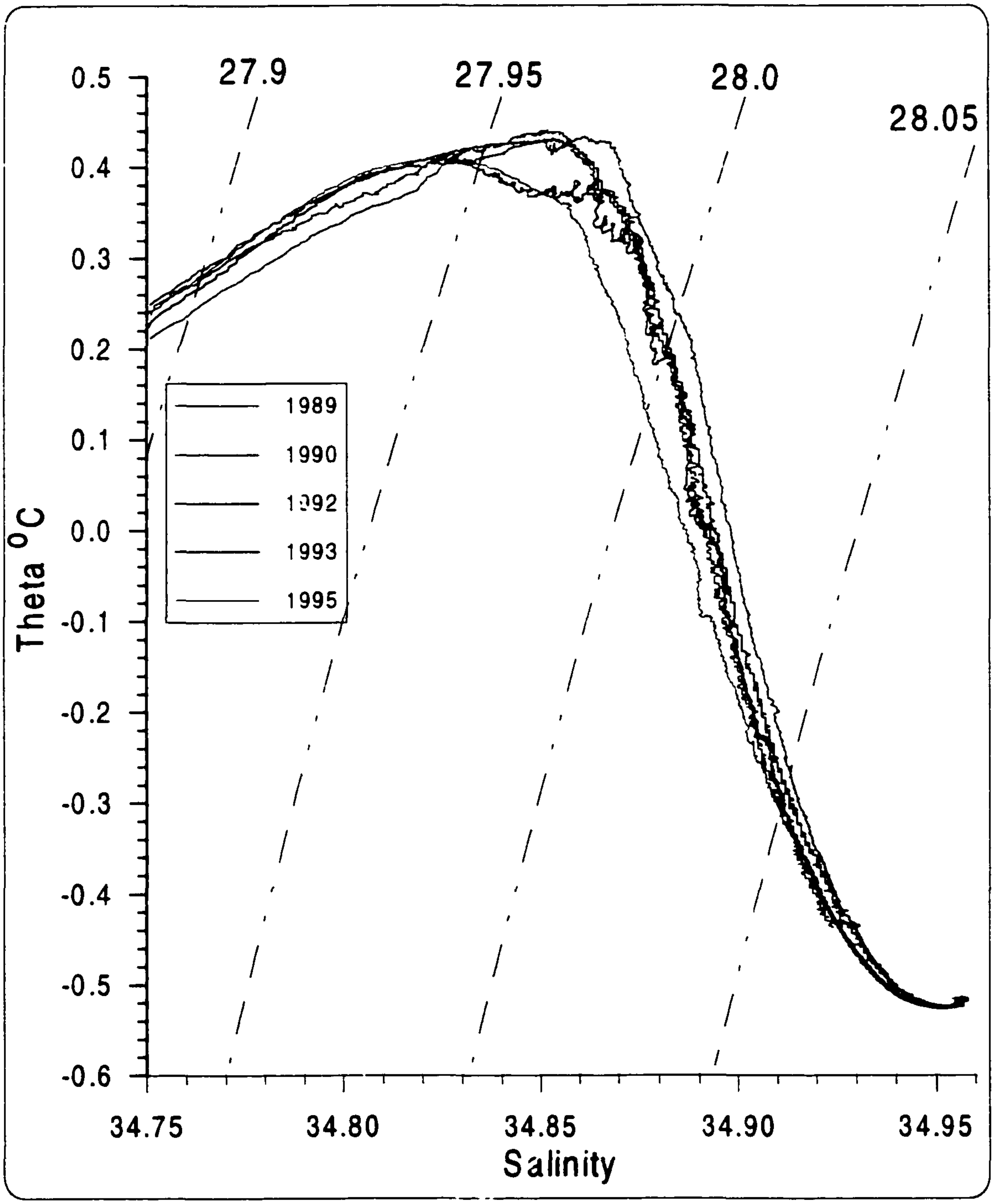

Figure 2c. CTD potential temperature versus salinity from Canada Basin Station A, 1989-1995: S=34.75 to S=34.96

Next, in the middle layer of the halocline, the local temperature minimum was observed at salinities from S=33.0 to S=33.1. Temperatures were colder than –1.50 °C in 1989 and 1990, and warmer than –1.48 °C in 1992,1993 and 1995. Between 1989 and 1992, depth of the temperature minimum ranged from 200 m to 170 m. In 1993 and 1995, however, the temperature minimum was shallower and observed at 140 m.

Together with the mixed layer, the upper and middle haloclines constitute the sum of Pacific-origin water in the Canada Basin. A measurement of the contribution of Pacific-origin halocline water in the water column can be estimated simply by subtracting the depth of the θ_{min} from the depth of the local θ_{max}. Between 1989 and 1992, the depth between the local θ_{max} and θ_{min} ranged from 80 m to 140 m. By 1993 and 1995, however, the depth decreased to 65 m, signalling that a reduction in the amount of Pacific-origin water had occurred. This reduction could be explained by either reduced Pacific or enhanced Atlantic inflow, given that the boundary between Pacific-origin and Atlantic-origin waters in the Canada Basin lay below the middle halocline between S=33.1 and S=34.4. It could also be explained by displacement within the Canada Basin.

In the lower halocline at S=34.4, a distinct shift in temperature was also evident over time. Between 1989 and 1992, temperatures cooled slightly from -0.45 °C to -0.48 °C, however, a marked decrease of 0.14 °C occurred between 1992 and 1993. This temperature decrease was evident in the salinity range S=33.6 to S=34.4 in 1993. In 1995 the temperature remained unvarying at -0.62 °C. Temperature and salinity profiles (Figures 3 and 4) showed that this colder, denser lower halocline lay 40 m higher in the water column in 1993 and 1995.

Farther down the water column, a clear difference in temperature was also apparent between 1992 and 1993 in both components of the Atlantic layer (Figure 2c). In 1993, the upper FSB component, defined by θ_{max}, was slightly colder (from 0.43 °C to 0.40 °C), fresher (from S=34.860 to S=34.830), and found higher in the water column (from 560 m to 450 m). Temperature-salinity values

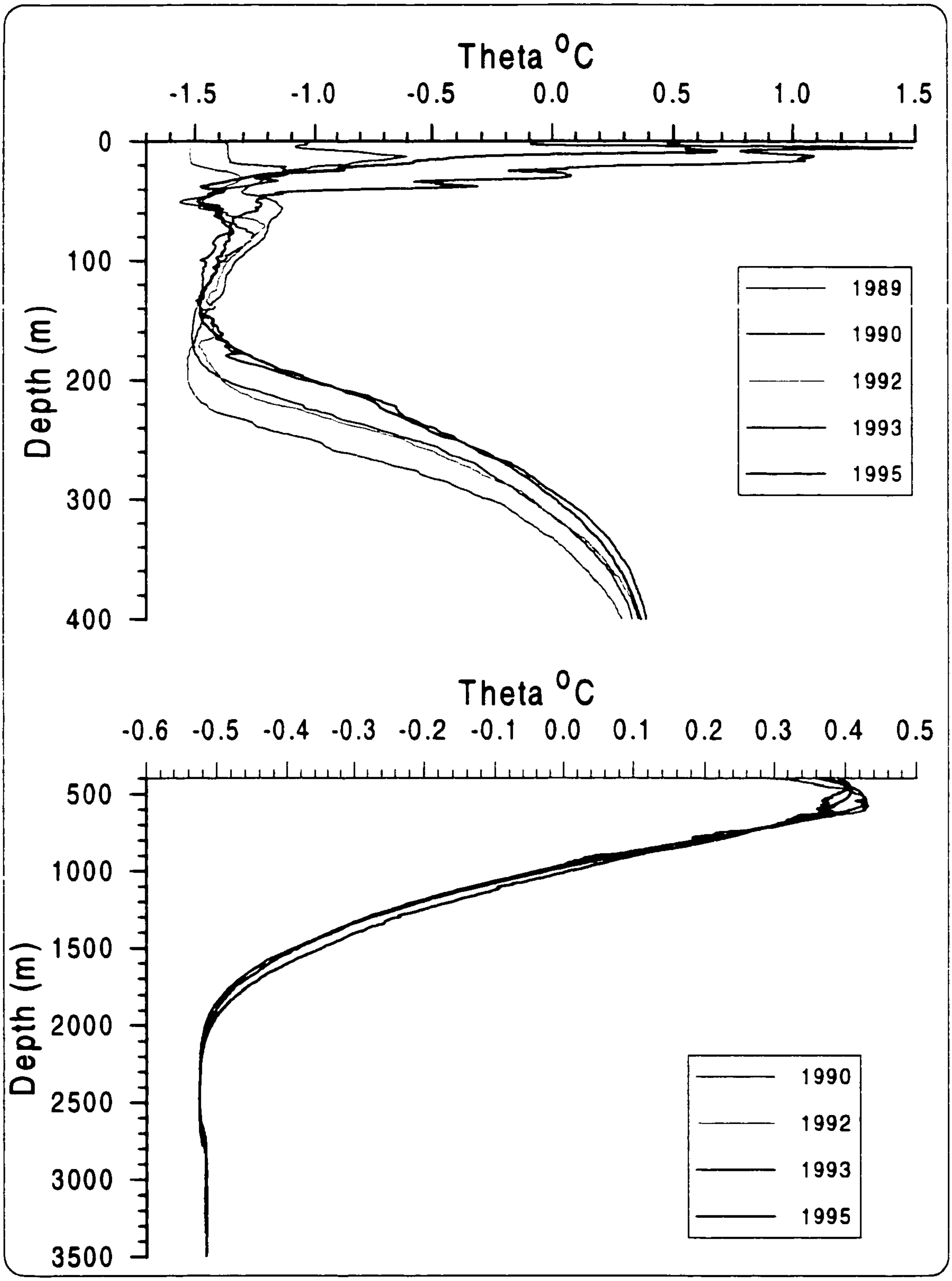

Figure 3. CTD potential temperature profile at Canada Basin Station A, 1989-1995.

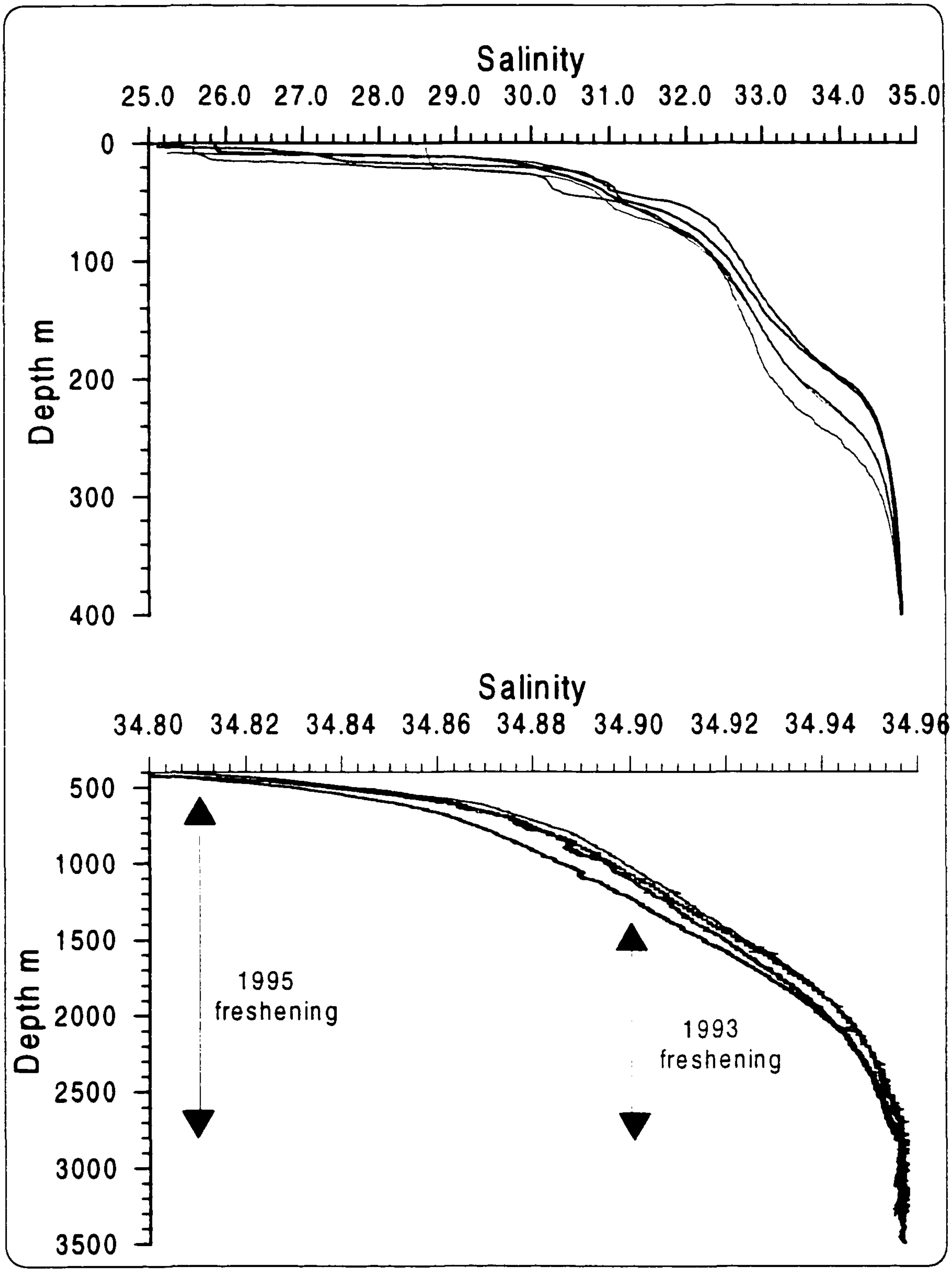

Figure 4. CTD salinity profile at Canada Basin Station A, 1989-1995.

differed appreciably from prior years and were reflected also in the temperature profile (Figure 3). In 1993, below the θ_{max}, temperature decreased sharply from 0.40°C to 0.37°C between 460 m and 550 m, was highly variable (temperature spikes) for the next 80 m, then decreased with depth at the same slope as other years. In 1995, θ_{max} occurred at the same salinity, depth, and temperature as in 1993, however the temperature profile decreased smoothly below θ_{max} from 450 m to 650 m.

The lower BSB component of the Atlantic layer, characterized primarily by lower salinity, was found to be slightly fresher between 1200 m and 2500 m in 1993 than in previous years (e.g. at 1600 m ΔS=-0.004 from S=34.929 to S=34.925). Freshening was paralleled by a slight increase in temperature (e.g. at 1600 m $\Delta\theta$=0.010) between 1400 m and 2000 m. These small variations were not apparent in the 1993 temperature-salinity plot in the range S=34.890 and S=34.950. By 1995, however, the BSB component of the Atlantic layer appeared markedly different in the temperature-salinity plot. Figure 2c illustrates that freshening, evident only in the FSB component in 1993 between S=34.830 and S=34.875, extended in 1995 from S=34.830 to S=34.910 and included both FSB and BSB components of the Atlantic layer. When viewed by depth, salinity was markedly fresher between 500 m and 2500 m in 1995 (e.g. at 1000 m ΔS=-0.011). Likewise, the 1995 temperature was warmer between 700 m and 2200 m (e. g. at 1000 m $\Delta\theta$=0.046 °C). Temperature and salinity profiles show that, below the FSB θ_{max} between 500 m and 2500 m, cold and salty water was replaced by warmer and fresher water in 1995. Further, in 1995, the BSB component was evident to 2500 m and water of salinity S=34.880 was found about 150 m deeper. This suggested that the BSB component of the Atlantic layer occupied more of the water column than in previous years.

In summary, analysis of temperature and salinity measurements demonstrated that distinct changes were first manifest in 1993 over much of the Canada Basin water column at Station A. Differences observed were: shallowing of the middle halocline and thinning of Pacific-origin water; shallowing and cooling of the lower halocline; shallowing, cooling and freshening of the FSB; and warming, freshening and an increased volume of the BSB. Beginning in 1993, the most significant modification was found in the Atlantic layer's BSB component. The 1995 temperature and salinity measurements between 500 m and 2700 m in the Canada Basin were similar to 1993 measurements between 500 m to 1500 m in upstream Eurasian Basin waters, reported by Schauer et al. (1997). This similarity pointed to the value of comparing upstream and downstream data sets. Physical and geochemical data from upstream stations will now be compared with Canada Basin data to determine if differences observed in the Canada Basin halocline and Atlantic layers could be traced to upstream BSB outflow.

3.3 Barents Sea outflow characteristics

BSB outflow properties were examined first by comparing physical measurements collected in the Nansen, Amundsen and Makarov basins in 1993 with measurements made in the Canada Basin from 1989 to 1995 (see Figure 1). Data from the western and eastern Nansen, and eastern Amundsen basin slopes at stations 21, 70, and 35 collected during the 1993 *Polarstern* ARK IVX/4 expedition (Schauer et al., 1997), from the southern Makarov Basin slope at stations E and 20 collected, respectively, during the 1993 *CCGS Larsen* expedition (McLaughlin et al., 1996) and the 1994 *CCGS Louis S. St. Laurent* Arctic Ocean section (Swift et al., 1998), were combined in a temperature-salinity plot (Figure 5). Temperature and salinity measurements from one Nansen Basin station upstream (Station 21) and one station downstream (Station 70) of the St. Anna Trough, presented by Schauer et al. (1997), identified the physical characteristics of the two distinct branches of Atlantic water—FSB and BSB— in the Nansen Basin. As Figure 5 shows, both FSB and BSB waters extended over a range of temperature and salinity values, signalling the presence of a water mass, not a water type (i.e. water defined by a single temperature or salinity). Measurements from downstream stations in the Amundsen (Station 35) and Makarov basins (Stations E and 20) indicated that water from both branches mixed with each other and with older, ambient basin waters, and that the Atlantic layer was comprised of two components, each reflecting attributes unique to their source waters. The FSB

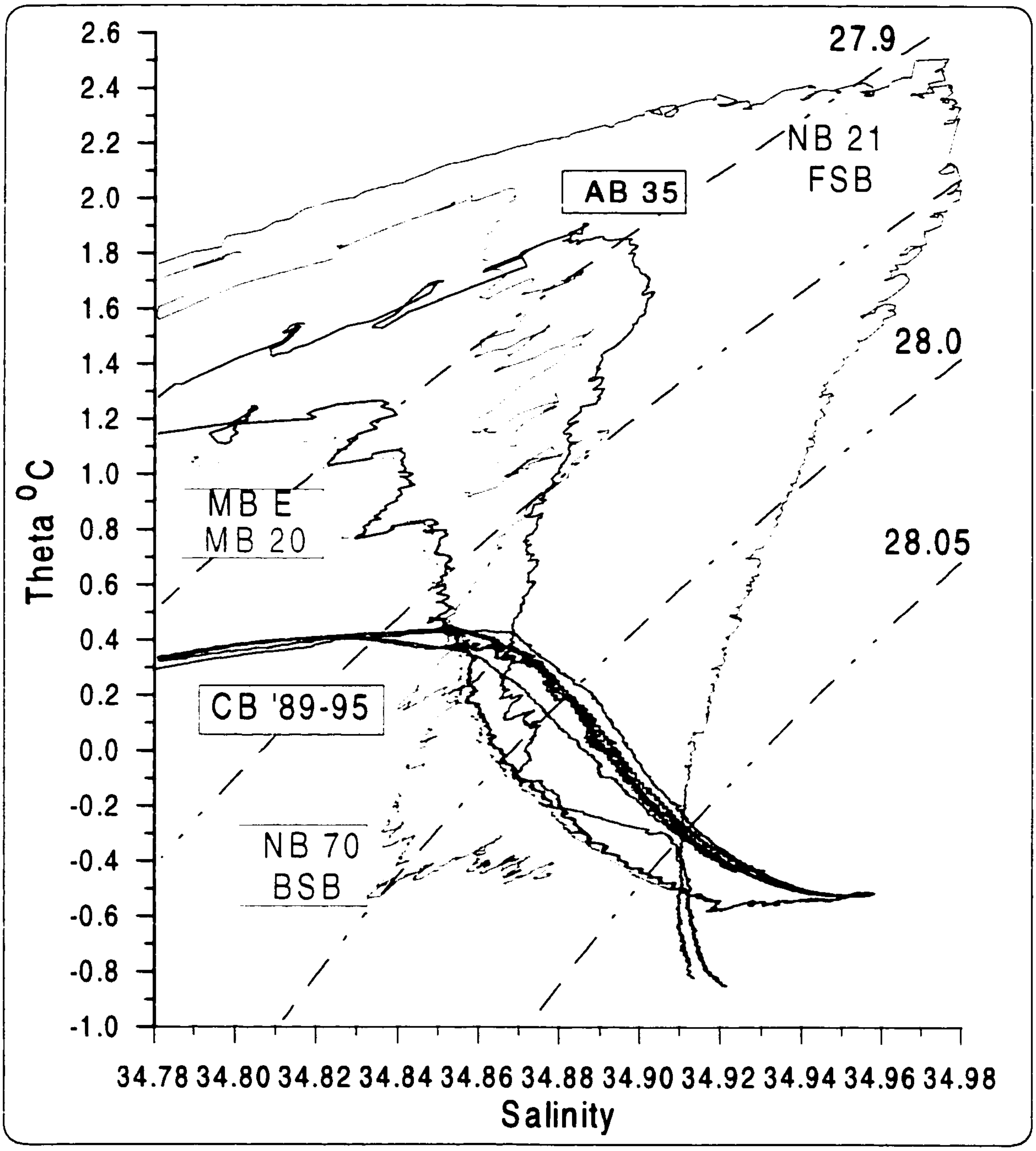

Figure 5. CTD potential temperature versus salinity:S=34.78 to S=34.98. Data are from Canada Basin Station A (1989-1995); Nansen Basin Stations 21 and 70, (1993); Amundsen Basin Station 35 (1993); and Makarov Basin Stations E (1993) and 20 (1994).

component, characterized by θ_{max}, began warm and saline and became progressively cooler and fresher along an isopycnal surface (i.e. σ_θ =27.9) as it travelled from Nansen to Amundsen and Makarov sub-basins. Conversely, the lower BSB component, characterized by colder and fresher water, became warmer and more saline following an isopycnal surface (i.e. σ_θ =28.0) as it travelled from the Nansen to the Amundsen Basin and, thereafter, decreased only slightly in temperature and salinity from the Amundsen to the Makarov Basin.

Temperatures and salinities observed in the Canada Basin's Atlantic layer presented a smooth, round contour significantly different in shape than temperature-salinity contours observed in upstream basins. The shape of the temperature-salinity plot suggested that the extent of mixing between the Atlantic layer's two components with ambient water in the Canada Basin was far greater than found in upstream basins, where the average characteristics of inflowing waters over time were reflected. Notwithstanding this mixing, FSB and BSB components of the Atlantic layer remained identifiable in the Canada Basin by a θ_{max} and an inflection in salinity near S= 34.890 respectively. The upstream basin-to-basin progression of FSB's θ_{max} along the isopycnal surface σ_θ =27.9 did not continue into the Canada Basin where θ_{max} was observed at σ_θ >27.95. The fact that θ_{max} was found at a higher density in the Canada Basin than it was upstream denoted long-term temporal variability in the characteristics of Fram Strait inflow (Loeng ,1990) and the recent warming of Atlantic inflow.

