https://doi.10.17895/ices.pub.19279133

Rapp. P.-v. Réun. Cons. int. Explor. Mer, 188: 11–22. 1989

A synthesis of the Arctic Ocean circulation

Knut Aagaard

Aagaard, Knut. 1989. A synthesis of the Arctic Ocean circulation. – Rapp. P.-v. Réun. Cons. int. Explor. Mer, 188: 11–22.

Moored current measurements in four different areas of the Arctic Ocean suggest that the principal large-scale advection occurs in narrow boundary currents along the margins of the major basins. These boundary flows are in a cyclonic sense in each basin and are therefore counter to much of the upper ocean drift suggested by the ice motion. In the interior of the Arctic Ocean (or at least in its Canadian Basin) the kinetic energy appears concentrated in the mesoscale eddy field, and there is evidence that this field is primarily generated along the Arctic Ocean margins. In addition, the Arctic Ocean has recently been found to sustain a large-scale thermohaline circulation driven by freezing along its periphery; this circulation appears to be at least comparable in magnitude to that of the Greenland Sea. If one also considers the major peripheral exchanges through the Fram Strait, the Barents Sea, the Canadian Archipelago, and the Bering Strait, then the image which emerges is of an Arctic Ocean which overwhelmingly is forced at its lateral boundaries, and in which much of the organized transport is trapped along these boundaries.

Knut Aagaard: NOAA/PMEL/MSRD, 7600 Sand Point Way N.E., Seattle, Washington 98115-0070, USA.

Introduction

This synthesis is very much a personal view of the large-scale circulation of the Arctic Ocean, and it is based principally on measurements with which I have been directly involved. It is not a comprehensive review of work in the Arctic Ocean, and in particular it does not deal with the extensive work of Soviet investigators. A central theme in the discussion is the importance to the Arctic Ocean of its lateral boundaries and the processes which occur there.

Boundary currents

I begin with moored current measurements we made over the continental slope north of the Barents Sea during the summer of 1980 (sites YE1 and YW2 in Fig. 1). The eastern mooring was at 458-m depth, close to the shelf break, while the western one was over the slope at 1126 m. The stick diagrams for the three current records on the eastern mooring are shown in Figure 2; each time series is about two months long. Up in the figure is parallel with the local isobath trend, in this case northeast. The recorded currents are remarkable both for their persistent set northeastwards along the slope, and for their strength, which increases downwards. Daily low-passed currents reached 30 cm s^{-1} at the deepest instrument on the eastern (upper) mooring and 25 cm s^{-1} at the deepest one on the western (lower) mooring. If we combine the results from the two moorings into a single section (Fig. 3), we see a deep and apparently narrow boundary current trapped over the upper slope, although we cannot be certain of the seaward extent of the current. Hydrographic sections taken in the same area (Aagaard *et al.*, 1981b) show a reduced slope of both the isotherms and the isohalines seaward of about the 1200-m isobath (cf. also Fig. 3), suggesting that the high-speed current core is in fact centered over the upper slope as indicated in the figure. Likewise, Lewis and Perkin (1983) observed the deep isotherms in this area rising inshore of the 2000-m isobath. Also note in Figure 3 that the speed increases with depth through the Atlantic layer and into the deep water, so that the boundary current is not uniquely associated with a particular water mass. A further important point is that this

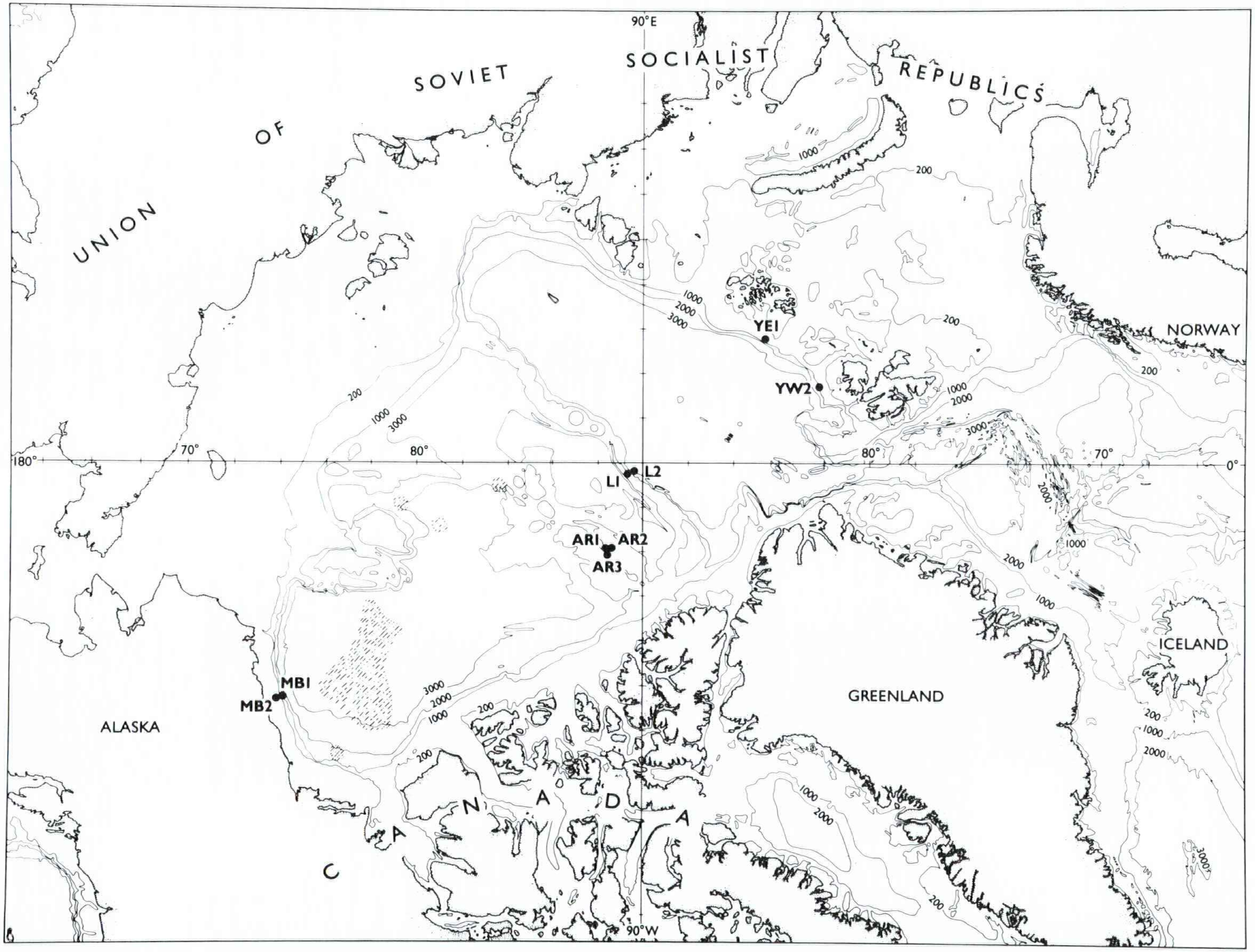


Figure 1. Mooring locations and selected eddy-observing areas.

