PHYSICAL OCEANOGRAPHY OF THE NORTH POLAR SEA

By **H. U. Sverdrup***

In 1879 when Commander De Long sailed north through Bering Strait on his ill-fated ship, the *Jeannette*, he hoped to discover new land. Although the north coast of Siberia had been charted by the Great Northern Expeditions sent out by Peter the Great in the first half of the 18th century and large parts of the archipelago to the north of Canada had been mapped by the expeditions searching for Franklin, the greater part of the Arctic was still unexplored. The northward extent of Greenland and of the island groups to the west of Greenland was unknown and the opinions of geographers as to the possible distribution of land and sea were divided. Many joined the German geographer, Petermann, in the hypothesis that the known part of Greenland represented only a portion of a large land mass which extended across the North Pole to Wrangel Land, now Wrangel Island (Ostrov Vrangelya). Others believed that the unknown region was one of numerous islands separated by shallow waters.

The drift of the *Jeannette* from 71°35N., 175°06W. to 77°15N., 154°59E. demonstrated that Wrangel Land was not continuous with Greenland. However, as the *Jeannette* remained in shallow water during the course of her two-year drift, the possibility that the unknown Arctic was an island region still existed.

In 1884 a number of objects from the *Jeannette*, including pieces of clothing marked with the names of members of the expedition, were found on an ice floe off southwestern Greenland. Professor H. Mohn in an article in the Norwegian *Morgenblad* suggested that the ice floe on which the articles were found had been carried by currents across the "Polar Sea". He collected other evidence as well, including the finding of driftwood from Siberian regions and implements of Alaskan Eskimo on the coast of Greenland, to substantiate his conclusion.

Professor Mohn's theory suggested to Fridtjof Nansen the idea that a large part of the unknown Arctic could be explored and the North Pole reached by allowing a ship, built to withstand the pressure of the ice, to be caught in the ice in the region where the *Jeannette* had been abandoned and letting her drift with the currents until released off the coast of Greenland.

Nansen's suggestion was regarded with scepticism by most arctic explorers. Some claimed that no ship could be built which would not be crushed by the ice. Others believed that the unknown waters were shallow and full of islands and that a ship might become hopelessly stuck in regions from which it would be impossible to return safely. Still others

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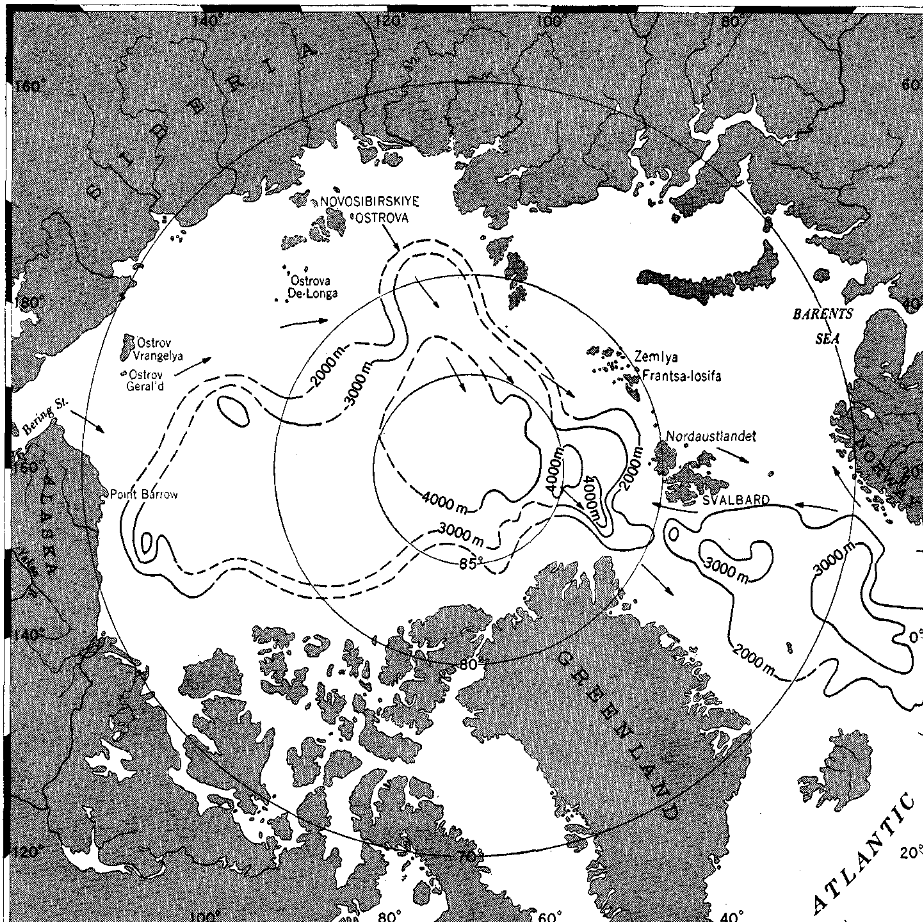
would not believe that the ice drifted across the unknown areas. However Nansen was not discouraged and he proceeded to carry out his plan. The *Fram*, which fulfilled all Nansen's requirements, was designed by Colin Archer and during the years 1893-6 completed the drift from the New Siberian Islands (Novosibirskiye Ostrova) to Spitsbergen.