Beginning in 1993, temperature and salinity characteristics in the Canada Basin's Atlantic layer appeared to be influenced by changes in Barents Sea outflow (Figure 5, Station 70), because the FSB component became fresher and colder, and the BSB component became fresher and occupied more of the water column. These observations suggested that composition of the Atlantic layer in the Canada Basin had been altered to include a higher volume of colder, fresher BSB water, evident from 400 m to 2500 m of the water column. Upstream and downstream temperature and salinity measurements, viewed over a larger salinity scale (Figure 6), showed that modification to both halocline and Atlantic layers in the Canada Basin water column was strongly associated with an increased Atlantic-origin

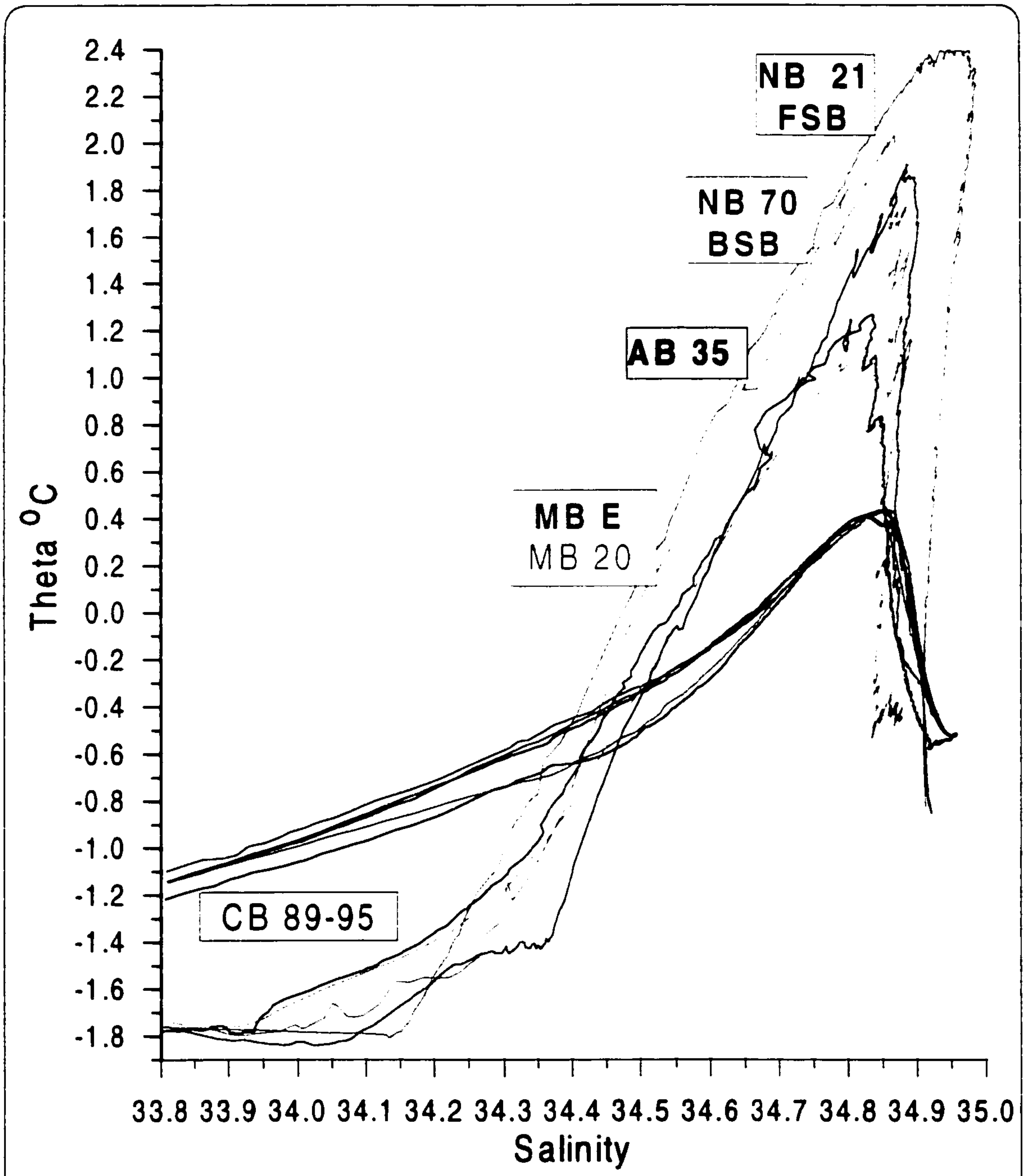

Figure 6. CTD potential temperature versus salinity: S=33.8 to S=35.0. Data are from Canada Basin Station A (1989-1995); Nansen Basin Stations 21 and 70 (1993); Amundsen Basin Station 35 (1993); and Makarov Basin Stations E (1993) and 20 (1994).

inflow, most likely from the Barents Sea. To identify the origins of halocline and Atlantic layer changes in the Canada Basin, geochemical measurements from upstream and downstream stations will now be compared.

3.4 Time-series geochemical observations

Geochemical measurements, collected at Station A in the Canada Basin from 1989 to 1995, were compared over time and compared with measurements from four upstream stations. Nutrient and ^{129}I isotope values were analyzed primarily to investigate whether geochemical differences were evident in the halocline and whether the source of these differences could be ascertained. Oxygen and CFC measurements were then analyzed to answer questions about the Atlantic layer's composition and to distinguish between non-shelf (FSB) and shelf-derived (BSB) water.

Nutrients and ^{129}I were selected to examine the boundary separating Atlantic and Pacific-origin waters within the halocline. Nutrients define the Atlantic/Pacific water mass boundary because Pacific-origin water is high in nutrients, and Atlantic-origin water low. Conversely, ^{129}I defines the Atlantic/Pacific boundary equally effectively because it signals the presence of Atlantic-origin water. Since the 1960s, Atlantic water has been enriched by ^{129}I radionuclide emission from European reprocessing plants, whereas Pacific-origin water, in contrast, exhibits low fallout ^{129}I concentrations (Smith et al., 1998). Although Canada Basin time-series ^{129}I measurements dating back to 1989 are not available, ^{129}I measurements from Canada and Makarov basins in 1993 and 1995 were used in conjunction with time-series nutrient measurements beginning in 1989 to determine the depth of the Atlantic/Pacific water mass boundary over this six-year period.

Analysis of source waters in the middle and lower halocline of the Canada Basin at Station A began by plotting silicate, ^{129}I, and salinity profiles from 1995 measurements (Figure 7). The silicate maximum, found near S=33.1, confirmed the presence of Pacific-origin water in the middle halocline. Likewise, the ^{129}I

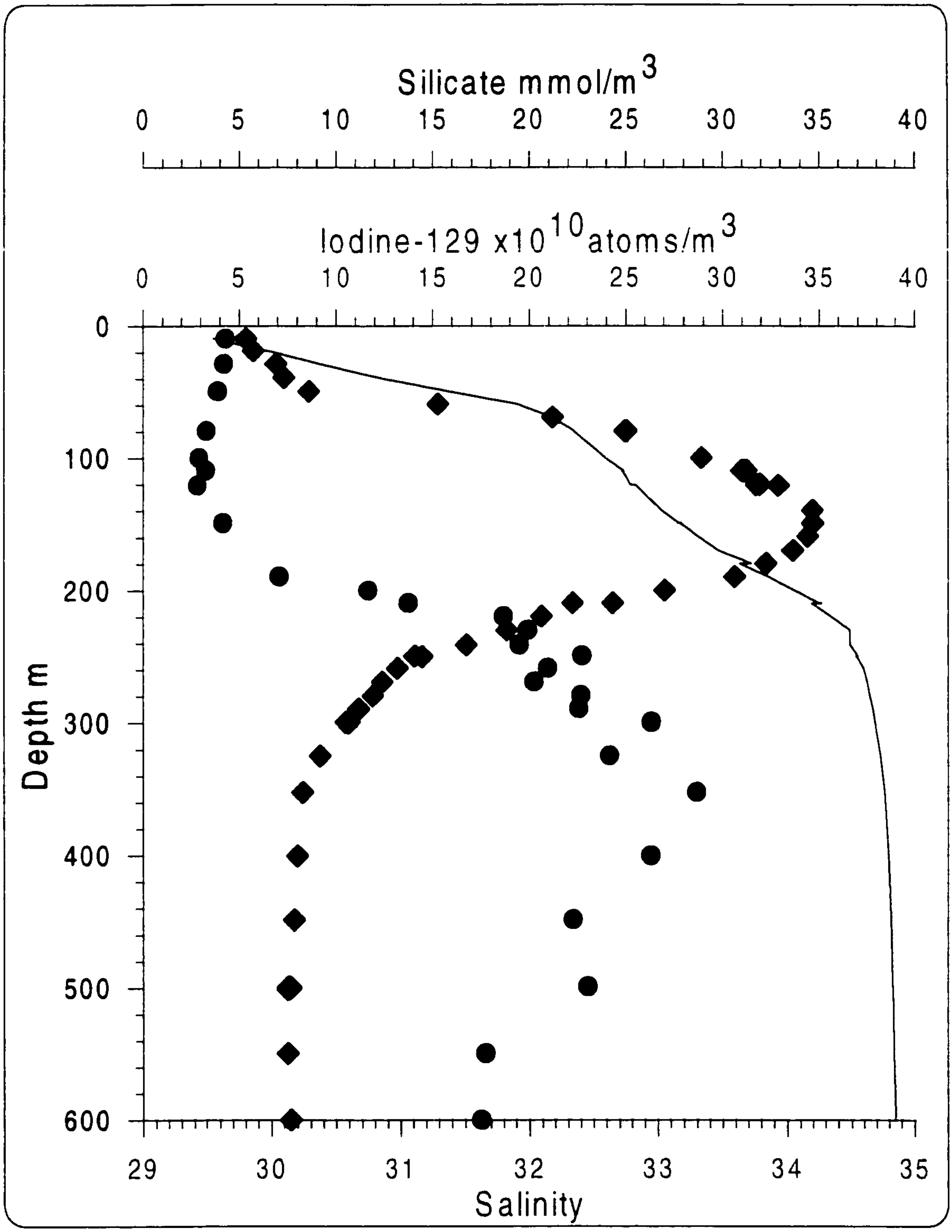

Figure 7. Silicate and ^{129}I profiles at Canada Basin Station A, 1995.

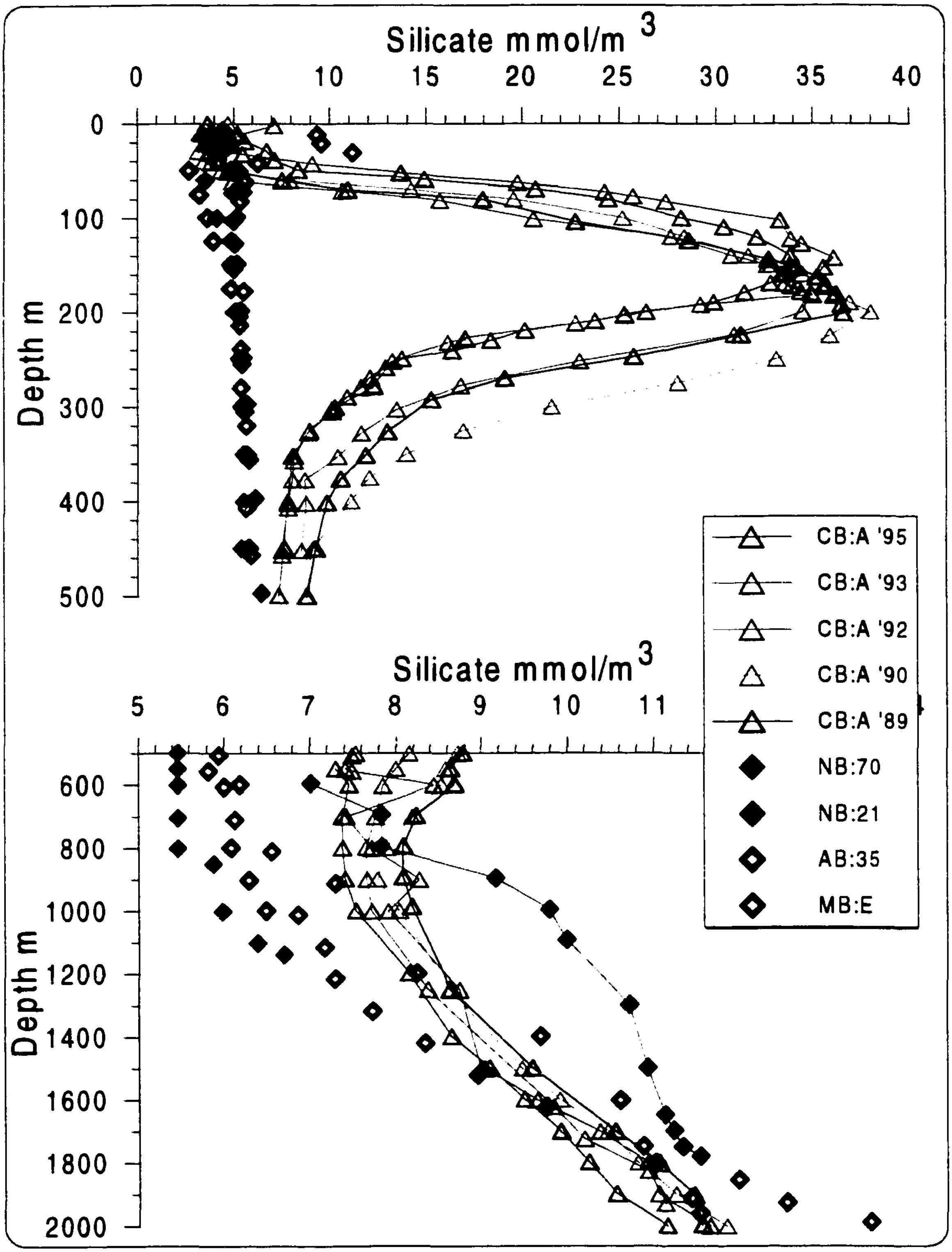

Figure 8. Silicate profiles (a) 0 m to 500 m (b) 500 m to 2000 m

maximum observed near S=34.8, confirmed the presence of Atlantic-origin water in the lower halocline. Intersection of these two profiles pointed to the location of the Atlantic/Pacific boundary, which in 1995 occurred at 240 m and S=34.4 in the lower halocline. Time-series silicate profiles from 1989 to 1995 (Figure 8a) indicated three kinds of changes. First, the zone of Pacific-origin water, as outlined by the silicate maximum, decreased in thickness from 175-220 m, between 1989 and 1992, to 150 m in 1993 and 1995. Second, the silicate maximum was located about 50 m higher in the water column in both 1993 and 1995 than in previous years. Third, in 1995 the concentration of the silicate maximum was lower than in previous years. Altogether, these findings demonstrated that the boundary between Pacific and Atlantic-origin waters in the Canada Basin halocline was shallower in 1993 and 1995 than in earlier years and suggested a recent displacement of Pacific-origin water from below.

A shift in the Atlantic/Pacific boundary was also evident when Station A time-series silicate measurements were plotted against salinity (Figure 9a). Between 1989 and 1993, concentration of the silicate maximum near S=33.1 in the middle halocline ranged 36-38 mmol m^{-3} but, in 1995, decreased to 33.5 mmol m^{-3}. Silicate decrease suggested either that more Atlantic-origin water was present due to shallowing of the Atlantic/Pacific water mass boundary, or that the silicate concentration of Pacific-origin BSWW had been reduced. Comparison of silicate measurements from the Nansen, Amundsen and Makarov basin stations in the same salinity range pointed to an increased contribution of Atlantic-origin water in Canada Basin water column below S=33.1. Atlantic-origin concentrations were much lower (5 mmol m^{-3}) than concentrations in Pacific water (>33 mmol m^{-3}). No data were available, however, to determine whether BSWW composition had been altered during this time.

Below the lower halocline, from S=34.4 to S=34.88, silicate concentrations in 1993 were also lower than previously observed. By 1995, lower silicate concentrations were observed from S=33.1 to S=34.88 in a region of the water column including the middle halocline, the Atlantic/Pacific boundary, the lower halocline, and both components of the Atlantic layer. The 1995 observation of lower

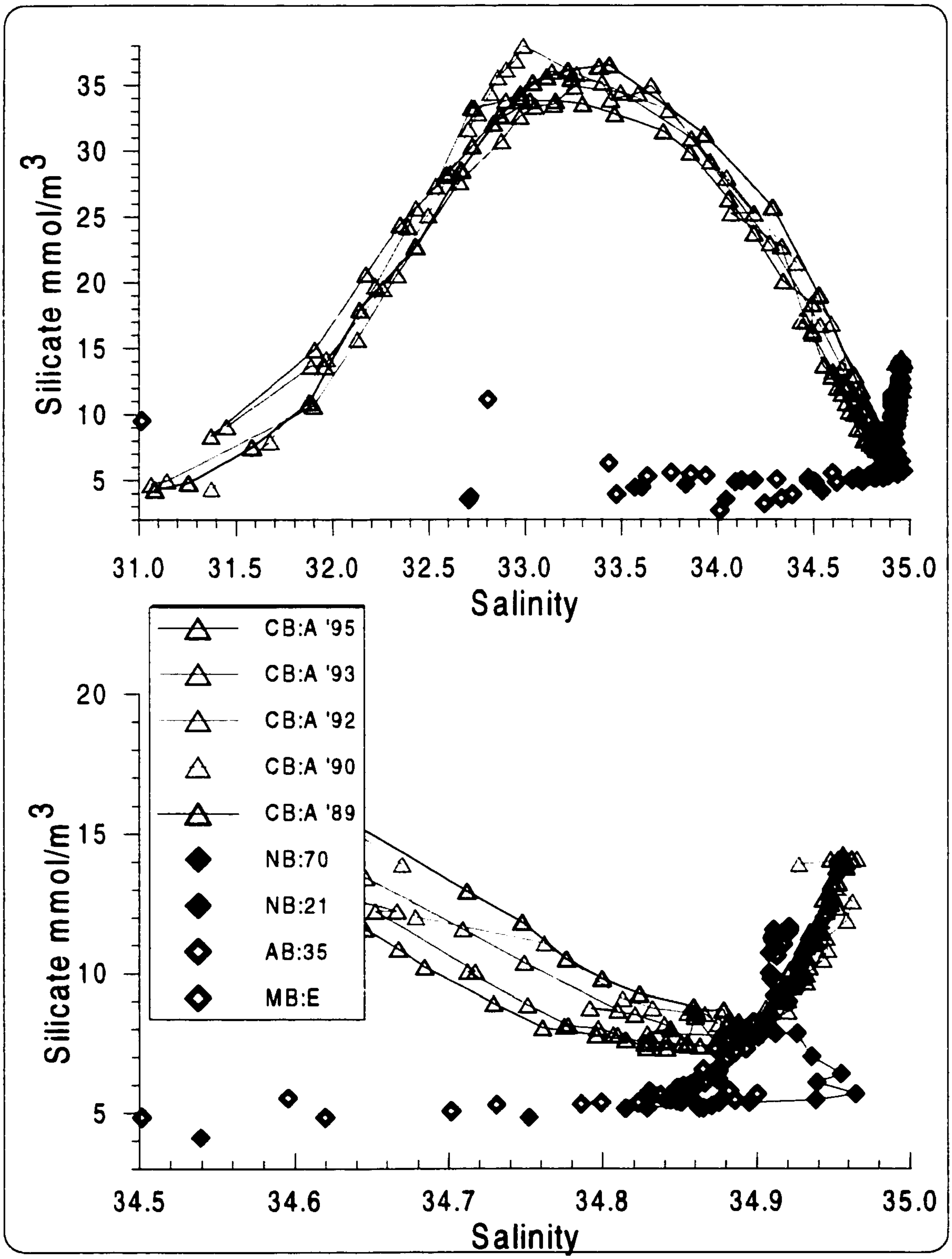

Figure 9. Silicate versus salinity: (a) S=31 to S=35,
(b) S=34.5 to S=35.0

silicate concentrations in the salinity range S=33.1 to S=34.4 further indicated that Atlantic water now occupied more of the halocline than in previous years, and that the boundary separating Pacific and Atlantic-origin waters was located higher in the water column. Decrease in concentration of the silicate maximum in 1995 near S=33.1 identified the extent of Atlantic-origin water's influence in the middle halocline.

Moreover, lower silicate concentrations in the water column at salinities from S=34.40 to S=34.88 in 1993 and 1995 suggested that differences in silicate concentration could also signal a modification to the composition of Atlantic layer water. At the two Nansen Basin stations, silicate concentrations were lower in BSB source water than in FSB source water below 300 m (Figure 8b) and when salinities were greater than S=34.80 (Figure 9b). Downstream in the Amundsen and Makarov basins, where both FSB and BSB waters comprise the Atlantic layer, low silicate concentrations below the salinity maximum indicated the presence of BSB water. Farther downstream, in the Canada Basin, lower silicate concentrations were observed in 1995 to a depth of about 1200 m (S=34.89), and these lower concentrations suggested that composition of the Atlantic layer now included a greater amount of BSB water.

Analysis of nitrate (Figures 10, 11) and phosphate (Figures 12, 13) time-series measurements corroborated silicate findings from Station A, notably: the nutrient maximum of the middle halocline was shallower and thinner in 1993 and 1995 than in previous years; nitrate and phosphate concentrations were lower in 1993 at salinities S>34.4 and, in 1995, lower at salinities S>33.1; and in 1995 the maximum nitrate and phosphate concentrations were lower than in previous years. Moreover, nitrate and phosphate concentrations were also lower in BSB than in FSB source water. These data signalled that the Atlantic/Pacific boundary was shallower and, accordingly, more Atlantic-origin water was found within the Canada Basin halocline. Lower concentrations of nitrate and phosphate at salinities S>34.4 pointed to an increase of BSB water in the composition of Atlantic layer.

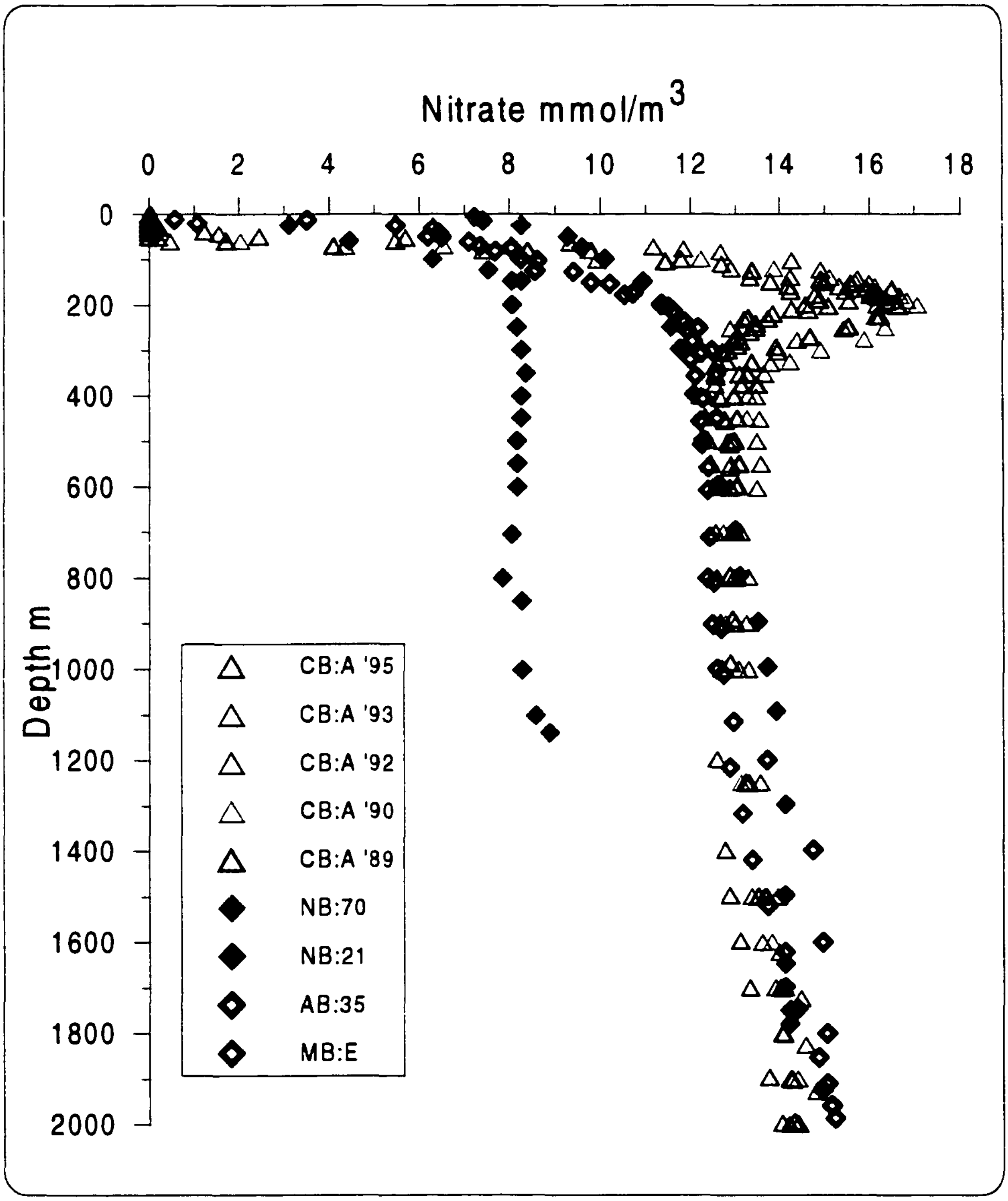

Figure 10. Nitrate profiles.