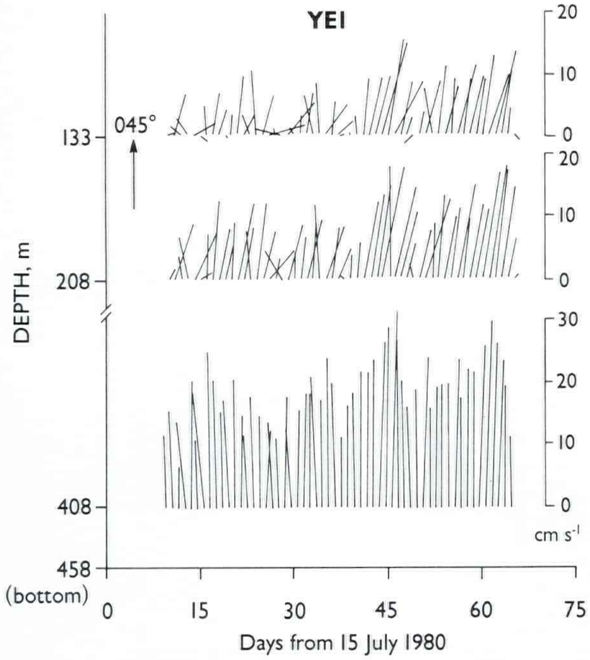
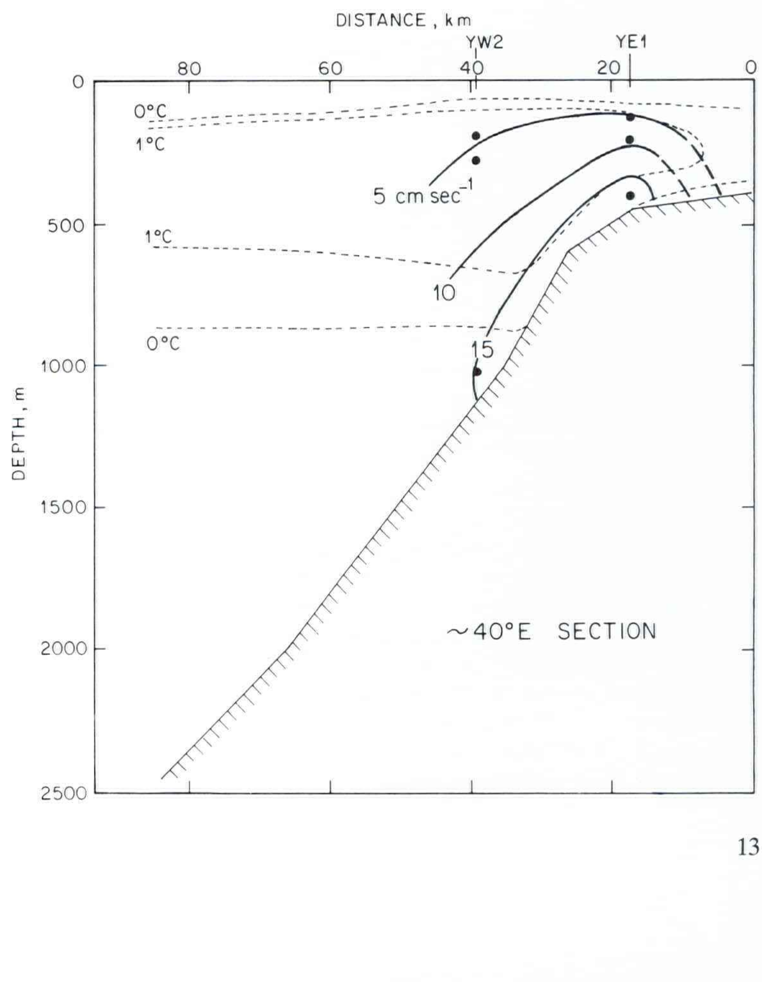


Figure 2. Daily low-passed velocities at mooring YE1 near 46°E during July–September 1980. The orientation arrow is directed northeast along the slope.

strong and deep flow along the basin boundary is counter to that near the surface, which is directed westwards towards the Fram Strait. The latter can for example be seen in the charts of inferred upper ocean currents by Thorndike and Colony (1982) which are shown in Figure 4.

Consider next the six-week moored current-meter records from the Lomonosov Ridge near 140°W made in 1979 (Aagaard, 1981). Mooring L1 was located immediately north of the ridge crest, i.e., on the Eurasian Basin side of the crest, at 1440-m depth, and L2 was 26 km farther north at the base of the ridge at 3565-m depth (Fig. 5). The current 200 m above the bottom near the base of the ridge was extremely slow, with a mean over the record of less than 0.5 cm s^{-1} and directed northeast along the ridge; the speed never exceeded 4 cm s^{-1}. In contrast, the maximum current just north of the ridge crest exceeded 12 cm s^{-1} 25 m above the bottom, and the record-long means were in the range 2–3 cm s^{-1}, with a flow component up the slope, suggesting overflow into the Canadian Basin. The data show this to have occurred in a series of pulses. Of particular importance to our discussion is the pronounced vertical shear, with the current intensifying downwards; at L1 this increase was in the mean 0.6 cm s^{-1}, i.e., 30 %, over 175 m. The flow along the Lomonosov Ridge is therefore reminiscent of that north of Svalbard and Franz Josef Land (Fig. 3), although weaker.

Figure 3. Composite velocity section across the southern Eurasian Basin slope near 40°E from July–September 1980, based on results from moorings YW2 and YE1. The current is directed into the figure and represents two-month means. Isotherms are based on summer 1980 hydrographic sections together with two-month mean temperatures recorded at the current meters.



