northern co-ordination and research centre
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SECOND REPORT ON THE BERING STRAIT DAM

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by

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INTRODUCTION

From time to time there have appeared in Russian journals statements of the possibility, in the future, of closing Bering Strait with a dam and pumping water across or through it. The direction of flow of the proposed pumping action, north or south, in the published articles is not always the same; in some a northward pumping is suggested, in others, southward. These ideas have attracted considerable public attention, as might be expected, and the habit of speculation of this kind appears to be contagious; proposals to close this or that strait in the Arctic Islands of Canada, for instance, or the Strait of Belle Isle, have appeared in some number. It is appropriate, therefore, to subject the Bering Strait scheme to some sort of critical appreciation, even though such review must necessarily be itself somewhat speculative; only very approximate arithmetic can be applied, and on many points it is possible only to make an educated guess at nature's response to a given event.

In a preliminary report on this subject (1) the conclusion was reached that to pump water through the dam in such quantity as to remove the arctic water layer from the Arctic Sea, and to maintain unfrozen Atlantic water at the surface, would be impossible. For purposes of argument, however, it was taken that this feat had been achieved and an estimate was made of its climatic and biological effects, which would be large. In this second report it is assumed that the building of the dam itself is quite possible, but that no effort is made to pump water in either direction. This is a less spectacular and less publicised version of the plan, but one whose effects might be significant, on the North American side rather than on the Russian or the European.

Bering Strait is only 74 kilometres (46 miles) wide and 45 metres (150 feet) deep. The Diomede Islands lie directly within the strait, between East Cape in Siberia and Cape Prince of Wales in Alaska. There is no southward outflow through the Strait of any significance. The northward inflow has been measured several times, with differing results; there is both annual and seasonal variation. The available measurements have recently been summarized by Coachman and Barnes (2), whose paper is quoted here: "According to these measurements, the transport of Bering Sea water to the north is about 1.4 million cubic metres per second in summer, and about one-fourth to one-third of this in winter. Thus the yearly average input to the Polar Basin may be estimated at $1 \times 10^6 m^3/sec$, which is in agreement with a recent Russian estimate of 37, 500 $km^3/year$ (3). This amount of water is ten times that introduced annually into the Arctic Ocean by all large Siberian rivers (4, 3). If this water entered the Arctic

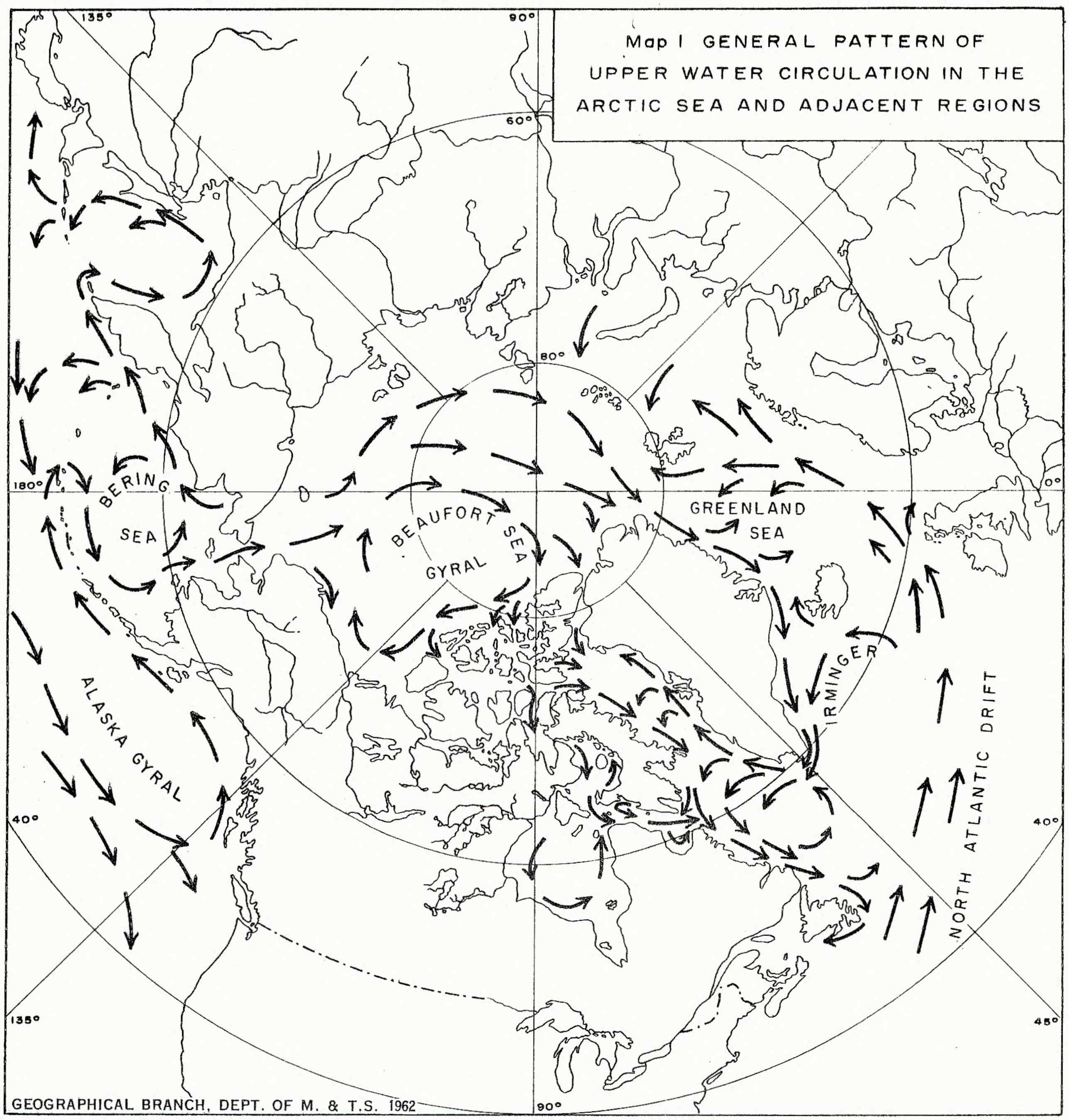
Ocean in a layer 100 metres thick without mixing, it would occupy a strip 100 miles wide from the Chukchi Sea to the North Pole."