In preparing his plans, Nansen had been right on every point except one. As Nansen, like everyone else, had expected to find shallow water in the North Polar Basin, the *Fram* was not equipped to take soundings in depths exceeding 1900 metres. She carried only some simple hand winches for soundings, 200 metres of bronze wire, about 1200 metres of single steel cord, and about 1900 metres of hemp line. Soon after the drift had started the depth was so great that even the hemp line was not long enough and new sounding lines had to be made from one of the ship's thick steel wire cables. This was a long and arduous task because the cable had to be separated into single strands which were then twisted into short pieces and soldered together. When the new line was completed eleven successful soundings were carried out under most difficult conditions. These gave depths ranging from 3400 to 4000 metres, showing that there was a deep basin in at least part of the North Polar Sea.

The discovery of the deep Polar Basin was the major geographical discovery of the *Fram* expedition. Since then our knowledge of the extent of this basin has increased only very slowly. The boundaries of the Polar Sea appear now to be fairly completely explored, and vague reports of land seen beyond the established boundaries have repeatedly been found to be erroneous. For some time the hypothesis of the tidal expert, R. A. Harris, that an extensive land mass should exist between the North Pole and Alaska attracted considerable attention, but results of tidal observations on the *Maud* expedition of 1922-4 removed the arguments on which Harris' hypothesis was based. Amundsen and Ellsworth flew from Spitsbergen to Alaska in 1926 in the dirigible *Norge* and, as expected, saw no land. Since then numerous flights have been made over different sections of the Polar Sea and nothing but pack ice has been reported.

Soundings are still few and far between, but the work accomplished on the Papanin North Polar Expedition in 1937-8 and during the drift of the *Sedov* in 1938-40 has added considerably to our information as to depths to the north of Spitsbergen and Franz Josef Land (Zemlya Frantsa-Iosifa), from where depths around 5000 metres have been reported. In latitude 86°26′5N., longitude 38°25′0E. the *Sedov* did not reach the bottom with a line of 5182 metres, but in an adjacent locality, 86°23′5N., 38°35′0E., bottom was reached at 4977 metres. The greatest depth sounded on the Papanin expedition was 4395 metres in 88°07N., 4°00W. In 1927 Sir Hubert Wilkins obtained a sounding in excess of 5000 metres, using sonic methods, to the north of Wrangel Island, but this result appears doubtful



Bathymetric chart of the North Polar Sea according to Wüst, showing the 2000-, 3000-, and 4000-metre contours. The arrows indicate the direction of the surface currents.

because in 1941 the Russian aviator Cherevichny obtained a maximum depth of 3430 metres in nearly the same locality.

