

AUG 5 1983

FILE COPY

00091

4151

On the Origin of the Water Masses of the Arctic Ocean

Knut Aagaard  
School of Oceanography  
University of Washington

running head short title: Arctic Ocean Water Masses

4

Abstract

Two new developments are occurring in our understanding of the hydrography of the Arctic Ocean. The first is a renewed appreciation of the importance of the shelf seas in determining the density structure of the Arctic Ocean, and in particular of the main pycnocline. The second development is the recognition that deep water is formed in the Arctic Ocean, the salinity of which is appreciably greater than in the seas to the south.

Knut Aagaard  
School of Oceanography WB-10  
University of Washington  
Seattle, Washington 98195  
U.S.A.

## On the Origin of the Water Masses of the Arctic Ocean

### Introduction

There is an old Norwegian folk tale which attributes the saltiness of the sea to a mill grinding **salt** on the sea floor. What I particularly wish to point out is that the water masses of the Arctic Ocean are **con-**ditioned by several such salt mills, **the** most easily identifiable of which are actually found at the sea surface. **In** this connection **it's** particularly important to note that at low temperatures the density of sea water is principally determined by its salinity, so that the density stratification in high-latitude seas follows the salt layering very closely.

**We** need also to recall the peculiar geometry of the Arctic Ocean: a large deep basin divided by high submarine mountain ranges, surrounded by enormous shallow shelf regions, and with only one deep connection with the seas to the south, **through Fram** Strait. The Arctic Ocean is in fact the world's largest mediterranean sea.

A composite section through the Arctic Ocean (Fig. 1) shows the major features of the temperature and salinity distribution. **In** particular we note that the uppermost nearly homogeneous cold, **low-**salinity layer is very thin, typically 25-50 m. Under this mixed layer we find a transition layer where the salinity, and **thereby also** the density, increase rapidly with depth. Even if this layer **also** is **thin**, though not nearly as thin as the mixed layer, it is of enormous importance, precisely because it contains a large density gradient. This serves to reduce both convection and turbulent exchange, and the transition layer therefore insulates the ice and the atmosphere from the thick layer of warm water (the Atlantic layer) found beneath the **transi-**tion layer. The importance of this for the climate of the Arctic can scarcely be exaggerated.

Below the warm Atlantic layer the remainder of the water column consists of deep water, in which the temperature decreases with depth. The temperature difference between the deep water on either side of the Lomonosov Ridge suggests that the deep water in the Canadian Basin is principally renewed by overflow of the Lomonosov Ridge from the Eurasian Basin. This is consistent with the approximately adiabatic temperature gradient found in the deep Canadian Basin (Coachman 1963).

### The Mixed Layer

The mixed layer is of local origin, and its general properties can be represented by the two stations portrayed in Figure 2, showing a mixed layer 20-30 m deep. Particularly note the underlying temperature minimum, which we shall refer to later. For many years it has been thought that the relatively low salinity of the mixed layer, which is strongly stabilizing, is formed by the addition of fresh water, in part from the great rivers which empty into the Arctic Ocean and in part from the influx of low-salinity water from the Pacific Ocean through Bering Strait. While this may in large part be correct, we should also note that if the convection in the mixed layer during winter is penetrative, then the cycle of winter convection and summer ice melting will by itself give rise to such a salinity stratification, regardless of the addition of fresh water from the rivers. Essentially this is because the summer and winter mixing processes are asymmetrical. Indeed, it is the effects of the annual cycle of freezing and ice melting which most nearly characterizes the mixed layer". Furthermore, since the mean residence time in the Polar Basin for water in the mixed layer is about 10 years, (Aagaard and Coachman 1975, Östlund 1982), this water will on the average experience 10 such annual cycles. Therefore, the water in the mixed layer, by the time it flows out of the Arctic Ocean, is

rather far removed from the outflow of fresh water onto the shelves. Finally we note that even though convection **is** of very great significance for the properties of the mixed layer, convection is limited to this thin layer, and deep local convection in the interior of the Polar Basin is probably impossible under **present** climatic conditions (cf. Foster 1975).

