JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 95, NO. C12, PAGES 22,193–22,208, DECEMBER 15, 1990

Using the Nutrient Ratio NO/PO as a Tracer of Continental Shelf Waters in the Central Arctic Ocean

CARA WILSON AND DOUGLAS W. R. WALLACE

Oceanographic and Atmospheric Sciences Division, Department of Applied Science, Brookhaven National Laboratory, Upton, New York

Historical nitrate, phosphate, and dissolved oxygen data from the central Arctic Ocean are examined with particular emphasis on the conservative parameters NO (9 * NO_3 + O_2) and PO (135 * PO_4 + O_2). The NO/PO ratio is shown to increase with depth in the Canada Basin, being ~0.78 in Surface and Upper Halocline Waters and ~1.0 in the Atlantic Layer and Deep Waters. Lower Halocline Water is marked by NO and PO minima and intermediate NO/PO. NO/PO ratios from the Arctic shelf seas are examined to determine possible source regions for the various water masses. The NO/PO ratio of Canada Basin Deep Water implies an upper bound of ~11% shelf water contribution to this water mass. A slight oxygen maximum core in the Lower Halocline Water is identified at a salinity of S=34.5 in the vicinity of the Alpha Ridge. This core appears to be diminished by diapycnal mixing and does not extend into the Beaufort Gyre.

BACKGROUND

The distribution of chemicals in the ocean can provide insight into the locations, processes and rates of water mass formation. Direct observation of water mass formation is particularly difficult in the Arctic; hence Arctic oceanographers have focused extensively on deriving such information from chemical oceanographic measurements. In this paper we examine the available historical data from the Arctic Ocean using perhaps the most basic chemical tracers: nutrients and oxygen.

Shelf Inputs to Halocline Water

The Arctic Ocean's strong halocline separates a mixed surface layer from a deeper, relatively warm Atlantic-derived layer. Chemical oceanographers have sub-divided the halocline into Upper and Lower Halocline Water types (UHW and LHW [*Jones and Anderson,* 1986]). The UHW is identified by a nutrient maximum which was originally explained as a signature of Pacific-derived waters coming in through the Bering Strait. These waters were recognised to be altered in the Chukchi Sea [*Coachman and Barnes,* 1961; *Kinney et al.,* 1970*a*]. *Moore et al.* [1983] attributed the high levels of all nutrients primarily to the Bering Sea source; however, they also suggested that "new" halocline waters formed over continental shelves might become enriched in nutrients through contact with sediments, and that the high nutrient content of halocline waters might therefore have a more widespread origin on other Arctic continental shelves. This idea was developed by *Jones and Anderson* [1986] who argued that nutrient regeneration within the confines of the Arctic Basin was primarily responsible for the maintenance of the nutrient maximum layer. Their reasoning implied that high nitrate and phosphate levels were less a function of proximity to the Bering Sea, but were more dependent on the physical nature of the continental shelf over which the UHW is formed. These authors attributed UHW to a Chukchi Sea origin on the basis of high silicate concentrations (attributed to a Bering Sea source) and hypothesised longer shelf residence times in this region which permit a greater contribution of bottom-regenerated nutrients.

Kinney et al. [1970*a*] speculated that the LHW, which exhibits higher salinity and lower nutrient content, was formed via mixing over the Siberian shelf of the Eurasian Basin. *Moore et al.* [1983] identified LHW as modified Atlantic water produced by upwelling via submarine canyons followed by cooling. *Jones and Anderson* [1986] argued instead that the LHW was produced by salinization of shelf water due to brine formation, in a similar fashion to UHW. The lower nitrate and phosphate content of LHW compared to UHW was argued to reflect short residence times of LHW over shelf sediments during formation. In this view, dilution of the supply of regenerated nutrients from shelf sediments is the primary control on halocline nutrient levels. These authors identified the Barents and Kara seas as likely source regions for LHW.

Shelf Inputs to Canada Basin Deep Water

Aagaard [1981] first postulated shelf-derived saline water as a contributing source to account for the high salinities of the Canada Basin Deep Water (CBDW) relative to other Arctic Ocean deep water masses. *Aagaard et al.* [1985] attempted to use a silicate-salinity relationship to show the contribution of shelf waters to the ventilation of the CBDW, and estimated that one third of the CBDW was shelf-derived. *Ostlund et al.* [1987] subsequently used a $\delta^{18}O$ mass balance to obtain an upper limit of only 10-15% shelf water contribution to the CBDW.

Nutrient-Based Conservative Tracers

A shelf-water source for the LHW was inferred by *Jones and Anderson* [1986] partly on the basis that this water type represented a NO minimum in the vertical. Both NO and PO are nutrient-based tracers, defined by *Broecker* [1974] as follows:

$$NO = 9 * [NO_3] + O_2 \quad (1)$$

Paper number 90JC01960.
0148-0227/90/90JC-01960$05.00

$$PO = 135 * [PO_4] + O_2 \quad (2)$$

These definitions utilise the traditional Redfield [*Redfield et al.*, 1963] ratios to account for the nutrient regeneration accompanying oxygen depletion in a water parcel isolated from the atmosphere. The parameters NO and PO are quasi-conservative below the surface layer, and are directly related to preformed nutrient levels.

In this paper we exploit differences in the relationship between nitrate and phosphate in order to infer sources of halocline waters, and to estimate the contribution of shelf water to CBDW. When using a nitrate to phosphate relationship as a tracer there are three possible ratios that could be used: NO_3/PO_4, the preformed values of NO_3/PO_4 ($°NO_3/°PO_4$), and NO/PO. The parameters NO, PO, $°NO_3$ and $°PO_4$ are all conservative tracers that are independent of biological processes for water removed from contact with the atmosphere. However calculation of $°NO_3$ and $°PO_4$ assumes knowledge of the"preformed" oxygen saturation, whereas use of NO and PO has no such requirement. High and variable oxygen supersaturations are observed in Arctic shelf waters in summertime [*Codispoti and Richards*, 1971; *Chen*, 1985]. Ice formation in wintertime restricts gas exchange and cooling can produce significant undersaturation [*Chen*, 1985]. Hence an appropriate preformed oxygen level is difficult to choose. We avoid this problem by using NO and PO. Although an air-sea oxygen flux can also affect the NO/PO ratio, this effect is relatively small: for example, a 100 μmol/L increase in oxygen (resulting from air-sea gas exchange) for typical nitrate, phosphate, and oxygen summertime shelf values of 3.8, 0.8 and 360 μmol/L respectively (values are averages of all shelf data) would cause an increase of only 0.03 in the NO/PO ratio (from 0.84 to 0.87).

Although NO has been used as a tracer in the Arctic Ocean, there has been no corresponding analysis of PO distributions and little of N/P nutrient ratios. An exception is the study by *Anderson and Jones* [1986], who exploited the differing NO_3/PO_4 ratios between Arctic Ocean Surface Waters and Atlantic- derived waters in the Fram Strait region to quantify mixing between near- surface water types. The NO_3/PO_4 ratios in the East Siberian and Laptev Seas have been discussed by *Codispoti and Richards* [1968].

Methods, Data Sources, and Data Quality

A surprising amount of Arctic Ocean chemical data exists that has not been discussed fully in the literature. Both the Marine Environment Data Service, MEDS, (Canada) and the National Oceanographic Data Center, NODC (United States), have data records containing chemical data collected from ice camps and ships in the Arctic Ocean from the 1900s to the late 1970s. Those data are examined here to attempt a more complete description of the chemical characteristics of the Arctic Ocean.

All data from stations within the Arctic Ocean for which oxygen and/or nutrient data existed were acquired from MEDS and NODC. Most of the data were from continental shelf regions. Data sets with a large degree of noise in their profiles were immediately discarded.

Most of the central Arctic Ocean data were collected from the T-3 ice island in the Canada Basin during 1958 and 1969-1971 from seven different occupations. In addition, we use large amounts of data collected in various Arctic shelf regions. Data sets are differentiated by a NODC assigned cruise number, hence we refer to the different occupations of the T-3 ice camp by "cruise number". When distinguishing between different stations taken as part of one cruise, we have used the station number from the data tapes. Figure 1 shows the general sampling location of each cruise. To identify data sources (i.e., the institution and chief investigator) the dates and locations of the cruises were compared with data sets listed in reports by *Birch* [1984] and *Kinney et al.* [1970*b*]. References to all cruises were found, but some were not adequately identified. Table 1 summarizes this information. Cruise 5845 are the data reported by Collin [1959], and cruise 2170 are the data discussed by *Kinney et al.* [1970*a*]. Cruise 2171 was collected by Arhelger and Kinney from the University of Alaska in 1969, but no discussion of the data has been found in the literature. Cruises 1678 and 1973 are data collected by English of the University of Washington; some of the physical data were discussed by *Smith and English* [1973] and by *Morison and Smith* [1981], but no analysis of the chemical data has been published. The methods used during cruises 2170 and 2171 are discussed in *Kinney et al.* [1970*b*]. Only cruises 2170, 2171, and 1973 had nutrient data.

The continental shelf data were broken down by geographical boundaries defined as follows: Chukchi Sea, 150°-180°W; East Siberian Sea, 145°-180°E; Laptev Sea, 110°-145°E; and Barents Sea, 30°-60°E (the Kara Sea did not have any nutrient data). Only stations with sounding depths less than 100 m were examined, except in the deeper Barents Sea, where 300 m was used as the cutoff. Station locations are shown in Figure 1. Data from the Chukchi Sea include data discussed by *Hufford et al.* [1974], *Codispoti and Richards* [1968,1971], and the shipboard data of *Kinney et al.* [1970*a*]. The data from the East Siberian Sea and the Laptev Sea are discussed by *Codispoti and Richards* [1968, 1971]. Table 2 summarizes this information.

The quality of the data was checked, where possible, by comparing oxygen, nitrate, and phosphate versus salinity plots for data from depths greater than 500 m. The deep water of the Canada Basin is probably homogenous because of its slow ventilation [*Wallace and Moore*, 1985; *Ostlund et al.*, 1987]. Cruise 2170, the data discussed by *Kinney et al.* [1970*a*], and data taken at the Arctic Internal Wave Experiment, AIWEX (Figure 1. [*Anderson and Swift*, 1990]) were used as standards. The oxygen and nutrient data from cruise 2171 and stations 20, 53, 57, and 61 of cruise 1973 (see Figure 1) showed good agreement with the AIWEX and 2170 data. From this comparison the oxygen data are probably comparable to within ~5 μmol/L, the nitrate to ~1.0 μmol/L, and the phosphate to ~0.2 μmol/L. Propagation of these errors provides uncertainties of ~10 and ~30 μmol/L for NO and PO values, respectively, and ~0.06 for the NO/PO ratio. Cruises 1571, 1377, and 1678 did not have enough deep data to perform this check. While oxygen data from these cruises have been included, most of the work presented is based on the oxygen and nutrient data from cruises 2170, 2171, and the four stations from cruise 1973.