Water transport in ocean currents is presented either in million cubic metres per second or in cubic kilometres per year, sometimes in cubic kilometres per hour. All three units involve many words, and when repeated often in one paper become tedious. I have already proposed (5) that one million cubic metres per second be called one "Sverdrup", after the late H.U. Sverdrup, and I suggest further that one cubic kilometre per year be called a "Bering"; these terms will be used in this report. One Sverdrup then equals 31, 536 Berings, and is the approximate rate of flow through Bering Strait. Since the rate of flow in ocean currents, especially in polar regions, varies greatly from season to season, it is often more convenient to use the Bering than the Sverdrup, the former being the total annual flow unit. On the other hand, using the Sverdrup involves smaller figures and greater arithmetic convenience.

Oceanographers have not yet settled on the precise names of certain northern bodies of water. In this paper the term "Arctic Ocean" refers to the waters enclosed by, and including, the Norwegian and Greenland Seas, the Barents, Kara and Laptev Seas, and Baffin Bay. Hudson Strait and Foxe Basin are considered to be separate inland bodies of water associated with this Arctic Ocean, and the channels between the Canadian Arctic Islands are channels of the Arctic Ocean. The southern boundaries of the Arctic Ocean on the Atlantic side, therefore, are the submarine ridges in Davis Strait, Denmark Strait (between Greenland and Iceland) the Wyville-Thomson Ridge between Iceland and the Shetlands, and the line between the Shetlands and western Norway. The central part of this water area, formed by the Polar basin itself, is here called the Arctic Sea (the "Polar Ocean" of Vowinckel and Orvig (6)).

The Arctic Sea is divided into two basins, each approximately 4000 metres deep, by the Lomonosov Ridge, discovered since the second world war by Russian expeditions; the top of this ridge lies between 1200 and 1500 metres below the surface (7), and extends from the north coast of Ellesmere Island to the Siberian shelf in the vicinity of the New Siberian Islands. Between Spitsbergen and Northeast Greenland lies the Nansen Ridge, about 1500 metres below the surface.

The pattern of inflow and outflow which form the Arctic Ocean circulation is illustrated in Map 1. To summarize first, qualitatively: Greater than the Bering Strait inflow from the Pacific is the Atlantic


Map I GENERAL PATTERN OF UPPER WATER CIRCULATION IN THE ARCTIC SEA AND ADJACENT REGIONS
135°
90°
60°
80°
180°
0°
40°
40°
135°
45°
90°
BERING SEA
BEAUFORT SEA GYRAL
GREENLAND SEA
IRMINGER
ALASKA GYRAL
NORTH ATLANTIC DRIFT
GEOGRAPHICAL BRANCH, DEPT. OF M. & T.S. 1962

contribution, most of which enters between Spitsbergen and Northeast Greenland, as the West Spitsbergen Current. There is also a not inconsiderable Atlantic inflow, according to Russian authorities (see below), east of Spitsbergen, from the northeastern part of the Barents Sea, which indeed is to be expected from the simple geography of the area. The rivers of Siberia and, to a much lesser extent, of North America, contribute a volume of water about one-tenth that of the Bering Strait inflow. Precipitation from the atmosphere and evaporation from the hydrosphere can be taken, for present purposes, as approximately equivalent and therefore as cancelling each other out.

The outflow channels from the Arctic Sea are two: From the northeast coast of Greenland and through the Canadian Arctic Islands. The East Greenland Current releases much of its water to the east within the Greenland Sea, that is, before it crosses the submarine ridge in Denmark Strait (8, 9). The Canadian Current, the name given to the southward flow along the east coast of Baffin Island, contains Arctic water from Smith Sound, Jones Sound and Lancaster Sound, and also mixed water from the northward extension of the West Greenland Current in Baffin Bay. Some of the Canadian Arctic outflow also comes through Prince Regent Inlet and Fury and Hecla Strait (10), joining the Baffin Island Current at the eastern end of Hudson Strait. The Labrador Current is composed of water from these Canadian channels and from the West Greenland Current.

For the quantitative expression of this transport equilibrium, and especially regarding the most northerly part of it, we are at present restricted to only a few estimates, and the estimation of the transport of ocean currents is at best an approximate affair. In choosing the particular figures given below, I have been guided by general considerations of averaging; transport of all the currents varies both seasonally and from year to year, therefore mean values must be taken. No more than an approximation can be achieved, but it is probable that starting from other values, and balancing the factors that must be balanced, the same answer would be reached in the end. Authorities for values taken are given in each instance, together with variant estimates and opinions. The real difficulty in this attempt to evaluate the effect of closing Bering Strait, the real source of inaccuracy or of generality, lies not in the transport values taken but in the decision on the fundamental effect on the equilibrium, as will appear below.

In the following quantitative account the larger unit, the Sverdrup, or million cubic metres per second, is used: It should be remembered that in all cases the figures given are averages for the year.

INFLOW

Bering Strait: 1.0 Sverdrup (2). Treshnikov (3) gives 1.19, Gordienko and Laktionov (11) give 1.17. These figures are in good agreement.

West Spitsbergen: 3.76 (7).

Barents Sea: 1.12 (7). Of the recent Russian authors on the subject, Timofeyev (7) is the only one who mentions this contribution from the Atlantic, quoting Timonov and Kuzmin (12).

