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RECENT CHANGES IN ARCTIC OCEAN THERMOHALINE STRUCTURE: RESULTS FROM THE CANADA/U.S. 1994 ARCTIC OCEAN SECTION

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Abstract: A comparison of historical oceanographic data from the Arctic Ocean with that obtained aboard the CCGS Louis s. St. Laurent during the Canada/U.S. 1994 Arctic Ocean Section unequivocally shows that the mid-depth layers of the Arctic Ocean are experiencing a major warming and ventilation event. The intrusion of new water is characterized by (a) higher values in the Atlantic Layer maximum temperatures, (b) a shallower core depth for the temperature maximum, (c) displacement of waters of Pacific origin in the upper 100–200 m, and (d) pronounced thermohaline inversions 40–60 m thick in the Atlantic Layer and Upper Deep waters. The largest temperature change, as much as 1°C, is seen in the core of the Atlantic Layer, suggesting that the event is related to an increase in the transport and/or temperature of water entering from the North Atlantic.

1. Introduction

The Arctic Ocean (Fig. 1) is an enclosed sea that exchanges water mostly with the Atlantic Ocean (Norwegian-Greenland Seas) through Fram Strait and the Barents Sea, with some inflow from the Pacific Ocean (Bering Sea) through Bering Strait and outflow through the Canadian Archipelago. The waters of the Arctic Ocean can be roughly subdivided into three layers: a surface layer, the Atlantic Layer, and deep water (*e.g.*, Aagaard *et al.*, 1985; Carmack, 1990; Jones *et al.*, 1990). The near-freezing surface layer (above about 50 m) and the halocline separating the surface layer from the Atlantic Layer contain water from both the Pacific and Atlantic Oceans mixed to varying degrees with river runoff and sea ice meltwater. Under the halocline is a warmer Atlantic Layer. The deeper waters, below the Atlantic Layer, are comparatively uniform, with small but significant gradients of salinity, temperature, and other properties.

Prior to 1985, almost all of the data for the Arctic Ocean available to western scientists came from a few scattered ice camps and from cruises to marginal seas. The Arctic Ocean was generally pictured as a fairly horizontally uniform, not especially dynamic body of water. With results from recent icebreaker expeditions of F. S. Polarstern