W. Wüst has revised the bathymetric chart of the North Polar Sea, but the recent soundings have not altered the presentation of the larger features, which was prepared by Fridtjof Nansen in 1904. However, much work remains to be done before the width of the continental shelves surrounding the basin and the details of the topography of the floor of the basin can be determined.

The deep Polar Basin is an elongated depression surrounded by wide continental shelves. The major axis of the depression is about 1600 nautical miles long and runs from North East Land (Nordaustlandet), Svalbard, to Alaska. The minor axis is about 800 nautical miles long. Off the coast of eastern Siberia the continental shelf is up to 500 miles wide and is very shallow, the 50-metre contour being found 300 miles from land. Off the northern coast of Alaska the shelf is only 50 to 100 miles wide and off the Canadian Archipelago it is probably about 100 miles wide, but soundings from this region are lacking. The area of the Polar Sea, including the Barents Sea, is about 7.25 million square kilometres (2.8 million square miles), and the volume of water is about 11.65 million cubic kilometres (2.8 million cubic miles). The average depth is about 1600 metres (1 mile) and the maximum depth is probably about 5000 metres (3.1 miles).

Currents

The main features of the circulation of the waters of the Polar Sea are a surface overflow of cold arctic water of low salinity and a subsurface inflow of warmer and more saline Atlantic water. This exchange of water takes place through the wide opening between Spitsbergen and Greenland, the other openings being too narrow and too shallow to be important. Bering Strait is of minor importance only; there, over the year, water from Bering Sea flows north through the Strait.

The major outflow of surface water takes place off east Greenland and is to a great extent maintained by the fresh water which is discharged into the Polar Sea by the large Siberian and Canadian rivers. The Yukon River also contributes since in spring and summer its waters flow north through Bering Strait along the Alaskan coast. The outflow of cold, low-salinity water from the Polar Sea exercises a widespread influence upon the oceanographic conditions in the northern North Atlantic and upon weather conditions over that ocean, and it is possible that year to year differences in weather conditions are related to variations in this exchange.

The main inflow of water into the Polar Sea takes place to the north of Spitsbergen. Atlantic water of the Gulf Stream System enters the North Sea to the north of Scotland and flows along the west coast of Norway. Off the north coast of Norway the current branches, one branch flowing east along the Murmansk coast, the other flowing north and passing along the west coast of Spitsbergen. To the north of Spitsbergen, in about latitude 80°N., the current submerges and continues as a subsurface current into the Polar Sea. Measurements of temperature and salinity on the *Fram* and *Sedov* expeditions have shown that water of Atlantic origin is found to the north of the New Siberian Islands, and observations in latitude 80°38N., 179°02W. by Cherevichny, with the Russian aircraft N-169, in 1941 show presence of Atlantic water near the "Pole of Inaccessibility."

The character of the deep-water circulation in the Polar Basin is not known though this water has been shown to be formed in the Norwegian Sea.

The surface currents of the Polar Sea depend to a great extent upon the winds. During the drift of the *Fram*, Nansen observed that the ice was not carried along in the direction in which the wind blew but that the ice drift deviated, on an average, 28 degrees to the right of the direction towards which the wind was blowing. From the many entries in Nansen's diaries it is evident that in his leisure hours he often speculated upon the cause of this anomaly. He arrived at the conclusion that the deviation of the ice drift must be ascribed to the effect of the rotation of the earth, which in the northern hemisphere tends to deflect any moving body to the right. Nansen reasoned further that the ice would set the water directly underneath it in motion and that the water would then move to the right in relation to the ice drift; this layer would set the next layer in motion, again to the right, and so on. Similar conditions could be expected in the open sea, and Nansen therefore reasoned that, in general, a wind current is directed to the right of the wind direction at the sea surface; with increasing depth, the current is deflected farther to the right and decreases in speed because of the effect of frictional forces. These ideas as to the character of wind currents were entirely new to oceanography. A few years after his return from the Arctic, Nansen discussed his ideas with Professor V. Bjerknes who called in one of his students, Mr. V. W. Ekman, a capable mathematician. Ekman expressed Nansen's theories mathematically and in 1902 published his classical paper on the theory of wind-driven currents in the ocean. The essential features of this theory are still valid.

