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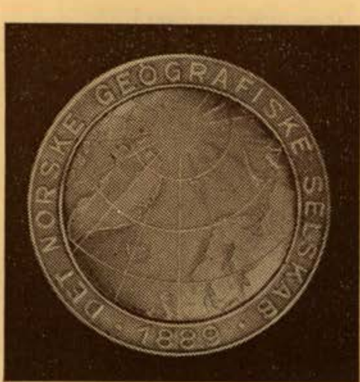

Særtrykk av Norsk Geografisk Tidsskrift, Bind XIV, Nr. 1—4. 1953

H. U. SVERDRUP

THE CURRENTS OF THE COAST OF QUEEN MAUD LAND

NORSK POLARINSTITUTT
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Observatoriegaten 1, Oslo

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THE CURRENTS OFF THE COAST OF QUEEN MAUD LAND

BY

H. U. SVERDRUP

Abstract.

The "coast" of Queen Maud Land is generally formed by floating shelf ice which is about 200 m thick whereas the depth to the bottom is 300 to 400 m. The prevailing wind blows parallel to the coast, towards the west. The wind current transports the low salinity, about 50 m thick surface layer towards the coast where it must descend. Therefore, directly off the shelf ice, we find low salinities to a depth of more than 200 m. In summer, when the surface layer has a temperature about zero degree, the water that sinks close to the shelf has a temperature that lies from 0.5° to 1.0° above freezing point. The question of melting at the bottom of the shelf ice is examined. The conclusion is that such melting may take place, but it cannot account for the nearly similar thickness of different ice shelves.

The coast of Queen Maud Land does not represent the border line of the land but the border line of the enormous ice masses that cover the land. Only in a few localities does the inland glacier terminate directly in the sea; in most regions it is fringed by floating ice shelves, some of which are nearly stationary whereas others are being pushed out into the sea until huge parts break off and drift away as the characteristic icebergs of the Antarctic.

The shelf ice that fringes Queen Maud Land appears to be about 200 m thick. It terminates in a vertical ice wall of which about 35 m rise out of the water as a barrier and about 165 m are submerged. At the rim of the shelf ice the depth to the bottom may be 300 to 400 m, except at a few localities where the ice rests on rocks or off ice tongues where soundings exceeding 2000 m have been obtained close to the barrier. The width of the ice shelves is in some regions probably more than 100 km.

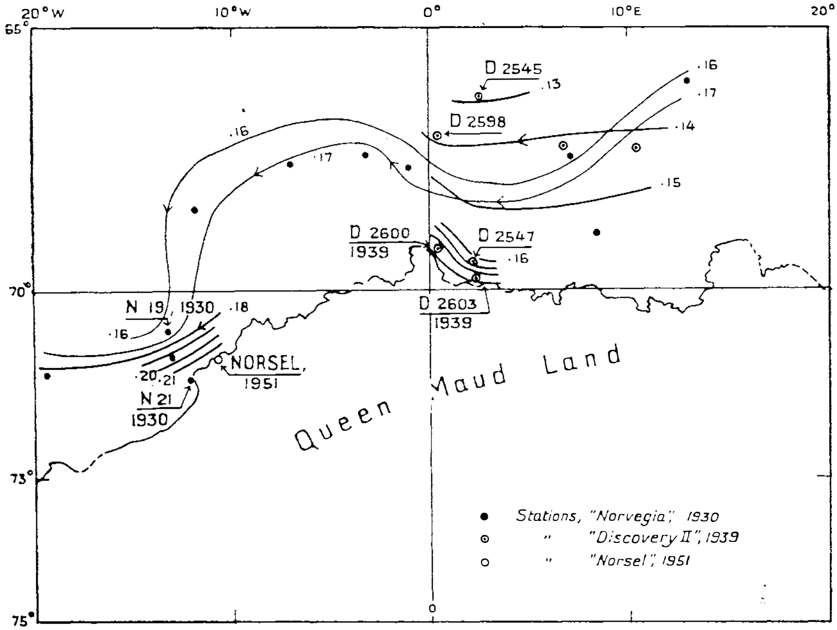

Fig. 1. Topography of the sea surface relative to the 400 decibar surface, represented by anomalies of dynamic elevation (in dyn m) and based upon observations on board the «Norvegia», 1930 and «Discovery II», 1939.