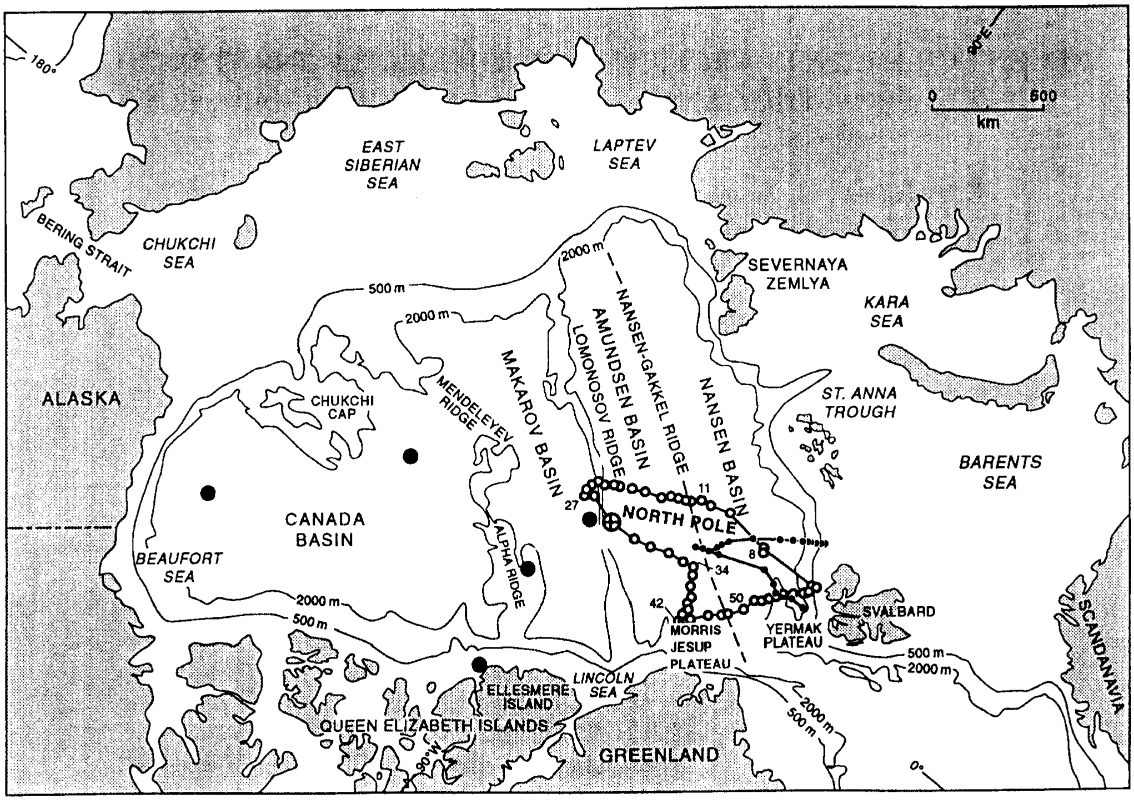

Fig. 1. The Arctic Ocean showing its geography and locations of some expeditions. The Arctic Ocean is divided into two large basins by the Lomonosov Ridge, the Canadian Basin and the Eurasian Basin. In turn, the Canadian Basin is divided by the Alpha and Mendeleyev Ridges into the Canada and Makarov Basins, and the Eurasian Basin is divided by the Nansen-Gakkel Ridge (sometimes called the Arctic Mid Ocean Ridge) into the Nansen and Amundsen Basins. Large filled circles represent ice camp locations. Small filled circles are the stations occupied during the 1987 POLARSTERN Expedition. Open circles are the stations occupied during the 1991 ODEN Expedition.

(ANDERSON *et al.*, 1989) and I. B. ODEN (ANDERSON *et al.*, 1994) (Fig. 1), a picture of a much more structured Arctic Ocean emerged. These results, together with gridded data from Russian surveys (GORSHKOV, 1983), provide a setting in which to discuss changes that are occurring in the Arctic Ocean.

2. Discussion

The most complete picture to date of circulation patterns within Arctic Ocean was drawn from the 1991 ODEN Expedition even though the expedition was largely confined to the Eurasian Basin (comprised of the Nansen and Amundsen Basins), with just a few stations in the Makarov Basin at the edge of the Canadian Basin (comprised of the Canada and Makarov Basins). Tracer concentrations, particularly of silicate and chlorofluorocarbons (CFCs), were key to providing insight into circulation. Silicate brought into the Arctic Ocean from the Pacific helps to label water masses and highlight processes in the Canadian Basin. CFCs are transient tracers introduced into the ocean from the atmosphere. Their increasing concentrations in the atmosphere provide a time scale that can give the relative residence times or "ages" of water masses at different locations and