The nitrate samples from the East Siberian and Laptev seas were frozen and analyzed later, while the phosphate samples were run on board [*L. Codispoti*, personal communication, 1990; *U.S. Coast Guard*, 1965]. While freezing might have altered some of the nitrate measurements, the overall effect on the NO/PO distribution is probably small. As a comparison NO/PO values were calculated using frozen phosphate values [*U.S. Coast Guard*, 1965] and compared to

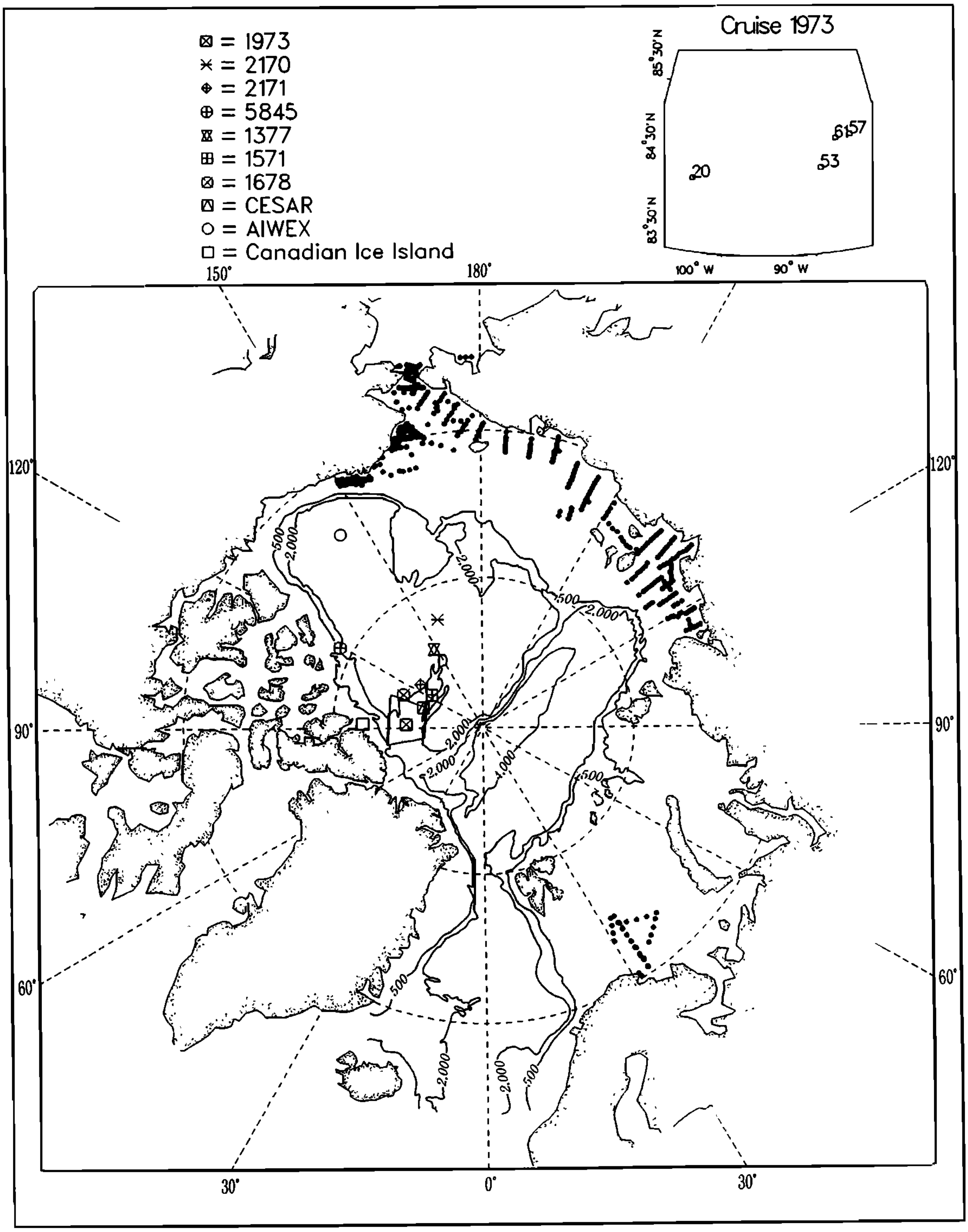

Fig. 1. Map showing the locations of the "cruises" on the T-3 ice-camp whose data are discussed in this paper. A portion of the area over the Alpha Ridge is blown up in order to identify individual stations from cruise 1973 referred to in the paper. All of the stations of the continental shelf data are shown. The locations of CESAR, AIWEX, and the Canadian Ice Island are also shown.

the NO/PO values using the field phosphate values. The difference is within the uncertainty in the NO/PO ratio stated above.

NO/PO Ratios in the Central Arctic Ocean

Profiles of NO and PO for cruises 2170, 2171, and stations 61, 57, 53, and 20 of 1973 are shown in Figure 2. Both NO and PO have maxima at ~150 m and minima at ~200 m. The extrema are slightly deeper at cruise 2170 but occur on the same salinity surface as data from cruises 1973 and 2171 (Figure 3). The NO and PO maxima both occur at ~S=33.1, and the minima at ~S=34.4, except for cruise 2170, which has the NO minimum at S=34.3. The NO minimum varies between its lowest value of 375 μmol/L at 1973 station 61 and 400 μmol/L at stations 20 and 53 of 1973. The NO maximum varies between 430 and 450 μmol/L. In all profiles the NO increases below the minimum to a value

TABLE 1. T-3 Canada Basin Data

NODC Cruise Number	Date	Source	Available Data	Number of Stations	Location
5845	June-Sept. 58	Collin [1959]	O_2,PO_4	19	Canada Basin
2170	March-April 68	Kinney et. al. [1970*a*]	O_2,NO_3, PO_4,SiO_4	2	Canada Basin
1377	June-Sept. 68	???	O_2	10	Canada Basin
2171	April-May 69	Arhelger	O_2,NO_3,PO_4,SiO_4	5	Alpha Ridge
1571	June-Sept. 69	???	O_2	12	Alpha Ridge
1678	Jan.-May 70	English	O_2	16	Alpha Ridge
1973	June-Dec. 70	English	O_2,NO_3,PO_4,SiO_4	30	Alpha Ridge
1973	June-Sept. 71	English	O_2,NO_3,PO_4,SiO_4	17	Alpha Ridge

TABLE 2. Continental Shelf Data

Sea	Date	Sources	Number of Stations
Chukchi	Aug. 63	Codispoti and Richards [1963]	39
	July-Aug. 64	Codispoti and Richards [1971]	6
	July-Aug. 68	Kinney et al. [1970*a*]	22
	July 69	Kinney et al. [1970*a*]	20
	Sept. 71	Hufford et al. [1974]	20
	July 72	Hufford et al. [1974]	15
	Aug.-Sept.72	Hufford et al. [1974]	35
		???	56
East Siberian	Aug. 63	Codispoti and Richards [1963]	66
	Sept. 63	Codispoti and Richards [1971]	6
Laptev	Aug.-Sept. 63	Codispoti and Richards [1963]	75
Barents		???	125

of 420-425 μmol/L below 400 m. These results are similar to data from the ice station CESAR (Canadian Expedition to Study the Alpha Ridge), which had an NO minimum of ~390 μmol/L (400 μmol/kg) at ~210 m (S=34.2) and an NO of ~413 μmol/L (424 μmol/kg) at 450 m [*Jones and Anderson*, 1986].

The PO profiles exhibit a less-sharp minimum than the NO profiles (cf. profiles of cruises 2170 and 2171, Figure 2). The PO minimum (400-420 μmol/L) occurs at 200 m (~S=34.4) and increases only slightly below the minimum. Note that the NO values vary over a small range, from 375 to 450 μmol/L, and the surface NO values are not considerably different from the deep (>400 m) NO values. In contrast, the PO values change considerably from surface values of 550 μmol/L to deep values of 425 μmol/L. This reflects variability in pre-formed nutrient levels for the different water masses since

$$^{o}NO_3 = (NO - O_2^{Sat})/9 \tag{3}$$

$$^{o}PO_4 = (PO - O_2^{Sat})/135 \tag{4}$$

where O_2^{Sat} is the oxygen saturation value.

Profiles of the NO/PO ratio are also shown in Figure 2. All of the plots are characterized by a low NO/PO ratio in the top 200 m, followed by a sharp increase to a ratio of ~1.0. The NO/PO ratio is constant at 0.78 in the surface water, the top 200 m for cruises 2170, 2170, and the top 150 m for stations 20 and 53 of cruise 1973. CESAR data had a surface NO/PO ratio of 0.80 [*Jones and Anderson*, 1986]. Stations 57 and 61 of cruise 1973 exhibit variable levels in their surface layers with relatively high surface values of 0.9, decreasing to 0.72 at 100 m. Data from the Canadian Ice Island (see Figure 1) on the continental shelf of Ellesmere Island [*Jones and Anderson*, 1990] also show some variability in surface NO/PO values, the ratio varying between 0.74 and 0.77 in the upper 100 m. Despite this variability, the surface layer NO/PO values are all significantly lower than the deep water ratio (~1.0).

Therefore on the basis of the NO/PO ratio there are at least two distinct water mass families in the Arctic Ocean. The surface water and UHW (S<33.5) are characterized by an average NO/PO ratio of 0.78, and the deeper waters (S>34.4) by a NO/PO ratio of 0.98 or greater.