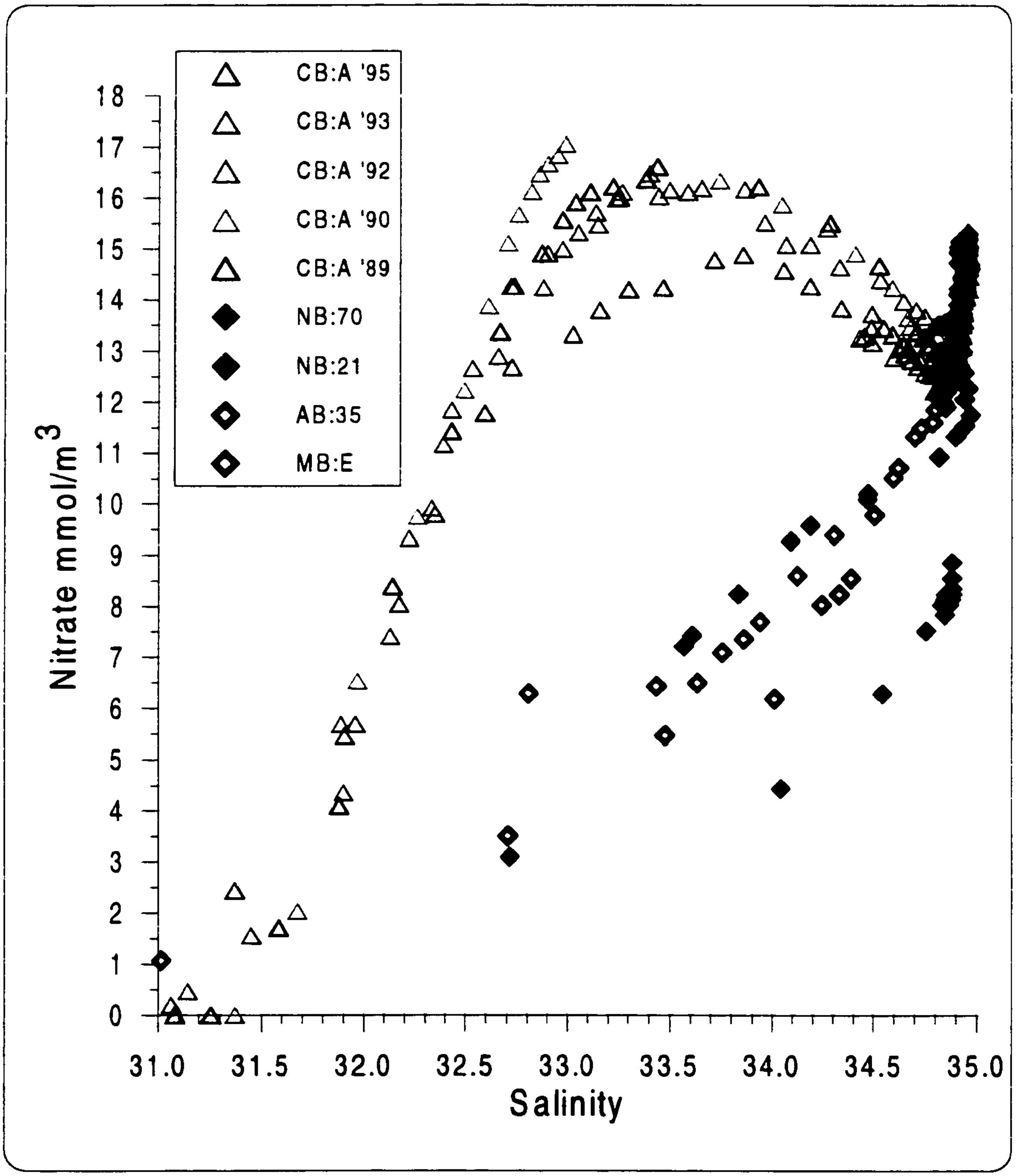

Figure 11. Nitrate versus salinity.

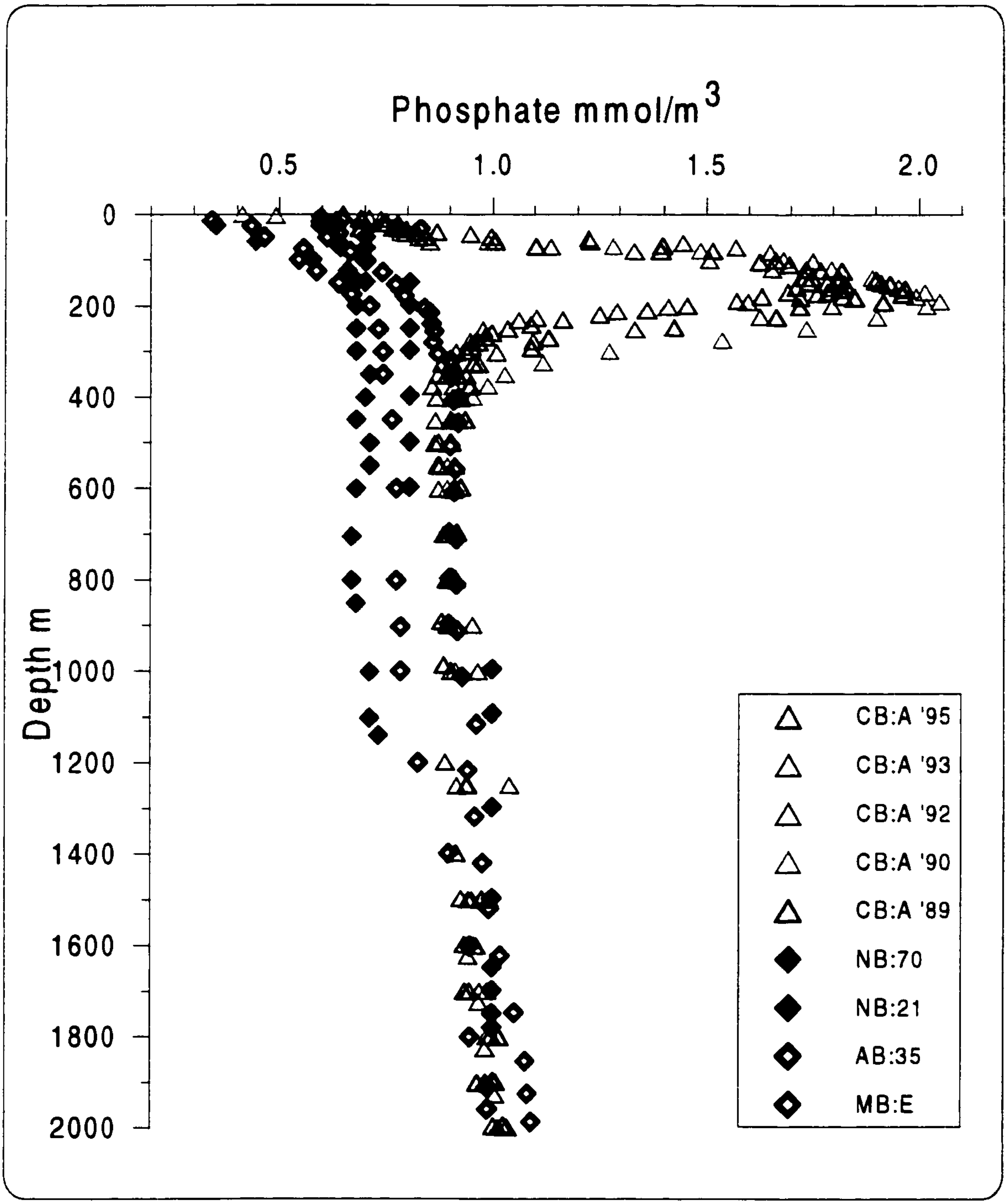

Figure 12. Phosphate profiles.

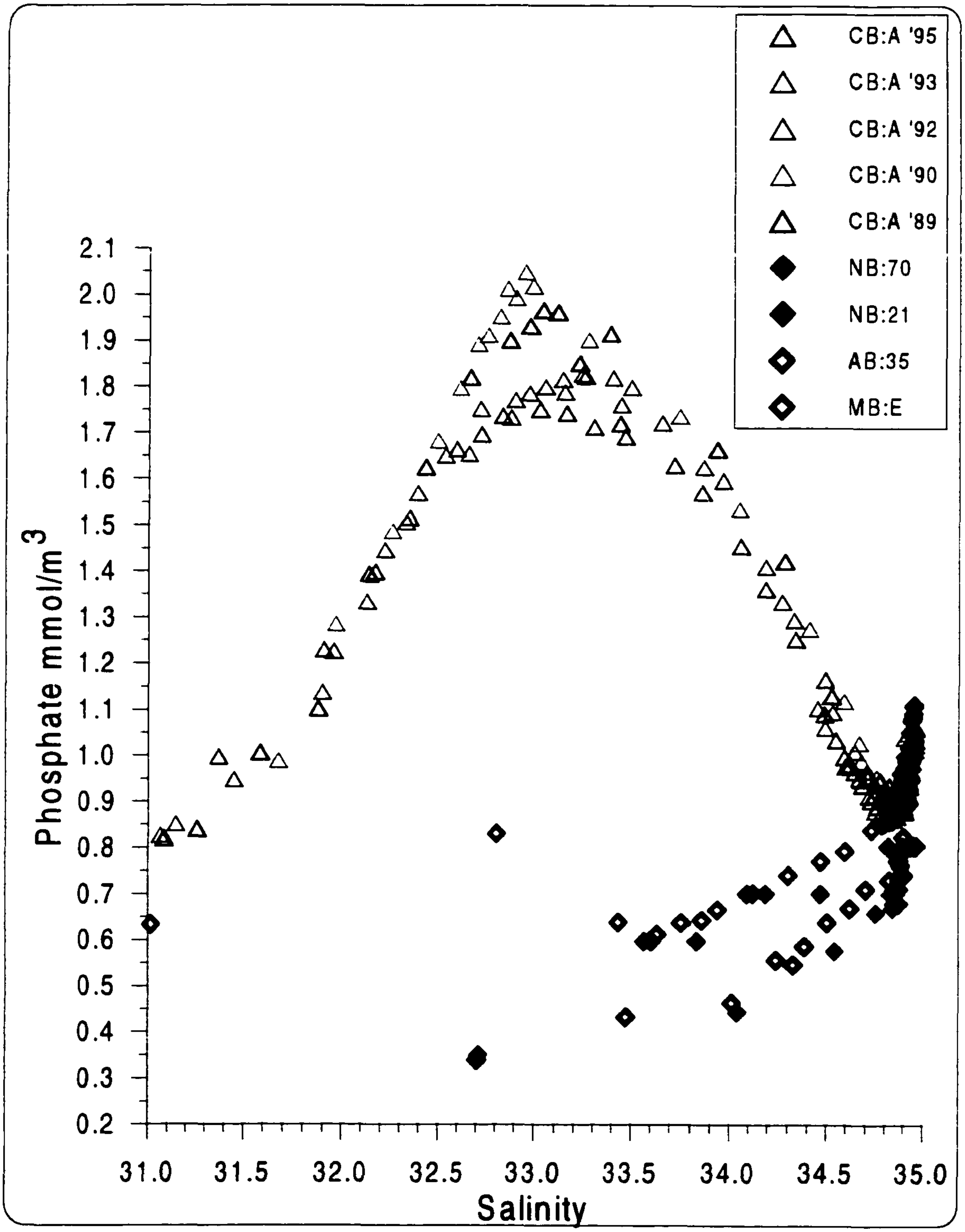

Figure 13. Phosphate versus salinity.

Canada Basin time-series oxygen profiles (Figure 14) at Station A also provided corroborating evidence that more Atlantic-origin water was found in the Canada Basin halocline. In 1993 and 1995, the oxygen minimum of the lower halocline at 210 m was 50 m shallower, and the concentration was 15 mmol m^{-3} higher than in previous years. By 1995, oxygen concentrations were higher at depths from 200 m to 1000 m, suggesting that these waters were more ventilated than in the past. The oxygen-salinity plot (Figure 15) showed that oxygen concentrations were higher between salinities S=33.1 and S=34.9. The plot also illustrated that oxygen concentrations throughout the water column in the three upstream basins were much higher than in the Canada Basin and, in addition, that BSB shelf source water was about 12 mmol m^{-3} higher than FSB source water. Thus, higher oxygen concentrations within the Canada Basin water column also pointed to the increased contribution of shelf-source (BSB) water within the Atlantic layer.

But oxygen is not a conservative tracer and cannot unequivocally identify shelf-source water. The conservative tracer CFC-11, measured at Station A in 1992, 1993 and 1995, however, provided more definitive identification. Since CFC-11 concentrations denote levels of ventilation, this tracer was used to identify shelf-source water, which exhibits high levels of ventilation at depth within the water column as a result of recent convection, from non-shelf source water. Furthermore, because CFC-11 solubility increases as water temperature decreases, this tracer's value in distinguishing cold, BSB shelf-water from warm, non-shelf FSB water is enhanced. CFC concentrations in the water column thus reflect both the atmospheric concentration at time of subduction (i.e. age) and the water's local temperature (i.e. source).

Comparison of CFC-11 measurements at Station A from 1992, 1993, and 1995 showed that the water column from 200 m to 1600 m was markedly more ventilated in 1995 and that the largest increase in CFC-11 concentration occurred in the lower halocline and the Atlantic layer between 300 m and 1000 m (Figure 16). Similarly, a CFC-11-salinity plot (Figure 17) demonstrated that the largest

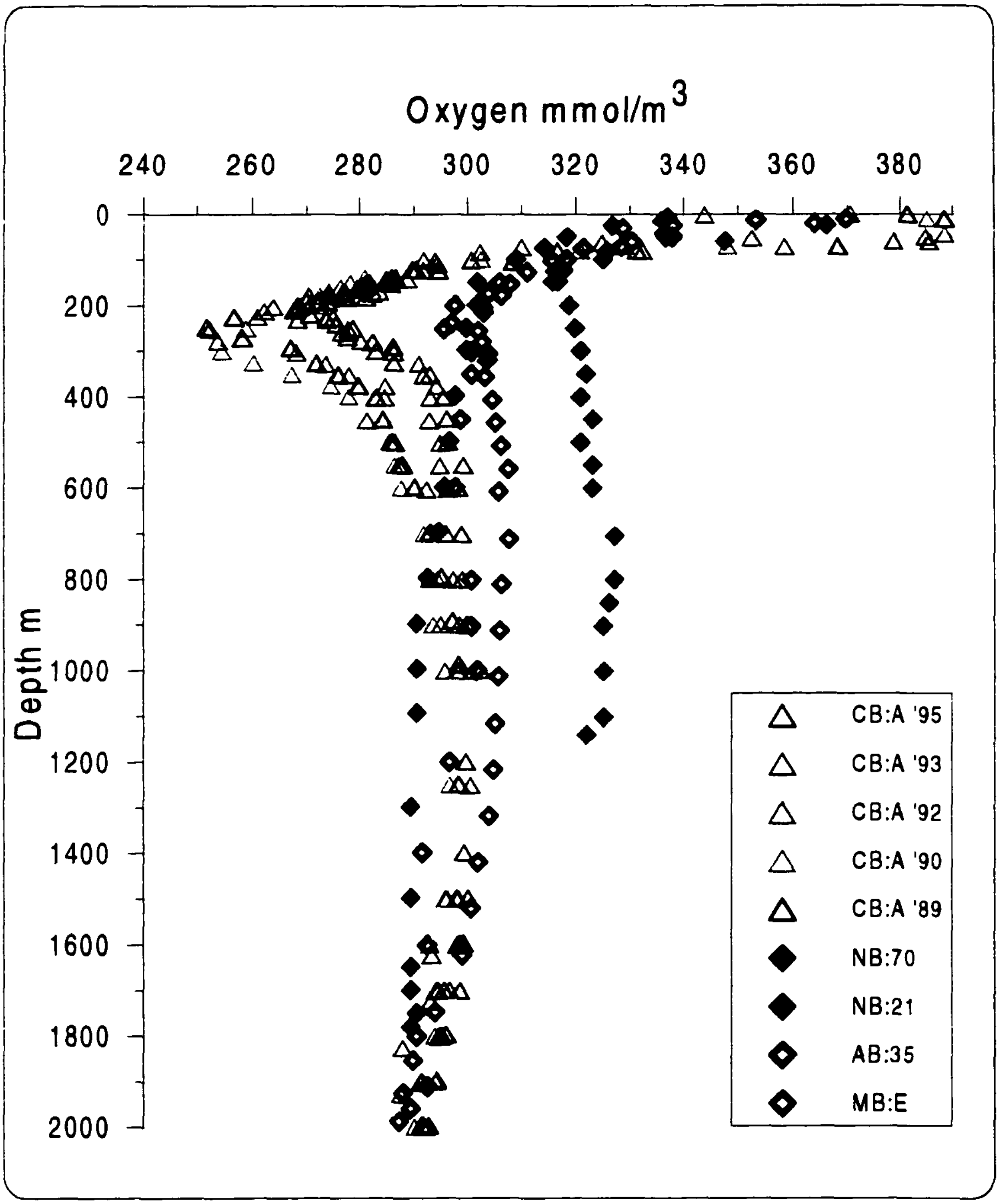

Figure 14. Oxygen profiles.

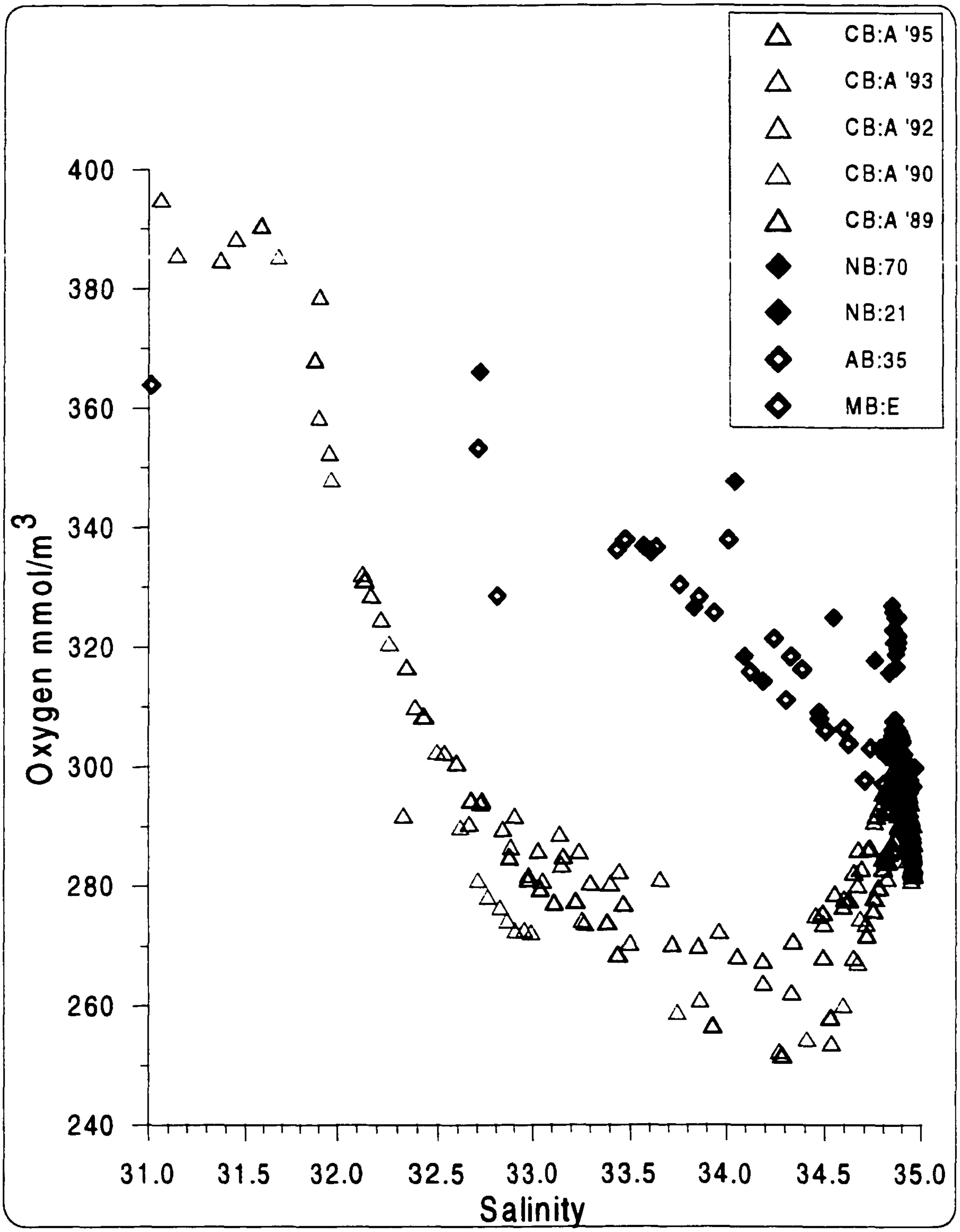

Figure 15. Oxygen versus salinity.