### The Transition Layer

Next we consider the transition layer. As **early** as during the Fram drift, Nansen (1902) had observed that **the** temperature remained near the freezing point down through the mixed layer and into the transition **layer**, but the significance of this has only recently become clear (Aagaard et al. **1981**). Our present understanding is **that** the **insulating properties** of the transition layer are in large measure maintained by the influx of water **formed** during freezing in certain shelf areas where prevailing offshore winds sweep the ice away from the coast. Large amounts of new **ice** are then formed in the open water. During the freezing salt is **expelled**, and if the effect is allowed to build up, a dense saline water at the freezing point is formed. This water can subsequently spread into the interior away from the shelves. Figure 3 shows an example of such ice conditions from the northern Bering and **Chukchi** seas after a period of northerly winds in the beginning of March. The dark areas are essentially open water. The results of such episodes can be clearly seen in Figure 4, a winter section across **the Chukchi** Sea. The extremely saline water, about 3 per mille greater than in **summer**, which has been formed during freezing in the large open areas that were shown in the previous figure, are on their way **northward** along the northwest coast of Alaska **and** into the polar Basin.

The intense ice formation in the shelf **polynias** represents the first of the arctic salt mills. What can we say about the location of these salt mills? Since the freezing point decreases with increasing salinity, the very **saline** shelf water formed during freezing will form a temperature minimum as it spreads within the transition layer in the Arctic Ocean. We saw an example of such a minimum in Figure 2. The chart of minimum temperatures in the Polar Basin (cf. **Treshnikov** and **Baranov** 1972) in fact points **to** a number of intense ice formation areas, first and foremost in the **shelf** regions from **Svalbard** to **Severnaya Zemlya**, and between Alaska and Siberia. **Aagaard et al. (1981)** have estimated that the transition **layer** is supplied with cold and **saline** shelf water through an annual mean outflow of such water from **the** shelves of  $2-3 \times 10^6 \text{ m}^3 \text{ sec}^{-1}$ . Major problems remain to be investigated, for example how the spreading into the interior occurs, and how stable the system is with respect **to** perturbations. **One** can conceive of a situation in which a reduced **supply** of fresh water to the shelf seas could lead **to** the formation of a sufficiently salt and dense water on the shelf during winter that this water no longer would maintain the transition **layer**, but rather would sink through it. The transition layer **would** then gradually become thinner and lose its insulating properties, allowing a much greater transfer of sensible heat from the Atlantic layer.

#### The Atlantic Layer

Beneath the transition layer lies the warm and saline Atlantic water, which though thick is without a pronounced density gradient. Even in the relatively cold Canadian Basin there is sufficient sensible **heat** in the Atlantic layer to melt an ice cover over 20 m thick. This warm water comes from the Norwegian Sea and flows into the Polar Basin

with the **West Spitsbergen Current**. Together with our colleagues in Bergen we have made a number of measurements in this current during the past few years. We have found that the mass transport is highly variable (Figure 5 shows two-week mean values in millions of cubic meters per second), and the same is true of the temperature of the warm inflow; the latter also shows a very large annual **cycle**. The distribution of maximum temperature in the Arctic Ocean (cf. **Treshnikov** and Baranov 1972) points toward a broad continuation of the warm **flow** eastward in the Eurasian Basin, and finally a spreading in the Canadian Basin.

This concept of a broad and diffuse flow probably needs revision, and this is particularly evident on the basis of current measurements made in the Arctic Ocean the **last** few years. For example, the **two-**month mean values from a current meter section across the slope between **Svalbard** and Franz Joseph Land (Figure 6) show that the strong eastward current is constrained to the steep bottom topography. The current is neither broad **in lateral** extent, nor is it coincident with the maximum temperature distribution. Instead Figure 6 suggests a boundary current along **the** slope which increases with depth. This boundary current carries both warm Atlantic water and cold deep water toward the east. Presumably the warm water farther into the interior of the basin, i.e., seaward of the slope, is carried by a weaker and more variable current. We have **also** found a similar boundary current in other places in the **Polar** Basin: along the whole slope north of Alaska and along the **Lomonosov** Ridge which divides the Polar Basin in two. Figure 7 shows the current measurements on the Eurasian side of the **Lomonosov** Ridge in the form of mean values over approximately 40 days. Note that the flow is again constrained to the slope and that it increases with depth.