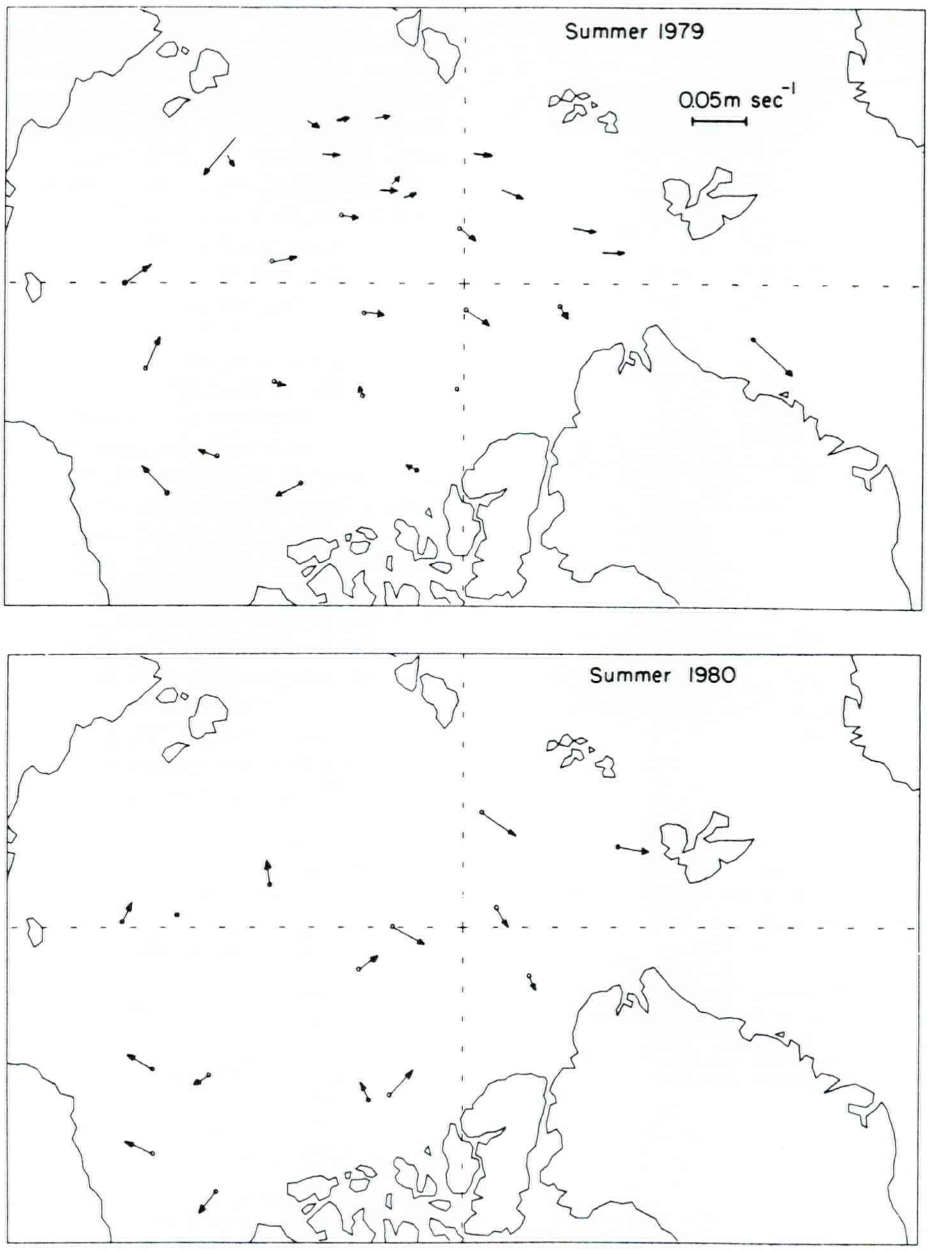


Figure 4. Upper ocean currents inferred from observed ice drift and geostrophic wind during the summers of 1979 and 1980. Circles denote mean drift buoy locations. Currents inferred from the drifts of the Fram and the Sedov are included in the 1979 chart. From Thorndike and Colony (1982).

That is, it is 1) trapped over the upper slope in a core a few tens of kilometers wide; 2) directed in a counter-clockwise sense around the basin; and 3) increasing in intensity with depth. As a working hypothesis, I propose that this boundary current is in fact continuous from Svalbard around the Eurasian Basin. This would be consistent with the observation in 1979 of an anomalously high $^{137}Cs/^{90}Sr$ ratio near 1500 m over the Eurasian Basin flank of the Lomonosov Ridge (Livingston *et al.*, 1984). This high ratio represents a unique signal from the Windscale nuclear fuel reprocessing plant on the Irish Sea, and Livingston *et al.* (1984) have presented evidence that probably no more than about three years were required for this water to move from Svalbard to the North Pole. The distance to the Pole around the perimeter of the Eurasian Basin is about 4000 km, so that windscale-tagged water would under our hypothesis have been carried by the boundary current

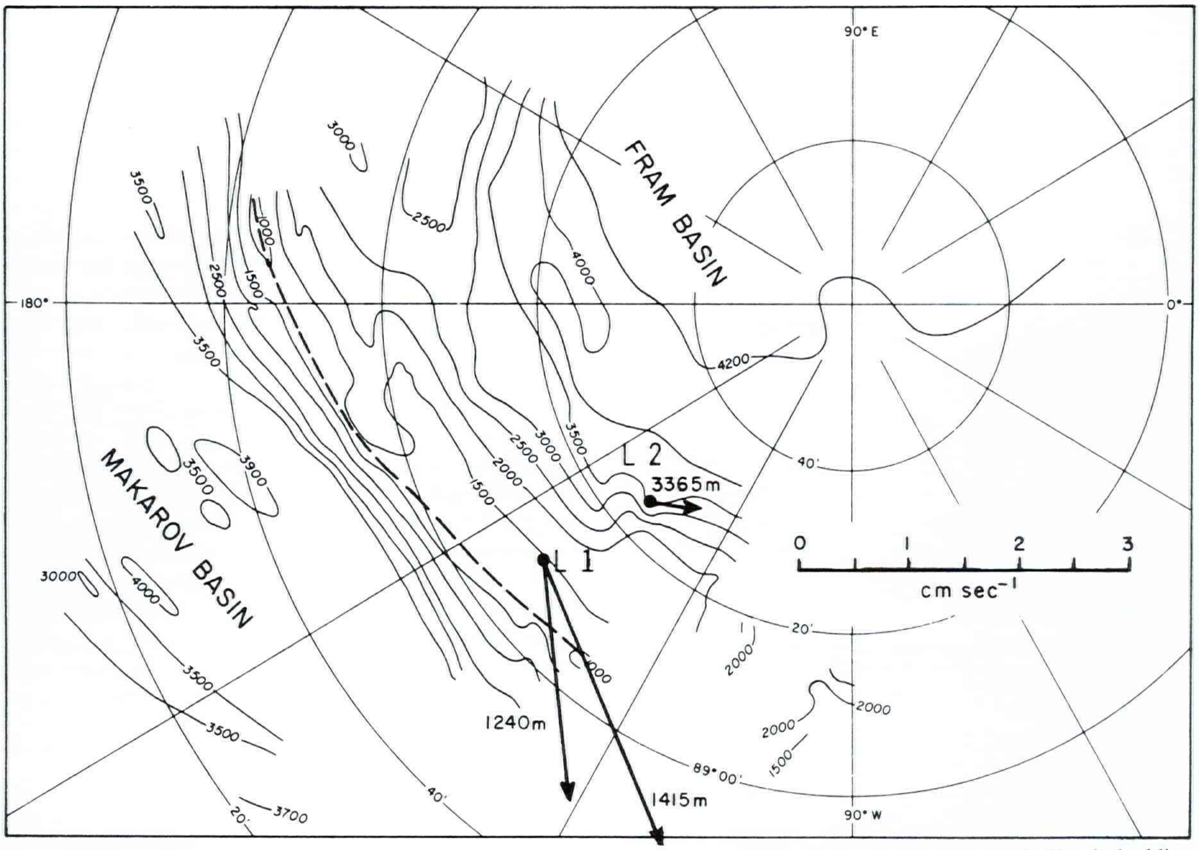


Figure 5. Six-week mean currents at moorings L1 and L2 over the Lomonosov Ridge during April–May 1979. The dashed line denotes the axis of the ridge. From Aagaard (1981).

along the basin margin with a speed of about 4 cm s^{-1}, which is well within the observed range.