This discovery of the character of wind-driven currents is an outstanding example of the fact that discoveries made in the Arctic may have a bearing on our general understanding of natural phenomena. In the Arctic a trained observer has nothing to distract him. He lives day after day and week after week with the events which happen around him and can study them with an intensity which is rarely possible under other conditions. The drift of the *Fram* provided particularly favourable conditions for studying wind drift because the ship was moving with the ice, its position could be determined accurately at intervals of a few days, exact and continuous wind records could be obtained, and the results could be analysed immediately. These conditions made it possible for Nansen to carry out observations with an accuracy which could never have been achieved in the open sea and gave him the opportunity to consider his results so carefully that he could evaluate the various factors involved.

There remained, however, one discrepancy between Ekman's theoretical conclusions and Nansen's observations. According to the theory, the surface wind current in the open sea should deviate 45 degrees from the wind direction, and this conclusion has subsequently been borne out by observations of ocean currents. But the ice drift in the Polar Sea deviated on an average only 28 degrees to the right. Nansen attributed this discrepancy to the resistance of the ice, a factor which was later investigated during the drift of the *Maud* from Herald Island (Ostrov Geral'd) to the New Siberian Islands.

As the wind never blows with uniform speed and direction over very large areas, ice in neighbouring regions of the Polar Sea moves in different directions and with different speeds. Because of these differences in motion the ice in some areas is torn apart and in others it is jammed together. In summer and early fall the ice moves fairly freely because the numerous openings which are formed in early summer do not freeze over; at the same time the ice decreases in thickness because of melting. In winter and spring, on the other hand, the ice is packed solidly together and has attained its maximum thickness. The more solid the ice cover, the greater will be the resistance against the motion. Where the resistance is great the angle of deflection will be small and the speed of the ice drift will be slow in relation to the wind speed. Observations on the *Maud* showed that the angle of deflection varied during the year from a minimum of 17 degrees in April to a maximum of 40 degrees in August and that the ratio between the speed of the ice and the speed of the wind varied between 0.014 in April and 0.024 in August.

The direction of the average surface drift depends upon the direction of prevailing winds. On an average for the year the prevailing winds show a clockwise, anticyclonic circulation over the Polar Sea, with the centre of the anticyclone probably located to the north of Alaska in about latitude 85°N. Nothing is known about the ice drift to the north of the Canadian Archipelago, but to the north of Alaska and eastern Siberia it is directed towards the west, turning somewhat towards the north off the central arctic coast of Siberia. To the north of Spitsbergen, the drift takes a southerly direction, and here there is evidence of a southerly current which is independent of the prevailing winds and which increases in speed as it approaches the coast of eastern Greenland, carrying large quantities of ice to the south.

No strong winds have ever been observed over the ice-covered Polar Sea. It appears very improbable that the average wind speed during 24 hours ever exceeds 15 metres per second in January and 10 metres per second in August. The corresponding maximum values of the ice drift cannot be expected to exceed 30 kilometres, or 16 nautical miles, in 24 hours. These figures apply to conditions at distances greater than about 50 miles from land where the ice movement is not hindered by land masses.