NO/PO Ratios in Arctic Continental Shelves

Halocline waters are formed over the continental shelves. We therefore examined the continental shelf data to attempt to distinguish geographical origins of the halocline water mass families on the basis of nutrient ratios. For each shelf station with NO and PO data, depth-averaged NO and NO/PO values were calculated. The averages were binned to obtain frequency distributions of the NO/PO ratio and NO value for each shelf sea, as shown in Figure 4. Most of the NO/PO ratios for the Chukchi Sea are between 0.75 and 0.85, the East Siberian are between 0.65 and 0.75, the Laptev are between 0.85 and 0.95, and the Barents Sea are between 0.90 and 1.0. A similar result is obtained using

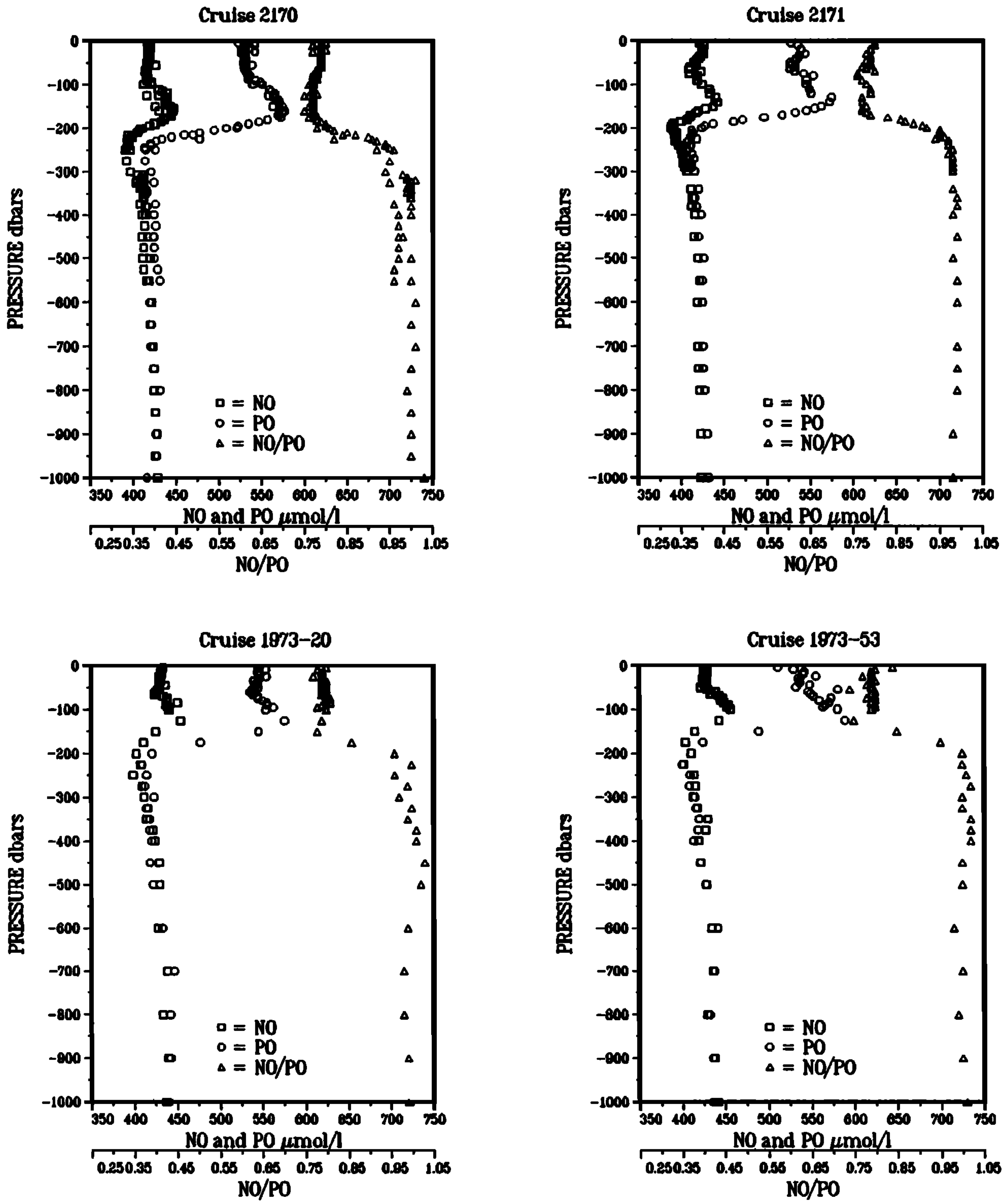

Fig. 2. Depth profiles of NO, PO, and NO/PO for cruises 2170, 2171, and stations 20, 53, 57, and 61 of 1973 taken on the T-3 ice-camp. Cruise 2170 are data from *Kinney* [1970], cruise 2171 are data collected by Arhelger and Kinney, and cruise 1973 data are collected by English.

the more standard NO_3/PO_4 nutrient ratio. For comparison, NO_3/PO_4 frequency histograms for each of the seas are shown in Figure 5. The Chukchi, East Siberian, and Laptev seas all have very low NO_3/PO_4 ratios, less than 5, and small ranges of values compared to the Barents Sea, where the ratio ranges from 0 to 20 (clearly, low or zero nutrient levels, when present, can give widely fluctuating NO_3/PO_4 ratios due to analytical noise).

All of the shelf data are summer data, except for the Barents Sea, which is roughly half winter and half summer data.

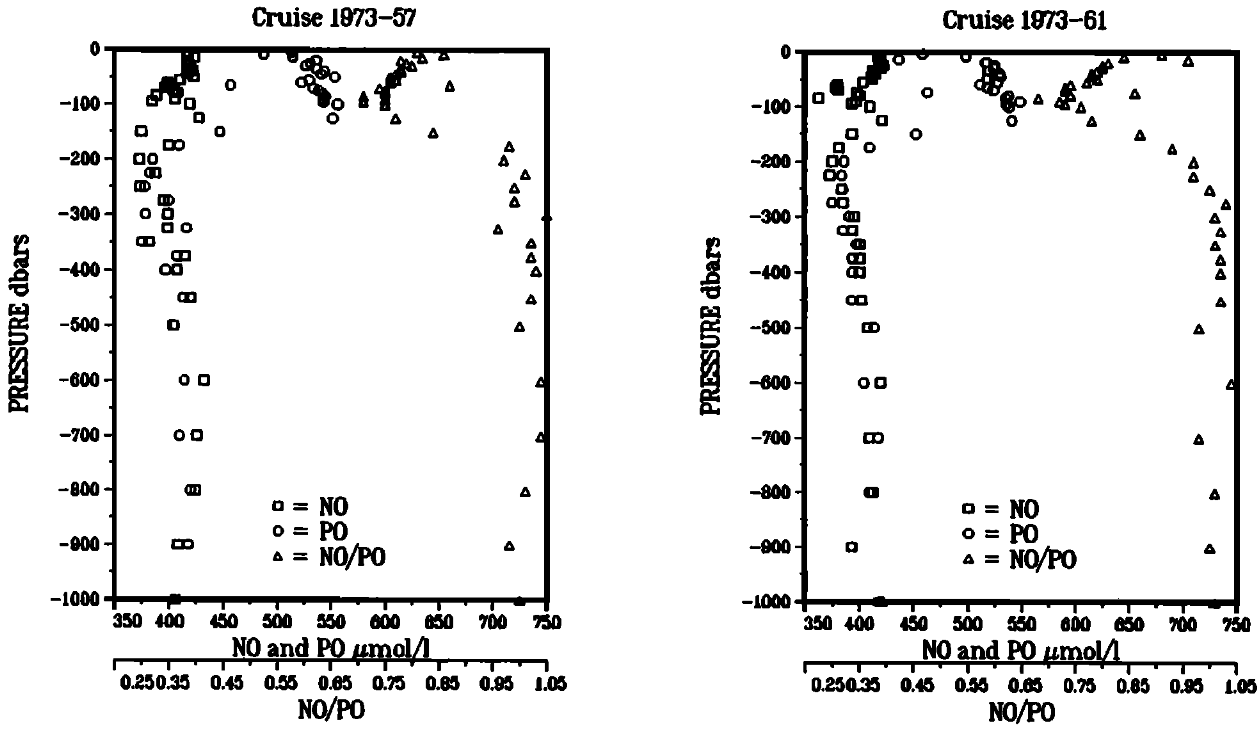

Fig. 2. (continued)

However, the inclusion of winter values is not the dominant cause of the higher NO/PO values seen in the Barents Sea. Excluding these values shifts the NO/PO distribution downward by less than 0.05.

The NO/PO ratio was also calculated with high quality data collected in the Nansen Basin and northern Barents Sea by the Arktis IV/3 cruise of the Polarstern during the summer of 1987 [*Anderson et al.*, 1989; *J. Swift*, , personal communication, 1990]. Stations in the Barents Sea and throughout the Nansen Basin had a consistent NO/PO ratio of 1.0 ± 0.01. There was no low NO/PO water in the Nansen Basin halocline.

The NO frequency distributions (Figure 4) show that most NO values for the Chukchi Sea are between 325 and 425 µmol/L (72%), the East Siberian are between 350 and 450 µmol/L (76%), the Laptev are between 375 and 425 µmol/L (73%), and the Barents Sea are between 350 and 425µmol/L (76%). The NO frequency distributions from the various seas are more similar than their NO/PO or NO_3/PO_4 distributions. There is a high prevalence of NO values of ~390 µmol/L (400 µmol/kg), the low NO value which characterizes the LHW [*Jones and Anderson*, 1986]. From this analysis, it would appear that the source of the LHW cannot be determined by its NO value alone. Not only is low NO water not unique to the Barents Sea, but it appears that the Chukchi Sea has a higher prevalence of "low NO" water than the Barents Sea.

Our analysis suggests that the NO/PO ratio can be used as a tracer of halocline water origins in the Arctic Ocean, and that the NO/PO ratio shows differences between the shelf seas more strongly than using NO alone. The NO/PO ratio of 0.78 in the UHW and the low NO/PO of Chukchi and East Siberian continental shelf waters is consistent with the hypothesis that the UHW is derived from the Chukchi Sea.

The water in the Chukchi and East Siberian is Pacific-derived, whereas the Barents Sea is Atlantic-derived [*Coachman and Aagaard*, 1974; *Coachman and Barnes*, 1961.] The surface waters of the North Pacific also exhibit markedly different NO/PO ratios than North Atlantic waters. Surface water in the North Pacific (44-53°N, 170-177°W) has NO/PO of between 0.87 and 0.91, whereas the North Atlantic surface water has NO/PO of ~1.0 (GEOSECS data [*Bainbridge*, 1976*a*, *b*]). While the NO/PO ratio of the North Pacific is higher than values observed within the Arctic Ocean, it seems clear that the source of the UHW is surface water from the Pacific that has been further modified on the shelves.