I turn now to the Canadian Basin of the Arctic Ocean, which at least in its deeper reaches appears to be far more isolated from the rest of the World Ocean than is the Eurasian Basin. In 1987 we retrieved two six-month long moored arrays from the Beaufort Sea slope north of Alaska, at sites MB1 (1008-m depth) and MB2 (170-m depth), shown in Figure 1. The record-length mean velocity profiles (Fig. 6) show some striking similarities to the current structure found in the Eurasian Basin. First, the current core in the Beaufort Sea apparently is also trapped over the outer shelf and continental slope, for farther in on the shelf the flow decreases (Aagaard, 1984), and the available evidence also suggests that it does so farther offshore and there in fact is directed westwards as part of the sluggish clockwise Beaufort gyre (Newton and Coachman, 1974). Second, the mean current over the slope is directed in a counterclockwise sense around the basin. Third, this current increases downwards and is in fact oppositely directed to the shallow surface flow, which in this area is directed westwards (Thorndike and Colony, 1982; Pritchard, 1984). A difference between the two basins appears to be that in the Canadian Basin the current does not extend as deep as in the Eurasian Basin. While we cannot determine the depth of the current maximum from Figure 6, it may be a few hundred meters, and certainly at 1000-m depth the current is negligible. During this same period we also measured the flow at 1200-m depth about 200 km farther west, and again we found the annual mean current along the slope to be negligibly small. In contrast, the boundary current in the Eurasian Basin extends to well below 1000 m and is still increasing downwards at that depth.

Interior flow

The next set of current measurements I want to discuss are from the Alpha Ridge (Fig. 1) and extended over five weeks during 1983. There were three moorings, 20, 32, and 37 km apart at about 1500-m depth over fairly rough topography, but far removed from the more linear large-scale features of the basin perimeter and the Lomonosov Ridge. The nine current records (Fig. 7) show a regime entirely different from what we have discussed so far. With three exceptions, the currents

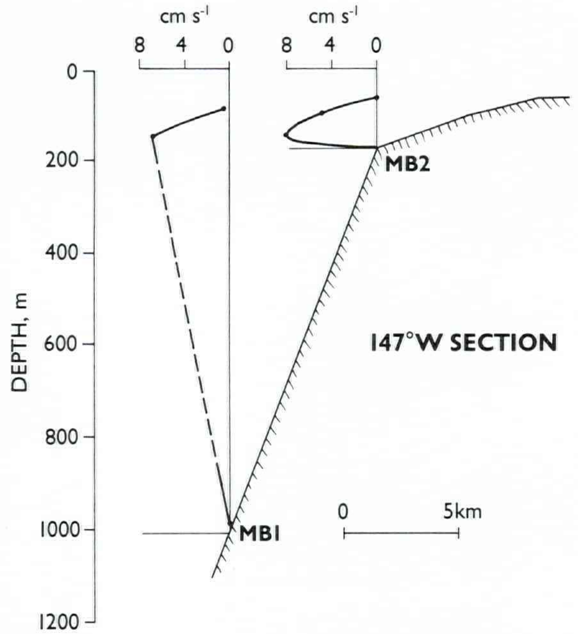


Figure 6. Mean velocity profiles during October 1986–March 1987 over the upper Beaufort Sea slope at moorings MB1 and MB2, near 147°W.

were below threshold (~ 1.6 cm s^{-1}) all or nearly all of the time. The exceptions are at the deepest instrument at AR1 and the shallowest instruments at AR2 and AR3. The first of these was located 25 m above the bottom at the top of a very steep slope, and it is likely that we are seeing the local effects of topography in amplifying an otherwise weak flow. However, even at this site, the current was below threshold for long periods. The other two instruments registering significant currents were located in the pycnocline, and the current registrations appear to represent intermittent activity of relatively small scale. The important point is that there is no suggestion of an organized large-scale flow near these arrays, nor is there any indication of deep vertical current structure such as we found along the basin boundaries.

The 1983 Alpha Ridge measurements are consistent with the suggestion of Manley and Hunkins (1985) that essentially the entire concentration of kinetic energy in the interior of at least the Canadian Basin of the Arctic Ocean is in the field of time-dependent motion; and that below the mixed layer the single largest identifiable contribution to the time-dependent motion is from the mesoscale eddy field. These energetic features were first clearly recognized during the early 1970s, when we