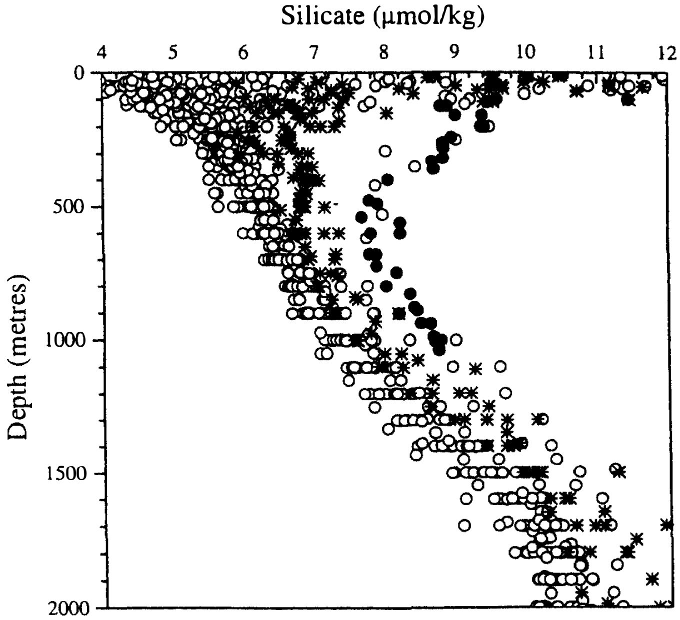

Fig. 2. Composite silicate profiles for 0–2000 m from the 1991 Oden *Expedition stations. The asterisks represent stations 24 to 28 in the Makarov Basin, and 39 and 41–46 near the Morris Jesup Plateau. The filled circles represent stations 40 and 43 near the Morris Jesup Plateau. The open circles represent all of the remaining stations in the Eurasian Basin.*

depths.

Profiles of silicate concentrations for all of the stations of the 1991 Oden Expedition fell into three groups with subtle but distinctly different concentrations (Fig. 2). For intermediate depth waters to a depth of about 1700 m, most stations had slightly lower concentrations characteristic of the Eurasian Basin. Intermediate concentrations were found in the Makarov Basin (Stations 24–28) and near the Morris Jesup Plateau (Stations 39, 41, 44–46). Highest concentrations were found also near the Morris Jesup Plateau at the two most southerly stations (Stations 40, 43). The transient tracer, carbon tetrachloride, was introduced into the atmosphere and hence into the surface ocean soon after the turn of the century, and its concentration in both the atmosphere and surface ocean has been increasing monotonically until very recent times. Its concentration in a water mass is hence a measure of the "age" or exchange time of a water mass. Carbon tetrachloride distributions near the Morris Jesup Plateau (Fig. 3) showed similar distinctions as the silicate distributions, with the highest values ("youngest" water) corresponding to the low silicate concentrations of the Eurasian Basin, intermediate values corresponding to those found in the Makarov Basin, and lowest values ("oldest" water) corresponding to the highest silicate values. The highest silicate concentrations were presumed to be in water that originated nearer to the source of high silicate, and the lowest CFC values would correspond to water farthest from the Morris Jesup Plateau, *i.e.*, the Canada Basin. The distinctions in water masses flowing out of the Canadian Basin together with salinity, temperature and tracer distributions throughout the Eurasian Basin led to the