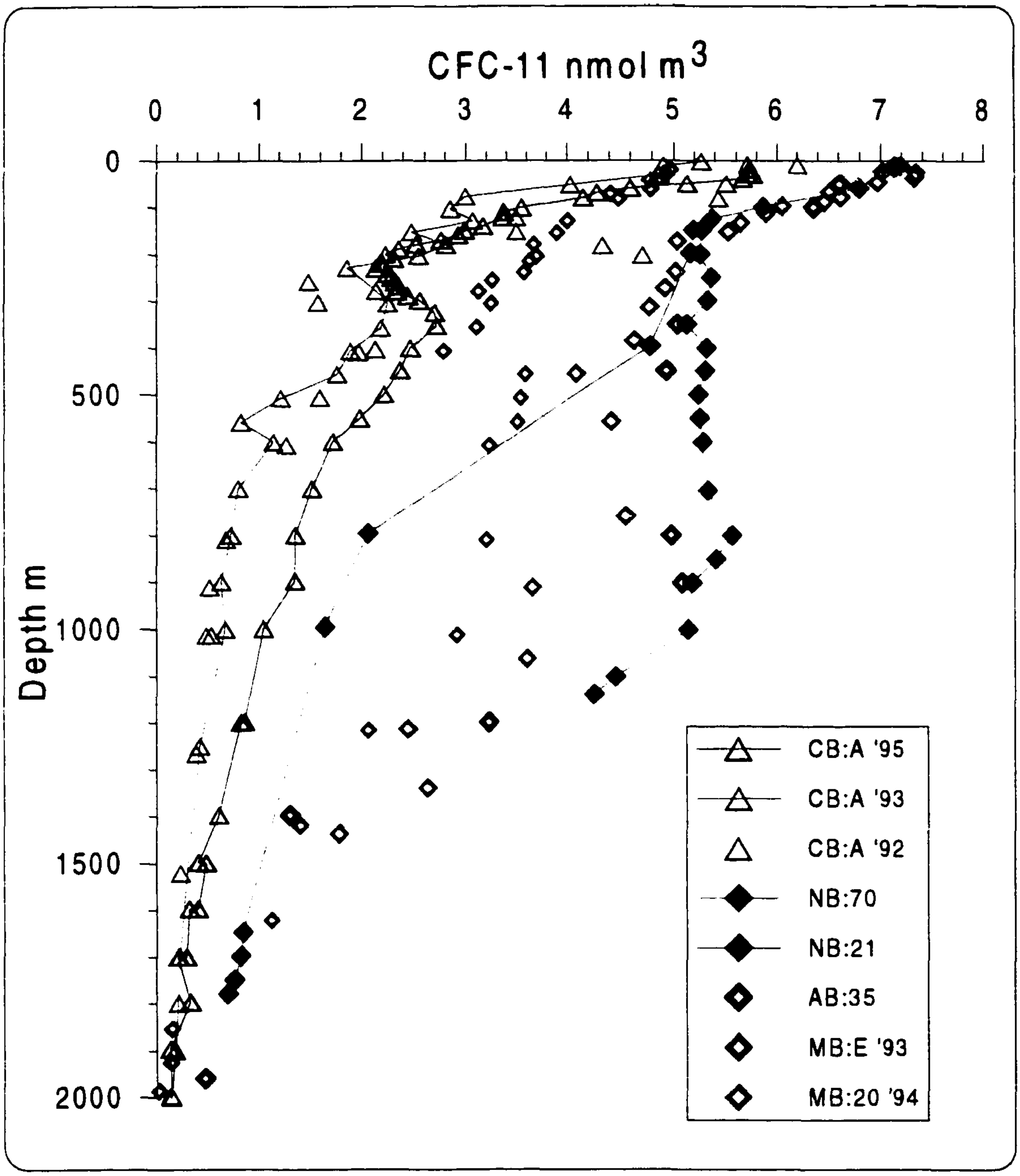

Figure 16. CFC-11 profiles

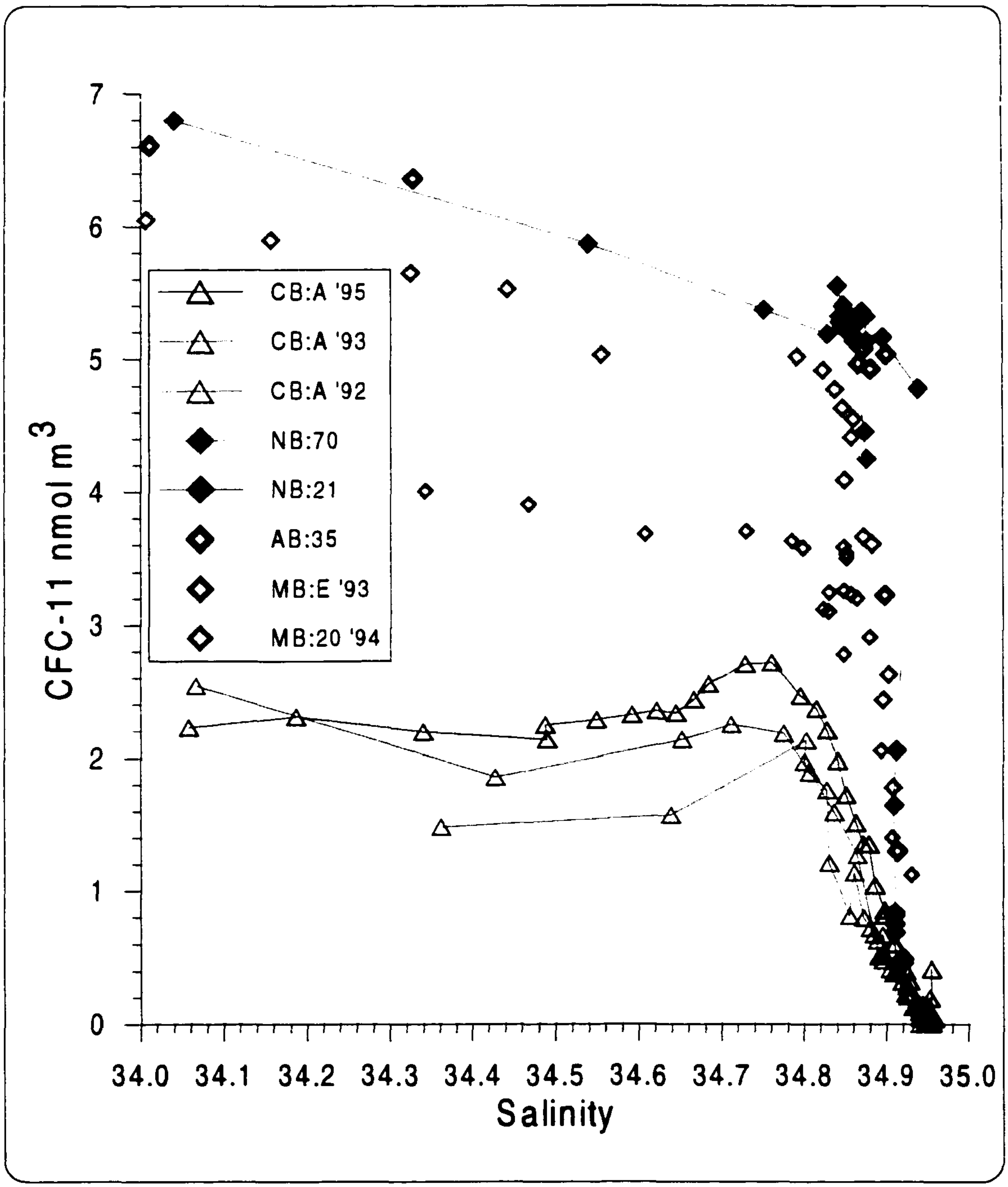

Figure 17. CFC-11 versus salinity.

CFC-11 increase in 1995 was found between S=34.4 and S=34.9 in both FSB and BSB waters.

Comparison of CFC-11 profiles from the Canada Basin with those from the three upstream basins clearly highlighted differences in ventilation between non-shelf and shelf-water. At Station 21, the station closest to Fram Strait inflow, waters were ventilated (4.8 nmol m^{-3}) to a depth of 400 m. By comparison, at Station 70, the station closest to Barents Sea outflow, waters were more ventilated (5.3 nmol m^{-3}) to a depth of 1100 m. Thus, ventilated waters downstream in the Canada Basin at depths more than 1100 m confirmed the contribution of Barents Sea outflow to the halocline, as well as a high amount of BSB water in the Atlantic layer. The 1995 increase in CFC-11 concentrations between 300 m and 1100 m provided compelling evidence that the Atlantic layer's composition had been modified as a consequence of increased BSB outflow upstream.

Since 1993 upstream measurements covered a large geographic expanse, differences in CFC-11 profiles were attributed to annual variability in Barents Sea outflow. For example, at Station 35 in the Amundsen Basin, a small local minimum (0.2 nmol m^{-3}) near 435 m at S=34.87 distinguished FSB water from BSB water. Downstream at Station E in the Makarov Basin, the local minimum was much larger (0.8 nmol m^{-3}). BSB water in 1993 was observed to 1100 m in the Nansen Basin, to 1400 m in the Amundsen Basin, and to 1600 m in the Makarov Basin. Increases in depth from basin to basin were caused either by variability in Barents Sea outflow, or by vertical stretching as described by Schauer et al. (1997).

Advance and spread of Atlantic water through the Arctic Ocean were tracked using ^{129}I measurements and observations of ^{129}I at depth in the water column were taken to indicate dense water outflow from the Barents Sea. ^{129}I profiles (Figure 18) from two Canada Basin stations in 1993 and 1995, together with measurements from one Makarov Basin station in 1993 illustrated that ^{129}I concentrations in the Canada Basin were higher between 300 m and 800 m in 1995 than 1993. Similar to CFC-11 measurements, the largest increase in ^{129}I was found between S=34.4 and S=34.9. A plot of ^{129}I and CFC-11 (Figure 19)

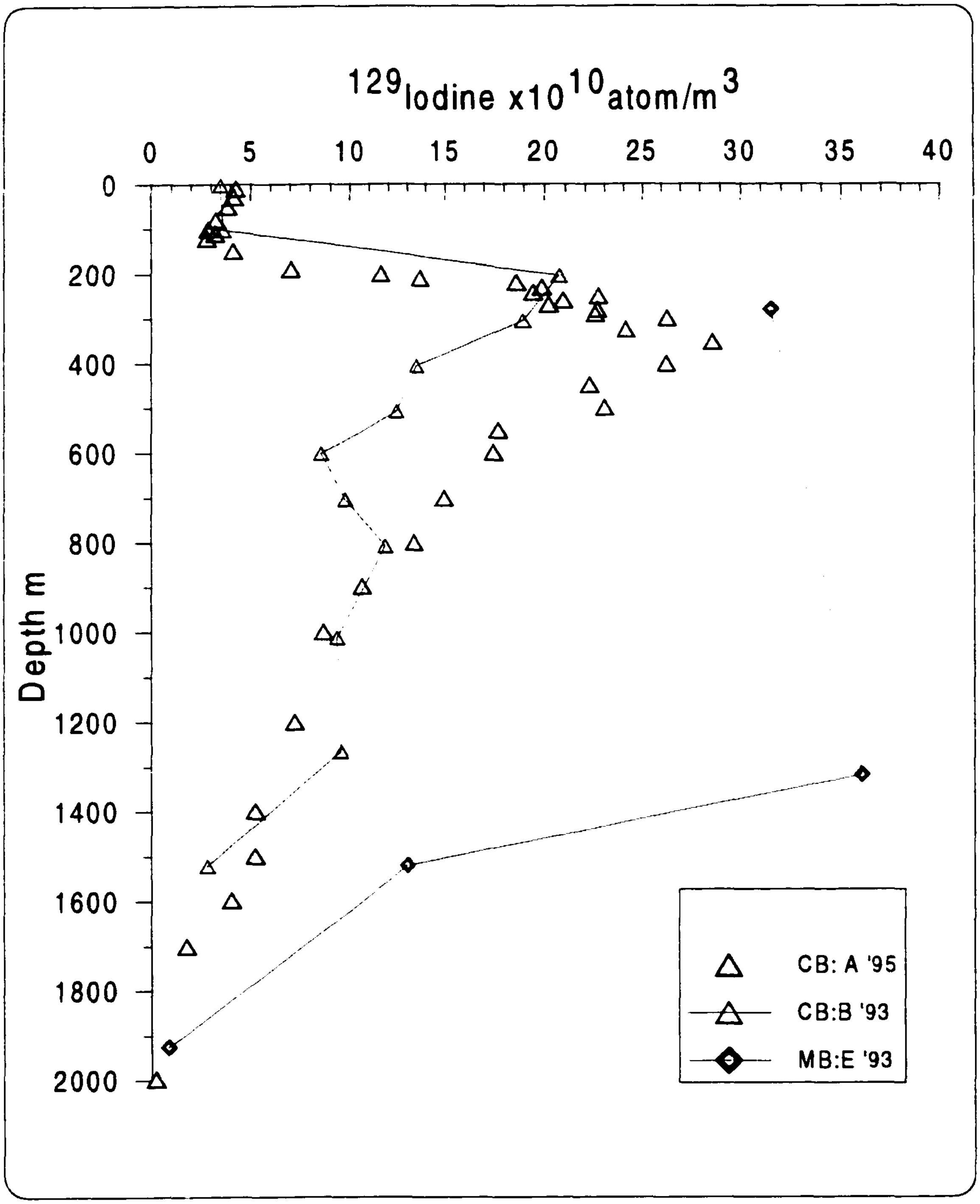

Figure 18. Iodine profiles in the Canada and Makarov basins.

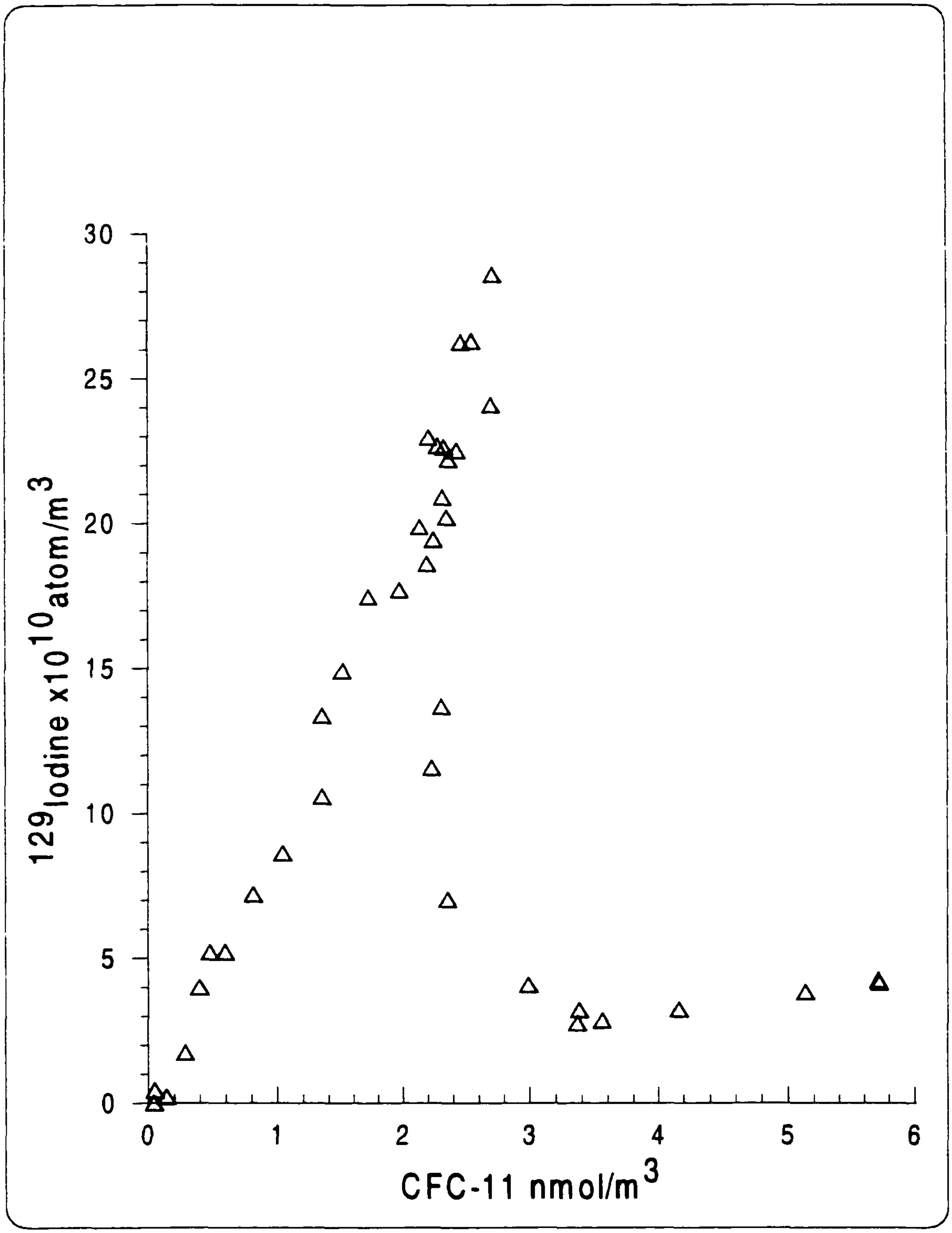

Figure 19. ^{129}I versus CFC-11 correlation diagram at Canada Basin Station A, 1995.

illustrated a pronounced delineation between Pacific and Atlantic-origin water and showed, within Atlantic-origin water, a high correlation (>0.9) between these two tracers because of their similar source functions.

Discussion of Canada Basin waters to this point has compared 1989-1995 data at one Canada Basin station with 1993 data from upstream stations. These comparisons indicated that Pacific-origin water occupied less of the water column at Station A and had been replaced by an increase in Atlantic-origin water after 1993. By 1995, the Atlantic layer was found to include more BSB water than in previous years, suggesting that its composition had been transformed by an increase in Barents Sea outflow.

3.5 Canada Basin sections

Comparison of time-series data from one location, however, precluded study of factors that influenced transport of waters within the Canada Basin. Physical and geochemical samples collected in 1993 and 1995 at stations forming a section from the Beaufort shelf to the basin interior (see Figure 1) were analyzed and compared to determine how these waters were transported. In 1993, the section comprised four stations and, in 1995, the section consisted of nine stations. A third section, comprised five stations in 1995, extended from Banks Island westward into the Canada Basin to a depth of 1200 m.

Temperature and salinity data from these sections were examined first to verify that differences noted at Station A were observable over a larger geographic area. Temperature-salinity diagrams from 1993 and 1995 illustrated that composition of the Atlantic layer was altered over time and across location within the Canada Basin. At Station FM, located on the continental margin at 1700 m depth, halocline water between S=33.1 and S=34.4 was nearly identical in 1993 to that observed farther offshore in 1995 at Station A at 3300 m depth (Figure 20a). At stations BB12 (700 m) and BB13 (1240 m), downstream along the Banks Island section, temperatures were warmer in 1995 at S=33.1 to S=34.4 and similar to measurements made upstream at Station A in previous years. Interleaving and mixing with colder water, however, was evident at both Banks Island stations.

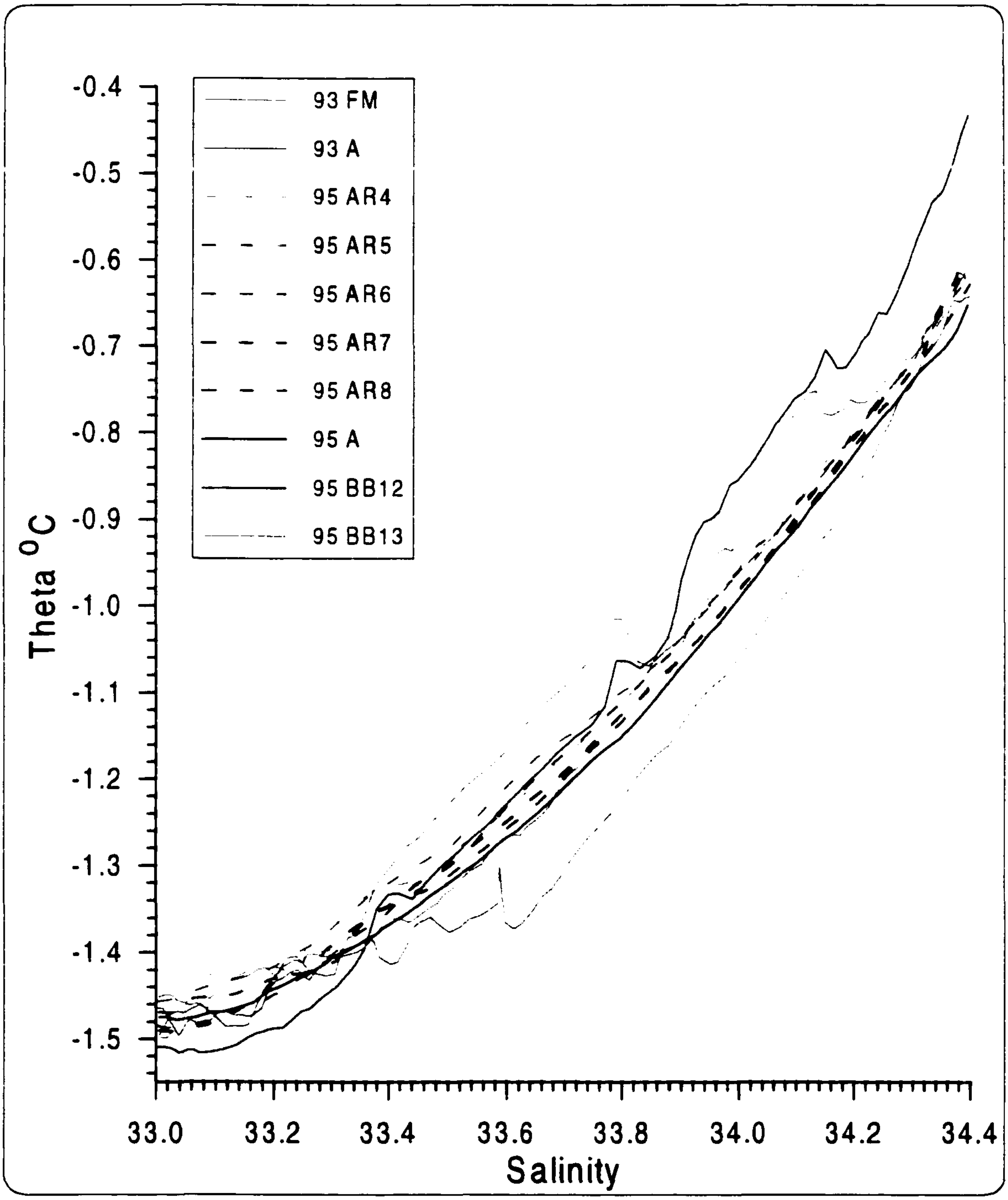

Figure 20a. CTD potential temperature versus salinity, S=33.0 to S=34.4. Data are from Canada Basin sections 1993 and 1995.