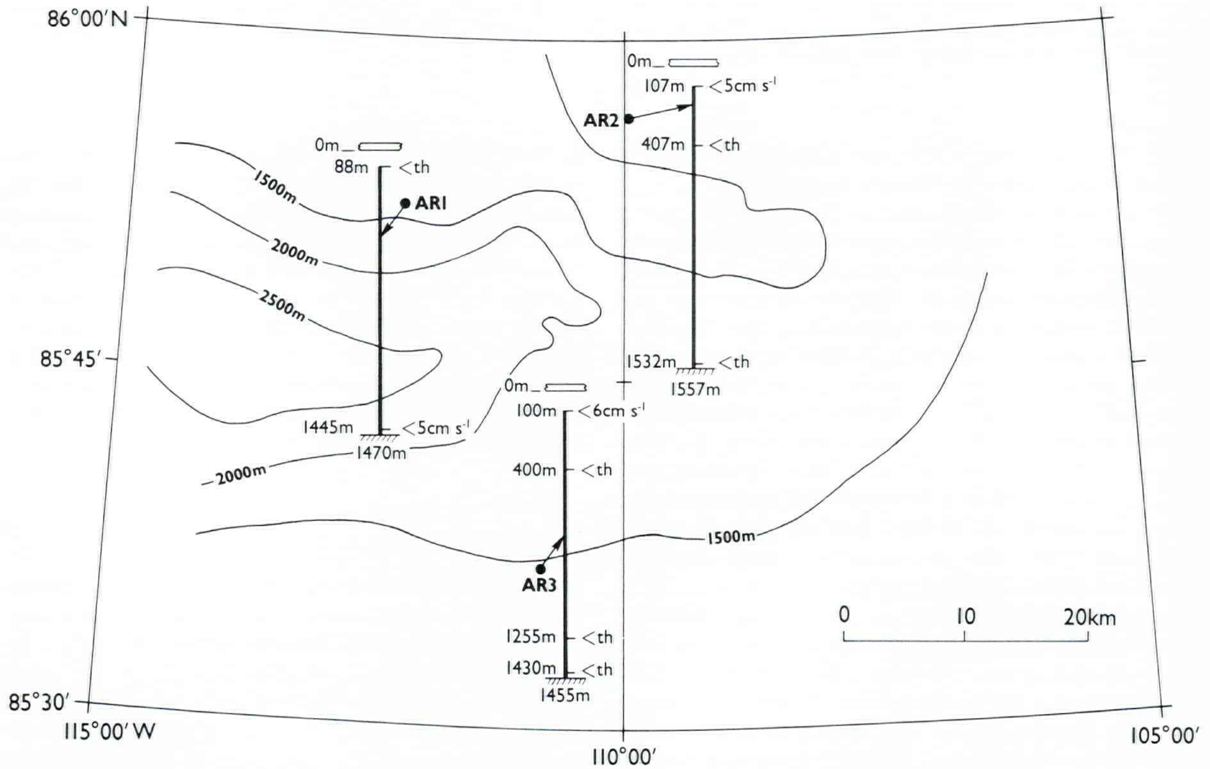


Figure 7. Maximum speeds during April–May 1983 at moorings AR1, AR2, and AR3 over the Alpha Ridge. The symbol "th" designates threshold velocity, approximately 1.6 cm s^{-1}.

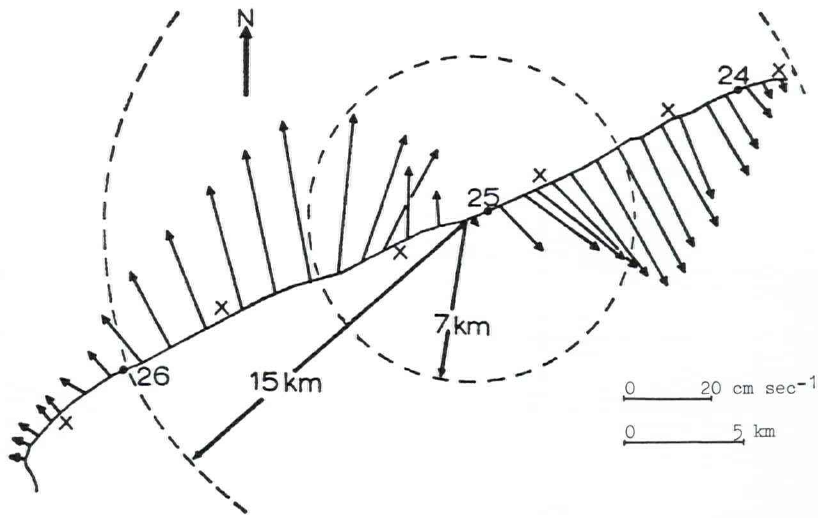


Figure 8. Two-hour mean currents at 150 m during 24–26 March 1972 near 76°N 149°W in the Canadian Basin. The dashed circles show the radius of maximum velocity and the extent of the eddy's influence. From Newton *et al.* (1974).

found small vortices, normally clockwise, imbedded in the main pycnocline (Newton *et al.*, 1974). An example is shown in Figure 8. The characteristic eddy diameter appears to be about 20 km, and the maximum speed typically near 25 cm s^{-1}, although flow more than twice that has been measured (Galt, 1967). Large numbers of these eddies have now been observed through much of the Canadian Basin, including some found at great depths (D'Asaro, 1988b). The present evidence indicates that the eddies are very long lived (of order a year or more), and that they quite likely constitute a significant transport mechanism within the interior of the Canadian Basin (Manley, 1981). An important feature of these eddies is that their hydrographic properties are anomalous and require a distant origin. Furthermore, dynamical constraints on their generation suggest that this origin is along the basin periphery (Hart and Killworth, 1976). It is in fact likely that a major generating area for at least those eddies within the Canadian Basin pycnocline is the northern Chukchi Sea, one specific site being the mouth of Barrow Canyon (D'Asaro, 1988a). The important point for our present discussion is that the Arctic Ocean periphery is therefore generating a major component of the motion in the interior.

Thermohaline circulation

I want next to deal briefly with the thermohaline circulation. Two hydrographic features are particularly important in this regard: 1) the strong halocline centered near 100 m, which also contains a very large nutrient maximum, and 2) the deep salinity maximum (Fig. 9). A variety of physical and geochemical work during the past few years has shown that both of these basin-scale features are likely to have their origin over the shelf seas bordering the Arctic Ocean, although many of the details of both the distributions and the responsible processes remain speculative (e.g., cf. Aagaard, 1981; Aagaard *et al.*, 1981a; Moore *et al.*, 1983; Aagaard *et al.*, 1985; Jones and Anderson, 1986; Wallace *et al.*, 1987; Smethie *et al.*, 1988). Over the shelves, the physical process ultimately responsible for the large-scale thermohaline circulation which maintains these major hydrographic features is brine rejection during sea-ice formation, although particularly in the Barents Sea, cooling of saline water of Atlantic origin may also be a critical factor (Swift *et al.*, 1983). The importance of the freezing process is that it can produce dense waters and drive convection even in an ocean as stratified as the Arctic Ocean is, given the right conditions. These conditions may include persistent divergent ice motion, such as occurs near a coast under offshore winds, or the presence of a reservoir in which to accumulate salt, such as would obtain in shallow water or in a region where the circulation provides long residence times. The important point is that these conditions are typical of many of the shelf seas surrounding the Arctic Ocean.

Once produced, the dense waters may flow off the shelf as sinking gravitational plumes (Fig. 10), subsequently spreading into the interior (Killworth, 1977; Carmack and Killworth, 1978; Melling and Lewis, 1982; Aagaard *et al.*, 1985). Brine-enriched waters have in fact been observed over the shelves by a number of investigators (e.g., Aagaard *et al.*, 1981a; Melling and Lewis, 1982; Schumacher *et al.*, 1983; Midttun, 1985; Aagaard *et al.*, 1985), but the critical issues of rates, plume mechanics, and modes of spreading remain substantially unknown.