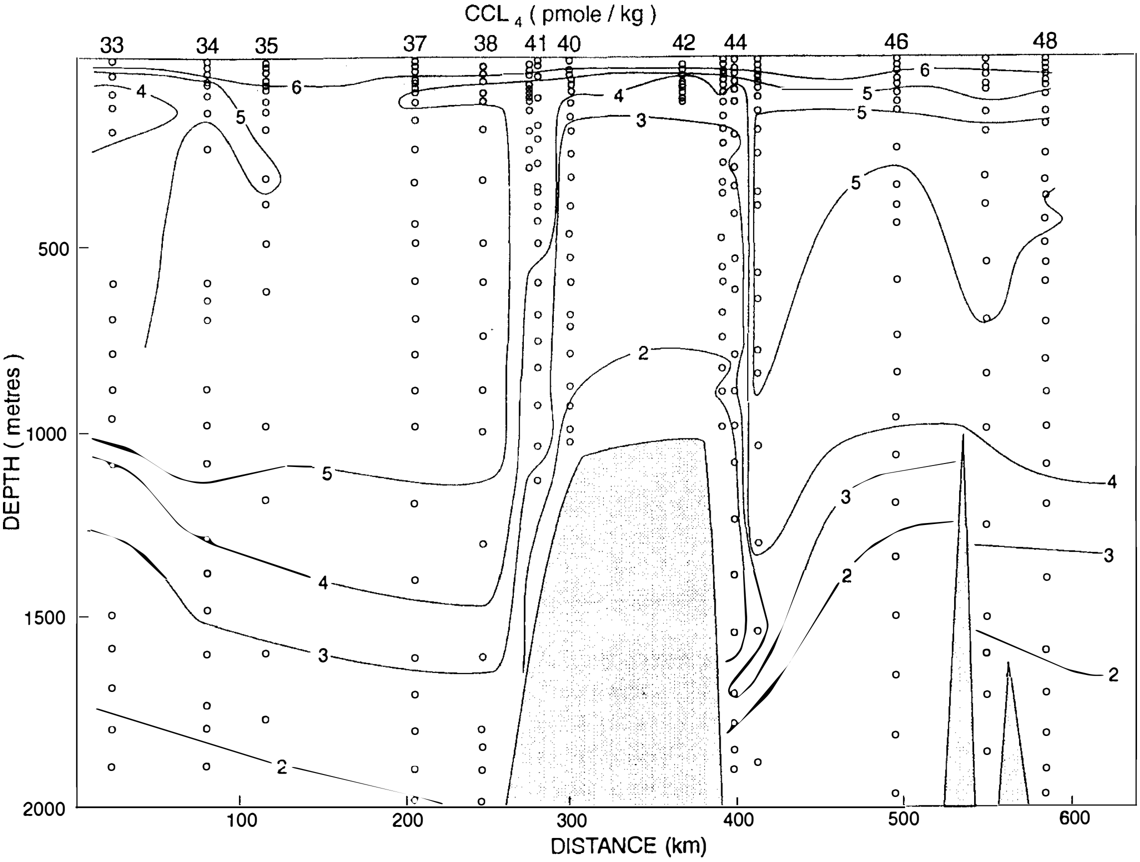

Fig. 3. *The carbon tetrachloride distribution (typical of all CFCs) near the Morris Jesup Plateau. Note that this is a "corner" section near station 42 (Fig. 1), with stations 42 to 46 to a large degree mirroring stations 37 to 40.*

circulation scheme for intermediate depth waters shown in Fig. 4a (RUDELS *et al.*, 1994).

The clue to the mechanism for the formation of the deep waters, below 2000 m, also came in large part from tracer distributions. Data from ice camps and the 1991 ODEN Expedition show that the highest silicate concentrations in the Canadian Basin are in the Canada Basin, with intermediate concentrations in the Makarov Basin and lowest values in the Eurasian Basin. It was hypothesized that slope plumes could cause the observed distributions. Dense water produced by brine released during ice formation on the large continental shelves could trigger slope plumes that carry some of the high silicate surface water to all depths. Such a mechanism would also "ventilate" deeper waters, with the rate of ventilation being reflected by CFC concentrations. These considerations led to the proposal of the formation and circulation of deep waters shown in Fig. 4b (JONES *et al.*, 1995).

The Arctic Ocean is not in a steady-state, and significant variability occurs over decadal time periods. The first suggestion that such variability may occur arose from observations made in the Eurasian Basin (QUADFASEL *et al.*, 1993). Further observations of variability became apparent during the LARSEN-93 Expedition. Near the Mendeleyev Ridge in the southern Canada Basin, a front was observed that separated the warmer Atlantic Layer waters generally found in the Eurasian Basin from the colder Atlantic