Thus, the "coast" of Queen Maud Land is formed by a vertical ice wall that does not reach to the bottom but represents the outer limit of a thick floating mass of ice below which the water may circulate to distances of 100 km or more from the border. We must expect that close to this remarkable type of coast the ocean currents show unique features.

Off the coast of Queen Maud Land the current runs towards the west, forming the southern part of the large clockwise gyral which is present in the Antarctic Ocean between longitudes 50°W and 40°E and between about latitude 58°S and the Antarctic Continent (e.g. Mosby, 1934). The existence of this gyral is associated with the character of the prevailing winds which near the continent blow from the east and to the north of about latitude 64°S blow from the west.

To the east of the zero meridian the coast line of Queen Maud Land runs east-west (see fig. 1) but to the west of the zero meridian the main direction of the coast line is towards S 60°W (240°). The bending of the coast line is probably of importance to the currents, because it seems that near the zero meridian the west-flowing current branches. One branch follows the coast and another branch continues to the west or bends somewhat to the north. This divergence of the current appears to have considerable influence upon the state of the ice. To the east of 0° the ice is generally packed against the coast but to the west, particularly between 10° and 20° W, the ice is more scattered with numerous leads which frequently are directed north-south, perhaps because of local winds. Between these longitudes several earlier expeditions have penetrated to the barrier, and in 1950 to 1952 the transport ship of the Norwegian-British-Swedish Scientific Antarctic Expedition, 1949—52, the 650 tons seal catcher "Norsel", passed 3 times in and out through a belt of pack ice which varied in width from about 500 km in February 1950 to about 1300 km in December 1951. In the last named month the "Norsel" succeeded in reaching the expedition's headquarters, "Maudheim" (lat. 71°03′ S, long. 10°56′ W), as early as on December 22. On all three occasions a broad lead was present directly off the barrier. In February 1950 the lead was only 20 to 30 km wide but in January 1951 and in December 1951 and January 1952 it was more than 100 km wide. During most months of the year the party at Maudheim observed open water or "water sky" off the barrier, indicating that the coastal current tends to carry the ice away from the coast.

The currents in the region are partly associated with the distribution of mass, and partly with the direct effect of the prevailing winds. The currents that are associated with the distribution of mass can be examined by means of the observations which were made on board Lars Christensen's ship, the "Norvegia" in 1930 (Mosby 1934) and by means of the "Discovery II" observations from 1939 (Discovery Reports, 1947), supplemented by a single station which was occupied from the "Norsel" in January 1951, when the ship was moored to the ice in Norsel Bay. Between longitudes 0° and 10°E the two sets of observations from 1930 and 1939 overlap, but they cannot be combined to one picture because of small systematic discrepancies. Therefore, two sets of lines have been entered in fig. 1 which shows the topography of the surface relative to the 400 decibar surface. The figure reveals a divergence of the current in the vicinity of the zero meridian, thus confirming the conclusion which was based mainly on the observed ice condition.

However, the most striking feature is the crowding of the iso-lines against the coast, which appears in the two areas in which oceanographic stations have been occupied close to the coast. In these areas surface velocities of about 5 cm/sec are indicated, representing averages over a distance of about 50 km.

Some further knowledge as to the currents was obtained during the Norwegian-British-Swedish Expedition, 1949—52. In February 1950 it was observed that close to the barrier in about long. 11°W, the current was running towards the west, that is parallel to the local direction of the coast, and with a speed of about 20 cm/sec. During the following two years the party at Maudheim observed that icebergs were constantly drifting parallel to the coast, towards the west, but the speed was not measured.

In January 1951, when the "Norsel" paid her second visit to the Antarctic, the author undertook a series of current measurements at depths of 150, 220 and 340 m. The measurements were made when the "Norsel" was moored to the ice and in a locality where the depth to the bottom was 400 m and where the total thickness of the floating shelf ice was about 186 m of which about 150 m was submerged. The measurements which at each depth were carried out during more than 24 hours, demonstrated the presence of strong currents of tidal character, the diurnal component being the most pronounced. They also revealed the residual currents which are shown in table I. According to these values the current at 150 m was directed towards 280°, that is parallel to the

Table 1.