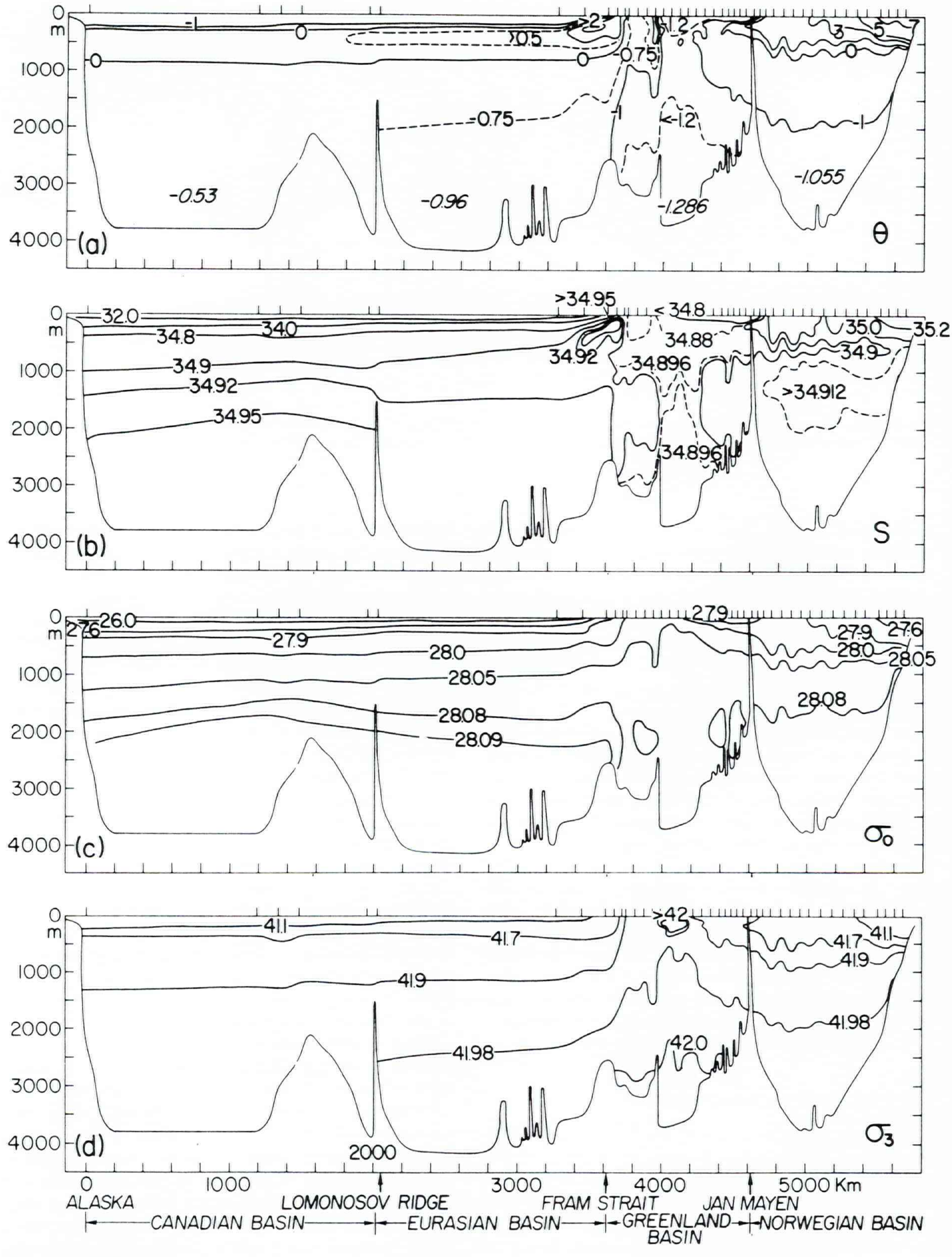


Figure 9. Distributions of potential temperature, salinity, and density across the Arctic Ocean and the Greenland and Norwegian Seas. From Aagaard *et al.* (1985).

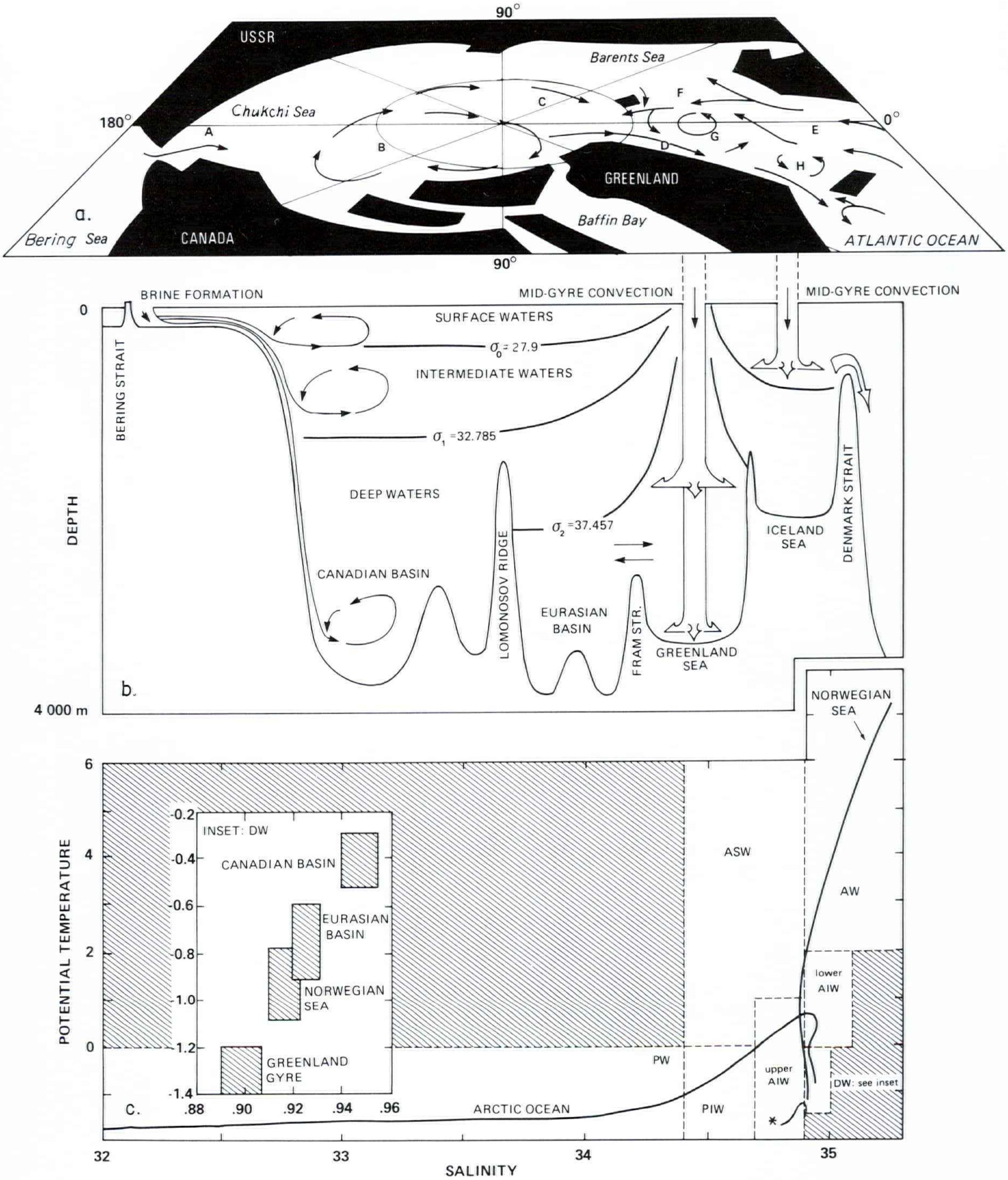


Figure 10. Schematic circulation and water mass structure in the Arctic Ocean and the Greenland and Iceland Seas. The upper panel represents near-surface circulation only. From Aagaard *et al.* (1985).