Our Arctic shelf NO computation does not include any contribution from NH_4^+ which might contribute to an apparent low NO/PO ratio. This cannot account for the low NO/PO ratios observed in the interior of the Arctic Ocean, as NH_4^+ would be completely oxidized by the time shelf water reaches the interior. We see no reason to postulate an unusual algal stoichiometry that might account for a lower NO/PO ratio. The lower NO/PO ratio of the shelf water could be due to river runoff, or denitrification occurring in shelf sediments. *Codispoti and Richards* [1968] indicate that runoff from the Lena River has a higher NO_3/PO_4 ratio than the surrounding shelf water, which suggests that denitrification might be the dominant factor. However, sediment denitrification rates measured in the Bering Sea [*Haines et al.*, 1981; *Koike and Hattori*, 1979] together with assumed shelf residence times of ~2 years can explain only ~30% of

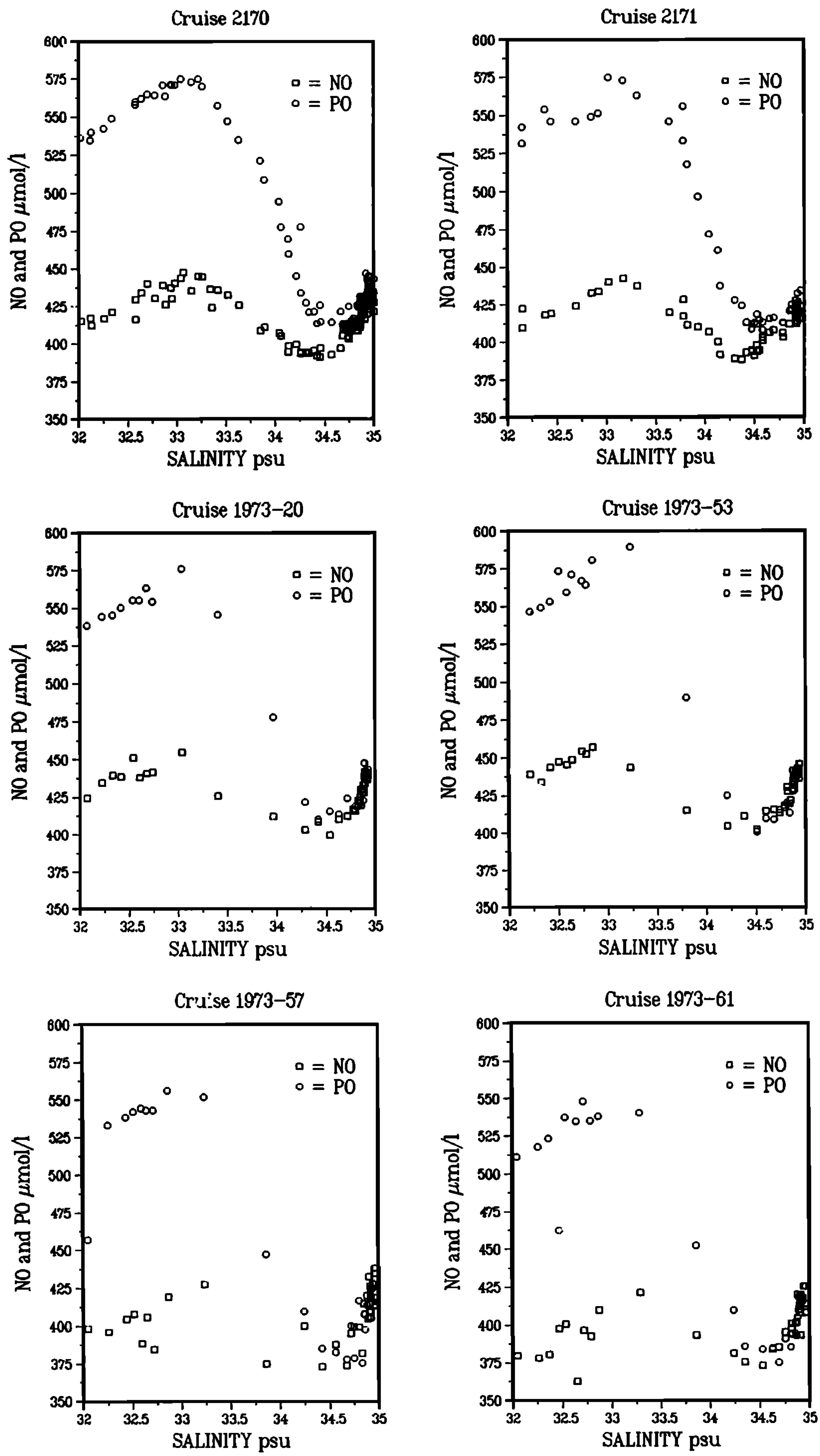

Fig. 3. Plots of NO and PO versus salinity for cruises 2170, 2171, and stations 20, 53, 57, and 61 of 1973 taken on the T-3 ice-camp. Cruise 2170 are data from *Kinney* [1970], cruise 2171 are data collected by Arhelger and Kinney, and cruise 1973 are data collected by English.

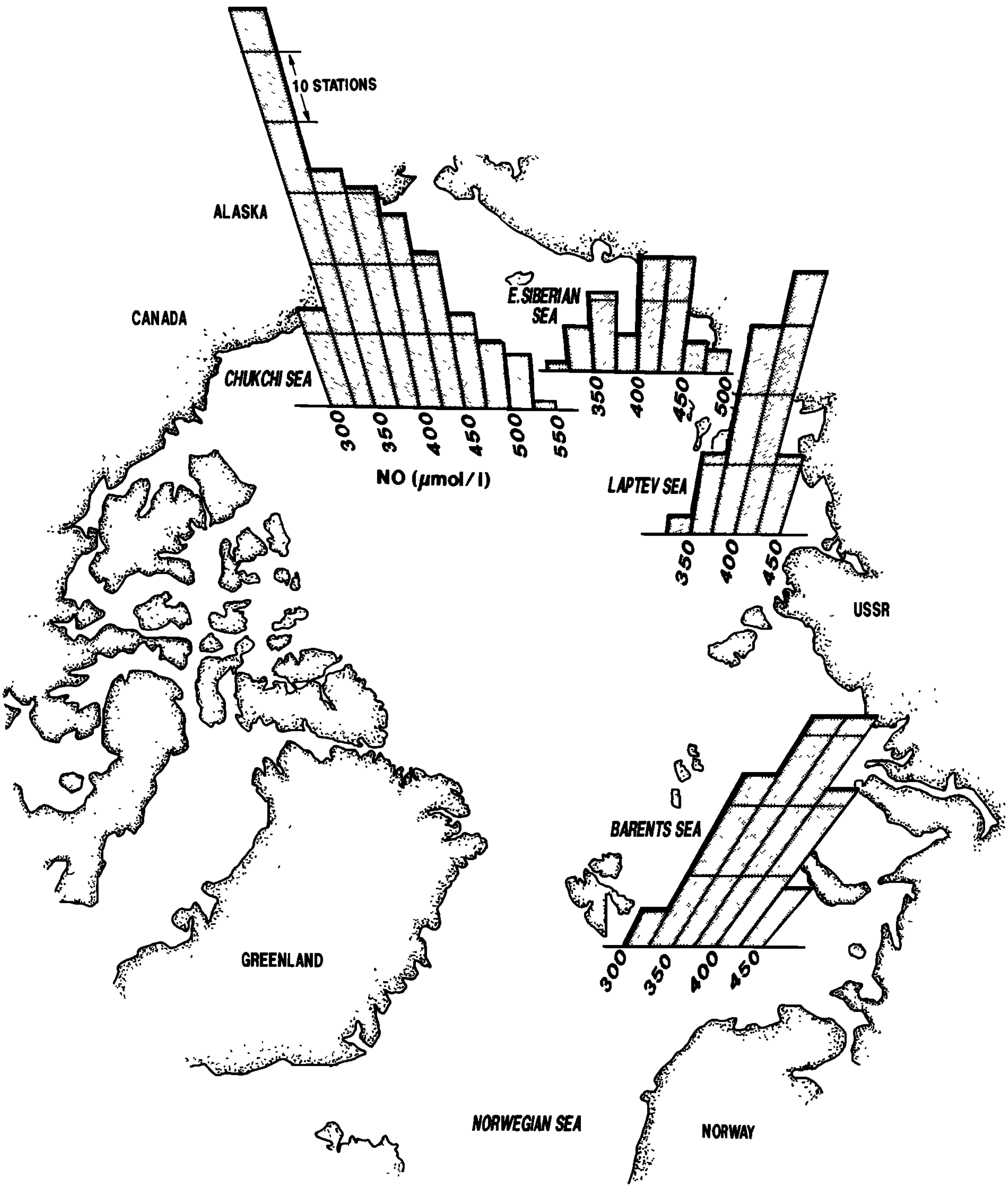

Fig. 4. Maps of the Arctic Ocean showing the frequency distributions of NO and NO/PO within the Chukchi, East Siberian, Laptev, and Barents seas. All data were collected during the summer, except for data from the Barents Sea, half of which are winter data.

the observed difference between North Pacific and Chukchi Sea waters.

The LHW has intermediate NO/PO ratios, suggesting that perhaps it is simply a mixing product between the UHW and the deeper Atlantic-derived water rather than a separate water type. However the contribution of an additional water type is confirmed by the NO minimum found in the LHW and by the T-S structure [*Jones and Anderson*, 1986]. The Barents Sea has been suggested as a source of the LHW because of the its presumed low NO values and high salinities [*Jones and Anderson*, 1986]. Our analysis of shelf NO values suggests that a Barents Sea source cannot be definitively indicated on the basis of the NO value alone.

For cruises 2170 and 2171, the S=34.2 end-member that defines LHW, occurs (on an apparent mixing line) at an NO/PO ratio of 0.90 (Figure 6). Hence the LHW could be