Total Atlantic: 4.88 Sverdrups

Fresh water inflow (land runoff): 0.127 (7). This is a more recent and probably more accurate estimate than the earlier figure of twice this value given by Sverdrup (13). The figures for precipitation and evaporation have been ignored here, on the understanding that they approximately cancel each other out.

Total Inflow to the Arctic Sea: 6.00 Sverdrups.

OUTFLOW

Smith Sound: 0.43 (14).

Jones Sound: 0.29 (14).

Lancaster Sound: 0.49 (10). Bailey (15) gives different figures for these three channels, finding in one year a net northward flow through Smith and Jones Sounds. He also reported, however, a greater outflow through Lancaster Sound than did Collin, and at the Davis Strait level both authors, together with Killerich (14) and Smith, Soule and Mosby (16) are in substantial agreement.

Davis Strait, northward: 1.00 Sverdrup.

Total inflow to Baffin Bay, N. and S.: 2.21

Davis Strait, southward: 2.21

Davis Strait, net southward (Arctic contribution): 1.21 (10, 16). Killerich (14) gives 1.32.

OUTFLOW continued.

Fury and Hecla Strait: 0.51 Sverdrup (10). Collin's estimate is the only one available. His study of the Lancaster Sound system shows that of the total 1.00 Sverdrup that flows eastward into the western end of Lancaster Sound, a little less than half goes out through that channel, the remainder turning south through Prince Regent Inlet. A small proportion of this may flow westward through Bellot Strait, but most of it must flow eastward through Fury and Hecla. This is a considerable current for so small a channel.

Total Canadian Outflow: 1.72 Sverdrups. This is the total for the water of Arctic origin flowing into Baffin Bay through the Canadian Archipelago, and out of Hudson Strait. The land runoff into Hudson Bay would increase this by a small amount, which is ignored here. The figure of 0.51 for Fury and Hecla Strait is in close agreement with the U.S. Coastguard estimate of 0.50 Sverdrups for the net outflow from Hudson Strait.

Northeast Greenland, southward: 4.28 Sverdrups. This is the calculated outflow from the relevant estimates above (total inflow less Canadian outflow); it is in fairly good agreement with the figure arrived at from Timofeyev's (7) material, 125,818 Berings or 3.97 Sverdrups. Killerich's (8) maximum estimate was 2.00. The higher figure is taken here simply because it balances the transport budget, and the estimates of inflow and outflow upon which it is based seem sound and reasonable. Incidentally, Timofeyev's (7) estimate for the Canadian Arctic outflow is substantially lower than the estimate used here (1.00 as against 1.72), but it was based upon the transport exchange at the Denmark Strait level, which is admitted by all to be still obscure. If Timofeyev's figure for the Canadian outflow were to be taken, the Northeast Greenland outflow would have to be increased far above his own estimate for it. As it is, it is probably too high.

VOLUME TRANSPORT FURTHER SOUTH

Denmark Strait: net southward: 2.8 (17); 4.76 (7).
The wide variation in estimates at this point in the circulation is no doubt partly due to actual wide seasonal and annual variation, but there are obviously other reasons as well. The precise body of water to which the estimates refer is not always clear. Timofeyev's (7, 18) figures are based upon sections within the strait itself, between latitudes 63° and

VOLUME TRANSPORT FURTHER SOUTH continued

69°N, and measure the total overflow over the sill, southward, a body of water which undoubtedly contains much more than northeast Greenland water from the Arctic Sea. Large contributions from the Greenland and Norwegian seas are also included. Dietrich's observations were made farther south, in latitude 60°N., and the 2.8 Sverdrups refer only to the upper current; there is another and much larger southward-flowing current below the 1000-metre level, with characteristics of about 1° to 3°C and salinity 34.9 o/oo, described as "deep Arctic water......formed in parts of the European Northern Sea during the winter vertical convection", mixed with warmer Irminger Current water. This deep current does not concern us here at all, but it may well be that part of it represents water which flowed over the Denmark Strait sill at depth, and which is included in Timofeyev's estimate for southward flow. There is another estimate of the southward flow in Denmark Strait, that of Zaicev (22), which is not given serious consideration here. Assuming that the volumes of the East Greenland Current and the southward current in Denmark Strait are in the ratio of 6:1 or 8:1, which is quite improbable, Zaicev reaches a figure of only 0.42 Sverdrup for the Denmark Strait current. This leads to the deduction that the southward current from Baffin Bay, through Davis Strait, has the enormous volume transport of 7.25 Sv., which is equally unacceptable. Whatever the truth on this point may be, it is clear that even considering Dietrich's upper current alone, a large proportion of it is Irminger Current water and only much less than half of it water from Northeast Greenland. To quote from Dietrich, in free translation: "We are dealing here with the East Greenland Current" (at latitude 60°N.). "It transports not only very cold East Greenland water but also warmer mixed North Atlantic and Irminger water of the Irminger Sea". Going by the actual temperature and salinity measurements at stations within this current, I am taking it that rather less than one Sverdrup is Arctic water from Northeast Greenland. In its passage from the northeast tip of Greenland the Arctic water separates, sending much of its volume eastward into the Greenland Sea circulation, taking part in the cold currents which run to the east of Iceland, as mentioned above (8, 9).

West Greenland Current:

The West Greenland Current picks up Labrador Sea (Atlantic) water in the region of southwest Greenland, and discards a great deal of its volume to the westward before reaching the Davis Strait ridge. The following are estimates of its volume transport at four different levels up the coast.

VOLUME TRANSPORT FURTHER SOUTH continued

Cape Farwell: Annual and seasonal variations are considerable here, and there is apparently a great increase in the current on rounding the Cape. Working from annual sections running southwest from the Cape, Soule (19) found an average variation of from almost 7 Sverdrups in March to over 4 in August, in the years between 1928 and 1949.