What is known at this point, is that the large-scale circulation driven from the shelves is not contained within the Arctic Ocean, but in fact exports distinctive Arctic Ocean waters southwards. A particularly important example is the saline deep water of the Arctic Ocean, which has recently been shown to exit through the western Fram Strait and mix with deep water from the Greenland Sea to form the Norwegian Sea deep water (Aagaard *et al.*, 1985; Smethie *et al.*, 1988; Swift and Koltermann, 1988). This deep water in turn prob-

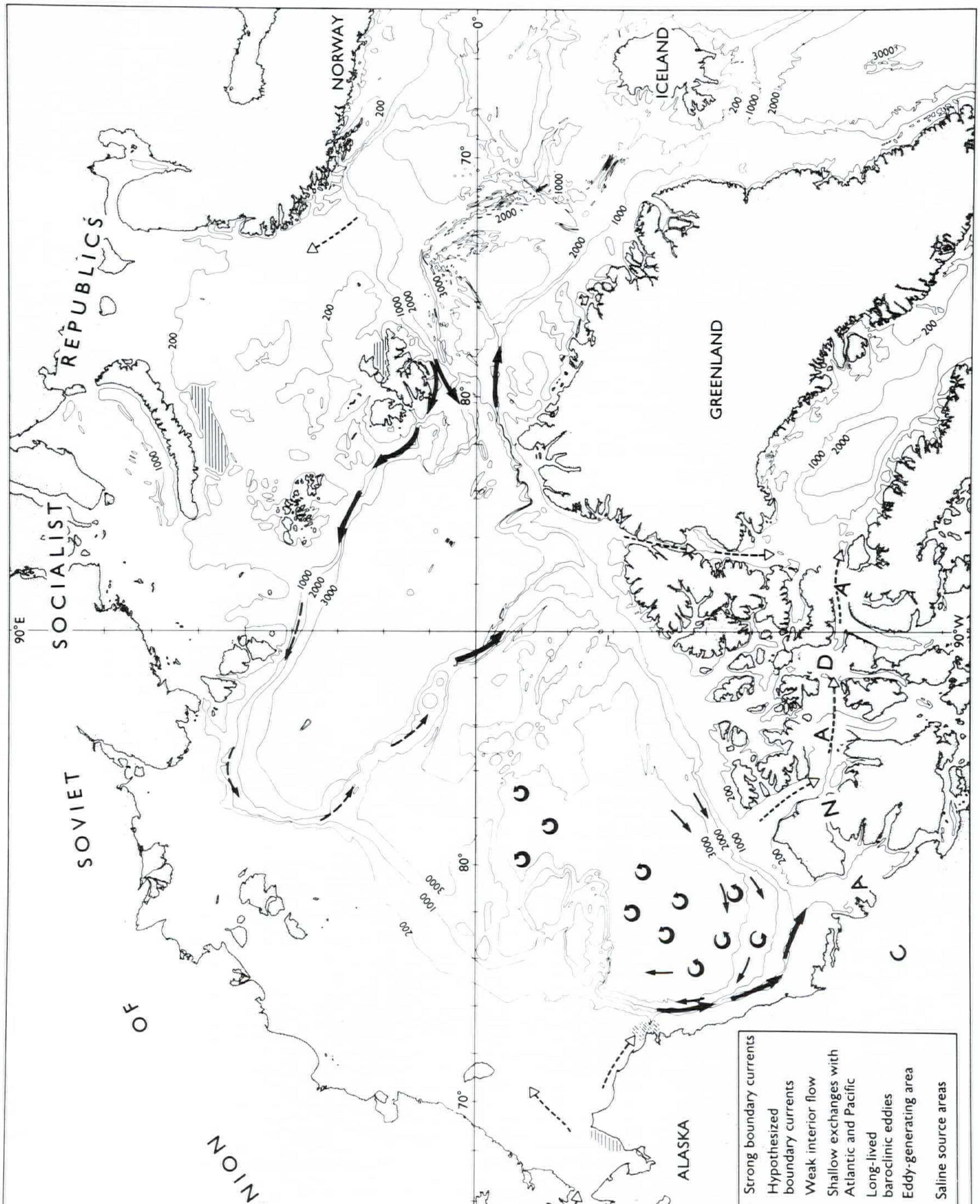


Figure 11. Schematic sub-surface circulation in the Arctic Ocean. Exchanges with the seas to the south generally extend to the sea surface. Known formation areas for saline shelf water and an eddy-generating area are also shown.

ably plays an essential role in the overflow of dense waters into the North Atlantic and thereby helps drive the global ocean circulation.

Consideration of the thermohaline circulation of the Arctic therefore leads to the same conclusion as did earlier arguments, viz. that processes along the basin periphery are forcing the interior structure and circulation of the Arctic Ocean.

Conclusions

As a schematic summary of these matters, I have indicated in Figure 11 the various features of the subsurface circulation of the Arctic Ocean which I believe to be particularly important. These include 1) the narrow counterclockwise boundary currents along the perimeter of the two major basins, which run counter to the surface circulation, and which may well prove to be the principal large-scale organized advective features of the Arctic Ocean (cf. Holloway, 1987, for a recent attempt to provide a dynamical explanation of such boundary currents); 2) the very weak interior circulation in at least the Canadian Basin, in which various transient motions predominate, including small but long-lived eddies formed at selected sites along the periphery; 3) the generation of a large-scale thermohaline circulation over certain of the shelves; and 4) the various exchanges with the seas to the south which occur through the Fram Strait, the Barents Sea, the Bering Strait, and several of the passages through the Canadian Archipelago. The image which I therefore wish to convey is of an Arctic Ocean which primarily is forced at its lateral boundaries, and in which much of the organized transport is trapped along these boundaries. The means by which the interior of the Arctic Ocean subsequently responds to this forcing remains a major area of investigation for the future.