In fact, the average surface currents are very weak. According to the drifts of the *Karluk*[1], the *Jeannette*, and the *Maud*, the ice drift from Point Barrow, Alaska, to De Long's Islands (Ostrova De-Longa) is at a

[1]The *Karluk*, one of the vessels of the Canadian Arctic Expedition, 1913-8, was caught in the ice at approximately 70°30N., 147°40W. in August, 1913 and in the following five months drifted to 72°08N., 173°50W. where she sank.

rate of about 1.0 nautical miles per day. The drifts of the *Fram* and the *Sedov* showed that the average speed of the drift from the New Siberian Islands to Spitsbergen is only slightly faster. Both the *Fram* and the *Sedov* drifted at greater speed, about 1.5 nautical miles per day, when they approached the opening between Spitsbergen and Greenland south of 80°N. The drift of the Papanin party from the region of the North Pole to latitude 71°N. off eastern Greenland averaged about 1.5 nautical miles per day.

Temperatures and Salinities

The surface layer of the Polar Sea has a low salinity because of the large discharge of fresh water from the rivers which flow into the Basin. As practically no evaporation takes place from the Polar Sea the small annual precipitation also contributes to the dilution of the surface layer. The total addition of fresh water from all sources is approximately 8300 cubic kilometres (2000 cubic miles) per year.

The effect of the rivers is particularly marked in summer, the time of the greatest discharge, when salinities below 3 parts per thousand may be found at distances of 60 miles from the delta of the River Lena. The greater the distance from the mouth of the river, the more thoroughly the river water has been mixed with the sea water; but even at a distance of 300 miles from the Siberian coast the salinity in the surface layer is below 30 parts per thousand. The salinity probably increases more or less regularly towards the Spitsbergen-Greenland opening where values between 32 and 33 parts per thousand prevail.

The temperature of the surface layer the year round is near freezing point, that is, -1.5° to -1.6°C. In winter, when the thickness of the ice increases by freezing and when every opening which is formed under the action of the wind immediately becomes covered by young ice, a completely homogeneous surface layer of water about 30 metres thick is developed. When ice freezes the greater part of the salts remains in the water and freezing therefore causes an increase in salinity of that water which is in direct contact with the ice. An increase in salinity means an increase in density; the denser water sinks and is replaced by water of slightly lower salinity from a greater depth. Thus the process of freezing maintains convection currents in the surface layer and provides a mechanism by which the surface layer becomes thoroughly mixed. The intensity of the mixing is so great that in winter the entire surface layer moves both in the same direction and at the same speed as the ice drift.

In summer, when the ice is melting, the meltwater reduces the salinity in the openings between ice floes and of the water that is in direct contact with the ice. The temperature at the surface rises to nearly 0°C in summer, but at a depth of 20 to 30 metres it remains close to the freezing temperature which was established during the preceding winter. The wind current in the surface layer decreases with depth and turns to the right, relative to the ice drift.

On the continental shelf off the coast of eastern Siberia the surface layer is very distinct, and the transition between it and the deeper waters is nearly discontinuous. In a vertical distance of less than 10 metres the salinity increases from about 29 to 33 parts per thousand, and the temperature increases by a few tenths of a degree. The density of the water increases from about 1.024 to about 1.027. At greater distances from the Siberian coast little is known about the sharpness of the lower boundary of the surface layers. The observations of the *Fram* clearly show that the surface layer is distinct and subject to a marked annual variation in temperature and salinity, but observations were not taken at sufficiently close intervals of depth for detailed examination. They do demonstrate, however, that the salinity of the surface layer increases towards Spitsbergen and it may therefore be expected that the rapid increase in salinity and density below the surface layer is less pronounced.

The increase in salinity and temperature below the top layer can be ascribed to the inflow of Atlantic water. When this water enters the Polar Sea its temperature is a few degrees above freezing and its salinity is nearly 35 parts per thousand. This water, however, has a density of nearly 1.028 which is considerably greater than that of the surface waters of the Polar Sea. When entering into the Polar Sea the Atlantic water therefore sinks below the Arctic water and gradually becomes mixed with the latter. Nothing is known as to the exact manner in which this Atlantic water spreads: but according to the observations of the *Fram* and the *Sedov* expeditions the Atlantic water can still be recognized to the north of the Siberian Islands by temperatures above 0°C at depths between 300 and 800 metres and by a slightly higher salinity.