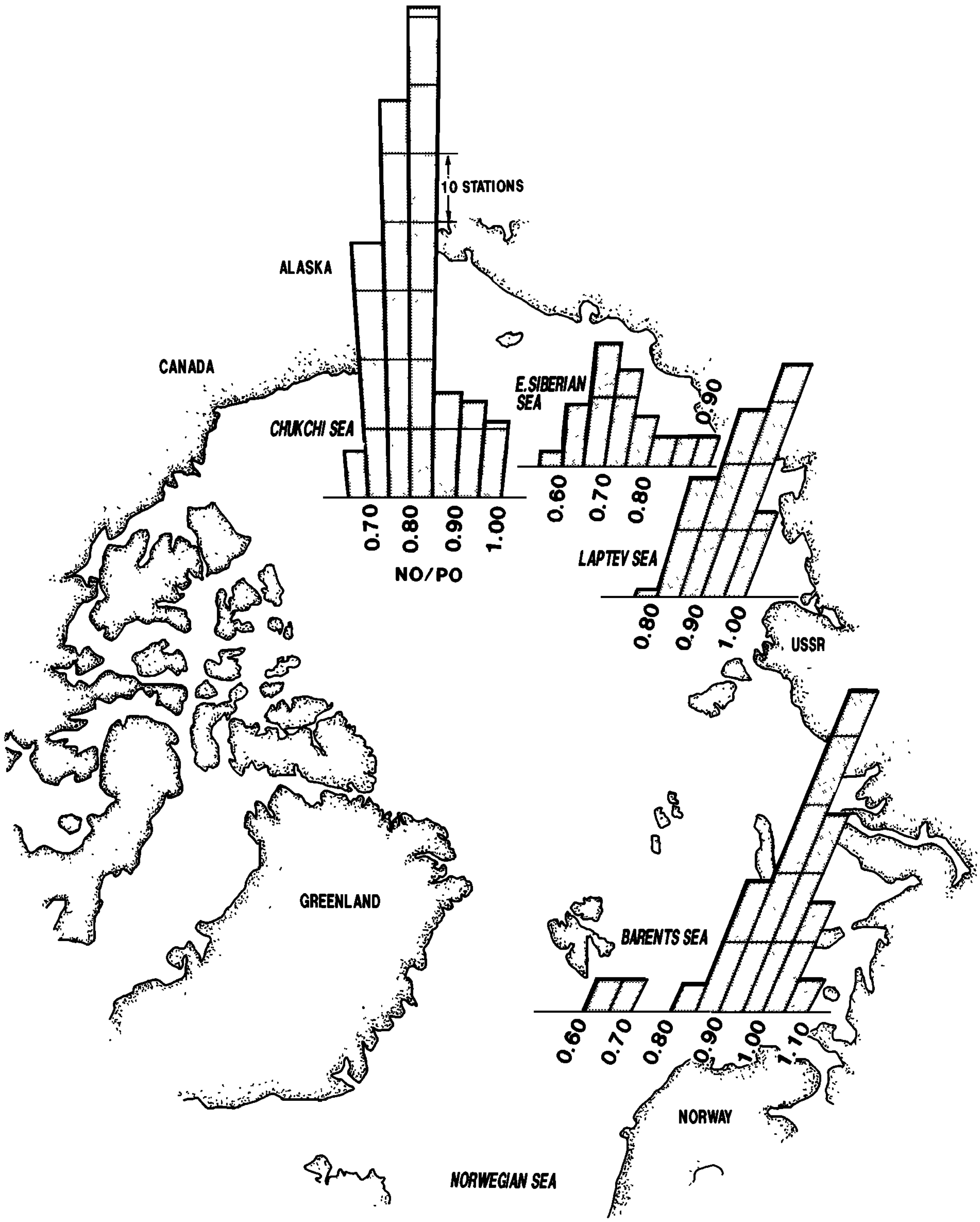

Fig. 4.(continued)

viewed as being composed of roughly half high NO/PO water (Atlantic-type) and half low NO/PO water (Arctic Shelf Water-type). The NO/PO ratio of LHW is lower than that observed in the Barents Sea (there are no available nutrient data for the Kara Sea), and is more consistent with ratios observed in the Laptev Sea. However the observed NO/PO ratio of LHW might have been decreased from its source ratio by diapycnal mixing within the Arctic interior. Summertime salinities in the Laptev Sea are generally <34.2, but ice formation almost certainly raises the shelf salinity in winter (but will not affect the NO/PO ratio). *Martin and Cavilieri* [1989] identify polynyas in the Laptev Sea as likely source regions for saline shelf waters. While the observed NO/PO ratio tends to support the speculation by *Kinney*

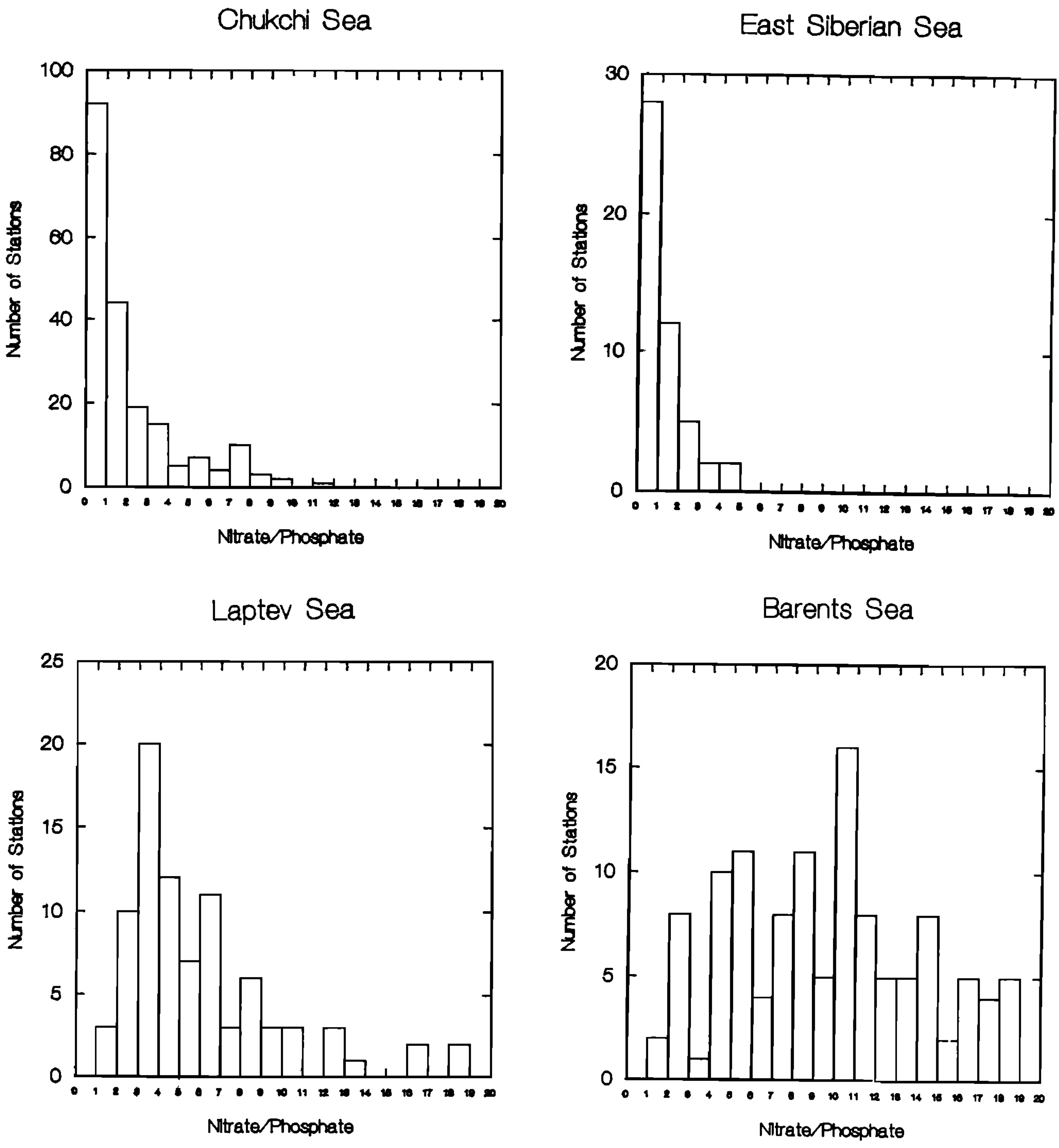

Fig. 5. Histogram showing the frequency distribution of the nutrient ratio NO_3/PO_4 for the Chukchi, East Siberian, Laptev, and Barents seas. All data were collected during the summer, except for data from the Barents Sea, half of which are winter data.

et al. [1970*a*] that LHW originates on the Siberian Shelves of the Eurasian Basin, we caution that definitive allocations of LHW origins should await a modern extensive survey of shelf and interior nutrient data.

Shelf Water Contribution to Canada Basin Deep Water

The shelf seas surrounding the Canada Basin have a low NO/PO ratio of ~0.78, whereas the major deep water sources (e.g., Greenland Sea Deep Water, Norwegian Sea Deep Water, and Eurasian Basin Deep and Bottom waters) have NO/PO ratios of ~1.0. For example, GEOSECS data taken in the Greenland Sea (69°-75°N, 0°-20°W) indicate that the NO/PO ratio in the deep water is between 1.00 and 1.02 [*Bainbridge,* 1976*a*]. Hence a mixture of Canada Basin shelf-derived water with parent deep water masses originating in the Greenland/Norwegian Seas (GNDW) should display a NO/PO ratio of less than 1. The NO/PO ratio of CBDW observed in the data from cruise 2171 is 0.99 and

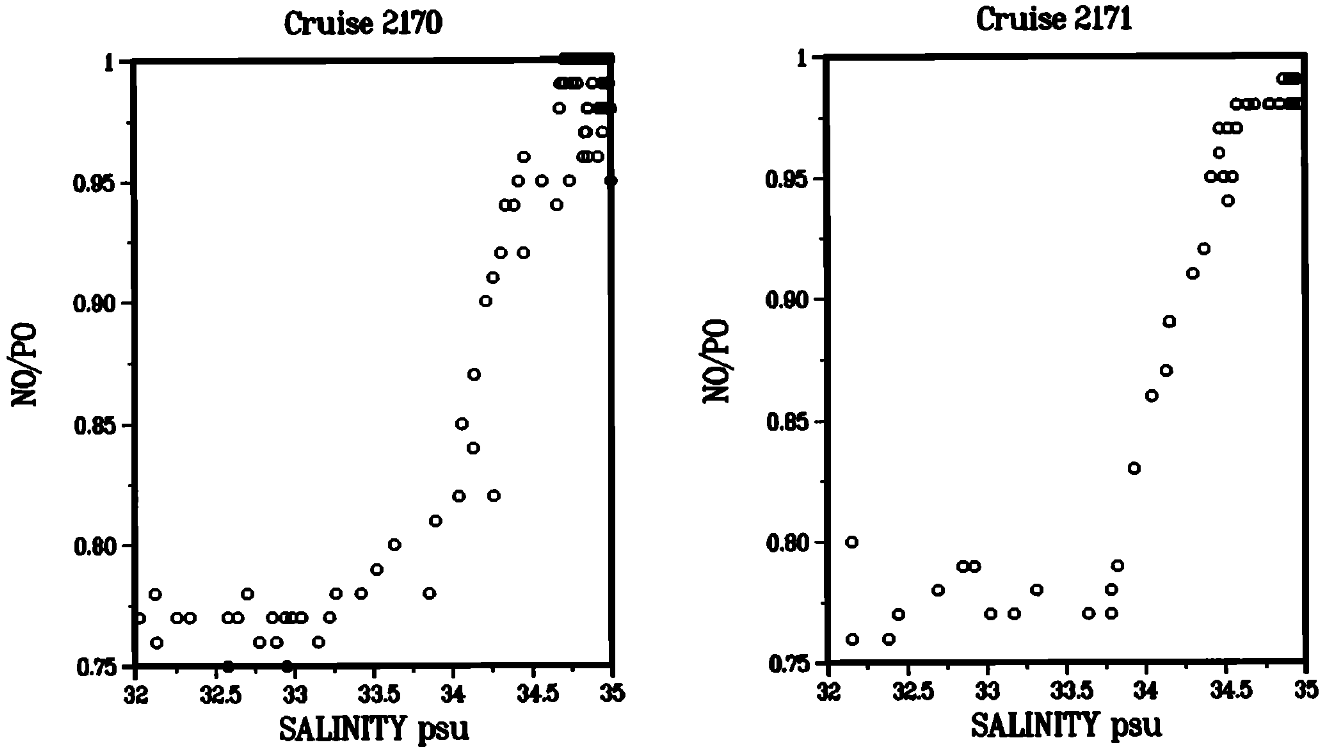

Fig. 6. Plots of NO/PO versus salinity for cruises 2170 and 2171. The S=33.1 and the S=34.2 end-members are marked.

recent high-quality data from AIWEX have an NO/PO ratio of 1.00 [*Anderson and Swift*, 1990].