Residual currents measured from M/S "Norsel" when moored to the shelf ice in lat. 71° 01′ S long. 10° 56′ W.

Date, 1951	Depth m	Current cm/sec	Current towards
19—20 January	150	7.4	279
23—24 January	150	6.6	281
20—21 January	220	1.8	248
20—21 January	340	3.8	131
23—24 January	340	1.7	260

shelf ice in that particular locality. This had to be expected, because actually the current meter was lowered along the ice and at 150 m it was still above the lower surface of the shelf ice. At 220 m the direction of the current coincided with the general direction of the barrier (240°), but at 340 m two sets of observations gave variable results. This last feature may indicate that irregularities are present and that, therefore, the agreement between the two sets of measurements at 150 m may be fortuitous. Still, it is of interest to observe that according to the dynamic calculations upon which the presentation in fig. 1 is based the velocity of the current at the surface is twice that at 150 m and the latter is four times that at 220 m. If these ratios are applied to the observed average velocity at 150 m, 7 cm/sec, one obtains a surface velocity of 14 cm/sec and at 220 m a velocity of 1.8 cm/sec. In order to obtain the true surface current, the pure wind current, 8 cm/sec (see below) must be added. This gives a surface velocity of about 22 cm/sec which happens to be in close agreement with the estimate of February 1950. The value at 220 m also happens to agree with the value that was measured.

Regardless of the validity of these computations the fact remains that the current along the coast attains its greatest velocities directly off the coast, a feature which must be associated with the fact that the current is maintained by the action of the prevailing wind. In January 1951 the average wind vector was 5.9 m/sec towards 292°. At the surface the pure wind current would, therefore, be about 8 cm/sec towards 247°, (Sverdrup et al, 1942, p. 494), which means that at the very surface the current would be directed slightly away from the coast.

The total transport of water is in all events at right angles and to the left of the direction of the wind vector (the average stress of the wind), that is, in January 1951 towards 202°. Wind vectors have not yet been computed for all months of the period (March 1950 to 15. Jan. 1952) from which observations are available, but easterly winds prevailed in all months, and the transport of the surface layer towards the coast must therefore be a permanent process.

Such a transport must take place everywhere off the coast of Queen Maud Land because the prevailing wind direction can be expected to be similar all along the coast.

The "Norvegia» and "Discovery II" observations show that at distances from the coast greater than about 50 km there is always present a characteristic surface layer which has a thickness of 30 to 40 m, and, in summer, a salinity in the vicinity of 34 ‰ and a temperature a little below or a little above zero degree. In winter the temperature drops to freezing point and the salinity increases somewhat, but the highest salinity observed in winter, 34.47 ‰, (observed on board the "Deutschland"), lies still above the salinity of the deep water, 34.70 ‰. If

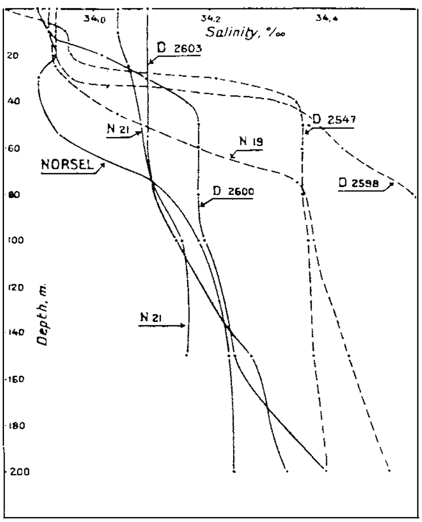

Fig. 2. Salinity as function of depth at four stations close to the edge of the shelf ice (full drawn lines) and at three stations at greater distances (dashed lines).