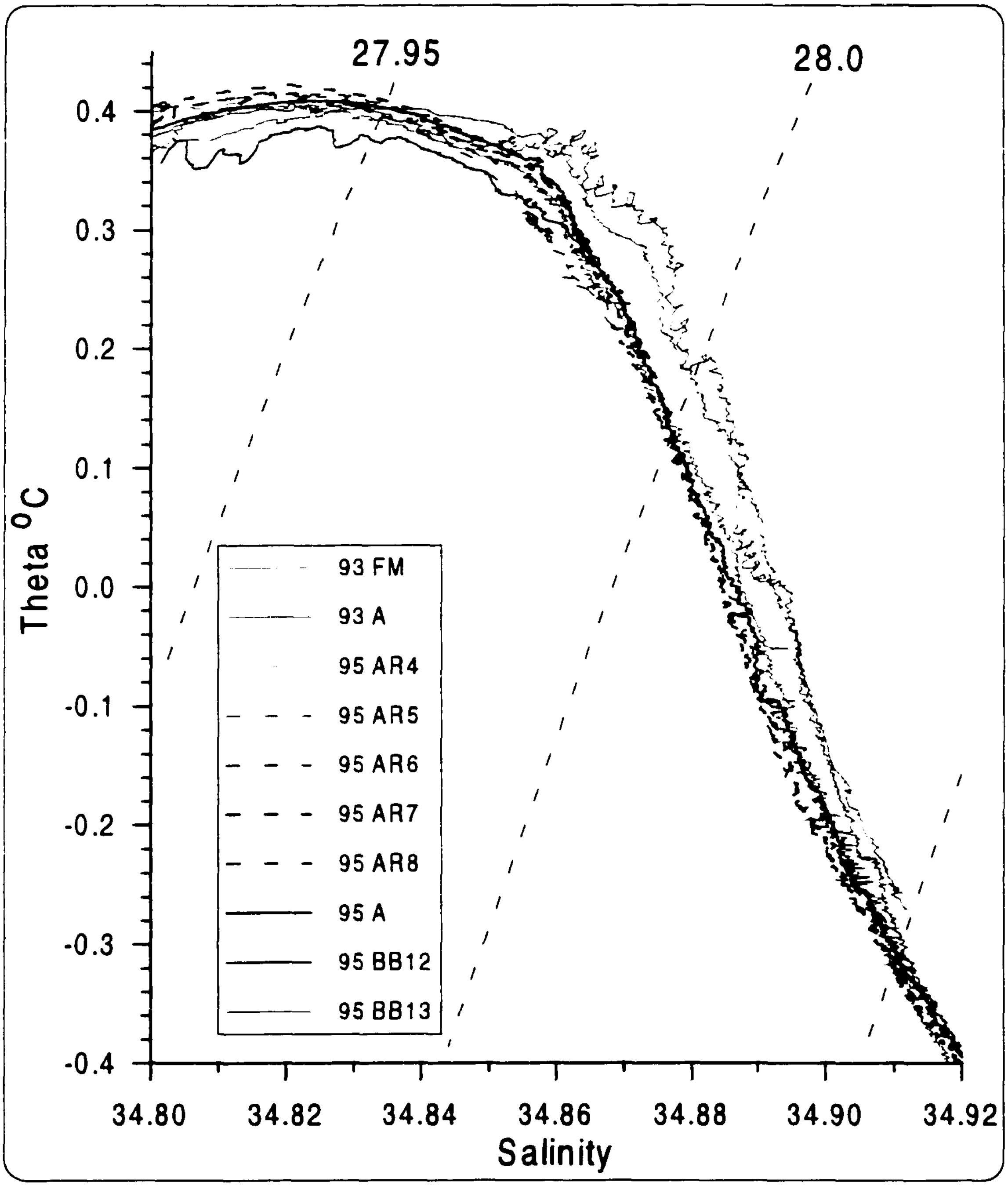

Figure 20b. CTD potential temperature versus salinity, S=34.80 to S=34.92

Lower in the water column between S=34.800 and S=34.950, differences across location were more apparent in both Atlantic layer FSB and BSB components (Figure 20b). In 1993, the FSB θ_{max} component was colder and fresher at both inshore stations, Station AM10 (548 m, θ=0.383 °C, S=34.816), and Station FM (θ =0.404 °C, S=34.815), in comparison to offshore Station A (θ =0.406 °C, S=34.828). In 1995 θ_{max} temperatures were slightly warmer than in 1993, ranging from 0.401 °C to 0.422 °C at S=34.822 at all stations along the section to Station A between 500 m and 3300 m.

Downstream at Station BB12, θ_{max} was 0.386 °C between S=34.826 and S=34.827 in 1995, and intrusions observable in the temperature-salinity plot indicated mixing. This 1995 Station BB12 temperature-salinity outline was similar to the 1993 outline at Station AM10 located approximately 410 km upstream. However farther offshore at Station BB13, the 1995 θ_{max} was warmer and observed at a higher salinity (θ = 0.404 °C, S=34.839) than at Station BB12. The 1995 salinity profile (not shown) illustrated that waters at Station BB12 were fresher than at Station BB13 from 300 m, where S=34.676, to the bottom, where S=34.852. The largest salinity difference (ΔS=0.015) was observed at 500 m.

Salinity measurements further showed that fresher BSB water was evident on the continental margin in 1993 at Station FM in waters below S=34.85, but were unobservable at Station A that year between S=34.85 and S=34.95. By 1995, salinities at Station A were almost identical to values observed at Station FM in 1993. For example, at 0.1 °C, the salinity was S=34.878 at both stations. This finding, together with differences in the lower halocline and FBS waters, meant that the modified Atlantic layer was first observed along the continental margin of the Canada Basin before spreading laterally into the basin interior. This progression reflected the influence of physical topography on boundary current inflow.

Farther downstream, BSB water in 1995 was observed to be colder and fresher at Station BB12 whereas, offshore at Station BB13, temperature and salinity measurements were found to be nearly identical in value to those observed upstream two years earlier at Station A. At 0.1°C, for example, the salinity was S=34.886 at Station BB13 in 1995 and S= 34.888 at Station A in 1993. Presence of

BSB-enriched Atlantic layer water at one station, Station BB12, announced the arrival of the boundary current's narrow leading edge along the continental margin at a depth of 750 m.

In effect, the BSB-enriched Atlantic layer served as a marker by which to trace the progression of upstream waters through the Canada Basin. In 1993, BSB-enriched Atlantic layer water first appeared over the continental margin in the southern Beaufort Sea at depths between 500 m and 1700 m. Two years later in 1995, the BSB-enriched Atlantic layer was observed offshore at 3300 m and, also, at a single station 410 km downstream near Banks Island. The offshore signal indicated lateral isopycnal spreading from the continental margin to the basin interior. The downstream signal represented the advance of the BSB-enriched Atlantic layer transported by the boundary current.

Comparison of temperature-salinity plots across nine stations along the 1995 section to the deep Canada Basin showed that the FSB component at S=34.82 was coldest at Station AR4 (525 m), and that the BSB component at S=34.88 was freshest at stations AR6 (1233 m), AR7 (2030 m) and AR8 (2806 m). These observations signified, respectively, the core of FSB and BSB components in the boundary current and suggested that their locations were related to their densities and depths within the water column. Lower halocline and FSB components were observed at shallower depths over the continental margin whereas the denser BSB component was observed farther offshore where the continental slope allowed for greater depths. In effect, the boundary current appeared constrained by basin topography, as Holloway (1987) proposed. Situation of the Atlantic layer's FSB core above the continental margin was consistent with the location of a topographically-steered boundary current. Location of the BSB core farther offshore, and removed from the region of maximum topographical curvature, would imply a weaker flow, but, as the following discussion shows, this was not the case.

Because temperature and salinity values could not disclose information about rates of flow, CFC-11 measurements from two 1995 sections, along with

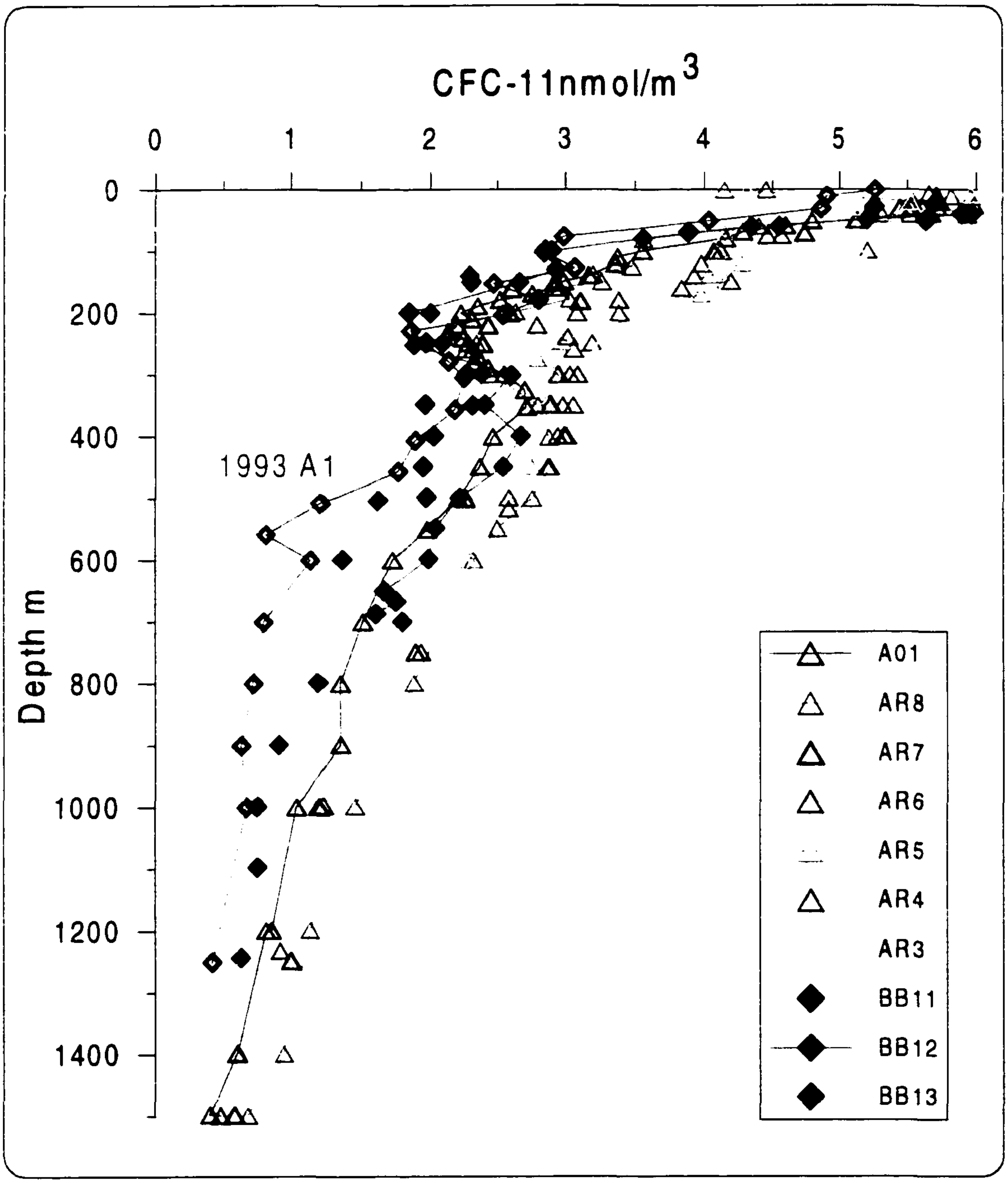

Figure 21. CFC-11 profiles from 1995 Canada Basin section stations and Station A in 1993.

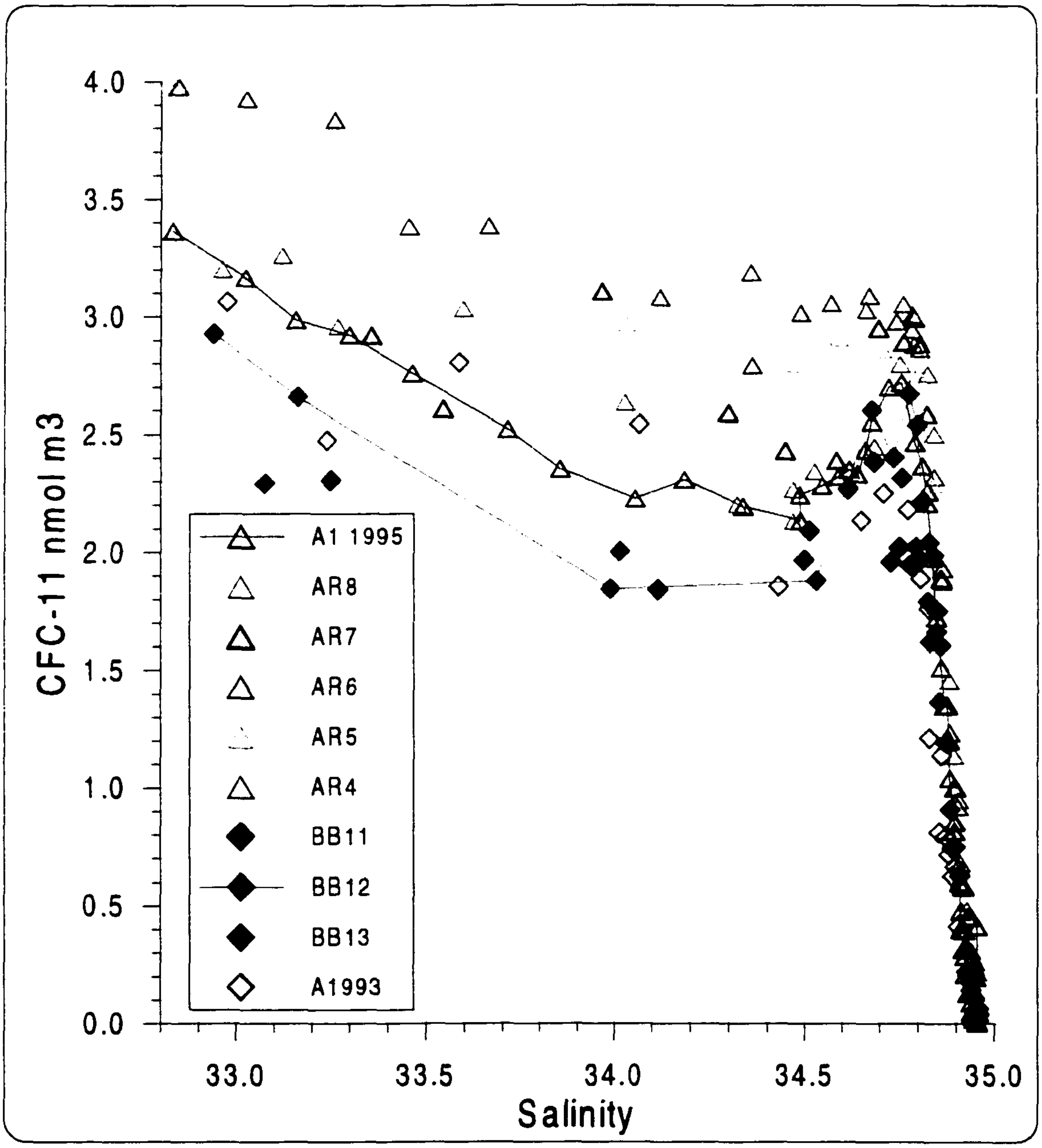

Figure 22. CFC-11 versus salinity from 1993 and 1995 Canada Basin section stations tation A in 1993.

1993 Station A concentrations, were employed as proxies to assess, in relative terms, the arrival of Atlantic-origin water (Figures 21 and 22). Starting with an examination of the lower halocline, high subsurface CFC-11 concentrations (3.0 nmol m^{-3} at S=34.4), indicative of a faster rate of delivery, were observed at the shallower stations AR4, AR5 (769 m) and AR6 below 200 m to depth. Lower CFC-11 concentrations (2.3 nmol m^{-3} at S=34.4) indicative of slower rate of delivery, however, were observed at stations AR7, AR8 and A located farther offshore between 160 m and 250 m at salinities from S=33.5 to S=34.6. These findings proved consistent with a topographically-steered boundary current transporting lower halocline water and confirmed that boundary current flow was most intense over a region of sloping topography and weaker farther offshore.

The boundary current, however, did not appear weaker offshore where the Atlantic layer's FSB and BSB components lay deeper in the water column. At Station AR7 in 1995, CFC-11 concentrations increased between 260 m and 320 m, and, below 320 m, were similar in value to those observed at nearshore stations. At Station AR8, CFC-11 concentrations likewise increased between 300 m and 360 m, and a sub-surface maximum was observed near 400 m at S=34.8. CFC-11 concentrations in 1995 were similar from stations AR4 through to AR8 in the FSB region of the water column at 500 m (S=34.83), suggesting a uniform rate of delivery from stations AR4 to AR8. Lower CFC-11 concentrations at Station A below 350 m signalled that the boundary current did not extend this far offshore. The marked increase in CFC-11 concentrations at salinities S>34.7 at stations AR7 and AR8 in 1995 was also evident when viewed in a CFC-11 salinity plot (Figure 22), and the highest CFC-11 concentrations were found between 800 m and 1500 m at Station AR8 in the Atlantic layer's BSB component. Although eddies are numerous in the Beaufort Sea (D'Asaro, 1988), temperature and salinity measurements at Station AR8 showed that high CFC-11 concentrations at this location were not due to eddy transport. These findings challenged the concept that flow removed from a region of sloping topography would be reduced. Rather, they suggested that boundary current flow is determined by both topography and the composition of waters transported by the boundary current, and each water component's location over the continental margin is determined by its density.

Downstream at stations BB12 and BB13 in 1995, CFC-11 measurements were lower (2.4 nmol m^{-3}) at S=33.5 (160 m) than upstream and were comparable to 1993 measurements at Station A. These findings indicated that increased ventilation observed upstream in the Canada Basin's lower halocline was not yet apparent downstream. Similarity between 1995 CFC-11 concentrations in the Atlantic layer's FSB and BSB components at stations BB12 and A, however, suggested that BSB-enriched Atlantic water had recently arrived at Station BB12 above the continental margin near Banks Island. Additional corroboration was provided by similar 1995 measurements of low nutrients at stations BB12 and A.

Farther offshore at Station BB13, however, CFC-11 concentrations in the FSB component were similar in 1995 to those observed at Station A in 1993, and ranged between 1993 and 1995 values in the BSB component below 600 m. These data suggested that the boundary current transporting the BSB-enriched Atlantic layer was apparent only at Station BB12 and had not yet fully arrived at Station BB13.

CFC-11 measurements were supported by ^{129}I analysis. Although ^{129}I was not sampled at every station along the 1995 sections, ^{129}I measurements corroborated the finding that the boundary current was located over the continental margin. The highest ^{129}I concentrations (34×10^{10} atoms m^{-3}) were observed in 1995 at 300 m (S=34.7) at stations AR5 and AR6 along the Station A section (Figure 23). Depth of the ^{129}I maximum in 1995 was shallower at Station AR6 than at Station A, signifying an increased presence of Atlantic-origin water in the Canada Basin. Downstream, ^{129}I concentrations at Station BB12 in 1995 were lower at 300 m (26×10^{10} atoms m^{-3}) and similar to those observed in 1995 at Station A, showing the boundary current's advance. At Station BB13, although ^{129}I concentrations appeared lower still (20×10^{10} atoms m^{-3}), they were higher than inshore at Station BB7 (12×10^{10} atoms m^{-3}). This indicated that BSB-enriched Atlantic water was starting to be apparent farther offshore.

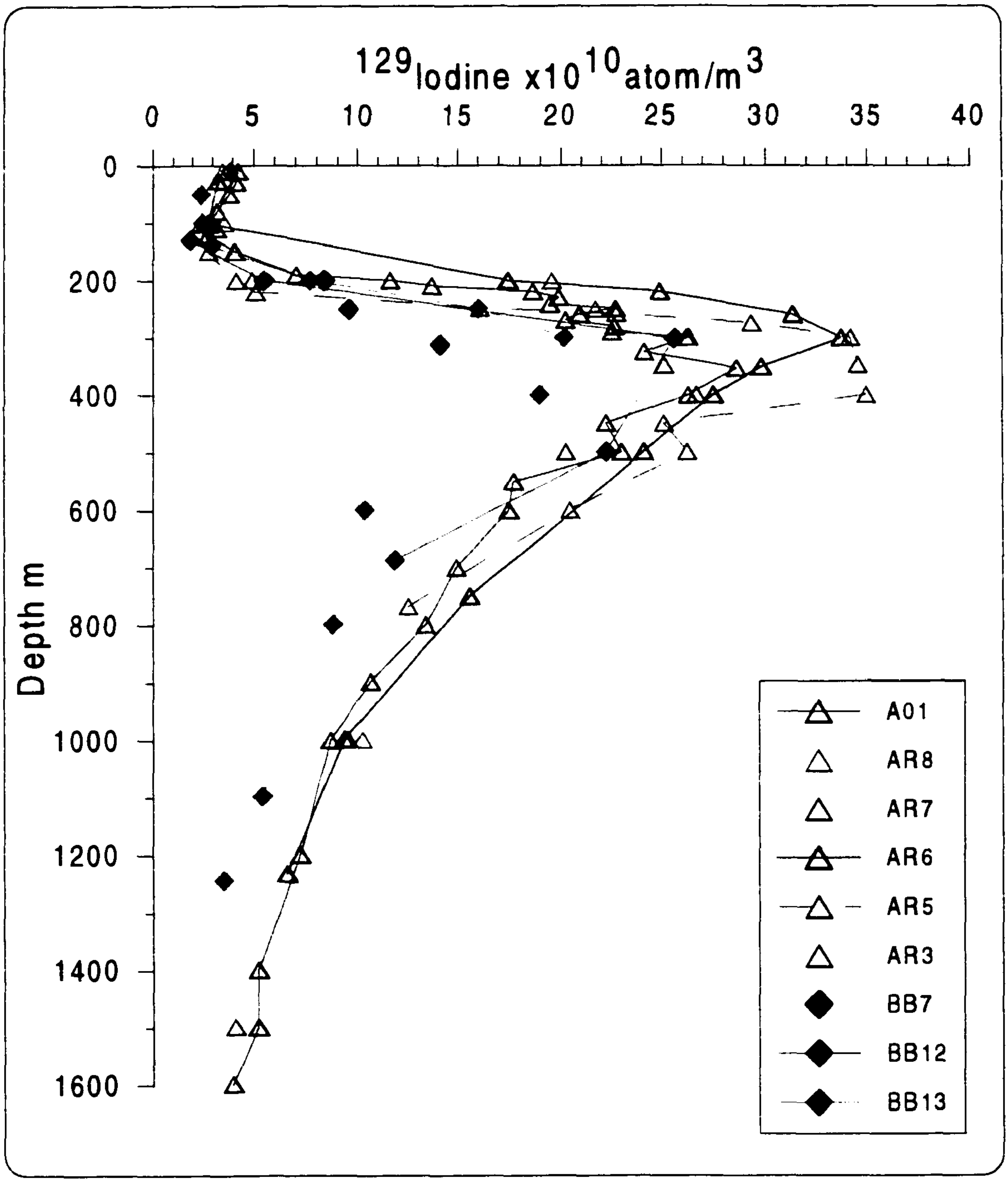

Figure 23. ^{129}I profiles from 1995 Canada Basin section stations

Temperature and salinity profiles (Figures 24 and 25) from stations along the 1995 Station A section indicated the presence of two additional delivery processes. At stations AR5 and AR6, located along the continental margin at depths from 600 m to 2000 m, temperature values decreased by 0.208 ^{o}C and salinity increased by S= 0.017 in a bottom boundary layer about 40 m thick above the sediment interface. Temperature and salinity values in this bottom boundary layer at Station AR5 (760 m) were the same as those observed farther offshore at 920 m depth. These measurements suggested that denser water was lifted upslope, perhaps as a result of tidal effects or, perhaps, as a manifestation of the neptune effect (Holloway, 1987). Evidence that another delivery process was at work could be seen at Station AR5, where cold S=33.1 middle halocline water was observed about 60 m deeper than at other stations. This suggested the presence of a shallow eddy influencing the water column to about 250 m. Silicate, nitrate, and phosphate measurements also indicated the presence of an eddy because the nutrient maxima of the middle halocline was found deeper in the water column at Station AR5.