Given these differences in NO/PO values between shelf and parent deep water masses, a mass balance of NO and PO can be attempted to estimate the amount of shelf water in CBDW. For the Atlantic derived or Greenland-Norwegian derived water an NO/PO ratio of 1.01 and NO and PO values of 450 and 446 μmol/L (NO_{GNDW} and PO_{GNDW}) were derived from GEOSECS data [*Bainbridge*, 1976*a*]. The NO distribution in the Canada Basin shelf waters (Chukchi and East Siberian seas) is variable, 94% of the observations lie in the range 300 to 500 μmol/L (Figure 5). Hence these values were taken as the range of shelf water NO (NO_{SW}) and using a NO/PO ratio of 0.80 yields 625-375 μmol/L for shelf water PO (PO_{SW}). The following equation was used, with X being the fraction of shelf water, and (1-X) the fraction of GNDW:

$$\frac{X*(NO_{SW})+(1-X)*(NO_{GNDW})}{X*(PO_{SW})+(1-X)*(PO_{GNDW})}=0.99 \qquad (5)$$

This yields a range of ~7-11% for the shelf water contribution.

Variability of the NO of the shelf water prohibits a more definitive calculation. The analytical significance of the 0.02 difference in NO/PO ratios between CBDW and other Arctic deep waters used in this calculation is, of course, questionable. Indeed the high-quality AIWEX CBDW data indicate an even smaller shelf water contribution. Collection of more nutrient and oxygen data of the highest possible quality from the deep Arctic Basins and the continental shelves will allow more precise limits to be placed on shelf contributions. Our estimate is consistent with the upper limit of 10-15% derived by *Ostlund et al.* [1987]. Hence the shelf-derived proportion of CBDW is much smaller than the initial estimate by *Aagaard et al.* [1985]. The strong possibility remains that the higher salinity of CBDW is a remnant of an earlier climate [*Ostlund et al.*, 1987].

A Lower Halocline Oxygen Maximum

Oxygen profiles for cruises 2170, 2171, stations 20, 53, 57, and 61 of 1973, 1377, 1571, 1678, and 5845 (stations 14-21) are shown in Figure 7. All the profiles indicate a subsurface oxygen maximum occurring below the oxygen minimum in the LHW except for data from cruise 2170. The oxygen concentration (and percent saturation, not shown) reaches a maximum slightly above 300 μmol/L and then decreases to about 290 μmol/L. The subsurface oxygen maximum occurs at ~S=34.5 (Figure 8), close to the salinity of the NO minimum (~S=34.4), which defines it as LHW. Cruises 1973 and 2171, the only cruises which show a subsurface oxygen maximum and had nutrient data, displayed slight nutrient minima at the same depth.

While the subsurface maximum represents only a small increase in dissolved oxygen, it is significant that it is observed from six separate cruises during 1958 and 1968-1971; hence this was, or is, a persistent feature in this region. To the best of our knowledge, this feature has not been previously described in the literature. The apparent absence of this feature at the CESAR station (86°N 111°W) in the Alpha Ridge area in 1983 [*Jones and Anderson*, 1986] could be the result of limited sampling in this depth range. No oxygen measurements were made at the LOREX (Lomonosov Ridge Expedition) ice camp at the North Pole [*Moore et al.*, 1983], but the phosphate data do not indicate any corresponding subsurface minimum.

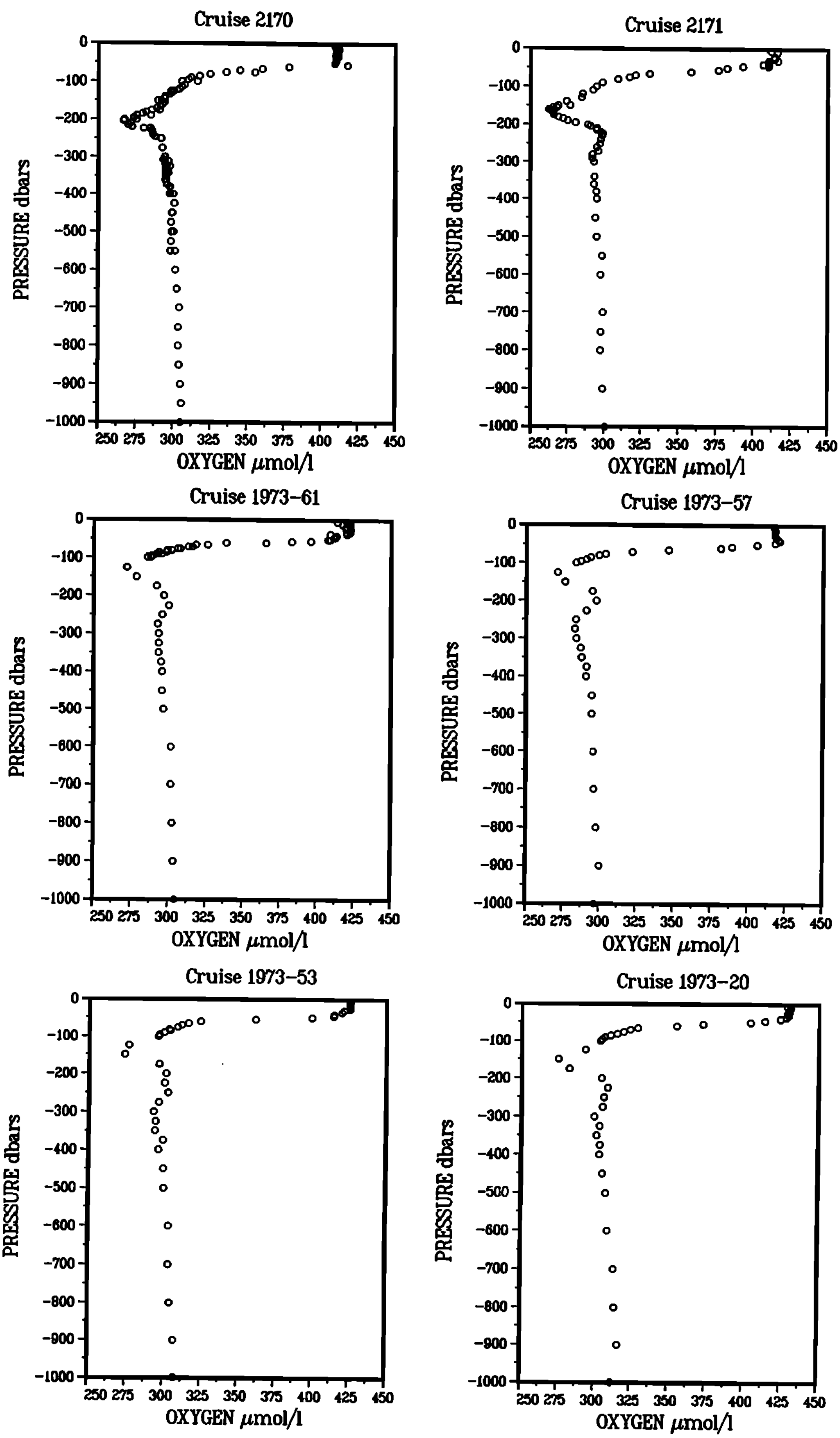

Fig. 7. Depth profiles of dissolved oxygen for cruises 2170, 2171, stations 20, 53, 57, and 61 of cruise 1973 and cruises 1377, 1571, 1678, and 5845, all taken on the T-3 ice-camp. Cruise 2170 are data from *Kinney* [1970], cruise 2171 are data collected by Arhelger and Kinney, cruises 1973 and 1678 are data collected by English, and cruise 5845 are data discussed by *Collin* [1959]. The subsurface maximum is visible in most profiles between 200 m and 230 m.

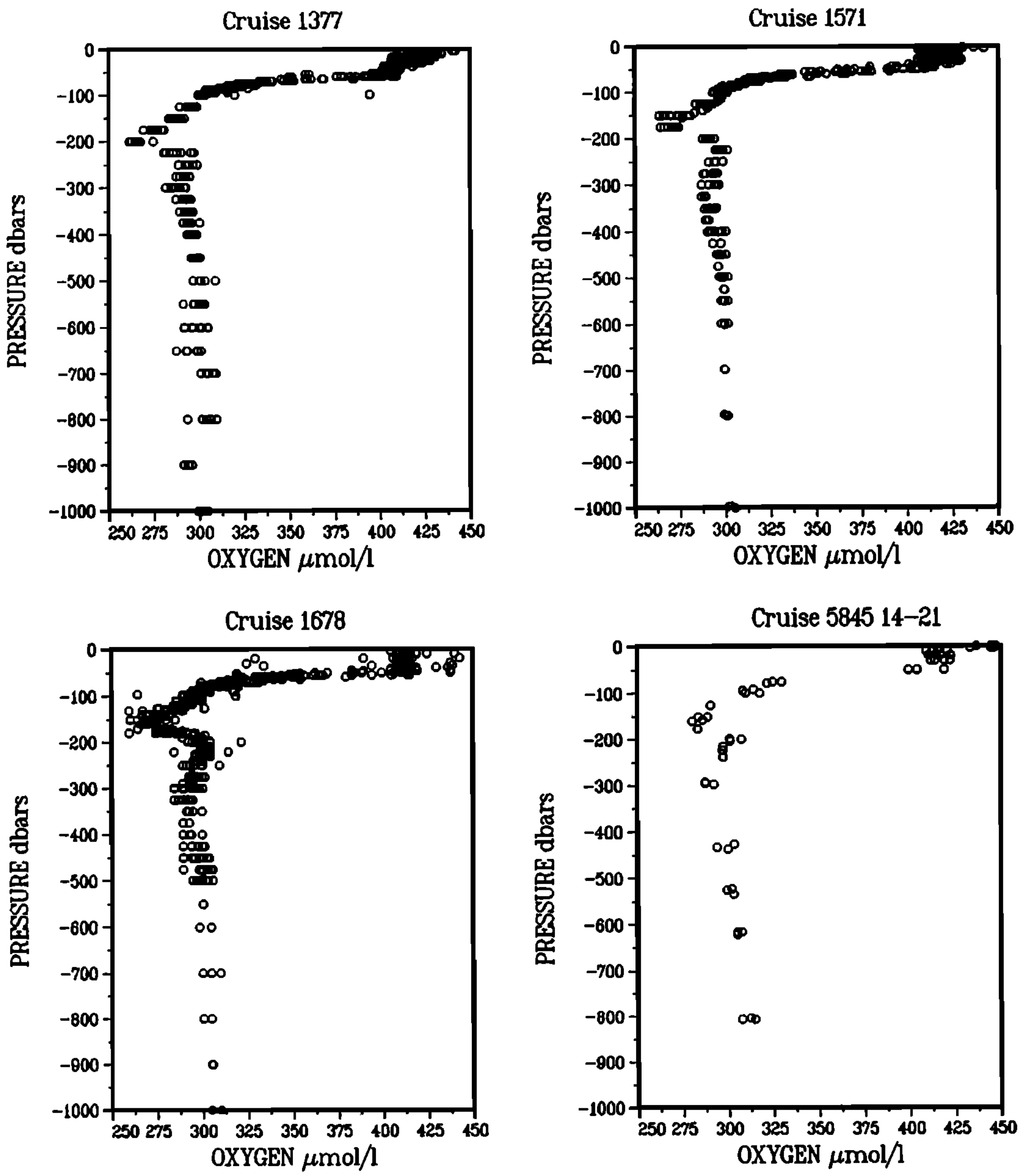

Fig. 7. (continued)