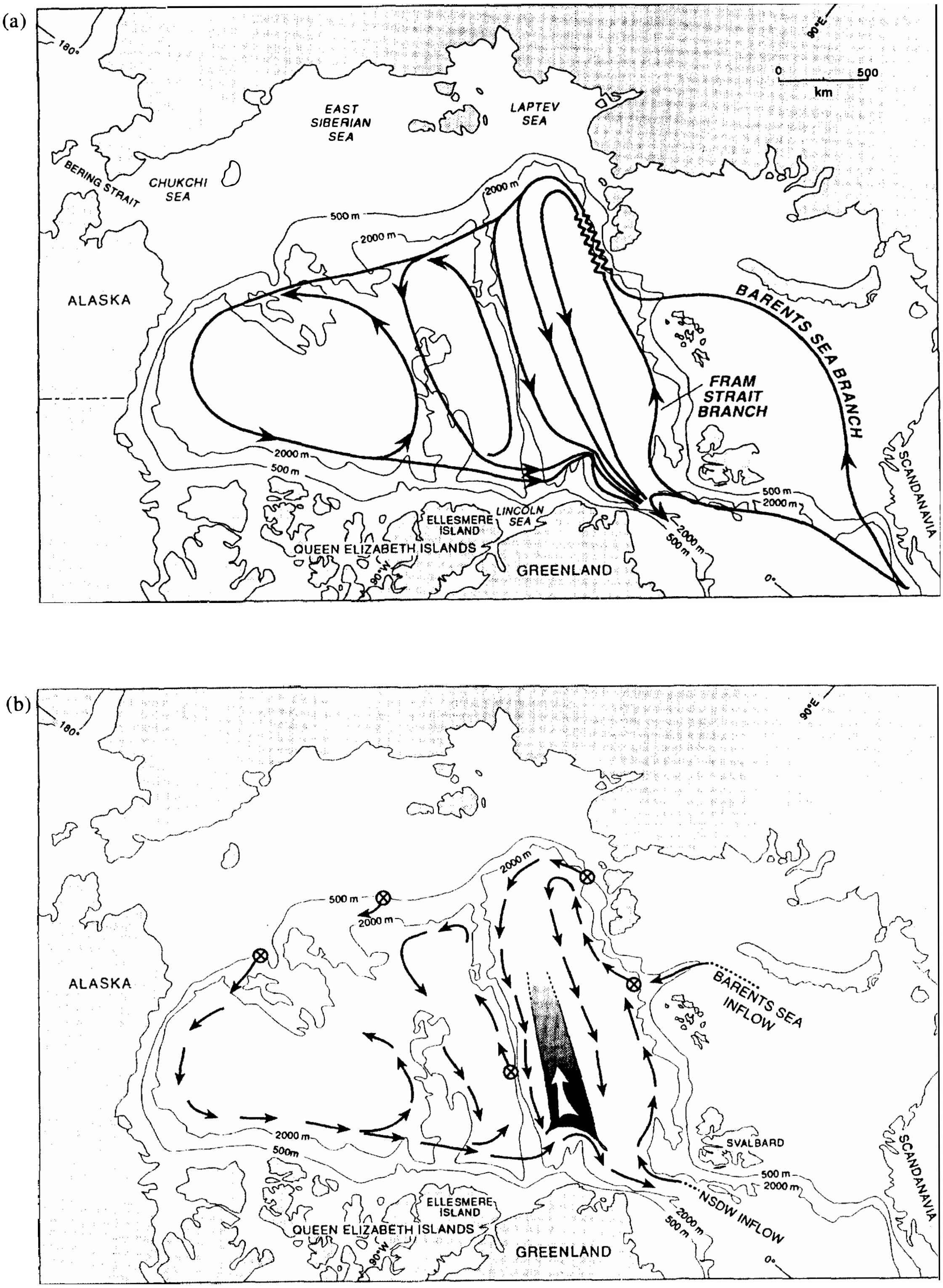

Fig. 4. (a) The circulation of intermediate depth waters, between 200 and 1700 m. (b) A circulation scheme consistent with the water mass characteristics observed from all data collected at stations shown in Fig. 1. The symbol of a cross within a circle represents the suggested source regions for plumes that reach the deep water. The shaded area represents the penetration of Canadian Basin water into the Amundsen Basin without specifically designating a flow pattern.

Layer water in the Canadian Basin (Carmack *et al.*, 1995; McLaughlin *et al.*, 1996). Other tracers as well as temperature (*e.g.*, silicate) showed changes in waters above the Atlantic Layer. These observations contrasted sharply with historical Russian data (Gorshkov, 1983) and with what was observed in more central regions during the 1991 Oden Expedition that showed the front between the warmer and colder Atlantic Layer water to be near the Lomonosov Ridge between the Eurasian and Canadian basins.