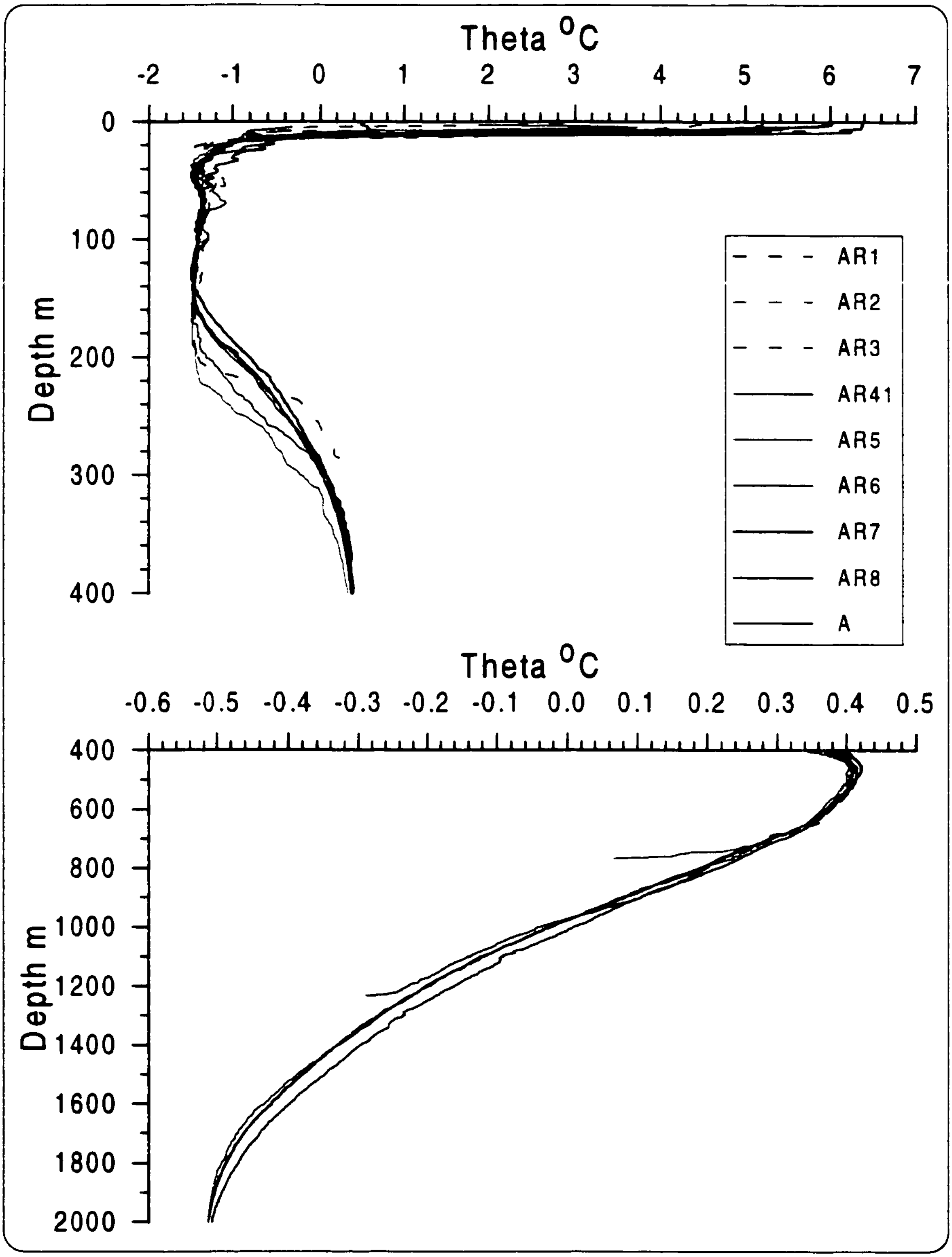

Figure 24. CTD potential temperature profiles from 1995 Canada Basin section stations.

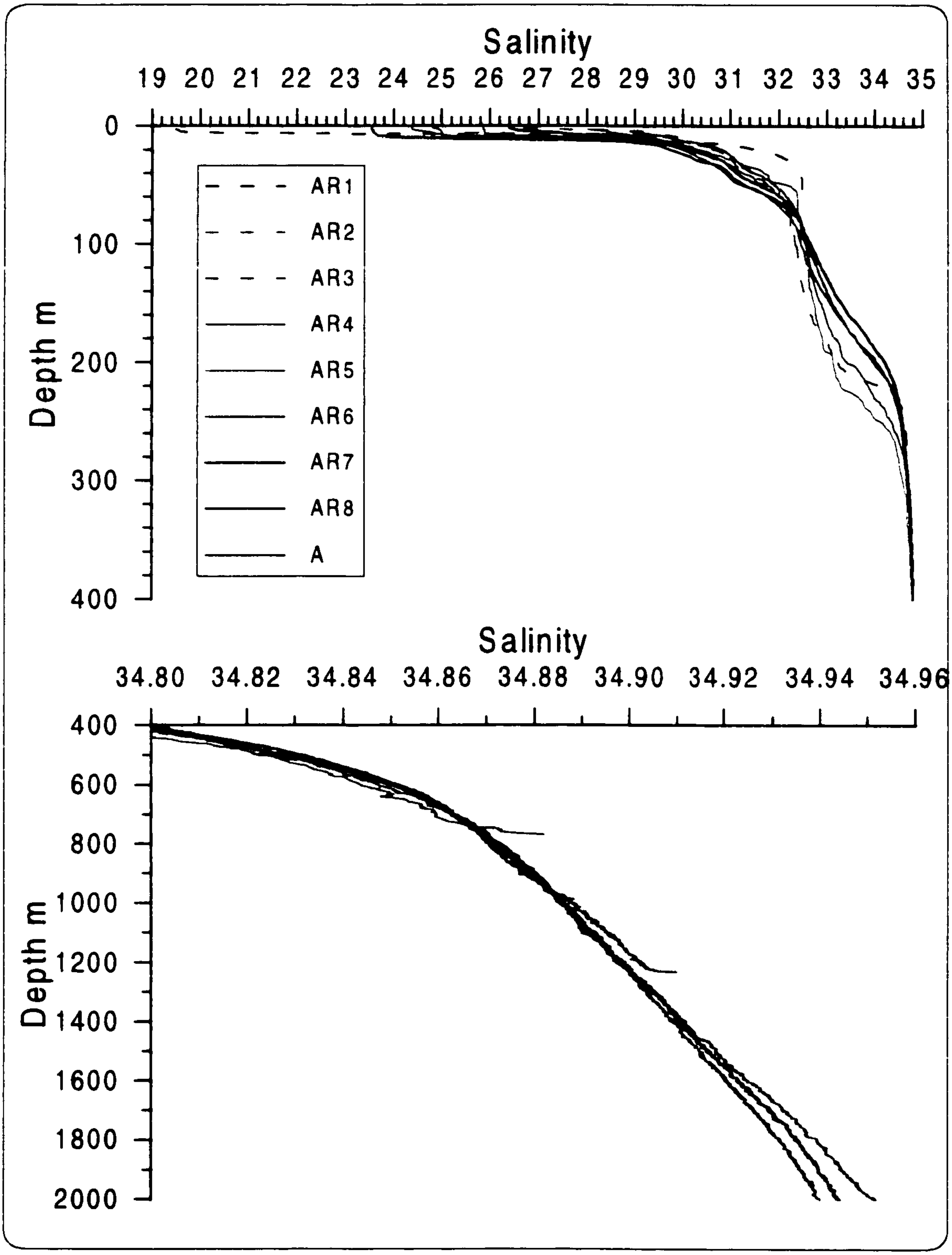

Figure 25. CTD salinity profiles from 1995 Canada Basin section stations.

4. Discussion

Discussion so far has investigated one central question: What was the Canada Basin's response to upstream basin change in the early 1990s? In particular, what differences were observed in the Canada Basin water column—and where and when did these first appear? Physical and geochemical measurements at Station A between 1989 and 1995 demonstrated that effects of upstream change were first observable downstream in 1993 in both Pacific-origin and Atlantic-origin waters. Differences were manifested in various ways—by lower nutrient concentrations in the middle and lower halocline; by lower temperature and nutrient concentrations and higher oxygen, ^{129}I and CFC-11 concentrations in the lower halocline; lower salinity, temperature, and nutrient concentrations and higher oxygen, ^{129}I and CFC-11 concentrations in FSB (θ_{max}) water; and lower salinity and nutrient concentrations and higher temperature, oxygen, ^{129}I and CFC-11 concentrations in BSB water. These data showed that Pacific-origin water had been eroded by Atlantic-origin water and that inflowing Atlantic water was characterized by a larger BSB contribution. Downstream effects were first apparent in 1993 at Station FM along the continental margin and, two years later, were detectable offshore at Station A, as well as farther downstream at Station BB12. Altogether, these observations attributed developments in the Canada Basin to events that had influenced Barents Sea outflow upstream. The discussion that follows will examine what events in the Canada Basin disclosed about the larger context of the Arctic Ocean system and, in particular, factors prompting an increase in Barents Sea outflow.

4.1 Displacement of Pacific-origin water

Temperature, salinity and nutrient data from the Canada Basin showed that Pacific-origin water occupied a narrower region of the upper layer in the water column in both 1993 and 1995 than in years before. This could be accounted for in three ways. Decrease in the inflow of Pacific-origin water into the Canada Basin is one explanation. However, this explanation is unsupported by direct measurements. Roach et al. (1995) used measurements from moored current meters and Doppler instruments to determine that the mean transport of Pacific-origin water through Bering Strait from 1990 to 1994 was about 0.83 Sv ($1 Sv = 10^6 m^3 s^{-1}$), a value consistent with earlier work by Coachman and Aagaard (1988). Time-series analysis of transport also showed that the first nine months of 1994 recorded the highest inflow of Pacific-origin water (1.14 Sv) in over fifty years. Additional confirmation of Pacific-origin inflow was provided by Munchow and Carmack (1997) who observed that northward transport through Barrow Canyon exceeded 1.0 Sv during a synoptic 1993 acoustic Doppler profiler survey.

An alternative—and more convincing—explanation is that inflow of Atlantic-origin water increased in the Canada Basin and thereby displaced the Pacific-origin layer from below and shallowed the Atlantic/Pacific water mass boundary. Nutrient and ^{129}I data from Station A in 1993 and 1995 demonstrated that the Atlantic/Pacific water mass boundary was, indeed, shallower than in previous years, and that increase in inflow of Atlantic-origin water resulted in these waters occupying more of the water column. Displacement of Pacific-origin water from the Makarov Basin in 1993 (McLaughlin et al., 1996) appears, in retrospect, to have been accompanied by contraction of Pacific-origin water in the Canada Basin. The last explanation, rearrangement within the Canada Basin, was not supported by observations from the SCICEX-96 expedition as isohalines were horizontal across the basin, i.e. water of salinity S= 33 was observed at 150 m at Station A in 1995 and in 1996 along a section from the Chukchi Cap to the Makarov Basin (Smethie et al., submitted).

Increase of Atlantic-origin inflow to the Canada Basin can be calculated inferentially by estimating the reduction in Pacific-origin water found in the water column. For such estimates to be meaningful, however, they must be calculated within the larger context of change upstream in the Makarov Basin. Disappearance of Pacific-origin water from the upper 200 m Makarov Basin water column required a replacement inflow of Atlantic-origin water of an estimated 145,000 km^3 (Makarov Basin area=968,000 km^2). Downstream at Station A, midway around the Canada

Basin, a decrease of 40 m required replacement of 42,000 km^3 of Atlantic-water inflow (Canada Basin area=2,102,000 km^2 x 0.5). Assuming these developments occurred between 1990 and 1993 (see below), transport of Atlantic-origin water to the Makarov and Canada basins appears to have increased by 1.2 Sv and 0.3 Sv, respectively.

Decrease in Pacific-origin water also diminished the freshwater content of the Makarov and Canada basins. Freshwater content was calculated relative to a mean Arctic Ocean salinity S=34.8 (Aagaard and Carmack, 1989) and integrated from the surface to the depth where S=34.8. Using 1979 salinity measurements in the Makarov Basin near the Lomonosov Ridge (Moore et al., 1983), the freshwater content was calculated to be 13 m. From 1993 salinities from the southern Makarov Basin (McLaughlin et al., 1996), the freshwater content was calculated to be 6-7 m, about half what it had been more than a decade earlier. This reduction was due to the replacement of Pacific-origin water by increased Atlantic-origin water inflow, estimated above to be more than 1 Sv. Freshwater content also decreased in the Canada Basin. Between 1992 and 1995 at Station A, the integrated freshwater content fell from 19 m to 17 m, illustrating that Pacific-origin water had been supplanted by Atlantic inflow. This decrease in total freshwater content of the Canada Basin occurred despite sea ice melt freshening in the upper layer (McPhee et al., 1998; Macdonald et al., 1999).

Where did Pacific-origin water displaced from the Makarov and Canada basins go? Results from additional studies provide some clues. Change in Pacific-origin outflow temperature was observed between 1989 and 1994 downstream in the Lincoln Sea by Newton and Sotirin (1997). Within the Pacific-origin component (50 m to 125 m depth) of boundary current waters, the temperature of the upper halocline increased markedly to -1.25 °C in 1993 from less than –1.5 °C before 1990. When viewed by temperature and salinity, the local θ_{max} increased from a barely discernable feature located between S=32.5 and S=33 in 1991 to a well defined maximum located between S=31.3 and S= 33.3 by 1993. Newton and Sotirin (1997) proposed that warmer temperatures were attributable to an increase in transport of upper halocline water out of the Canadian Basin which appeared to peak in 1993.

Timing of these Lincoln Sea observations was coincident with reports of the absence of Pacific-origin water in the Makarov Basin — near the Lomonosov Ridge in 1991 (Anderson et al., 1994) and, in 1993, at the southern boundary near the Mendeleyev Ridge (McLaughlin et al., 1996). Also, observation that the denser Pacific-origin component preceded the arrival of combined upper and middle halocline waters in the Lincoln Sea was similar to description of waters near the relocated Atlantic/Pacific front where changes were apparent first at depth (McLaughlin et al., 1996).

Pacific-origin outflow was also evident farther downstream in 1991 above the Morris Jesup Plateau at stations located along the continental slope where water depths were between 1400 m and 2300 m (Anderson et al., 1994, their stations 39 and 44). The silicate-salinity correlation was unlike the classic nutrient maximum curve, with a peak centered near S=33.1. Instead silicate concentrations at these locations were 10-12 mmol m^{-3} between S=32 and S=32.8, then increased sharply to 30 mmol m^{-3} at S=33.2 (Figure 26). In effect, the silicate-salinity curve appeared incomplete, signalling the presence of the middle but not the upper halocline. Temperatures at S=33.2 were also slightly warmer at these stations than at nearby stations.

In summary, observations from the Makarov Basin, Lincoln Sea and Morris Jesup Plateau suggest strong connection between upstream and downstream events. Upstream, disappearance of Pacific-origin water by 1993 from the Makarov Basin corresponded, downstream, with the arrival of progressively warmer Pacific-origin water in the Lincoln Sea that began in 1991 and peaked in 1993. The offset nature of the Atlantic/Pacific front upstream near the Mendeleyev Ridge was mirrored downstream in the order that Pacific-origin water arrived—middle halocline first, identified in 1991 by increasing temperature in the salinity range S=32.5 to S=33 in the Lincoln Sea and high Pacific-origin silicate concentrations only at salinities S>33.2 near the Morris Jesup Plateau; then upper halocline, identified by warmer temperature in the salinity range S=31.5 to S=33.3 by 1993.

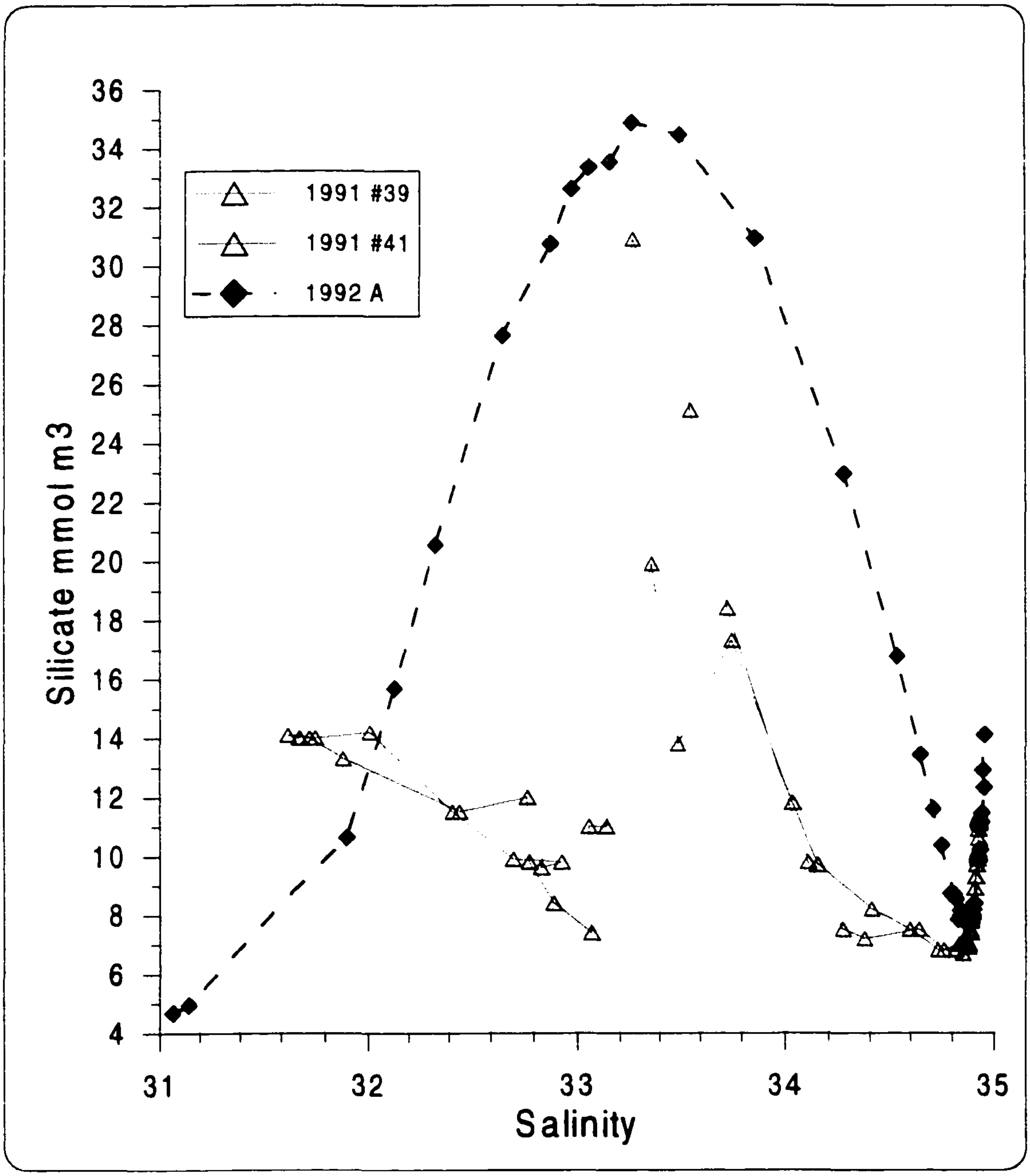

Figure 26. Silicate versus salinity correlation from 1992 Canada Basin Station A and Oden-91 stations located near the Morris Jesup Plateau.

Moreover, the time-series temperature observations in the Lincoln Sea indicate that Pacific-origin water was displaced from the Makarov Basin over a period of about three years.

Where these waters went beyond the Lincoln Sea was unclear. Two main outlets from the Arctic Ocean exist—one through the Canadian Archipelago, the other through Fram Strait. Pacific-origin water, found between 50 m and 200 m in the Makarov Basin, could exit via Nares Strait to Baffin Bay, and/or via Fram Strait, as either route offers sufficient sill depths. Likewise, removal of Pacific-origin water between 150 m and 200 m from the Canada Basin could be accommodated through the Archipelago or Fram Strait. Circumstantial evidence of outflow via the Archipelago was provided by Belkin et al. (1998), who suggested that the "Great Salinity Anomalies" (GSA) of the 1980s and 1990s, which originated in the Labrador Sea, may have been enhanced by freshwater outflow from the Archipelago. Observations from the Canada Basin study reported here identified that a large volume of freshwater exited from the western Arctic Ocean between 1991 and 1993 and this outflow may have contributed to the 1990s' GSA.

4.2 Change in Atlantic-origin water

Canada Basin data collected between 1989 and 1995 implied a reduction in the presence of Pacific-origin water by 1993—and a concomitant increase in Atlantic-origin water inflow. Between 1989 and 1995, Atlantic-origin water in the Canada Basin was also marked by differences in physical and geochemical properties. Within the Canada Basin's upper layer, lower halocline water was shallower, colder, and lower in nutrients in 1993, and more ventilated in 1995, than between 1989 and 1992. Differences were also observed in both FSB and BSB components of the Atlantic layer. Colder, fresher, and more ventilated FSB water was found higher in the water column, and warmer, fresher, and more ventilated BSB water was observed at greater depths than in the past. Comparison to 1993 upstream basin waters demonstrated that changes in the lower halocline and in both Atlantic layer components were attributable to Barents Sea outflow. This suggested that the Canada Basin's Atlantic layer included more BSB water after 1993 than before.

Water mass analysis methods (Macdonald, 1989) were used to quantify change within the Canada Basin's Atlantic layer composition in 1995. Physical and geochemical tracer concentrations of source waters were first determined, using data from stations closest to the point of inflow. Measurements from stations 20 and 70 in the Nansen Basin were used to characterize FSB and BSB source waters, and measurements from Station A in 1992 served as reference points to characterize the Canada Basin's Atlantic layer. Following this, source water properties (Table 1) and Station A tracer concentrations were used in a positive least-squares algorithm program to calculate and compare composition of Canada Basin waters between 1992 and 1995.

Table 1. Summary of source water properties (units of temperature are °C, units of $Si(OH)_4$, NO_3, PO_4 and oxygen are mmol m^{-3}, and units of CFC-11 and CFC-12 are nmol m^{-3}).

Source	Salinity	Theta	$Si(OH)_4$	NO_3	PO_4	Oxygen	CFC-11	CFC-12
CB θ_{max}	34.85	0.43	8.5	13	0.91	298	0.6	1.5
CB S_{min}	34.88	0.19	7.5	13.2	0.92	298	0.3	0.8
FSB θ_{max}	34.98	2.7	6	11.7	0.8	289	4.6	2.3
FSB S_{min}	34.91	-0.2	7.8	12.2	0.88	285	1.8	1.0
BSB θ_{max}	34.85	1.8	5.1	8	0.66	287	5.2	2.5
BSB S_{min}	34.84	-0.5	5.3	7.8	0.69	292	5.2	2.5

This model showed the 1995 composition of the Canada Basin's BSB component between 1000 m and 1200 m was comprised of 80% Canada Basin water, which implied that composition of this component had been enriched 20% between 1992 and 1995 by outflow from the Barents Sea. Another estimate of the increased inflow of BSB water into the Canada Basin was calculated on the basis of the increased depth (150 m) within the boundary current. Given the distance from the Mendeleyev Ridge to Station A was approximately 2300 km, the BSB boundary current's width was about 230 km (see Figure 27), and the change occurred over three years, this 20% enrichment required an outflow from the Barents Sea of about 0.8 Sv. When this estimate is combined with the flow of Atlantic water required to reduce the extent of Pacific-origin water by 40 m and delivered by a 120 km wide boundary current, a total of an additional 0.9 Sv of Atlantic-origin water was delivered over the past three years to the Canada Basin.