Ivigtut: 7.40 (16), in July - September; 4.64 (14) in October.

Godthaab: 5.3 (16).

Holsteinsborg: 1.3 (16).

Labrador Current: 7.00 off Hamilton Inlet (14). A little to the south, off South Wolff Island, Smith, Soule and Mosby (16) and Soule (19, 20) give estimates which average close to 5.0.

These figures of volume transport are summarized in Table 1.

TABLE 1.

TRANSPORT BUDGET FOR THE ARCTIC SEA

AND

TRANSPORT OF PERIPHERAL CURRENTS

(Above 1,000 Metre Level)

	Inflow	Outflow
Bering Strait	1.0 Sv.	
West Spitsbergen	3.76	
Barents Sea	1.12	
Land runoff	0.12	
Smith Sound		0.43 Sv.
Jones Sound		0.29
Lancaster Sound		0.49
Hudson Strait (net, E.)		0.51
N.E. Greenland		4.28
	6.00	6.00

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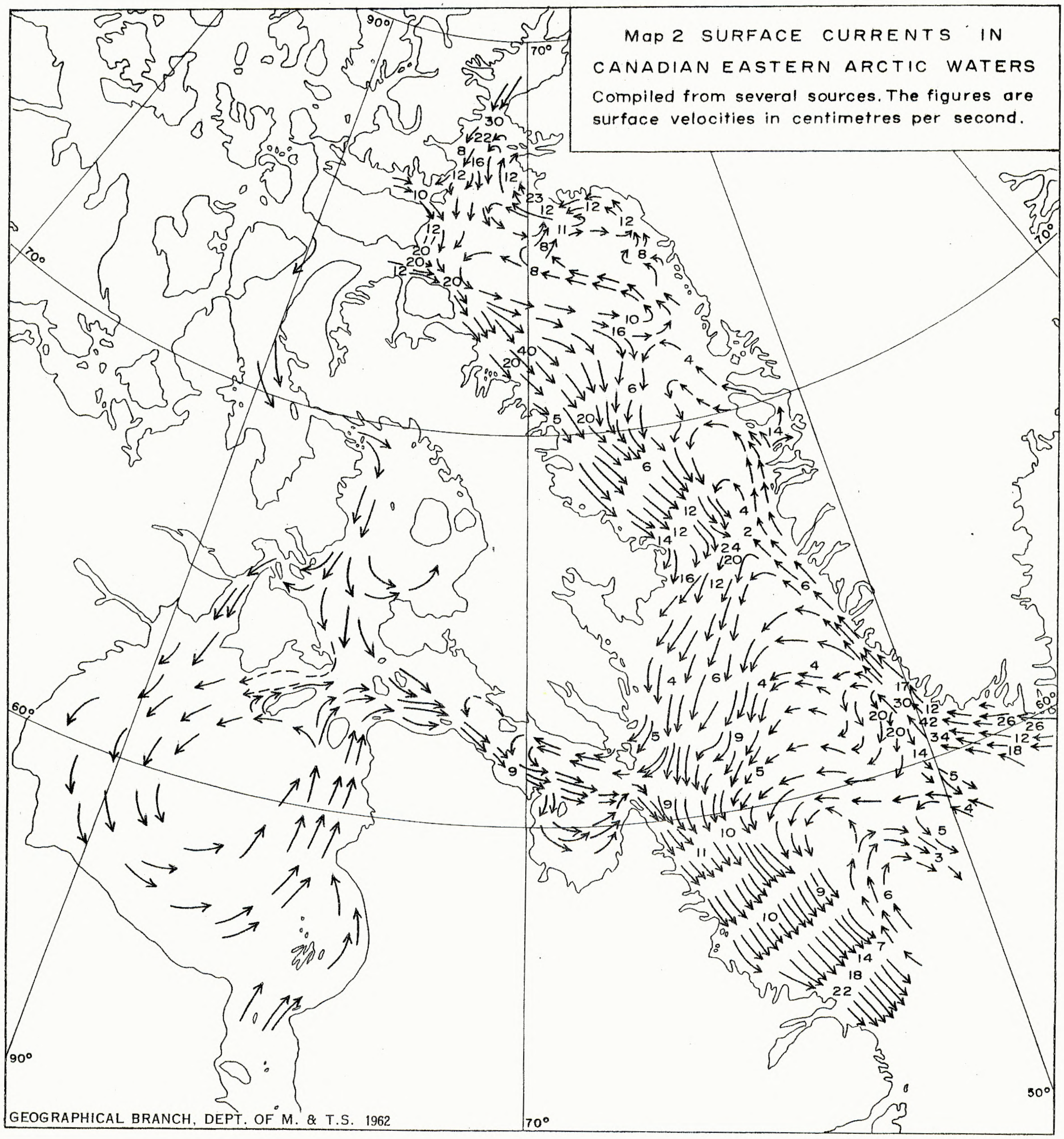
Map 2 SURFACE CURRENTS IN
CANADIAN EASTERN ARCTIC WATERS
Compiled from several sources. The figures are
surface velocities in centimetres per second.
GEOGRAPHICAL BRANCH, DEPT. OF M. & T.S. 1962
90°
70°
60°
50°

Denmark Strait, net. S.	4.76 Sv.
East of Cape Farewell S.	2.80
West of Cape Farewell N.W.	6.00
Ivigtut, N.W.	7.00
Godthaab, N.	5.30
Holsteinsborg, N.	1.30
Hamilton Inlet, S.	7.00
South Wolff Island, S.	5.00

- - - - - - - - - - - - - - -

THE PROBABLE EFFECTS OF THE DAM

The Bering Strait current amounts to a little more than one-fifth of the Atlantic inflow to the Arctic Sea, the two being in the proportion of 1 to 4.88. In terms of heat carried, the Bering Strait is less than one eighth as effective as the Atlantic inflow (7). The heat change caused by damming the strait is ignored here. The Bering Strait water as it is lies below the surface of the Arctic Sea and its heating effect upon the surface is not significant (2). In fact for the purposes of the present discussion the whole question of the vertical arrangement of the water masses in the Arctic Sea, interesting as it is, may be dismissed. All we are concerned with is the probable change in the equilibrium of the surface currents on closing Bering Strait, and in particular, the changes that might occur in the flow and composition of the East and West Greenland Currents, the Canadian Current and the Labrador Current.