In 1994, the Canada/US Arctic Ocean Section Expedition traversed the Arctic Ocean from the Pacific to the Atlantic (Fig. 5). The 1994 Arctic Ocean Section Expedition showed that the penetration of warmer Atlantic Layer water had occurred over a considerably larger area than was apparent in the from the Larsen-93 Expedition. This expedition provided major new insight into the character of the Arctic Ocean. The 1987 Polarstern and 1991 Oden expeditions showed that the Arctic Ocean is not horizontally homogeneous, that there are major distinctions among the water masses of the different basins. The Canada/US Arctic Ocean Section Expedition showed clearly that significant variability over large regions occurs over decadal time periods. A section plot of temperature obtained during this expedition shows the extent of the warmer Atlantic Layer (Fig. 6). The warmer Atlantic Layer water extends essentially along the whole cruise track across the Canadian Basin (Fig. 6a). Historic and ice camp data show the

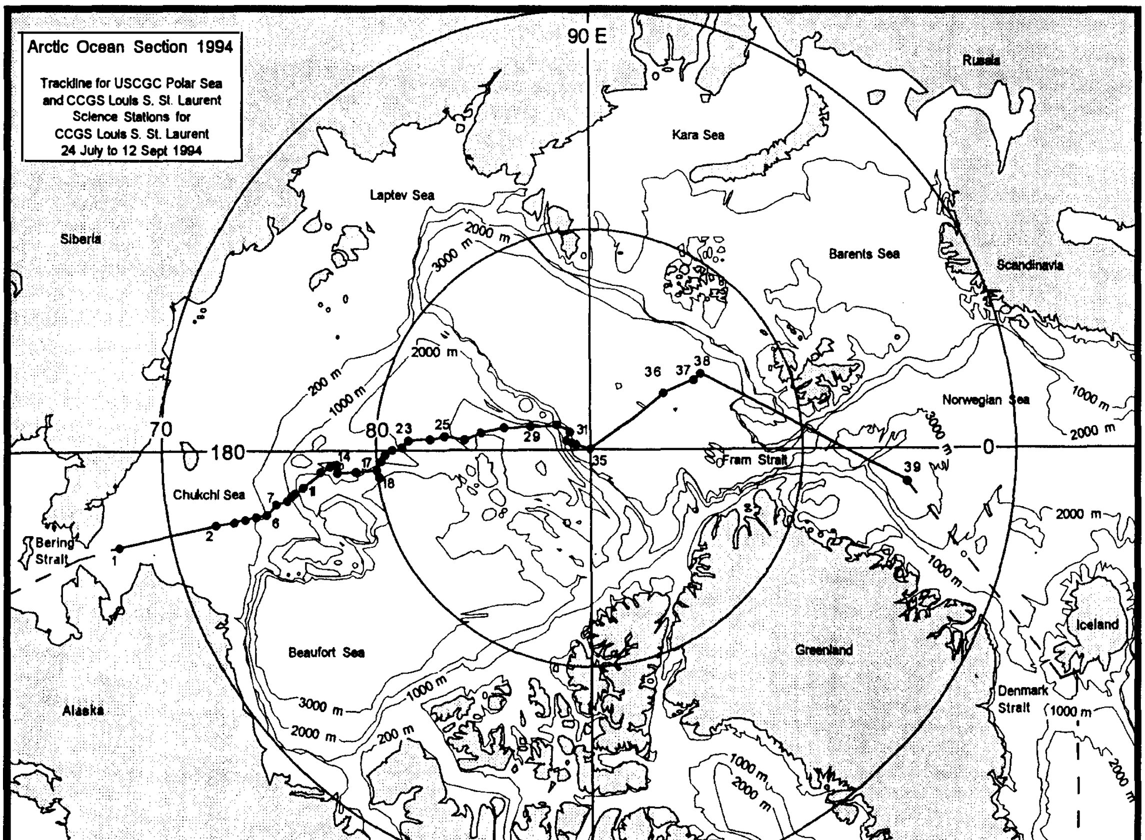

Fig. 5. The station track of the 1994 Arctic Ocean Section Expedition.