The oxygen maximum and the NO minimum, at ~S=34.5 and ~S=34.4, respectively, are indicators of the LHW. However, note that the cores of the NO minimum and oxygen maximum lie slightly beneath the S=34.2 end-member identified by *Jones and Anderson* [1986] as the LHW on the basis of a change of slope of the T-S relation. According to the basin-wide water-mass classifications of *Carmack et al.* [1989], S=34.4 is a boundary between Polar Intermediate Water and Arctic Intermediate Water.

The strength of the signal decreases at stations further west along the Alpha Ridge and into the Canada Basin. The profile with the strongest signal, station 57 of cruise 1973, is the furthest east on the Alpha Ridge, at 85°N 84°W. The maximum becomes less pronounced at stations 61, 53, and 20. Cruise 2170, which is the furthest west and in the Canada Basin rather than above the Alpha Ridge, does not show this signal at all. Data from the Beaufort Sea do not indicate this feature as evidenced by AIWEX data, at 74°N 144°W [*Anderson and Swift,* 1990] and data collected at the T-3 ice-camp in 1959-1960 at 72°N 130°-163°W [*Kusunoki et al.,* 1962].

The geographical variability of the oxygen maximum might prove to be a tool for tracing the spreading of the LHW in the Canada Basin. The oxygen maximum is presumably diminished as a result of oxygen consumption and/or mixing. These two processes would have differing effects on the NO minimum: diapycnal mixing will tend to increase the NO at the minimum, whereas oxygen consumption should have no effect on NO. Oxygen consumption rates in the Arctic Ocean [*Wallace et al., 1987*] are sufficient to remove 10 μmol/L of oxygen in ~1 year. However, for the oxygen maximum to be eradicated by consumption within the Arctic basin requires the unlikely scenario of preferential oxygen consumption in the oxygen maximum layer com-

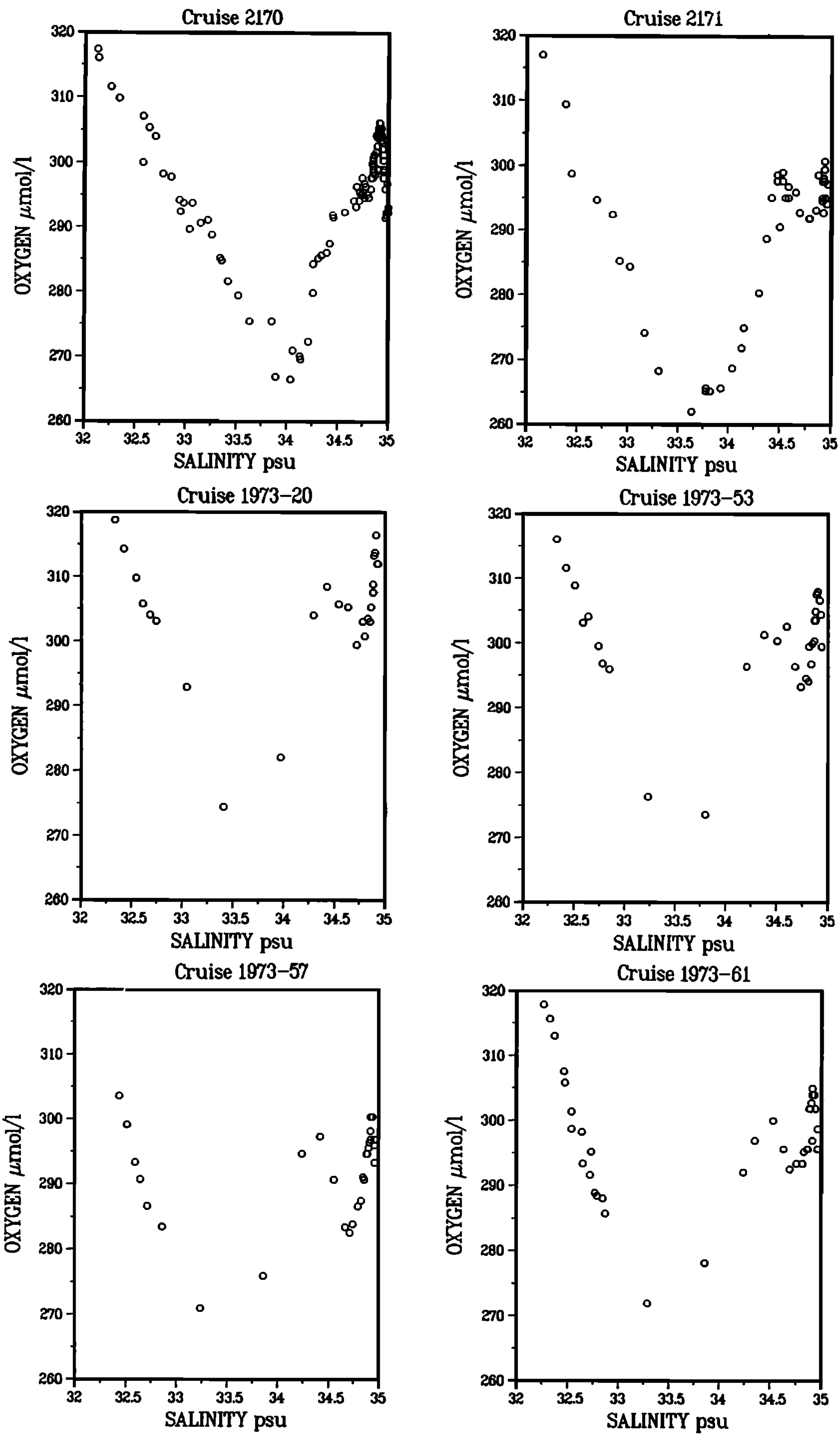

Fig. 8. Plots of dissolved oxygen versus salinity for cruises 2170, 2171, stations 20, 53, 57, and 61 of cruise 1973, and cruises 1377, 1571, 1678 and 5845, all taken on the T-3 ice-camp. Cruise 2170 are data from *Kinney* [1970], cruise 2171 are data collected by Arhelger and Kinney, cruises 1973 and 1678 are data collected by English, and cruise 5845 are data discussed by *Collin* [1959]. The subsurface maximum occurs between S=34.4 and S=34.5.

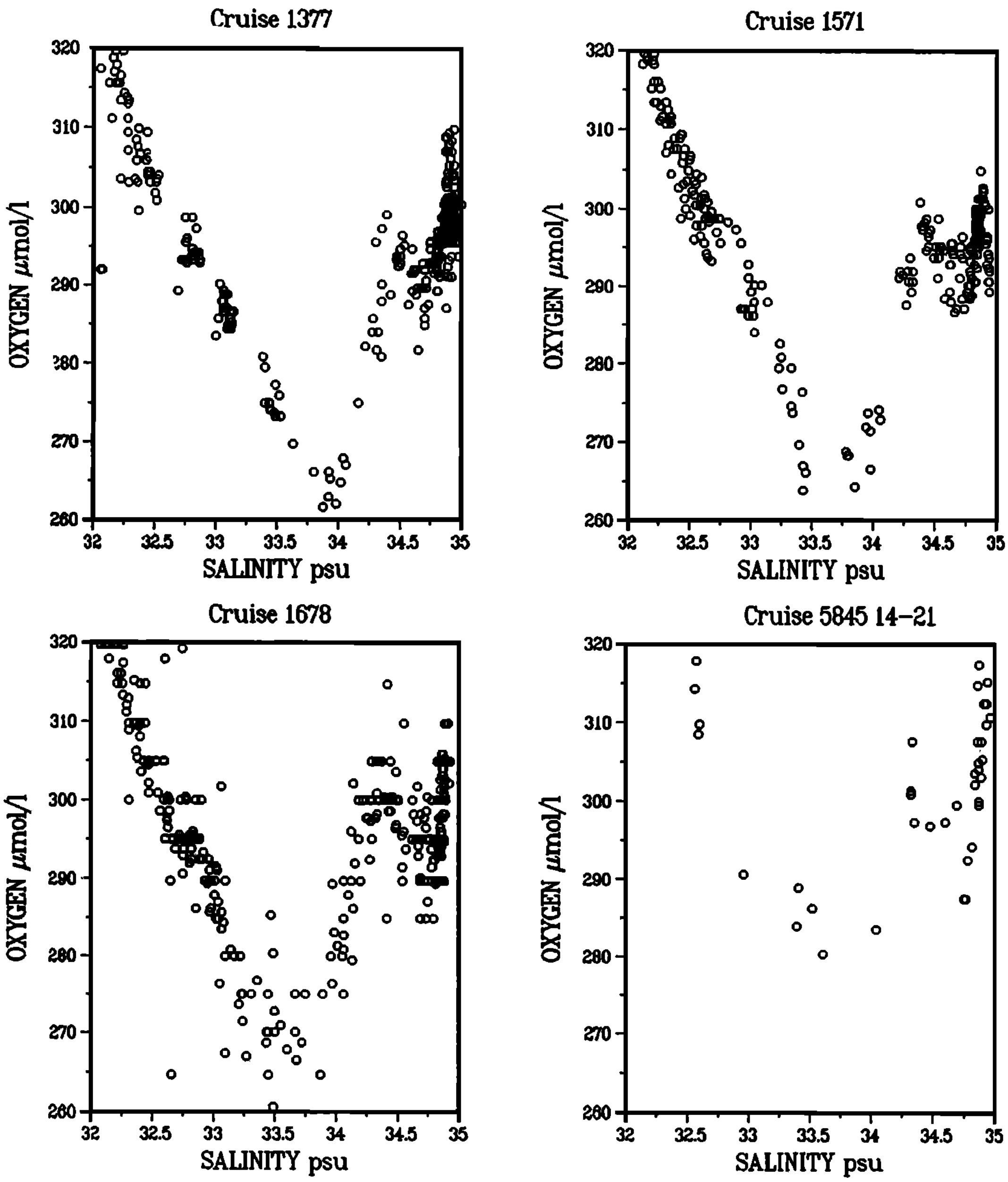

Fig. 8. (continued)

pared to the layers immediately above and below. The NO minimum for cruise 2170, which has no oxygen maximum, is broader with higher NO values (by 6 μmol/L) than the NO minimum at cruise 2171 (which has the oxygen maximum) suggesting strongly that mixing, probably diapycnal, is the dominant cause for the demise of the oxygen maximum across the Canada Basin. The distribution of the oxygen maximum is consistent with a source of LHW in the Eurasian section of the Arctic Ocean. Future surveys should collect detailed oxygen and nutrient data in the vicinity of S=34.4 in order that the spatial variability of the oxygen maximum and NO minimum can be resolved.