It might be expected, as already suggested (5), that if the inflow to the Arctic Sea is suddenly decreased by 1.0 Sverdrup, then the outflow from the Arctic Sea is decreased by that amount, and that therefore the Canadian and East Greenland outflows would be slowed down to the extent of one Sverdrup shared between them according to their present proportion, namely 1.72: 4.28, or 1:2.5. But it may not be as simple as this. Closing Bering Strait would have effects upon the Pacific circulation, noted below, and might be expected to feed its effects back to the North Atlantic and hence to the Arctic Sea by way of Cape Horn and the Cape of Good Hope. Another point which would certainly enter the question is the effect of the atmospheric pressure pattern in the North Atlantic and Arctic upon the movement of the waters beneath it. Is the Atlantic water pushed in, as it were, to the Arctic Sea, or is it pulled in to replace surface water flowing out? Is the Arctic water outflow a wind-drift as some think? The probability is that the outflow from the Arctic Sea would indeed be reduced, but not by the whole volume of the Bering Strait present inflow; that an adjustment would take place in the steady state and that the Atlantic inflow would be increased slightly. The precise proportions must await a different approach, and a better understanding of the forces involved. For present purposes, I propose to do the approximate arithmetic necessary to show what would happen if the Arctic outflow were reduced by the full one Sverdrup; to treat that as a maximum effect and to work from there.

Consider first the current immediately to the east of Cape Farewell. The 4.28 Sverdrups which we have taken as the volume transport of the East Greenland Current at Nordostrundingen (the northeastern extremity of Greenland) is shared, downstream, between the southward current over the Denmark Strait sill and the Greenland Sea circulation. Not all of it is Arctic water; according to Kiilerich (8) up to 20% of it is returning Atlantic water, as is to be expected from the depth of the current. The contribution of the East Greenland Arctic water to the current immediately to the east of Cape Farewell is apparently small, following Dietrich (17), quoted above. Let us assume that the present average proportions at this point in the current, where the transport has been taken as 2.8 Sv., are of the order of .75 Arctic water to 2.05 Atlantic water, and that the respective mean temperatures of the two components are -1.5 and 5°C. The average temperature for the whole current is obtained from the formula

$$\frac{ax + by}{a + b}$$

(where a and b are the volumes per second of the two water bodies, and x and y their respective mean temperatures), and comes to 3.26°C.

The East Greenland Current is greater than the Canadian Arctic outflow in the proportion of 2.5:1. At Nordostrundingen therefore the reduction in outflow upon closing Bering Strait, assuming the total reduction to be one Sverdrup, would be 0.715 Sv. This is shared between the Arctic and Atlantic components of the current, and the Arctic share has to be reduced again to allow for eastward diversion in the Greenland Sea. Without adequate quantitative data to work from, the Greenland Sea and Denmark Strait circulations being still far from satisfactorily studied, it is possible only to guess at a reasonable figure. Quite arbitrarily, but with the quite apparent fact in mind that the loss of East Greenland water to the Greenland Sea must be considerable, I propose to reduce the volume transport of Arctic water (.75 Sv.) by one half of .715 Sv., or .357. The new figure is thus .395 (.40) Sverdrups, for the Arctic water component immediately to the east of Cape Farewell.

A new difficulty arises at this point. We have reduced the Arctic component in the East Greenland Current east of Cape Farewell. Is the whole current thereby the less in volume, or does Atlantic (Irminger) water make up the difference? Or is the result somewhere in between? Working on this same current after it has rounded Cape Farewell, Soule, Carter and Cheney (21) comment that in 1948 "a deficiency in the Irminger Current was partially compensated for by a direct contribution from the North Atlantic eddy..." If the deficiency in the Arctic water were similarly compensated for, the transport would remain approximately the same, and whereas this might make little difference in summer, it would increase the heat transport of the current in winter. Balancing the summer effect, when the lesser velocity of the compensated current would allow for greater solar heating, against the winter effect of greater heat transport, let us take it that any such compensation would have only minor significance. We now have the current off Cape Farewell to the east with a reduced transport of 2.4 Sv., made up of .40 Sv., Arctic water and 2.0 Sv. Irminger water, giving an average temperature value of 3.99°C. (If the Irminger water is allowed to make the current up to the original 2.8 Sv., the resultant temperature is 4.07°, not very much higher).

The reduction in the Arctic water, therefore, caused by closing Bering Strait, causes a rise in the average temperature of the water of .66 or two-thirds of a degree centigrade, which by itself is by no means insignificant. The accuracy of the transport volumes taken here, and of the component proportions, are of secondary importance. The change to be expected will be of the order of two-thirds of a degree.

The current to the west of Cape Farewell, after rounding the cape, has increased in volume by picking up more Irminger water and Labrador Sea Atlantic water. The transport figure here (see above) is of the order of 6.00 Sverdrups, at least in the early part of the year, when the East Greenland and Atlantic water are in approximately equal proportions, according to Soule (1951). There is considerable variation in these proportions from year to year, and the East Greenland contributions can apparently fall to zero in September. This means that at that time of year the effect of the Bering Strait dam upon the West Greenland current may be nil.