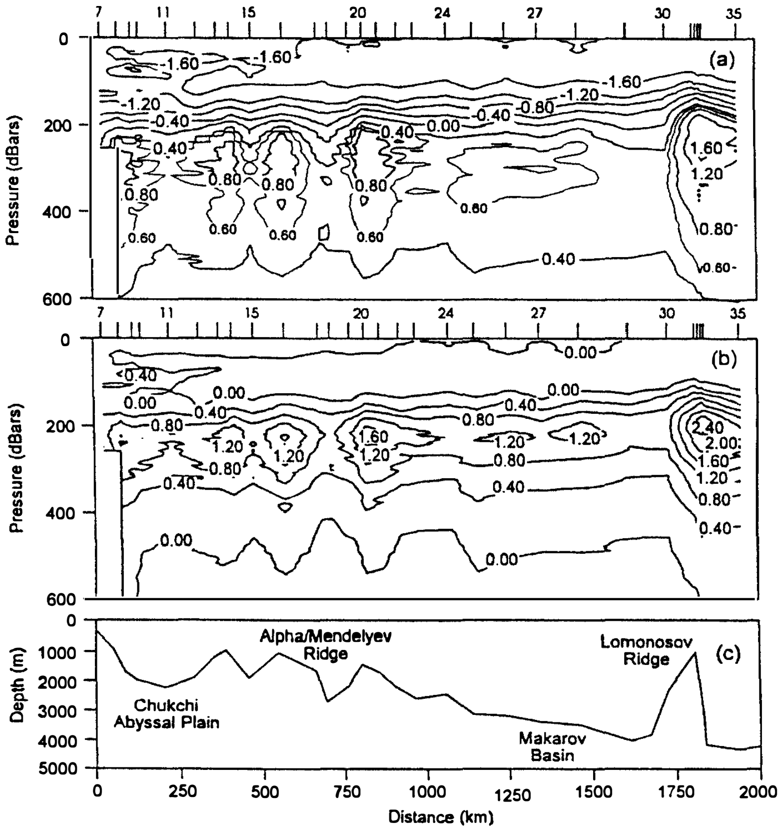

Fig. 6. Sections across the Canadian Basin. (a) Temperature (Θ). (b) Temperature "anomaly", the difference between temperatures in (a) and the historical data set. (c) Bathymetry along the section.

maximum temperature in the Canadian Basin to be near 0.5°C and to occur at a depth between about 400 and 500 m. Only at a few stations near the center of the Makarov Basin does the core temperature of the Atlantic Layer come close to values previously found in the Canadian Basin. The nature of the change that has occurred is highlighted in a plot of the difference between the temperatures observed in 1994 and the historic data reported earlier (Gorshkov, 1983) (Fig. 6b). Not only has the maximum temperature of the Atlantic layer increased by more than 0.3°C, but also the depth at which the maximum temperature occurred has decreased by more than 100 m.

A second illustration of decadal variability in the Arctic Ocean is shown by changes in silicate concentrations in the halocline. Russian data (Gorshkov, 1983) and data from ice camps (*e.g.*, Jones *et al.*, 1990) show silicate profiles to have a maximum concentration at depths of roughly 100 m in the upper halocline of the Canadian Basin. These data show the silicate maximum throughout most of the Canadian Basin and extending over the Lomonosov Ridge into the Eurasian Basin. In 1991, no silicate maximum was observed at the North Pole, almost exactly where a strong silicate maximum had been seen in 1979 (Moore *et al.*, 1983), although a hint of its presence may have been indicated by somewhat elevated silicate concentrations in the Makarov Basin (Anderson *et al.*, 1994). The silicate maximum in the halocline was not seen beyond Station 14 of the 1994