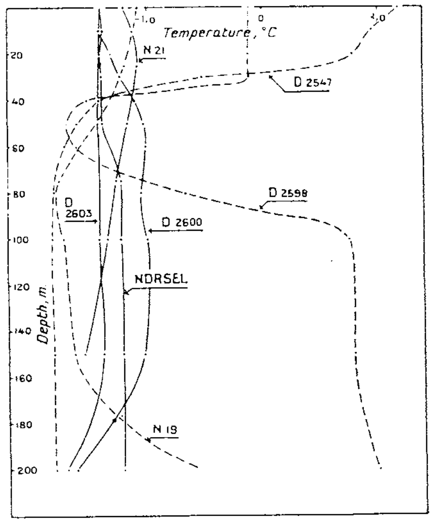

Fig. 3. Temperature as function of depth at four stations close to the edge of the shelf ice (full drawn lines) and at three stations at greater distances (dashed lines).

the iso-haline 34.4 ‰ is taken as representing the lower boundary of the surface layer, the thickness of the layer is less than 60 m.

This shallow layer of low salinity is transported towards the shelf ice under the influence of the prevailing wind stress. Continuity then requires a descending motion off the shelf ice, meaning that close to the shelf ice we must expect a thick layer of low salinity water. This is exactly what we find. Fig. 2 shows the salinity between the surface and a depth of 200 m at two stations very close to the barrier (N 21, 1930 and Norsel, 1951), at two stations at distances of less than 25 km from the coast (D 2600 and 2603, 1939), at two stations about 60 km from the coast (N 19, 1930 and D 2547, 1939) and at one station about 300 km from the coast (D 2598; 1939). The striking feature is that at all four stations in the vicinity of the coast the salinity remains less than 34.25 ‰ down to a depth of 150 m, whereas at about 60 km from the coast the salinity is nearly 34.4 ‰ between 80 and 150 m, and at greater distances it is close to 34.7 ‰ at 150 m.

Fig. 3 shows the temperature distribution at the same stations and reveals the surprising feature that at all four stations close to the coast

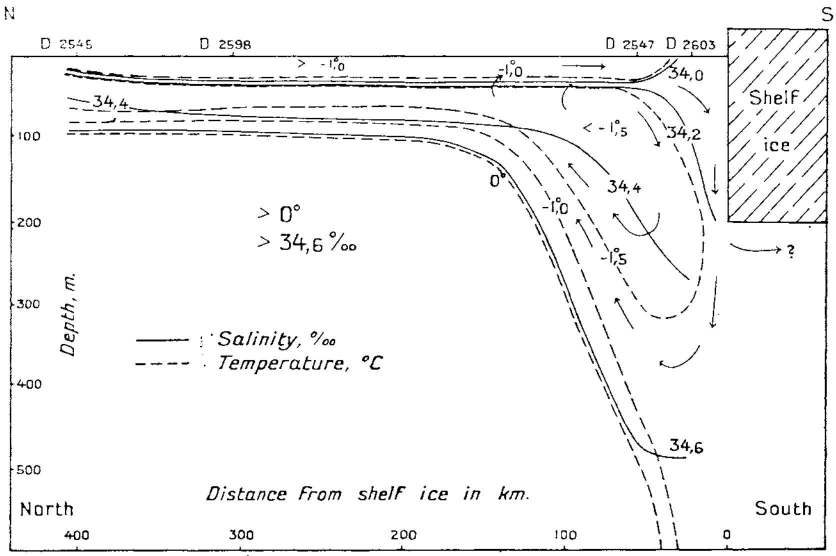

Fig. 4. Vertical section at right angles to the coast line in about long. 2°E Gr, showing distribution of temperature (dashed lines) and salinity (full drawn lines). Probable vertical circulation is indicated.