Taking the Atlantic water with a mean temperature of 5.5°C., and the East Greenland water before and after the dam as at 3.33° and 4.0°, the effect west of Cape Farewell is reduced to a rise of about 0.35° during the spring and summer. At the level of Ivigtut this effect is further reduced by the addition of more Labrador Sea water, possibly as much as 1 Sv., which gives a rise of 0.3° as the effect of the dam. North of Ivigtut the West Greenland current becomes progressively reduced by the loss of water to the westward. Moreover, the temperature rise of a little less than one-third of a degree, gained so far, would become progressively less as the effects of long winter cooling increased northwards. It is reasonable to suppose that the effects of the Bering Strait dam would not be measurable in the West Greenland current north of the Davis Strait ridge at the level of Holsteinsborg.

To continue downstream: The Canadian outflow from the Arctic Sea consists entirely of Arctic water, altogether 1.72 Sverdrups, of which 1.21 enter Baffin Bay through Lancaster, Jones and Smith Sounds. The remainder, 0.51 Sv., flows out, according to our present scheme, through Fury and Hecla Strait, Foxe Basin and Hudson Strait. The Canadian share of the outflow reduction upon closing Bering Strait is 0.285 Sv., or say 0.3, shared between Baffin Bay and Hudson Strait. The Baffin Bay reduction is .211, so that the inflow to Baffin Bay from the north becomes 1.21 - .211, or 1.00 Sverdrup. The Hudson Strait share of the reduction is 0.089, reducing the flow from .51 to .42.

Within Baffin Bay itself, and the Foxe Basin-Hudson Strait Channel, the effects of this reduction would in all probability be negligible, beyond a slight upward sun-warming effect in summer owing to the reduction of transport pressure from the north of about one-sixth. There is no significant admixture of warmer water which would increase in proportion on the reduction of the Arctic water; most of the heat of the West Greenland current has turned west and south in the Labrador Sea.

There would be a slight change in the waters off southeast Baffin Island, immediately south of the Davis Strait ridge. Allowing 1.21 Sv., at approximately -1.5^{o} for the Canadian current water, and 1.00 Sv., at 1^{o}C. for the West Greenland water from Baffin Bay, the mean temperature of the current is $-.42^{o}$ before building the dam and $-.3^{o}$ afterward. In the Labrador Current off Cape Chidley the effect would be greater, owing to the addition of the Hudson Strait contribution and the warming of the West Greenland water south of the Davis Strait. Allowing a total transport here of 3 Sverdrups, made up of 1.72 Sv., Canadian current water at -1^{o} (this should perhaps be lower, but the precise values taken are immaterial), and 1.28 Sv., of West Greenland water at 1^{o}C., the average temperature in the core of the current is $-.15^{o}$ before the dam, .31 after, giving a rise of $.46^{o}$.

In the Labrador current farther south, off South Wolff Island (south of Hamilton Inlet), the effect is much the same as farther upstream. Here the current is about 5 Sv. strong, made up of 3 Sv. from the Chidley region and 2 Sv. added Atlantic water from the Labrador Sea, most of which has split off from the West Greenland current. At $-.15^{o}$ and 4^{o} respectively, the mean temperature before the dam is 1.51°; after closing the dam, with the Labrador current water and the West Greenland water raised to .31 and 4.25° respectively, the new figure is 1.98°, a rise of $.47^{\circ}$.

The most significant changes, therefore, which we have so far discovered, are in the region immediately east of Cape Farewell, Southwest Greenland, and in the Labrador current. In the latter water, a rise of about half a degree is to be expected. A change in the hydrographic balance in Ungava Bay is also to be reckoned with, since West Greenland water in small amounts enters there through the eastern end of Hudson Strait.

What would these heat increases mean in terms of biological production, ice conditions, and weather? As regards the weather, no prognostications are to be offered here. No doubt southeast Greenland and the coast of Labrador would become somewhat milder and foggier, even foggier than they are at present, and the climate of the extreme south of Labrador would come to resemble that of Newfoundland more than it does at present. Newfoundland itself would be affected. But I am sure that my competence in this whole matter ceases when the question emerges from the water; and as in the preliminary report on this subject, I continue to regard the variables in the atmospheric effects too many and too illusive to make reasonable prophecy possible.

The atmospheric effects anyway would be the least important; man does very well in any climate provided the resources necessary for him are there and can be developed, or can be imported and maintained economically. In the present respect, the biological effects in the sea are the nub of it.

As regards these biological effects, and also changes in ice conditions, it should be made clear to begin with that the changes to be expected upon the closing of Bering Strait are much less than have already taken place since 1915 in West Greenland. The warming in the hydrospheric climate that occurred between 1915 and about 1945 in West Greenland involved a rise in mean temperature far above the change to be expected, from the analysis given here, on building a Bering Strait dam. Nature has done much better than man could do; and since the climate on the large scale is probably in a cooling phase (the events of 1915-45 may be looked upon as a short-term reversal of a general downward trend), the closing of Bering Strait could not be expected to be any permanent defense against this cooling. It would, however, change the heat and water transport pattern of the north, a change which would appear at its maximum in the coastal waters of Labrador. I am assuming always that stopping the Bering Strait inflow to the Arctic Sea would not cause an equivalent increase in the inflow from the Atlantic side.

The events to be reckoned with, then, are (1) a rise in the temperature of the coastal waters of southwest Greenland of about one quarter of a degree Centigrade, (2) a temperature rise in the Labrador current of almost one half a degree, and (3) a reduction in volume transport in both the West Greenland and the Labrador currents amounting to approximately 0.15 or between one sixth and one seventh of their present transports. These are the maximum changes to look for; they could well be less.