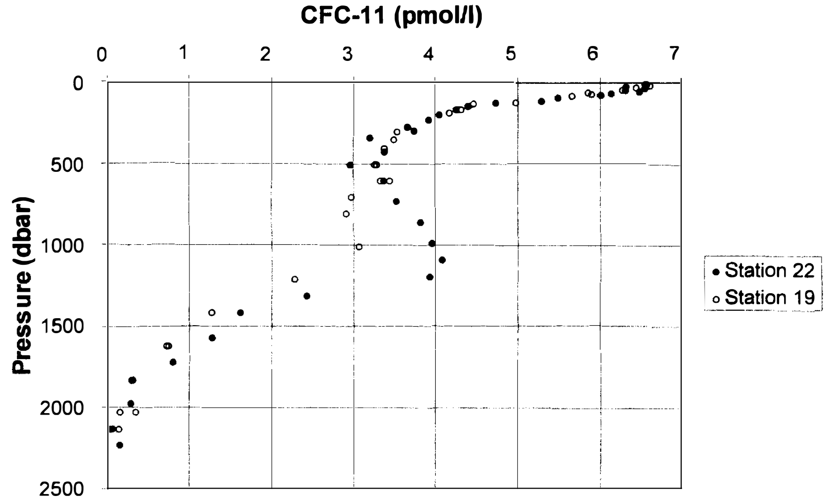

Fig. 7. *CFC-11 profiles (typical of all CFCs). Station 19 (open circles) is typical of the Canada Basin stations. Station 22 (filled circles) shows the more recently ventilated "younger" water of the bolus centered at 1000 m.*

section.

Observations of dense water on the continental shelves formed during winter freezing exist, but the observation of a direct connection between this process and the formation and ventilation of deep water has been elusive. A sign of a recent ventilation event was observed at Station 22 where a bolus of colder and fresher water was found centered at a depth of 1000 m. Evidence of its recent formation is provided by CFC concentrations that are higher than those for nearby stations (Fig. 7). This may be the first direct observation of the process that produces and ventilates the deeper waters of the Arctic Ocean.

What seems apparent from these results is that the fronts in the Atlantic Layer and halocline that existed over the Lomonosov Ridge in times past have in part broken down or shifted from their earlier observed positions. Warm Atlantic Layer water flowing along the Eurasian slope that previously turned at the Lomonosov Ridge now has penetrated into the Makarov Basin in a substantial way. Halocline water characterized by a nutrient maximum is more strongly confined to the Canadian Basin, in fact possibly to only the Canada Basin. The penetration of the warm Atlantic Layer water and the displacement of the high silicate halocline water may be in part the result of warmer water entering the Atlantic Ocean. QUADFASEL *et al.* (1993) show a plot of changes in the maximum sea surface temperature in Fram Strait at 78°N during 1980–90. During that time, temperatures varied typically about 5°C, while the annual mean temperature over a period of 5 years changed up to about 3°C. The maximum temperature in the Atlantic Layer also changed up to 1°C along the Eurasian slope over a decadal time scale, with a temperature as high as 2.8°C observed approaching the Laptev Sea in 1990. Thus, the increased temperature of the Atlantic Layer in the Canadian Basin could be a reflection of this warmer water flowing into the Canadian Basin.

3. Conclusion

Finding warm water where it had not been previously observed has implications regarding observations of climate change. Global climate models have cast the Arctic Ocean as a bellwether of global warming. The sensitivity of high latitudes to change in such models is, however, due to albedo feedback effects in these regions. We interpret the observed warming of Arctic Ocean waters to be driven by changes in the transport of Atlantic waters through Fram Strait and the Barents Sea. The increase in temperature of waters in the Canadian Basin is thus a result of advection, not albedo effects, and is sufficiently large to mask changes in water temperature and probably ice thickness that would result from the greater warming in polar regions predicted by general circulation models. While the temperature increase is undoubtedly a "climate" signal, it is not considered to be the signal of the global warming in polar regions due to albedo effects as predicted by GCMs, and it should be taken as a warning regarding the interpretation of any time series measurements in the Arctic Ocean as indicators of global warming.

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