(Note also that a component of **the** mean current is directed **at** an angle across the ridge into the Canadian Basin. This probably represents a deep overflow of **the** ridge, as discussed earlier. The details of the current meter records show that the overflow occurs in pulses.) The impression from these various measurements is that a boundary current carries both the Atlantic and the deep waters relatively rapidly around the edge of the basin. This is in agreement with the discovery in 1979 near the **Lomonosov** Ridge of isotopes at **1500** m depth which could **only** have come from the **Windscale** nuclear fuel reprocessing **plant** in the Irish Sea and which had a maximum of three **to** four years to reach the Pole **from Spitsbergen** (H.D. Livingston, personal communication). The distance around the edge between these points is about 4,500 km, which for **an** average current speed of 5 ~~cm sec~~<sup>see-1</sup> would take three years.

The role of the interior of the basin in such a circulation scheme **is not clear**, nor do we know how the spreading into the interior occurs. The temperature and salinity **correlations** in the various portions of the basin show that not **only** does the maximum temperature diminish rapidly away from Fram Strait, but the salinity maximum which characterizes the original inflow of warm water disappears completely. This water mass transformation within the Polar Basin is yet *one* more link in the **large-scale** thermodynamics which operates in **all** the seas north of the **Greenland-Iceland-Faroe** Ridge. In these seas warm and saline water from the Atlantic is transformed to cold but still relatively saline water masses (Swift and Aagaard 1981). In part these waters then flow into the Atlantic where they sink to great depths and spread to and ventilate nearly all parts of the World Ocean.

### The Deep Water

Finally there are the properties of the deep water itself. We note first that the salinity in the deep water within the **Arctic** Ocean " is a few hundredths per mine higher than it is immediately south of **Fram** Strait. Even though the difference is small, it is obvious in the temperature-salinity correlations for stations taken in the vicinity of Fram Strait (**Fig. 8**). Note particularly that the salinity in the Greenland Sea decreases with depth while that in the Arctic Ocean increases. In the deeper part of the water column the latter effect is sufficiently strong to give the T-S curve a sharp bend toward increasing salinity. Farther into the interior of the basin we find still more saline **water**, in excess of 34.95 per mine in the T-S diagram from stations near the **Lomonosov** Ridge (**Fig. 9**). The fact that the deep water in the Polar Basin is more saline than in the basins south of Fram Strait can only mean that there are salt sources in the Polar Basin which modify the deep water. In effect, deep water **is** therefore formed in the Arctic Ocean itself, and this conclusion is in direct contrast to earlier ideas in which the deep water of the Arctic Ocean comes from the south through Fram Strait.

What might be the source of this salt? There are at least two **pos-**  
**ibilities**. One is that the salt comes from the warm Atlantic layer, e.g., through salt fingering, or through upwelling and cooling on the shelf. We have often seen evidence of such **upwelling** north of Alaska (Aagaard et al. 1981), and we can probably assume that it is a frequent occurrence along the shelf edge all around the Polar Basin. If indeed **salt** fingering or **upwelling** is the origin of the deep salt maximum, then it would have to occur quite near Fram Strait, because the salinity in the warm layer is rapidly reduced away from the strait. There  
are also other problems with such mixing schemes. For

example, Figure 10 shows the silicate distribution near the Lomonosov Ridge. It is clear that simply cooling and slightly reducing the salinity of the silicate-poor Atlantic layer cannot alone give rise to the deep water; the difference in silicate is too large.

Another possibility is that the salt comes from the shelves where it is expelled upon freezing as we have already discussed. Figure 11 shows a section from the Chukchi Sea from February 1982, and the very saline water, as much as 36.7 per mille, which is flowing northward in a 60-km wide layer along the bottom shows clearly that such an origin of the deep salinity maximum is not improbable. We note however that such water would have to be mixed, probably with water from the Atlantic layer, in order to achieve the properties of the deep water.