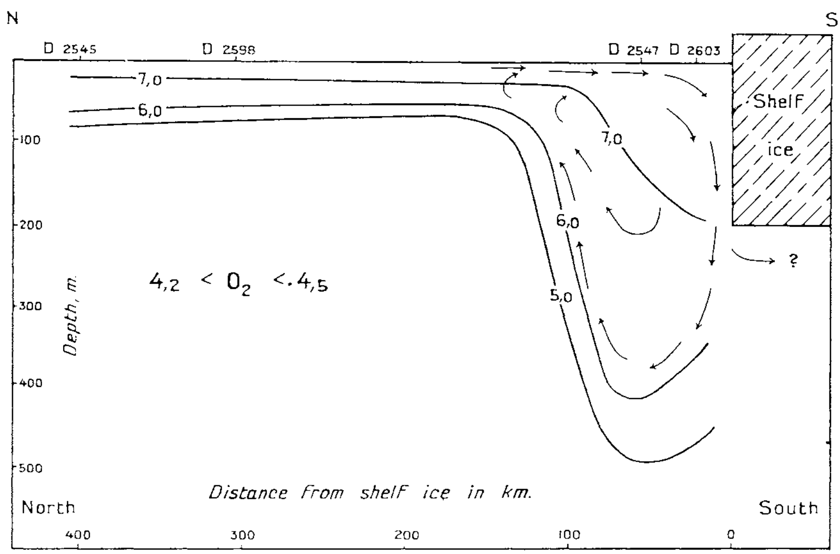

Fig. 5. Vertical section at right angles to the coast line in about long. 2°E Gr, showing distribution of oxygen content in ml/L. Probable vertical circulation is indicated.

the temperature lies between — 1° and — 1.4° down to a depth of 150 m. At the stations about 60 km from the coast the temperature is relatively high in the surface layer but between 60 and 150 m it is from — 1.6° to — 1.8°. At 300 km from the coast a minimum temperature of — 1.7° is found at 50 m. It is particularly noteworthy that from the "Norsel" the thermometers were lowered at a distance of only about 5 m from the ice wall but still the temperature was 0.7° above freezing point. This feature may be taken to indicate that the water sinks very fast along the ice wall, but it will be shown that some other explanation must be sought.

The features which have been described are also represented in a vertical section (fig. 4) that runs N-S in about longitude 2°E and in which observations at four "Discovery II" stations have been combined. When drawing the iso-lines it has been taken into account that the strongest current occurs close to the shelf ice and that the width of the fairly strong current is only 50 to 100 km. The depression of the isohalines and the relatively high temperature along the ice appear clearly. Arrows have been entered indicating the probable vertical circulation that may account for the observed features.

The character of the oxygen distribution, which is shown in fig. 5, confirm our conclusions. The high oxygen values near the shelf ice must be explained as related to a vertical circulation of the type that is indicated. One might assume that the high oxygen values resulted from vertical convection which in winter might reach to a depth of about 400 m, but such an explanation is incompatible with the fact that the temperature of the water very close to the shelf ice is from 0.5° to 0.9° above freezing point. This situation can be maintained only if the water in contact with the ice is rapidly renewed.

It is of interest to examine how rapidly the water close to the shelf ice may be expected to be renewed. For this purpose we may first attempt an estimate of the downwards velocity off the barrier. Assuming that the wind blows parallel to the coast the transport by the pure wind current is directed towards the coast and the total volume transport across a one cm wide vertical surface, T, is obtained from the equation:

$$T = \frac{\tau}{\varsigma\, 2\, \omega\, \sin\varphi} = 2.6 \times 10^{-3} \frac{\varsigma^{1}\, V^{2}}{\varsigma\, 2\, \omega\, \sin\varphi}$$

where τ is the stress of the wind, V the wind velocity, ς^1 and ς the densities of the air and the water, ω the angular velocity of the earth, and φ the latitude. With $V = 600$ cm/sec and $\varphi = 70^\circ$ we obtain

$$T = 0.85 \times 10^4 \text{ cm}^3/\text{sec}.$$

If the sinking takes place evenly from the barrier and out to a distance of 10 km $= 10^6$ cm, the average downwards velocity would be 0.85×10^{-2} cm/sec and with this velocity the water would need 17.6×10^6 seconds or 20 days in order to sink 150 m. This figure gives probably the order of magnitude of the time involved. It follows that during the sinking the same water mass cannot remain in contact with the ice wall because, if so, the "Norsel" observations would have shown decreasing temperatures along the ice wall. The constant temperature indicates an effect of intensive horizontal mixing, which also would explain the downwards increase in salinity which appears in fig. 4. The strong tidal currents, which according to the "Norsel" measurements attain velocities up to 18 cm/sec would contribute to the maintenance of the horizontal mixing.