The reduction in velocity of flow reduces the Coriolis effect upon the currents in question. This effect results from the fact that whereas we treat the motion of currents as though they moved in a stationary frame of reference, in fact the frame of reference is rotating with the motion of the earth, and with bodies as large as ocean currents this difference has to be allowed for. The effect is a twisting to the right, in the northern hemisphere, of all moving bodies; it is maximal at the poles and zero at the equator. Specifically, this means that the East Greenland and West Greenland currents, and the Labrador current, press in to the coast with a force proportional to their velocities. A reduction in the velocities allows the currents to shed more water to the left of their courses under the effects of any local pressure systems that may exist, a phenomenon that has already been demonstrated empirically for the West Greenland Current by Kiilerich (23). Kiilerich showed that the transport of that current varies from year to year and that the extent to which it holds close to the Greenland coast is proportional to the transport.

The importance of this change centres in the eastern entrance of Hudson Strait. At this point the reduction in transports of the Canadian Current and the West Greenland Current allows easier access for the West Greenland water into Hudson Strait. It has already been suggested (24) that a lessening of the intensity of circulation of the North Atlantic and Arctic system, which appears to be under way at present, would allow more West Greenland water to move over to the Canadian side and thus cause a warming for some years locally, during a period of general Atlantic cooling. The reduction of transport resulting from the Bering Strait dam would accentuate this effect, and permanently. In Ungava Bay, this would result in the invasion of Atlantic subarctic species such as the Capelin (Mallotus villosus), the Atlantic cod (Gadus morhua), which is at present normally found only in the extreme northeast of the bay, and perhaps also the redfish (Sebastes sp). These are already on the verge, as it were, of becoming part of the normal Ungava Bay fauna. The Capelin was reported in very large numbers in 1959 (25), when the cod was also much more widespread than usual, and Sebastes was found in the northern part of the bay in the same year by Templeman (26). The extra push resulting from the Bering Strait dam would be expected to establish these species in Ungava Bay. They would no doubt be migrants, as the cod is at present, leaving the bay in the late fall and reappearing in the summer.

What is to be expected in Ungava Bay is also to be looked for, and more so, in northern Labrador. Capelin and cod would be abundant, and in fact the whole fauna of the Labrador would be expected to show a northward shift, the precise extent of which cannot be forecast.

The expected marine climatic change in the Labrador Current would be something new, for the 1915-45 warming had very little effect on the Labrador coast, owing to the blanketing action of the cold Canadian Current from Baffin Bay. The same was true in East Greenland, where the East Greenland Current, which increased in intensity, shielded that coast from the Atlantic influence. But with the Bering Strait dam the Canadian Current becomes decreased in flow, allowing an increased West Greenland and Labrador Sea influence along the Labrador coast.

The simple way to estimate the biological changes, which has been applied here, is to examine the changes which actually took place in West Greenland and to adjust for the difference between the temperature rise which actually occurred there and the forecast change which is to be expected in Labrador (and in West Greenland) on closing Bering Strait. The West Greenland events are abundantly documented (27, 28, 23, 29 etc.), so far as changes in distribution of fish and mammals are concerned, but there is a serious lack of continuous temperature measurements year after year, during the critical years of temperature rise. From what records exist, summarized by Dunbar (28), it is apparent that the temperature increase in the core of the current was of the order of 2^{o}C at the most, and that the present temperature regime in the Labrador Current, in which the main water mass lies between 0.0 and 2.0^{o}C (30), corresponds to the present West Greenland condition approximately between Disko Island and Upernavik; it is a little too low for the successful growth of cod eggs and larvae. A rise in 0.5^{o}C in the Labrador Current water would bring the Labrador conditions closer to the present situation in the neighbourhood of Holsteinsborg, or in the stretch between Sukkertoppen and Disko Bay. Judging from what is known of the spawning areas of cod in West Greenland and on the Labrador coast at present (31, 32), this would extend the spawning grounds of the Labrador fish considerably northward, so that spawning might well take place along the whole of the southern half of the coast; according to Thompson (32) cod eggs and larvae are found, on the Labrador coast, only in the southern part, south of Hamilton Inlet. A spread northward of the spawning area would be accompanied by a summer distribution of abundance of post-spawning fish up to Cape Chidley and into Ungava Bay. It would be accompanied by a general rise in the total productivity of the Labrador Water.

The sea mammals would probably be little affected in the Eastern Arctic. Labrador at present is not rich in seals, and the walrus has disappeared. Winter conditions in Ungava Bay and in Hudson Strait would not be significantly changed. Changes in summer ice conditions are difficult to forecast, if not impossible, but it is very doubtful that the summer population of seal, consisting now (in Ungava Bay), mainly of bearded seals (Erignathus), would be altered one way or the other. The ice in Baffin Bay probably would be affected so little as to be unimportant in this discussion; West Greenland water increase would be negligible, and the most that could be expected would be a slightly decreased output of sea ice through Davis Strait.

The Beaufort Sea Area.

The Faunistic effects to be expected in the waters north of Alaska and the Mackenzie district are clear; the area would become strictly arctic in the marine environment, rather than subarctic. That is to say, there would be no admixture of Pacific (Bering Sea) water at all, and the Pacific elements in the fauna would either disappear or become even less important, as relicts, than they are now. The important species concerned are the Pacific cod (Gadus macrocephalus), Pacific herring (Clupea pallasii), starry flounder (Platichthys stellatus), and capelin (Mallotus villosus). None of these is of any great significance at present in the Beaufort and Chukchi Seas, and the loss of them would therefore be quite unimportant. On the positive side, the change to strictly arctic conditions would favour the mammals, especially the seals.