Temperature and salinity findings in the Atlantic layer at Station A generally corresponded with those reported in Melling's (1998) Canada Basin study. Melling found that temperature decrease in the Canada Basin's lower halocline correlated with an increase in depth of the lower 0°C isotherm over time. He suggested that this relationship was a product of Barents Sea outflow, and added that outflow might have been denser in the 1990s than in the 1970s. Station A findings corroborated the influence of Barents Sea outflow on Atlantic-origin water and established that this influence was evident in the Canada Basin after 1993. Melling, however, also reported a cooling and freshening of the Atlantic layer's θ_{max} which he attributed to variation in Fram Strait inflow. Additionally, he associated warming in the water column between 1000 m and 1500 m with an increase in FSB and a decrease in BSB inflow. These explanations were not substantiated by measurements from Station A or from upstream stations. Rather, upstream and downstream data indicated that such cooling and freshening, as well as warming at depth, were consequences of increased Barents Sea outflow. Water mass analysis from Station A similarly confirmed that the Atlantic layer's composition after 1992 included 20% more BSB water.

Melling's use of temperature to infer middle halocline ventilation merits further consideration because the relationship between temperature and ventilation is complex. Critical to understanding the relationship between temperature change and change in ocean ventilation is the shelf location and the process whereby subduction occurs. To illustrate with measurements from Station A: CFC-11 and oxygen concentrations increased in two regions of the Canada Basin's water column, one where water became cooler, the lower halocline—and one where water became warmer, the Atlantic layer's BSB component. Modifications to

Atlantic-origin water indicated that advection of far-field events, such as ventilation associated with cooling, or freezing on the Barents Sea Shelf, cannot be interpreted the same way as advection of local freezing events. For example, dense water produced by ice forming on the deep Barents Sea Shelf, far-field to the Canada Basin, can contribute both colder, fresher, and ventilated water to the lower halocline, as well as warmer, fresher, and ventilated water to depths below the θ_{max} core of the Atlantic layer. In contrast, dense water produced by ice forming on the shallow Chukchi or Beaufort shelves, local to the Canada Basin, contributes colder, more saline and ventilated water to the Pacific-origin halocline. In summary, temperature change in the Canada Basin was shaped by events that occurred on both far-field and local shelves, thus complicating inferences about the relationship between temperature change and degree of ventilation.

4.3 Upstream events

The preceding discussion traced modifications in the composition of Canada Basin waters to the Barents Sea upstream. Attention will now focus on examining variability in upstream conditions which influenced volume and density of Barents Sea outflow and, accordingly, precipitated developments downstream. Variability in the Barents Sea region has long been observed. By the early-twentieth century, this variability was attributed to differences in both atmospheric and ocean circulation (Helland-Hansen and Nansen, 1912). To investigate upstream variability, recent atmospheric and ocean studies will be examined for evidence of change in the Barents Sea region during the late 1980s—the period immediately preceding observation of events downstream in the Canada Basin. This date was chosen for two reasons. Indication of Arctic Ocean change was first made downstream of Fram Strait in 1990 where θ_{max} was 1 °C warmer than in 1989. Second, given the distance from the St. Anna Trough to the Canada Basin is about 5100 km, effects of increased Barents Sea outflow were estimated to reach the Canada Basin in about eight years, assuming a 2 cm s^{-1} boundary current speed (Aagaard, 1989). Thus, differences observed in the Canada Basin in 1995 required that Barents Sea outflow increased as early as 1987.

4.3.1 Barents Sea atmospheric forcing

Observations from the Canada Basin suggested that an increase in Barents Sea outflow occurred in the late 1980s and examination of atmospheric literature has identified events that contributed to such an increase. For example, Walsh et al. (1996) observed a seasonally robust decrease in sea-level pressure between 1987 and 1994 based on analysis of 1979-1994 Arctic Ocean Buoy Program (AOBP) data. This decrease, they noted, implied an increase in cyclonic wind forcing. Subsequent modelling studies identified that two atmospheric modes exist in the Arctic, that they oscillate over time, and that they exert influence on upper ocean circulation. Using a wind-forced coupled ice-ocean model, Proshutinsky and Johnson (1997) identified two regimes of wind-forced circulation—one anticyclonic and one cyclonic. These regimes, they proposed, either strengthened or weakened the anticyclonic thermohaline ocean circulation, depending on whether wind forcing augmented or opposed direction of surface flow. Using a high resolution ocean-ice model, forced by 1979-1993 atmospheric conditions, Maslowski et al. (submitted) described Arctic Ocean circulation in the upper layers as oscillating between two wind-driven regimes, which supported Proshutinsky and Johnson's hypothesis. Thompson and Wallace (1998) also identified a bimodal pattern in the polar vortex, which they termed the "Arctic Oscillation" or, when viewed over time, the AO index. They drew their conclusions from a model based on sea level pressure, temperature, zonal wind, and geopotential height from the surface to the stratosphere.

Altogether, what have these models suggested about the timing and effects of atmospheric variability on Barents Sea outflow during the late 1980s? Beginning with timing, Walsh et al. (1996) noted sea-level pressure decreased in 1987, thereby beginning a negative cycle unprecedented in duration. Their data showed the sea-level pressure anomaly was more negative in 1988 than any time in the previous half-century. According to Proshutinsky and Johnson's (1997) time-series, an anticyclonic regime appeared between 1984 and 1988, followed by a cyclonic regime after 1989. Thompson and Wallace's (1998) time-series results indicated that the AO index increased markedly in the late 1980s and registered higher between 1989 and 1990 than any time since the 1960s. All studies indicated that a substantial shift in atmospheric conditions occurred between 1987 and 1990. Both Walsh et al. (1996) and Proshutinsky and Johnson (1997) showed that this shift was toward increased cyclonic conditions.

Certain effects were likely attendant with increased cyclonicity over the Barents Sea region. The rate and volume of Atlantic water transported northward would increase and, upon arrival in the Barents Sea, would be warmer because less time existed for cooling. Increased cyclonicity would also strengthen the Icelandic Low in winter and extend it farther into the Barents, Kara, and Laptev Seas (Johnson et al., 1999). Such an atmospheric configuration would favor Atlantic water transport into the Barents Sea, rather than transport into Fram Strait, since the BSB has been held to be more sensitive to increased cyclonicity than the FSB (Zhang et al., 1998). Additionally, a predominance of autumn cyclonic winds over the Barents Sea would produce divergent ice motion thereby increasing ice production. Polyakov et al. (1999) used observational and coupled ice-ocean model data to examine seasonal differences between anticyclonic and cyclonic regimes. They reported that the 1990s cyclonic regime was accompanied by an intense inflow of warm, salty Atlantic water which entered the Arctic Ocean primarily via the Barents Sea. Their analysis also showed increased ice transport between these two regions.

Johnson et al. (1999) extended their model to 1997 and presented patterns of sea-level pressure for transitions between consecutive regimes. Of the four transitions to a cyclonic regime that occurred between 1953 and 1997, the 1989-1997 transition exhibited the strongest decrease in sea-level pressure and showed the affected region to be far larger than in the past, extending from the North Atlantic near southern Greenland to the Canadian Basin. Extensive low sea-level pressure observed over the Arctic Ocean after 1989 in Johnson et al.'s model (1999) complemented AOBP measurements reported by Walsh et al. (1996). Johnson et al. (1999) also suggested that the three previous cyclonic regimes produced atmospheric conditions which could account for all three "Great Salinity Anomalies," described by Belkin et al. (1998). Altogether, the preceding studies have pointed to one conclusion—an increased import of Atlantic water to the Barents Sea after 1987. This increased Atlantic inflow would be accompanied by increased Barents Sea outflow after 1987.

4.3.2 Variability and dense water formation in the Barents Sea

Studies of the Barents Sea offered evidence that corroborated an increased inflow of Atlantic water. Although few direct measurements were available, research provided a small amount of data on variability of inflowing Atlantic water. Blindheim (1989) calculated net Atlantic water inflow at 1.9 Sv from current meter measurements collected in 1978 between Fugloya and Bear Island. Since then, variability estimates of inflow through the western Barents Sea have been generated by a wind-driven model using local conditions (Adlansvik and Loeng, 1991). Like Proshutinsky and Johnson's (1997) large-scale results, Adlansvik and Loeng's (1991) model suggested that two climatic conditions influence inflow into the Barents Sea—one characterized by warm oceanic temperatures, cyclonic atmospheric circulation and high inflow; and, another characterized by cold oceanic temperatures, anticyclonic atmospheric circulation, and low inflow. Modelling showed that peak inflow occurred during winter, and that Barents Sea inflow was high after 1988 (Loeng et al., 1997). Between 1986 and 1987, inflow ebbed to a 17-year low and, from 1987 to 1988, the low to high difference was the largest ever calculated for the period 1970 to 1992.

Outflow variability has been scarcely documented in Barents Sea studies. Loeng et al. (1997) provided the sole direct measurement of outflow from the eastern Barents Sea, calculated at 1.9 Sv using current meters deployed in 1991-1992 between Novaya Zemlya and Frans Josef Land. Data showed that flow rates in the lower layer were higher than the upper layer, and that highest net outflow occurred in December (3.3 Sv). Variability in Barents Sea outflow during the late 1980s was also inferred from hydrographic measurements. A layer of cold dense bottom water 100 m thick was observed in the eastern Barents Sea in 1982; and, in 1983, all but a 25 m layer of cold dense bottom water had been replaced by warmer water (Midttun, 1989). This sequence of events was repeated again between autumn 1988 and autumn 1989 (Loeng, pers. comm.). Loeng et al. (1997) concluded that a large volume of dense bottom water exited the Barents Sea in 1988 and estimated that winter outflow of dense water in 1982/83 and 1988/89 may have exceeded 4 Sv. In contrast, Loeng et al. (1997) reported that almost no dense water exited during the winter of 1992. Although measurements of outflow were few, there appeared to be close correspondence between modelled peak inflow and observed high outflow in 1988. Loeng (1990) reported that Atlantic water transit time from the western to the eastern Barents Sea was six to 12 months.

Increased transport of warmer Atlantic water to the Barents Sea after 1987 was also evident in temperature measurements. Loeng et al. (1992) reported that a rapid increase in temperature was observed in early 1989 over the entire southwestern Barents Sea to 35 ^{o}E, and after 1989 water was almost 1^{o}C warmer than the mean. In contrast, the previous warm inflow (1982) spread eastward more slowly, suggesting by comparison that inflow rate was higher in 1989. Observations of warm water in the southwestern Barents Sea supported the hypothesis offered by Adlansvik and Loeng (1991) which held that cyclonic conditions were related to an increase in transport of warm water.

Variability in density in Barents Sea outflow in the late 1980s has been unreported in the literature, although Midttun (1985) showed that dense waters of varying salinity and volume were formed regularly on the Novaya Zemlya Shelf and appeared to flow eastward through the St. Anna Trough. Midttun (1989) later proposed that both the characteristics and volume of inflowing Atlantic water contributed to variability in salinity of dense water observed on the eastern Barents Sea. Midttun observed that density increased with cooling and, also, with the addition of salt from brine rejection.

Further, dense water production has been associated with ice formation and export as well as cooling in open water regions within the winter ice pack (polynyas). Martin and Cavalieri (1989) identified polynyas located north, west, and east of Novaya Zemlya, whose areal extent they related to low pressure systems in the atmosphere. Within the polynya region, they reported that annual ice formation

(10-17 m) contributed a significant amount of brine to underlying waters, when compared to brine produced by undisturbed first-year ice (1 m).

Another factor associated with variability in dense water outflow is entrainment. Arctic literature has reported that dense water flows off shelves in plumes into the ocean, entraining ambient water en route. Schauer and Fahrbach (1999) reported that plume flow rate was faster from the Barents Sea Shelf and entrained more water where large differences in density existed between plume and surrounding waters. High entrainment, they observed, increased buoyancy and thereby limited the depth to which the plume sank after leaving the shelf break. Schauer and Fahrbach concluded that proximity of dense water formation to the shelf break was instrumental in producing water of sufficient density to renew the ocean at depth. Proximity of the Novaya Zemlya polynyas to the St. Anna Trough and shelf break suggested that dense water produced by the polynyas entrained little water during outflow.

Taken as a whole, the literature has shown that several factors influence dense water production in the Barents Sea, its subsequent outflow to the Nansen Basin, and its eventual delivery to the Canada Basin downstream. These include: characteristics and volume of inflowing Atlantic water; extent of entrainment with ambient shelf-water; and ice export from polynyas located near the St. Anna Trough. However, the variability of these factors, and their effects, during the late 1980s, on the density of Barents Sea outflow have not been studied and remain subjects for investigation.

Another point deserves mention. Two sources appear to supply dense water and influence variability of Barents Sea outflow. One source is dense water formed in polynyas near the St. Anna Trough, likely characterized by annual outflow. The second source is dense water produced in the eastern Barents Sea, characterized by episodic outflow. One cause of episodic outflow appears to be a high inflow of Atlantic water which may displace dense water from the eastern basin. Alternatively, a critical volume of dense bottom water may be required to initiate flow from the eastern basin and this may take more than one year to produce.

In summary, both the atmospheric and the oceanographic literature strongly suggested that Atlantic water inflow increased to the Barents Sea in 1988/1989 and that a resulting increase in outflow—perhaps as much as 4 Sv—from the Barents Sea via St. Anna Trough occurred in early 1989. Using these dates as reference points, the rate at which upstream changes were delivered downstream to the Canada Basin can now be calculated.

4.4 Transport of upstream change

The boundary current delivering fresher, more ventilated Atlantic-origin water to the Canada Basin was observed along the 1995 section to Station A. Analysis of physical and geochemical data collected at stations extending from the continental shelf to the basin interior defined a boundary core located above the continental margin. However, CFC-11 data showed that the shape of the boundary current delivering upstream water was defined by the density of water transported and topography. Lower halocline water from nearshore stations (AR3 to AR6) was significantly more ventilated than water at offshore stations (AR7 and AR8). However, nearshore and offshore waters in the Atlantic layer below 300 m were ventilated equally.

The boundary current's size and shape was approximated on the basis of CFC-11 concentrations. Using such data, the upper part, observed between stations AR3 and AR6, extended over a distance of 120 km. The breadth of the lower part, observed between stations AR5 and AR8, extended over a distance of some 230 km. A cross-section of the boundary current is illustrated in Figure 27, showing the broader character of the current at depth. CFC-11 measurements suggested that the boundary current extended from the continental margin to the base of the continental slope (about 350 km wide) and was more expansive in character than portrayed in the literature (Holloway, 1987).

Aagaard (1989) described a deep boundary current located over a topographical slope and observed that the boundary current speed in the Nansen Basin increased with depth. However, contrary to Aagaard's 1987 finding that the current was negligible in the Canada Basin at 1000 m, CFC-11 data revealed a

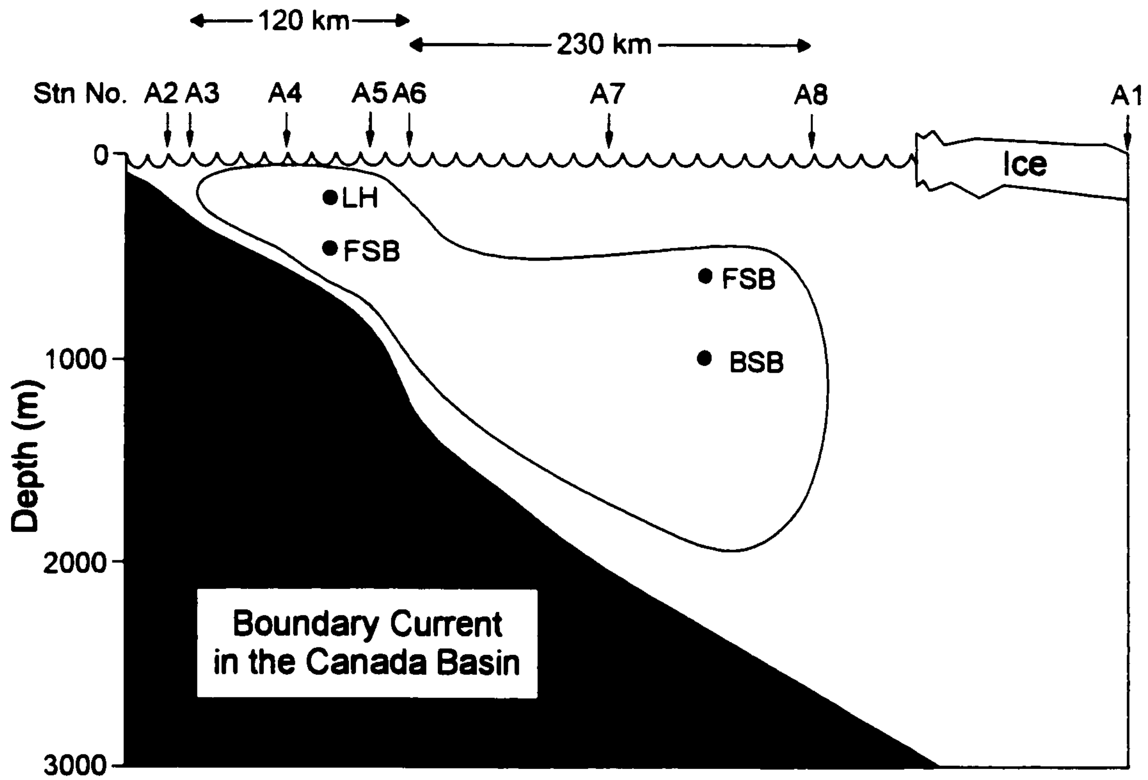

Figure 27. Cross-sectional representation of the boundary current as observed along the southern Canada Basin.

boundary current at depths greater than 1500 m. These data further confirmed that change in Canada Basin circulation had occurred after 1993 and that the basin's boundary current now resembled that of the Eurasian Basin upstream.

Measurements made downstream in the Canada Basin, along the Banks Island section, showed that the ventilated Atlantic layer was found only at Station BB12. This finding suggested that the boundary current's leading edge had arrived and was narrow in form. Surprisingly, at downstream stations, both components of the Atlantic layer were well ventilated but the lower halocline was not. This observation suggested that the second and deeper stream within the boundary current was transported at a faster rate than the shallower stream, a notion advanced by Aagaard (1989). Measurements at Station BB12 could not be not be attributed to an eddy because temperature and salinity data suggested otherwise.

4.4.1 Boundary current rate

Evidence of a colder, fresher Atlantic layer in the Canada Basin signalled that the 1989 Barents Sea outflow had arrived downstream in 1993, having travelled some 5100 km in four years. Transit time and distance suggested that boundary current speed in the Atlantic layer was about 4 cm s^{-1}. Aagaard (1989) reported current speeds of 2-3 cm s^{-1} farther upstream using current meters moored in 1979 over the eastern flank of the Lomonosov Ridge at a depth of 1400 m.

Boundary current speed may be related in some way to atmospheric circulation. That is, the speed of the boundary current transporting Atlantic-origin water may be faster during cyclonic regimes—when there is increased transport of Atlantic water across the Barents Sea—and slower during anticyclonic regimes. Because the speed of an intrusive density-driven current increases approximately with the square root of its height (Simpson, 1987), an increase in the thickness of the Atlantic layer would cause an increase in boundary current speed. Although measurements are too sparse to corroborate this hypothesis, a comparison of the thickness of the Atlantic layer in 1992 at Station A, when upstream conditions were anticyclonic, to the thickness in 1995, when upstream conditions were cyclonic showed that the Atlantic layer was more than 200 m thicker in 1995.

Another estimate of boundary current speed was also derived from CFC-11 and tritium/^{3}He age calculations. It should be noted that CFC-11 ages were found by Frank et al. (1998) to be slightly older than tritium/^{3}He ages because the former represents an average age of the mixture whereas the latter represents the age of the younger component. Frank et al. (1998) reported that the mean current speed of FSB water in the eastern Nansen Basin in 1993 was approximately 1 cm s^{-1}, and about 2 cm s^{-1} for BSB water. The mean spreading rate of both FSB and BSB waters in the central and southern Canadian Basin in 1996 was estimated by Smethie et al. (submitted) at 0.5 cm s^{-1}. Using tritium/^{3}He measurements, they estimated the age of FSB water in the southern Canadian Basin near the Chukchi Cap to be 16.5 years, and the age of BSB water to be 19 years.

At Station A in the Canada Basin, the age of FSB water was estimated to be 22 years (Figure 28) on the basis of CFC-11 measurements, assuming an 85% saturation (Frank et al., 1998) and CFC-11 atmospheric source history (Walker et al., submitted). The age of FSB water in the boundary current, at Station AR5, was slightly younger at 21 years (Figure 29). Ages of BSB water at Station A in the Canada Basin, and in the boundary current at Station AR5, were estimated to be about 28 years. Assuming that FSB waters lost contact east of Spitsbergen some 6600 km upstream and BSB waters lost contact on the Barents Sea Shelf about 5600 km upstream, these ages infer mean boundary current speeds of FSB and BSB waters in the Canada Basin at 1.0 and 0.6 cm s^{-1} respectively.

Current meter measurements and tracer estimates of current speed differ for several reasons. Current meter measurements provide a synoptic picture of current speed at a fixed location and depth over a period of time. Whether this picture illustrates a transient or steady state remains unknown. Tracer estimates represent an average speed over a much longer time, often in terms of decades, and are approximate due to uncertainties in calculation. The distance travelled, in the case of the FSB, for example, is difficult to estimate because of the ambiguity in

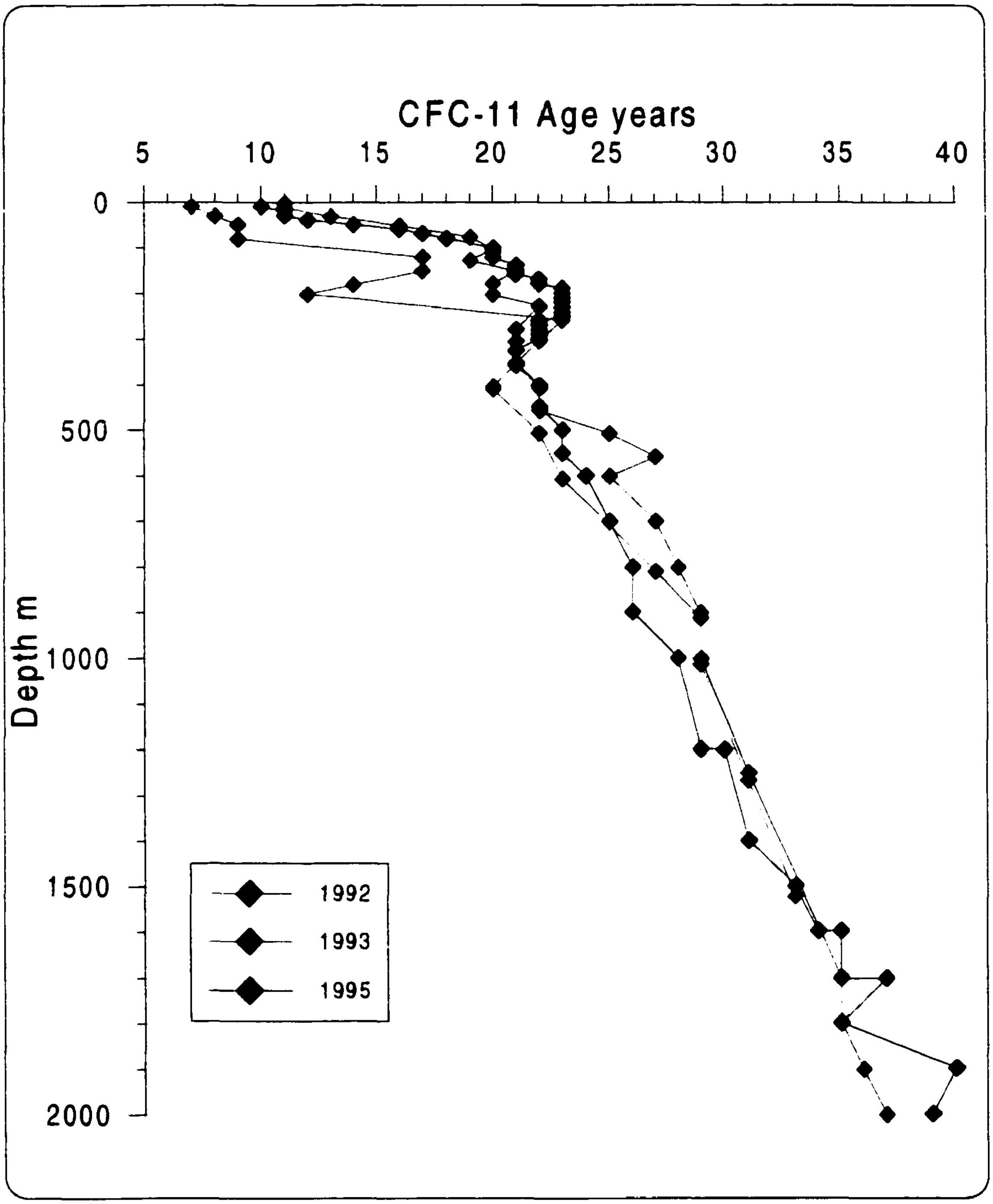

Figure 28. CFC-11age profiles from Canada Basin Station A, 1992, 1993 and 1995.