Summary

1. The conservative parameters NO and PO are not identical within the Arctic Ocean, and their ratio can be used to distinguish two separate water mass families. Comparison with NO/PO ratios for the North Pacific and Greenland/Norwegian Sea surface waters supports the designation of a Pacific- sector, low NO/PO water, and an Atlantic-sector, high NO/PO water. The NO/PO ratio in the Pacific sector seas is lower than that in North Pacific surface waters, which is possibly indicative of denitrification in Arctic shelf regions. The NO/PO ratio can be used to distinguish the Surface Layer and UHW from the LHW and deeper waters of the Arctic Ocean.

2. It is not possible to clearly determine the source of the LHW by tracing its low NO value only. The shelf seas surrounding the Arctic Ocean have widely ranging distributions of NO, most of which are centered around the "low" NO value characteristic of the LHW.

3. The shelf seas surrounding the Arctic Ocean have relatively distinct NO/PO ratios. The NO/PO ratios support

the Chukchi Sea as a source for the UHW. The intermediate NO/PO value of the LHW is consistent with a source in the Laptev Sea region but might have been altered by diapycnal mixing during transit. A high quality data set from the various shelf seas and more detailed within-basin surveys are required to refine source assignments.

4. Using the NO/PO ratios observed in the shelf water of the Canada Basin and in the Canada Basin Deep Water, we have calculated an upper limit of ~11% for the amount of shelf-derived water mixed into the CBDW.

5. A previously unreported, albeit subtle, oxygen maximum has been observed above the Alpha Ridge. There is a subsurface oxygen maximum, and a nutrient minimum, in the LHW at ~S=34.5. This oxygen maximum is evident over the Alpha Ridge but apparently absent in other parts of the Canada Basin (e.g., the Beaufort gyre). A picture of the spreading of LHW could be provided by detailed mapping of this non-conservative oxygen signal (and the associated conservative NO signal) on the S=34.5 surface during future expeditions to the Arctic Ocean.

Acknowledgments. We thank L.G. Anderson, E.C. Carmack, L.A. Codispoti, C.N. Flagg, E.P. Jones, and R.M. Moore for their comments and criticisms on earlier drafts. One of us (C.W.) gratefully acknowledges support from the Department of Energy's Division of University and Industry Programs, Office of Energy Research, as a Science and Engineering Research Semester Program participant. This research was performed under the auspices of the United States Department of Energy under contract DE-ACO2-76CH00016.

References

Aagaard, K., On the deep circulation in the Arctic Ocean, *Deep Sea Res.*, *28*, 251-268, 1981.

Aagaard, K., J. H. Swift, and E. Carmack, Thermohaline circulation in the Arctic Mediterranean Seas, *J. Geophys. Res.*, *90*, 4833-4846, 1985.

Anderson, G. C. and J. H. Swift, Arctic Internal Waves Experiment (AIWEX) hydrographic data. *SIO Ref. 90-10*, 29 pp. Scripps Inst. of Oceanogr., La Jolla, Calif., 1990.

Anderson, L. G. and E. P. Jones, Water masses and their chemical constituents in the western Nansen Basin of the Arctic Ocean. *Oceanol. Acta.*, *9*, 277-283, 1986.

Anderson, L. G., E. P. Jones, K. P. Koltermann, P. Schlosser, J. H. Swift, and D. W. R. Wallace, The first oceanographic section across the Nansen Basin in the Arctic Ocean, *Deep Sea Res.*, *36*, 475-482, 1989.

Bainbridge, A. E., GEOSECS Atlantic Final Hydrographic data report, GEOSECS Operations Group, Scripps Inst. of Oceanogr., La Jolla, Calif., 1976*a*.

Bainbridge, A. E., GEOSECS Pacific Final Hydrographic data report, GEOSECS Operations Group, Scripps Inst. of Oceanogr., La Jolla, Calif., 1976*b*.

Birch, J.R., et al., *Arctic Data Compilation and Appraisal*, vol.7, *Can. Data Rep. Hydrogr. Ocean Sci.* 5, Inst. of Ocean Sci., Sidney, B.C., 1984.

Broecker, W.S., "NO", A conservative water-mass tracer, *Earth Planet. Sci. Lett.*, *23*, 100-107, 1974.

Carmack, E. C., R. W. MacDonald, and J. E. Papadakis, Water mass structure and boundaries in the Mackenzie shelf estuary, *J.Geophys. Res.*, *94*, 18,043-18,055, 1989.

Chen, C. T., Preliminary observations of oxygen and carbon dioxide of the wintertime Bering Sea marginal ice zone, *Continental Shelf Res.*, *4*, 465-484, 1985.

Coachman, L. K., and K. Aagaard, Physical oceanography of Arctic and Subarctic seas, in *Marine Geology and Oceanography of the Arctic Sea*, edited by Y. Herman. Springer Verlag, New York, 1974.

Coachman, L. K., and C. A. Barnes, The contribution of Bering Sea water to the Arctic Ocean, *Arctic*, *14*, 147-161, 1961.

Codispoti, L. A., and F. A. Richards, Micronutrient distributions in the East Siberian and Laptev seas during the summer 1963, *Arctic*, *21*, 67-83, 1968.

Codispoti, L. A., and F. A. Richards, Oxygen supersaturations in the Chukchi and East Siberian Sea, *Deep Sea Res.*, *18*, 341-351, 1971.

Collin, A. E., Canada oceanographic activities on IGY Drift Station "Bravo", *Fish. Res. Board Can. Man. Rep. Ser. (O&L)*, *40*, 34 pp., 1959.

Haines, J. R., R. M. Atlas, R. P. Griffiths, and R.Y. Morita, Denitrification and nitrogen fixation in Alaskan continental shelf sediments, *Appl. Environ. Microbiol.*, *41*, 3412-3421, 1981.

Hufford, G. L., S. H. Fortier, D. E. Wolfe, J. G. Doster, and D. L. Noble, Physical oceanography of the western Beaufort Sea, Websec 71-72, An ecological survey in the Beaufort Sea, *USCG Oceanogr. Rep.*, *373-64*, 1974.

Jones, E. P., and L. G. Anderson, On the origin of the chemical properties of the Arctic Ocean halocline, *J. Geophys. Res.*, *91*, 10,759-10,767, 1986.

Jones, E. P. and L. G. Anderson (1990) On the origin of the properties of the Arctic Ocean Halocline north of Ellesmere Island: Results from the Canadian Ice Island. *Cont. Shelf Res.*, *10*, 485-498, 1990.

Kinney, P., M. E. Arhelger, and D. C. Burrell, Chemical characteristics of water masses in the Amerasian Basin of the Arctic Ocean, *J. Geophys Res.*, *75*, 4097-4104, 1970*a*.

Kinney, P., D. C. Burrell, J. J. Kelley, and D. W. Hood, Chemical characteristics of Arctic water masses, *Rep. R-69-15*, Inst. of Mar. Sci., Univ. of Alaska, College, Alaska, 1970*b*.

Koiki, I., and A. Hattori, Estimates of dentrification in sediments of the Bering Sea shelf, *Deep Sea Res.*, *26*, 409-415, 1979.

Kusunoki, K., J. Muguruma, and K. Higuchi, Oceanographic observations at Fletcher's Ice Island (T-3) in the Arctic Ocean in 1959-1960, *Res. Pap. 22*, Arctic Inst. of North America, New York, 1962.

Martin, S., and D. J. Cavalieri, Contribution of the Siberian Sea polynyas to the Arctic Ocean Intermediate and Deep Water, *J. Geophys. Res.*, *94*, 12,725- 12,738, 1989.

Moore, R. M., M. G. Lowings, and F. C. Tan, Geochemical profiles in the Central Arctic Ocean: Their relation to freezing and shallow circulation, *J.Geophys. Res.*, *88*, 2667-2674, 1983.

Morison, J., and J. D. Smith, Seasonal variations in the upper Arctic Ocean as observed at T-3, *Geophys. Res. Lett.*, *8*, 753-756, 1981.

Ostlund, H. G., G. Possnert, and J. H. Swift, Ventilation rate of the deep Arctic Ocean from carbon 14 data, *J. Geophys. Res.*, *92*, 3769-3777, 1987.

Redfield, A. C., B. H. Ketchum, and F. A. Richards, The influence of organisms on the composition of seawater, in *The Sea*, vol. 2, edited by M. N. Hill, pp. 26-77, Interscience, New York, 1963.

Smith, J. D., and T. S. English, Seasonal variations of density and depth of the mixed layer in the Arctic Ocean, *Eos Trans. AGU*, *55*(2), 1973.

U.S. Coast Guard, Oceanographic cruise USCGC *Northwind*, Chukchi, East Siberian and Laptev seas, *USCG Oceanogr. Rep., no. 6, CG 373-6*, 69 pp, 1965.

Wallace, D. W. R., and R. M. Moore, Vertical profiles of CCl_3F(F-11) and CCl_2F_2(F-12) in the central Arctic Ocean Basin, *J. Geophys. Res.*, *90*, 1155-1166, 1985.

Wallace, D. W. R., R. M. Moore, and E. P. Jones, Ventilation of the Arctic Ocean cold halocline: rates of diapycnal and isopycnal transport, oxygen utilization and primary production inferred using chlorofluoromethane distributions, *Deep Sea Res.*, *34*, 1957-1979, 1987.

D. W. R. Wallace and C. Wilson, Oceanographic and Atmospheric Sciences Division, Department of Applied Science, Brookhaven National Laboratory, Upton, NY 11973.

(Recieved May 1, 1990;
accepted July 17, 1990.)