In conclusion it will be examined if the transport of water of temperature somewhat above freezing point may have bearing upon the thickness of the shelf ice. As an example we will consider the Maudheim shelf ice which is 30 km wide and which at Maudheim has a thickness of 186 $\pm$ 5 m with the upper surface 37.5 m above sea level and with about 150 m submerged. The average annual accumulation during the last 16 years corresponds to 36.4 cm of water which would render an annual increase of the thickness of the shelf ice of 40 cm. In 1950—52 the measured accumulation amounted to more than 100 cm of firn but still the general height above sea level changed by less than 5 cm during twenty months (Robin, 1953, and verbal communication from V. Schytt).

Robin points out that in view of these facts and particularly in view of the fact that in case of the "eastern shelf ice" which is about 80 km wide, the thick inland ice, in a relatively short horizontal distance, tends to thin out to a floating ice shelf of thickness close to that at Maudheim, it appears as if the shelves tend to attain an "equilibrium thickness". Robin is of the opinion that such an approximate equilibrium thickness may be maintained by an increase of the area of the shelf ice. He states:

"In the absence of differential movement between different levels of the ice shelf, the following equation should hold:

$$\frac{\text{Annual net accumulation}}{\text{Equilibrium thickness of ice shelf}} = \frac{\text{increase in area per year}}{\text{total area}}$$

Annual net accumulation in the above would also include any loss or gain on the bottom surface of the shelf ice due to melting or freezing of the sea water."

In order to examine if melting at the bottom may be of importance one may compute the heat needed for melting an amount of ice equivalent to the accumulation at the surface, and compare this amount to the heat content of the water that is transported towards the coast by the wind. In this manner one may at least learn if the wind circulation is of importance to the problem.

With the Maudheim shelf ice 30 km $= 3 \times 10^6$ cm wide, and with an annual accumulation corresponding to 40 cm of ice we find that during one year 120×10^6 cm^3 $= 110 \times 10^6$ g of ice must melt along a one cm wide strip in order to offset the accumulation. With the heat of melting equal to 80 g cal/g the average amount of heat required is found to be 280 g cal/sec.

Furthermore, it must be taken into account that since the temperature of the ice rises when approaching the bottom of the ice, heat is conducted upwards. The temperature at 100 m below the surface is about — 17° C, but at the bottom, 186 m below the surface, the temperature must equal freezing point of the sea water, about — 1.9° C. Assuming a linear increase in temperature and a coefficient of heat conduction equal to 5×10^3 (Sverdrup et al, 1942, p. 74) we find that for a one cm wide strip of the shelf ice the average upwards flow of heat amounts to 26 g cal/sec. Thus, the total amount of heat that on an average must be supplied to the bottom is close to 300 g cal/sec.

The volume transport of water towards the shelf ice has previously been estimated at 8 500 cm^3/sec.; the mass transport is, therefore, 8 700 g/sec. In summer the temperature of the water that reaches the shelf ice is about 0.7° above freezing point, and for the whole year the deviation of the temperature from freezing point may be estimated at about 0.3°. With this value and with the specific heat of the sea water equal to 0.94, we find that on an average for the whole year the amount of heat which the wind current transports towards the shelf ice and which may be used for melting ice amounts to 2 450 g cal/sec. Therefore, if only about 12 per cent of the heat content which the wind current transports is used for melting ice at the lower surface of the shelf ice, the effect of accumulation is offset.

The above figures indicate that in case of the Maudheim shelf ice melting from below may be a very important factor in maintaining a stationary thickness of the ice, but serious difficulties arise if one attempts to generalize this conclusion and apply it to other ice shelves. It is of particular importance to observe that there is no reason why melting from below should lead to an «equilibrium thickness» of about 200 m or that this value should apply to ice shelves in different localities and of different widths. It is indeed probable that the thickness of ice shelves varies somewhat, but so far no striking differences have been recorded. The «eastern shelf ice» (east of Maudheim) has, as stated above, nearly the same thickness as the much narrower Maudheim shelf ice. It is even much more noteworthy that the very wide Ross Ice Barrier also has a thickness of about 200 m.

This discussion leads, therefore, to the conclusion that melting from below may take place in some localities where it may reduce the net accumulation, but the process cannot be expected to be of major importance to the possible equilibrium thickness of the ice shelves.

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