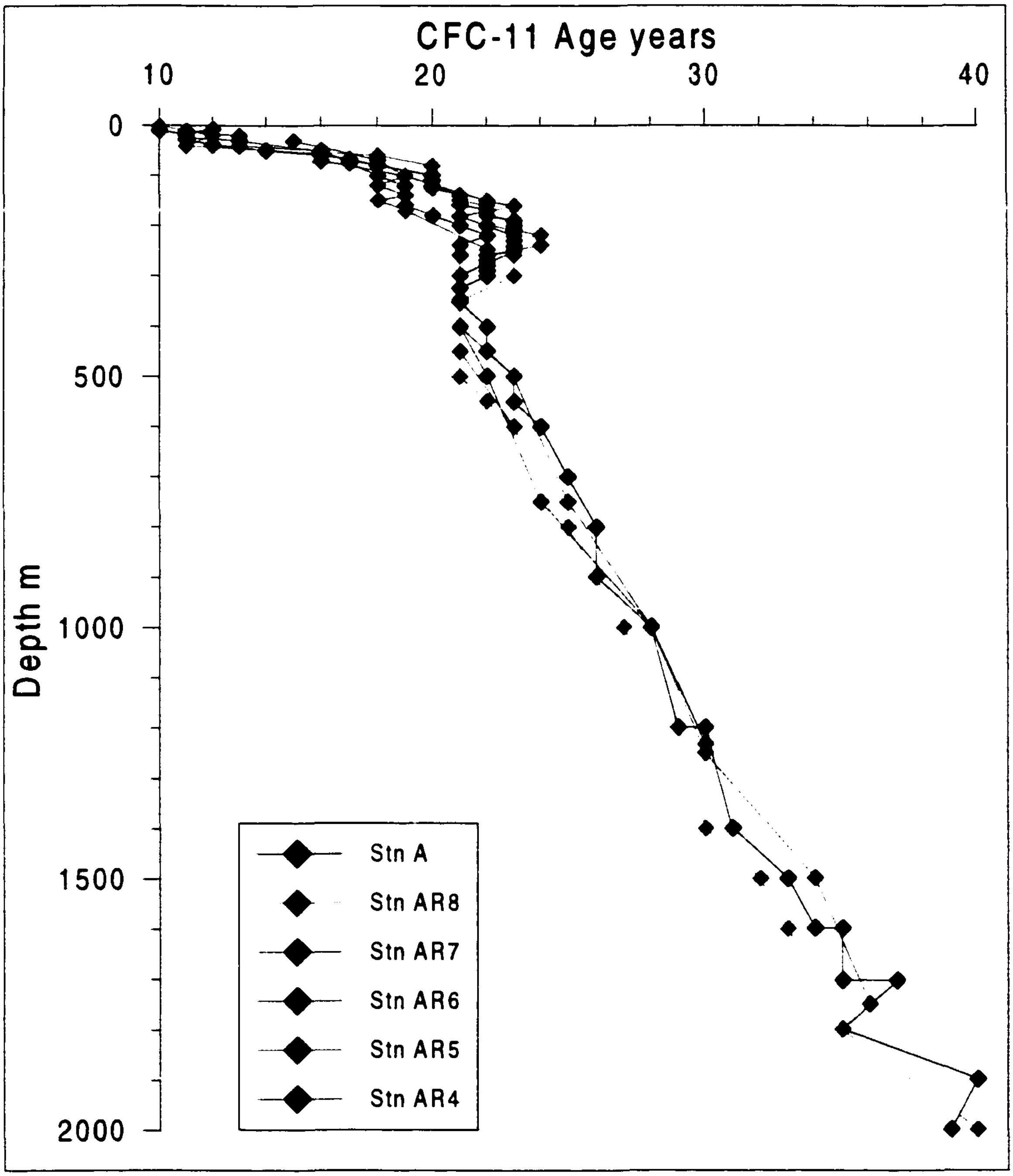

Figure 29. CFC-11 age profiles from 1995 Canada Basin section stations.

locating where the FSB water lost contact with the atmosphere. Also, the apparent age calculation does not differentiate between time spent on the Beaufort Shelf after convection and time in transit, nor does it allow for mixing *en route* between younger boundary current water and older ambient water. Additionally, the current speed itself may also vary depending on atmospheric forcing.

4.5 Arctic atmosphere-ocean system

The suite of events observed in the Canada Basin after 1993 reflected broader changes evident across the larger Arctic Ocean during the 1990s. Discussion to this point in the inquiry has examined modifications to the Canada Basin's water column which were traced upstream to events in the Arctic Ocean system—in particular to an increase in Barents Sea outflow and, beyond this, to the 1989 atmospheric transition to increased cyclonicity that appeared to sponsor these modifications. A search to explain events in the Canada Basin, however, has led to consideration of a more complex question, notably: Can the 1989 transition to increased cyclonicity be connected to Arctic Ocean circulation and other changes? In chronological order, these included: warmer FSB water in the Atlantic layer in 1990; a shift in the Atlantic/Pacific front's location by 1993; and increases in ventilation at depth observed in the Amundsen Basin from 1991 to 1994, and in the Makarov Basin from 1993 to 1994.

Warming reported in 1990 in the Atlantic layer's FSB component in the Nansen Basin was observed downstream three years later in Amundsen and Makarov basins. Unprecedented decrease in the sea level pressure north and east of Greenland in 1989, a manifestation of the atmospheric transition to increased cyclonicity, likely increased the volume and rate of warm Atlantic water transported into the Arctic Ocean. Although earlier discussion showed that transport via the Barents Sea was favored over the Fram Strait route, 1990 measurements of warm water in the western Nansen Basin demonstrated that water about 1 °C warmer also entered the Arctic Ocean via this passage. Carried by the Arctic Ocean boundary current, water warmer than the historical record could be seen as far afield as the Makarov Basin by 1993, an observation which indicated the speed of its transport downstream. In effect, increased cyclonicity appeared to influence the rate at which the boundary current travelled.

Increased volume of Atlantic inflow, moreover, may also have been strongly associated with relocation of the Atlantic/Pacific front eastward from the Lomonosov Ridge to the Mendeleyev Ridge, observed in 1993. The perennial contest between Atlantic and Pacific waters for dominion over the upper layer of the Arctic Ocean appeared to have been decided in the Atlantic's favor by the predominance of Atlantic water across the Makarov Basin, once the preserve of the Pacific. Effects of the atmospheric cyclonic regime may well have tilted the balance in the Atlantic's favor by increasing transport of Atlantic water into the Arctic Ocean. A resulting displacement of Pacific water increased freshwater outflow which, in league with relocation of the water mass front, may have steered a greater amount of freshwater through the Archipelago to the Labrador Sea.

Observations of ventilated water to depths greater than 1500 m downstream also illustrated the influence of increased atmospheric cyclonicity on the Barents Sea, where transport of warm water appeared to prompt outflow of existing dense water into the Nansen Basin. This outflow, perhaps as much as 4 Sv in volume (Loeng et al., 1997), was observed downstream to depths greater than 1500 m in the Makarov Basin by 1993 and, by 1995, was observed to a similar depth in the Canada Basin. These findings testified to far-field effects of both the Barents Sea and the cyclonic atmospheric regime. In addition, the depth of the boundary current in the Canada Basin was extended by about 500 m in 1995, suggesting that the speed of this thermohaline flow was faster. Finally, the fact that both ventilation levels and the depth of ventilation in the Makarov Basin were found to increase between 1993 and 1994, perhaps foreshadows higher levels of ventilation at greater depths in the Canada Basin in years to come (See Figure 16).

The interplay between atmosphere and ocean outlined above allows formation of a hypothesis that portrays two modes of atmosphere-ocean interaction and extends Proshutinsky and Johnson's (1998) concept of two atmospheric

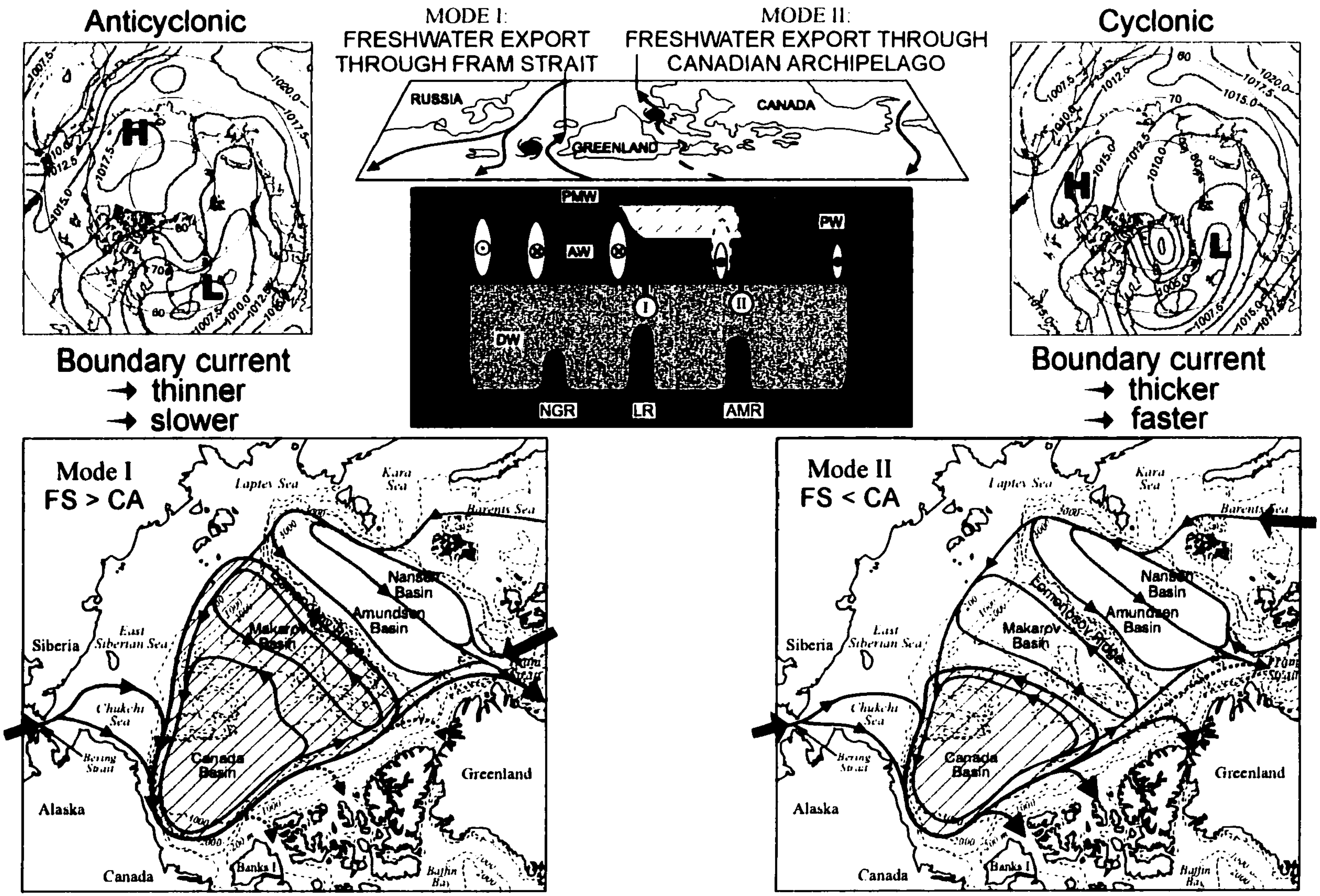

Figure 30. Two Arctic atmosphere - ocean modes: a hypothesis.

regimes to encompass the ocean's response (Figure 30). One part of the hypothesis describes an anticyclonic regime characterized by reduced cyclonic circulation which, in turn, engenders a specific ocean response—namely the reduced transport of Atlantic water which, upon arrival in the Arctic Ocean, is colder. Weaker Atlantic inflow is likewise associated with location of the Atlantic/Pacific front over the Lomonosov Ridge and freshwater export primarily through Fram Strait. During the anticyclonic mode, the Arctic Ocean boundary current appears thinner and slower.

Alternatively, the cyclonic regime is characterized by increased cyclonic circulation which acts upon the ocean to increase delivery of Atlantic water, which is warmer on arrival. Increased Atlantic inflow is likewise associated with eastward location of the Atlantic/Pacific front over the Mendeleyev Ridge, and increased freshwater export through the Archipelago. During the cyclonic mode, the Arctic Ocean boundary current appears to be thicker and transport is faster. Although modellers have chronicled atmospheric oscillations over the past half-century, the ocean's response has been recorded only recently and after an atmospheric transition of extreme magnitude. Whether the post-1989 shift from an anticyclonic to cyclonic regime will be followed by an equally dramatic shift to an anticyclonic regime remains to be seen, and the ocean's response recorded.

Such a hypothesis provokes two different but important questions. The first question relates to atmosphere-ocean circulation. Given the Arctic atmosphere influences Arctic Ocean circulation—and conditions freshwater export—how does this modified ocean, in turn, act upon the atmosphere to complete the interactive cycle illustrated in Figure 31. No less interesting an issue is the way in which Arctic atmospheric oscillations correspond to the global atmosphere-ocean system.

A second question, provoked by the hypothesis and observations upon which it was based, concerns transport of warm FSB Atlantic water. Warming of the FSB, observed in 1990 in the western Nansen Basin, and in the southern Makarov Basin in 1993 and 1994, was still not evident in the Canada Basin by 1995. In fact, FSB water in the Canada Basin was found to be colder in 1995 than in previous years, which raised a question about the whereabouts of warmer FSB water. The presence of warmer, ventilated FSB water from Chukchi Cap to the Alpha Ridge led Smethie et al. (submitted) to conclude the boundary current bifurcated once more at the Chukchi Rise, with one branch flowing into the Canada Basin interior and the other continuing along the basin margin. This bifurcation conceivably delayed boundary current delivery within the Canada Basin. Moreover, given that BSB outflow effects took about six years to reach the Canada Basin and that the FSB's speed was half that of the BSB (Frank et al., 1998), warmer FSB water could not reach the Canada Basin before 2001, thereby accounting for its 1995 absence.

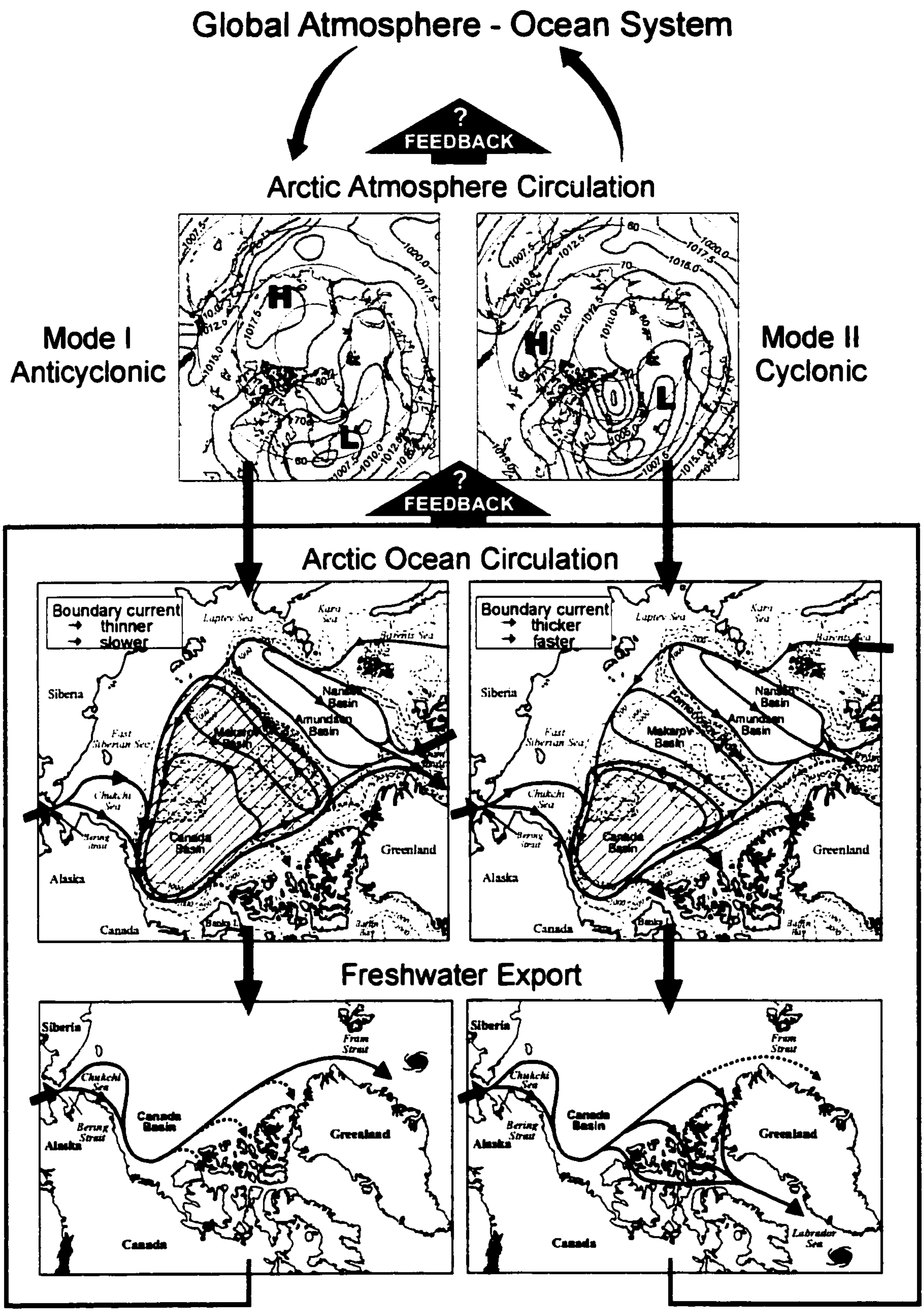

Figure 31. Relationship between Arctic atmosphere circulation, Arctic Ocean circulation, freshwater export and the global atmosphere-ocean system.

5. Conclusion

Not often does study of a single oceanographic station over a brief six-year period illuminate the interplay of a larger oceanic and atmospheric system. Fortune looked favorably, however, at a time-series study of the Canada Basin waters during the 1990s at a time of unprecedented change in the Arctic Ocean. Results of this study, which demonstrated modifications to the composition of basin waters, provoked a search for explanation that led to the Barents Sea, some 5000 km away and, beyond this, to the larger Arctic Ocean-atmosphere system.

More specifically, physical and geochemical measurements made between 1989 and 1995 revealed that Pacific-origin water in the Canada Basin diminished in volume after 1993 and were supplanted by an increased inflow (0.9 Sv) of Atlantic-origin water. This Atlantic-origin water, in turn, was found to be fresher and more ventilated than in the past and the source of these changes was traced to an increase in Barents Sea outflow. Composition of the Atlantic layer was shown to have included 20% more BSB water in 1995 than in 1992.

To account for increase in Barents Sea outflow, arctic atmospheric studies were examined which concluded that a dramatic shift toward increased cyclonicity occurred after 1988 (Walsh et al., 1996). Modelling studies portrayed the arctic atmosphere as oscillating between cyclonic and anticyclonic regimes. Transition from anticyclonic to cyclonic circulation in 1988-1989 was calculated to be of a magnitude and extent unparalleled in nearly 50 years (Johnson and Proshutinsky, 1999). A change of unprecedented order in the late 1980s was also identified by the Arctic Oscillation Index (Thompson and Wallace, 1998). Cumulatively, such studies underscored the strength of the transition marking the beginning of a cyclonic mode within the Arctic domain in the late 1980s.

Oceanographic studies of the Barents Sea likewise portrayed ocean circulation in a dynamic state in the late 1980s. Notably, warmer Atlantic water was rapidly transported across the Barents Sea in early 1988 and, by autumn 1989, a large volume of dense water—perhaps as much as 4 Sv (Loeng et al., 1997)—had left the Barents Sea Shelf to join the boundary current that connects Nansen Basin waters to waters downstream in the Canada Basin. Observations of oceanographic change were consistent with observations of atmospheric change. Increased cyclonicity, in other words, increased transport of warmer Atlantic water northward and, due to the geographic position of the extended low, affected inflow via the Barents Sea rather than Fram Strait. The Barents Sea response, as expressed in increased dense water outflow, marked the beginning of an eight-year or longer atmospheric-ocean cycle eventually observed downstream in the Canada Basin some five or six years later. In effect, the Canada Basin was the site where the message in a bottle signifying upstream change was collected and read.

Large outflow from the Barents Sea in 1989 established a reference point from which the boundary current's speed could be calculated. Mean boundary current speed between the St. Anna Trough and the Canada Basin was about 4 cm s^{-1} which slowed to about 1 cm s^{-1} within the Canada Basin. Compared to earlier estimates, the boundary current speed appeared to have increased. Whether cyclonic atmospheric circulation accelerates the boundary current, and anticyclonic circulation retards it, remains to be proven by further investigation.

Prior to this study of the Canada Basin, observations and modelling of sea-ice transport had shown an inextricable relationship between atmosphere and ocean circulation. This study, however, has demonstrated that influence of atmospheric circulation—in this case through a cyclonic mode—reached far below the ocean surface and was detectable at depths greater than 1500 m. Penetration of atmospheric influence to such depths may be attributable to conditions unique to the Arctic. In particular, cooling and ice formation on the saline Barents Sea Shelf produced ventilated water dense enough to be observed at depths from 400 m to 1500 m downstream in the Canada Basin. This study has similarly suggested that cyclonic circulation was also manifested in the re-positioning of the Atlantic/Pacific front and in the resulting export of freshwater from the Makarov and Canada basins. In short, study of the Canada Basin between 1989 and 1995 has made the influence of the atmosphere on ocean circulation more transparent.

Study of the Canada Basin in the 1990s took place as one regime of atmospheric circulation was ending and another beginning. Data from this study forms part of an emerging ocean-wide literature that provides a basis for a more comprehensive description of the Arctic Ocean under cyclonic atmospheric circulation. Signs of a new regime are already evident (Johnson and Proshutinsky, 1999) and these signs extend an opportunity to chronicle the Arctic Ocean's response to anticyclonic circulation. Whether the anticyclonic regime will decrease Atlantic inflow sufficiently for the Atlantic/Pacific front to return to the Lomonosov Ridge remains to be seen. In the battle of the titans marking the struggle between Atlantic and Pacific oceans for possession of the Makarov Basin, only the gods—in the form of atmospheric structure and forcing—will ultimately decide.

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