The deep water of the Polar Sea is extremely uniform. According to Nansen's observations, it has a temperature between -0.8° and -0.9°C, increasing very slightly towards the bottom. Originally Nansen believed that the increase of the temperature towards the bottom was the effect of heat flow from the interior of the earth. Later on it was shown that since water is slightly compressible, its temperature must increase a little if it is brought adiabatically (without adding or subtracting heat) under higher pressure. The observed increase in temperature towards the bottom corresponds exactly to the adiabatical effect and renders, therefore, no evidence for heating through the ocean bottom.

Nansen's original values for the salinity were somewhat too high, but he subsequently revised them and arrived at the conclusion that the salinity was the same as that of the deep water of the Norwegian Sea, that is, about 34.94 parts per thousand. This value was confirmed by data collected at several stations in the Polar Sea on the *Nautilus* expedition in 1931.

In fact Nansen concluded that the character of the deep water in the Polar Basin corresponded in every respect to that of the Norwegian Sea at a depth of 1200 to 1500 metres. The *Nautilus* observations indicated a similar depth, but from a re-examination of all available information Wüst concludes that the depth is 1750 to 2000 metres. It seems certain that the deep water of the Polar Basin is formed in the Norwegian Sea by the cooling, mixing, and sinking of surface water and that it then flows across the ridge separating the Norwegian Sea from the Polar Sea. This ridge, which approximately follows the parallel of 80°N., has not been sounded in its entire length, only the half of the ridge closest to Spitsbergen being well known. In this part the shallowest soundings give depths less than 700 and 800 metres. It therefore seems probable that the ridge is somewhat lower nearer Greenland where soundings indicate a depth of about 1800 metres, and that the inflow of water takes place through the Greenland side of the opening.

In conclusion it should be emphasized that our information about the character of the waters is available only from the Siberian-European side of the North Polar Basin. The larger region to the north of the American Continent is still unknown.

References

De Long, E. (ed.) 'The voyage of the *Jeannette*'. 911 pp. Boston, 1884.

Ekman, V. W. "Om jordrotationens inverkan på vindströmmar i hafvet". *Nyt Mag. for Naturvidenskab*, Vol. 40, No. 1 (1902) pp. 37-63.

Harris, R. A 'Arctic tides'. U.S. Dept. of Commerce and Labor, Coast and Geodetic Survey, 103 pp. Washington, 1911.

Nansen, F. 'Farthest north'. 1301 pp. New York, 1897.

"The oceanography of the north polar basin". 'The Norwegian North Polar Exped., 1893-1896'. Scientific Results, Vol. 3, 427 pp. Christiania, 1902.

"The bathymetrical features of the north polar seas, with a discussion of the continental shelves and previous oscillation of the shoreline". 'The Norwegian North Polar Exped., 1893-1896'. Scientific Results, Vol. 4, 232 pp. Christiania, 1904.

Sverdrup, H. U. "The wind-drift of the ice on the North-Siberian shelf". 'The Norwegian North Polar Exped. with the *Maud* 1918-1925'. Scientific Results, Vol. 4, No. 1, 46 pp. Bergen, 1928.

"The waters of the North-Siberian shelf". 'The Norwegian North Polar Exped. with the *Maud* 1918-1925'. Scientific Results, Vol. 4, No. 2, 131 pp. Bergen, 1929.

"Oceanography". 'Scientific results of the *Nautilus* exped. 1931'. Vol. 2, No. 1, pp. 16-63. Cambridge, Mass., 1933.

Wüst, G. "Die morphologischen und ozeanographischen Verhältnisse des Nordpolarbeckens". 'Veröffentlichungen des deutschen wissenschaftlichen Instituts zu Kopenhagen'. Reihe I: Arktis, No. 6. Gebrüder Borntraeger, Berlin-Zehlendorf, 1942.