The Beaufort Sea changes would thus be of little importance in terms of sea-food. Ice conditions would probably become a little more troublesome along the coast, comparable to Siberian shelf conditions beyond the influence of non-Arctic water. Although coastal ice conditions in the Beaufort Sea are apparently largely a matter of local winds, the lack of Pacific water would in this regard be a disadvantage. Apart from this, the problem of sea transportation from the south presents little difficulty; suitable locks or gates could be built into the dam and maintained at small cost compared with the cost of the dam as a whole. Climatically, little change is to be expected except for the better, towards drier and more open skies in summers. There is, however, one result to be expected which holds considerable scientific interest, even though its economic bearing may be small; namely the possible fate of the Beaufort Sea gyral, or anticyclonic (clockwise) circulation at the surface.

From just north of Bering Strait roughly to the Pole, from there to the north coast of Ellesmere Island, and thence along the Canadian Archipelago shelf back to the mainland Canadian coast and the coast of Alaska, there is a wide gyre of upper water circulation to the right, forming a large eddy in the surface circulation of the Arctic Sea as a whole. At first sight this is a curious and unexpected situation; one would expect the Bering Strait current, on entering the Arctic Sea, to turn sharply to the right in accordance with the Coriolis effect. A small portion of it in fact does this, but most of it continues due north and is not deflected to the right until it nears the Pole. The reason for this appears to be that the Bering Strait water is drawn towards the East Greenland outlet, across the Pole, where it meets a bottleneck and is deflected to the right to form the eddy. Part of the gyral water forms the outflow through the Canadian Arctic Islands.

If Bering Strait were closed, this gyral would no doubt disappear. Coachman and Barnes (2) have shown that the gyral is composed partly of Bering Strait water, lying just below the surface, and that the slightly higher temperatures belonging to the Bering Current can be traced along the gyral. Closing the Strait would have the effect of putting the southern Beaufort and Chukchi Sea water in the same position as the Siberian shelf water; there would be a general movement of water away from the coast, spreading partly toward the northeast Greenland "gate", partly toward the Canadian Arctic island channels.

Bering Sea and North Pacific

Damming a river normally forms a lake; but to dam a stream of one Sverdrup transport, on the periphery of a system so vast as the Pacific Ocean, could not be expected to have any significance at all to the North Pacific. Applying the principle used here for the Arctic Sea, to the Bering Sea, but in reverse, closing an outlet should result in diminishing the inflow by that amount. The Bering Sea would become either more sluggish in circulation, or the intensity of circulation would be reduced and the outflow in the East Kamtchatka Current would be increased, producing a new equilibrium. If the outflow were increased, the effect would be the outpouring of more cold water into the Sea of Ohkotsk and the Oyashio Current. The effect on the North American side would be very small. The intensity of the circulation in the Alaska Gyral might be raised a little, but significant temperature changes are not to be expected.

Seasonal Oscillation

Both the Bering Strait and the Atlantic influxes oscillate quite markedly by season, and the two are in opposite phase. The Bering Strait inflow is strongest in summer, weakest in winter, according to Basakov, quoted by Timofeyev (7); the Atlantic inflow at the Faroe-Shetland Channel is strongest in winter, weakest in summer, according to Tait (33). Information on the Atlantic inflow at the Spitsbergen level is lacking; a considerable lag might be expected. If the Spitsbergen-Barents inflow has an oscillation at all similar to the Faroe-Shetland Channel, then closing Bering Strait would presumably have the effect of increasing the amplitude of the Atlantic oscillation; at present the winter maximum is of the order of five or six times the summer minimum. Increasing this difference would have the effect of increasing the oscillation in the Arctic outflow, which at present is strongest in the spring.

POSTCRIPT

On the analysis given here, and it must be repeated that such an analysis is of necessity somewhat speculative, it appears doubtful whether the benefits gained from a Bering Strait dam would be worth its cost. Moreover, the benefits are largely eastern Canadian, felt to a lesser extent in Greenland and possibly Iceland. Considering that Bering Strait is contained by territory which is neither Canadian nor Danish, the contingency of the dam ever being seriously considered is, I think, remote. It is, however, a highly intriguing possibility at the very least, and it would be a pity to drop the subject completely. The most progressive and helpful step would be to build a working model of the Arctic Basin with a removable dam in Bering Strait, somewhat like the Hecate Strait model recently completed at Nanaimo, but bigger. In the meantime, the Bering Strait scheme must remain, in the words of the Soviet Minister of Fisheries, "something to think about for the future".

SUMMARY

1. A reasonable budget of water transport into and out of the Arctic Sea is offered, made up from all available sources. The total budget is considered to be 6.00 Sverdrups (million cubic metres per second), averaged over the year. This is equivalent to 189,216 Berings (cubic kilometres per year).

2. The maximum temperature effect to be expected after closing Bering Strait is estimated to be a rise in the mean temperature of the West Greenland Current in Southwest Greenland of about one quarter of a degree Centigrade, a rise in the mean temperature of the Labrador Current of a little less than one half of a degree, and a reduction in the volume transports of both currents amounting to between one-sixth and one-seventh of their present transports. Effects are also to be expected in the Greenland and Norwegian Seas, but these are not estimated here.

3. Only very short and cursory summaries of the effects in the atmosphere are offered, for reasons of their general unpredictability. Ice conditions would be expected to be ameliorated to a small extent in summer, from Baffin Bay southward. The present seasonal oscillation in the flow of the Labrador and West Greenland Currents might be altered, in the direction of greater amplitude.

4. Marine biological effects are summarised as a northward shift in general productivity in both West Greenland and Labrador, which would include the spawning areas of the Atlantic cod. Atlantic cod and other subarctic fish species would become more abundant and widespread in summer in Ungava Bay and eastern Hudson Strait; but they would remain migratory. No significant changes in the distribution and abundance of the marine mammals are to be expected.

5. These effects cannot be called spectacular, and it is emphasised that they are much less than like changes in West Greenland in the 1915-45 warming period. Where ocean currents and climatic change are concerned, the efforts of man, at present, compare poorly with the accomplishments of nature.

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