At this point it is important to emphasize that the Arctic Ocean should not be considered a single oceanic entity, for there are major differences between at least its two primary basins, the Canadian and the Eurasian. For example, the transient tracer data suggest much longer time scales for the deep renewal in the Canadian Basin (centuries) than in the Eurasian Basin (decades) (cf. Östlund *et al.*, 1987). Similarly, the admittedly very sparse current data suggest that the deep circulation along the periphery of the Canadian Basin is much weaker than in the Eurasian Basin (contrast Figs. 3 and 6). As the presently meager database in the Arctic Ocean continues to expand, it is likely that we will find numerous substantial differences in circulation, mixing, and hydrography between the various basins of the Arctic Ocean, and at all levels.

Finally, I note that in 1993 it will be 100 years since the "Fram" set out on the first great scientific exploration of the Arctic Ocean. I can think of no more appropriate way to celebrate that event than with a major oceanographic effort to elucidate the circulation of the Arctic Ocean. It would further be appropriate that that effort be marked by the concern for international cooperation which characterized Fridtjof Nansen's later humanitarian work. Indeed, such cooperation is a necessity if we are to make substantial progress.

Acknowledgements

The companionship at sea and on the ice of highly competent and pleasant colleagues has always made the field work a joy. I especially thank Clark Darnall, who has been pivotal in these efforts over many years. The current measurements in the Eurasian Basin in 1980 (YE1 and YW2) were a joint effort with Arne Foldvik, whose friendship I prize and with whom conversations about the ocean are always stimulating. Generous scientific funding during the 15-year period of measurements used in this synthesis has come from the National Science Foundation, the Office of Naval Research, and the Minerals Management Service/National Oceanic and Atmospheric Administration. The paper was written with financial support from the Office of Naval Research under contracts N00014-84-C-0111 and N00014-88-F-0070. This is contribution No. 1039 from NOAA/ Pacific Marine Environmental Laboratory.

References

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

Aagaard, K. 1984. The Beaufort Undercurrent. *In* The Alaskan Beaufort Sea, pp. 47–71. Ed. by P. W. Barnes, D. M. Schell, and E. Reimnitz. Academic Press, Orlando.

Aagaard, K., Coachman, L. K., and Carmack, E. C. 1981a. On the halocline of the Arctic Ocean. Deep-Sea Res., 28: 529–545.

Aagaard, K., Foldvik, A., and Rudels, B. 1981b. Expeditionen YMER- 80: Fysisk oceanografi. Ymer, 101: 110–121.

Aagaard, K., Swift, J. H., and Carmack, E. C. 1985. Thermohaline circulation in the Arctic mediterranean seas. J. geophys. Res., 90: 4833–4846.

Carmack, E. C., and Killworth, P. D. 1978. Formation and interleaving of abyssal water masses off Wilkes Land, Antarctica. Deep-Sea Res., 25: 357–369.

D'Asaro, E. A. 1988a. Generation of sub-mesoscale vortices: a new mechanism. J. geophys. Res., 93: 6685–6693.

D'Asaro, E. A. 1988b. Observations of small eddies in the Beaufort Sea. J. geophys. Res., 93: 6669–6684.

Galt, J. A. 1967. Current measurements in the Canadian Basin of the Arctic Ocean, summer 1965. Technical Report No. 184, University of Washington, Department of Oceanography, Seattle.

Hart, J. E., and Killworth, P. D. 1976. On open ocean baroclinic instability in the Arctic. Deep-Sea Res., 23: 637–645.

Holloway, G. 1987. Systematic forcing of large-scale geophysical flows by eddy-topography interaction. J. Fluid Mech., 184: 463–476.

Jones, E. P., and Anderson, L. G. 1986. On the origin of the chemical properties of the Arctic Ocean halocline. J. geophys. Res., 91: 10759–10767.

Killworth, P. D. 1977. Mixing on the Weddell Sea continental slope. Deep-Sea Res., 24: 427–448.

Lewis, E. L., and Perkin, R. G. 1983. Supercooling and energy exchange near the Arctic Ocean surface. J. geophys. Res., 88: 7681–7685.

Livingston, H. D., Kupferman, S. L., Bowen, V. T., and Moore, R. M. 1984. Vertical profile of artificial radionuclide concentrations in the central Arctic Ocean. Geochim. cosmochim. Acta, 48: 2195–2203.

Manley, T. O. 1981. Eddies of the western Arctic Ocean: their characteristics and importance to the energy, heat, and salt

balance. Ph. D. thesis, Columbia University, New York.
Manley, T. O., and Hunkins, K. 1985. Mesoscale eddies of the Arctic Ocean. J. geophys. Res., 90: 4911–4930.
Melling, H., and Lewis, E. L. 1982. Shelf drainage flows in the Beaufort Sea and their effect on the Arctic Ocean pycnocline. Deep-Sea Res., 29: 967–986.
Midttun, L. 1985. Formation of dense water in the Barents Sea. Deep-Sea Res., 32: 1233–1241.
Moore, R. M., Lowings, M. G., and Tan, F. C. 1983. Geochemical profiles in the central Arctic Ocean: their relation to freezing and shallow circulation. J. geophys. Res. 88: 2667–2674.
Newton, J. L., Aagaard, K., and Coachman, L. K. 1974. Baroclinic eddies in the Arctic Ocean. Deep-Sea Res., 21: 707–719.
Newton, J. L., and Coachman, L. K. 1974. Atlantic water circulation in the Canada Basin. Arctic, 21: 297–303.
Östlund, H. G., Possnert, G., and Swift, J. H. 1987. Ventilation rate of the deep Arctic Ocean from carbon 14 data. J. geophys. Res., 92: 3769–3777.
Pritchard, R. S. 1984. Beaufort Sea ice motions. *In* The Alaskan Beaufort Sea, pp. 95–113. Ed. by P. W. Barnes, D. M. Schell, and E. Reimnitz. Academic Press, Orlando.
Schumacher, J. D., Aagaard, K., Pease, C. H., and Tripp, R. B. 1983. Effects of a shelf polynya on flow and water properties in the northern Bering Sea. J. geophys. Res., 88: 2723–2732.
Smethie, W. M., Chipman, D. W., Swift, J. H., and Koltermann, K. P. 1988. Chlorofluoromethanes in the Arctic mediterranean seas: evidence for formation of bottom water in the Eurasian Basin and deep-water exchange through Fram Strait. Deep-Sea Res., 35: 347–369.
Swift, J. H., and Koltermann, K. P. 1988. The origin of Norwegian Sea deep water. J. geophys. Res., 93: 3563–3569.
Swift, J. H., Takahashi, T., and Livingston, H. D. 1983. The contribution of the Greenland and Barents seas to the deep water of the Arctic Ocean. J. geophys. Res., 88: 5981–5986.
Thorndike, A. S., and Colony, R. 1982. Sea ice motion in response to geostrophic winds. J. geophys. Res., 87: 5845–5852.
Wallace, D. W. R., Moore, R. M., and Jones, E. P. 1987. 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.