Finally, it is appropriate to point out that our basic understanding of the hydrography of the Polar Basin is very meager and is built upon an extremely limited data base. Major problems remain largely untouched, including a series of questions of climatic consequence. We stand in dire need of a major scientific effort in the Arctic Ocean.

## Acknowledgments

It is a genuine pleasure to acknowledge my indebtedness to Arne Foldvik. His flow of ideas, unfailing enthusiasm, good sense, and sound physical intuition have made our professional association at sea and ashore a richly stimulating one. The data represented by Figures 5, 6, and 8 are in large measure due to that association. For my own part, the data gathering and analysis for this manuscript have been funded by the Office of Naval Research under contract N 00014-75-C-0893; the National Science Foundation under grant DPP 77-17342; and the Marine Minerals Service through interagency agreement with the National Oceanic and Atmospheric Administration as part of the Outer Continental Shelf Environmental Assessment Program, University of Washington contract NOAA NA 81-RAC-00057. This is Contribution No. 0000 from the School of Oceanography, University of Washington, Seattle, Washington 98195, U.S.A.

## Figure Captions

1. Longitudinal section of temperature and salinity from the Greenland Sea over the North Pole to the **Chukchi** Sea. From Coachman and Aagaard (1974) .
2. Temperature, departure from the freezing temperature, and density ( $\sigma_t$ ) at two stations on the outer shelf north of Alaska in October 1976 and March 1977.
3. Satellite photograph (visible band) of the **Chukchi** and northern Bering seas, 6 March 1978. The darker areas of the sea (e.g., south of St. Lawrence Island, in the lower center of the figure) represent essentially ice-free conditions. From Aagaard et al. (1981).
4. Salinity section across the central **Chukchi** Sea, February-March 1977. The water was at the freezing temperature. From Aagaard et al. (1981).
5. Estimated northward transport of the West Spitsbergen Current during 1976-77, two-week means. One Sverdrup is  $10^6 \text{m}^3 \text{sec}^{-1}$ . Calculations by D. Hanzlick, to be published.
6. Composite section of temperature and of along-slope component of current north of the Barents Sea, summer 1980. The currents are two-month mean values.
7. Five-week mean currents near the central portion of the **Lomonosov** Ridge, April-May 1979. From Aagaard (1981).
8. Potential temperature-salinity observations from below 1400 m near Fram Strait, November 1977.
9. Potential temperature-salinity observations from below 850 m near the central portion of the **Lomonosov** Ridge, April-May 1979.
10. Composite profiles of silicate near the central **portion of the Lomonosov** Ridge, April-May 1979. Adapted from Moore et al. (1983).
11. Salinity section across the northeastern **Chukchi** Sea, March 1982. The water was at the freezing temperature.

## References

- Aagaard, K. 1981. Deep-Sea Res. 28A, 251.
- Aagaard, K. & Coachman, L.K. 1975. Eos 56, 484.
- Aagaard, K., Coachman, L.K. & Carmack, E.C. 1981. Deep-Sea Res. 28A, 529.
- Coachman, L.K. 1963. p. 143 in Proceedings of the Arctic Basin Symposium. Arctic Institute of North America, Washington, D.C.
- Coachman, L.K. & Aagaard, K. 1974. p. 1 in Marine Geology and Oceanography of the Arctic Seas. Springer-Verlag, New York.
- Foster, J.D. 1975. AIDJEX Bull. 28, 151.
- Moore, R.M., Lowings, M.G., & Tan, F.C. 1983. J. Geophys. Res. 88, 2667.
- Nansen, F. 1902. The Norwegian North Polar Expedition, 1893-96. Scientific Results. 3. Brøgger, Christiania.
- Östlund, G. 1982. J. Geophys. Res. 87, 2035.
- Swift, J.H. & Aagaard, K. 1981. Deep-Sea Res. 28A, 1107.
- Treshnikov, A.F. & Baranov, G.I. 1972. Struktura tsirkulyatsii vod Arkticheskogo Basseina. Gidrometeoizdat, Leningrad.





















