Micronutrient distributions in the East Siberian and Laptev seas during summer 1963[1]

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ABSTRACT. The dominant factors influencing the micronutrient distributions observed in the East Siberian and Laptev seas during the summer of 1963 appear to be the summer phytoplankton bloom, respiratory processes, the outflow of the Lena River, and the different origins of the high-salinity waters found in the two seas.

RÉSUMÉ. *Distribution des microéléments nutritifs dans la mer de Sibérie orientale et dans la mer de Laptev au cours de l'été 1963.* L'éclosion estivale du plancton, les processus respiratoires, la décharge du fleuve Léna et les origines diverses des eaux de haute salinité semblent être les facteurs dominants qui influencent la distribution des microéléments nutritifs observée dans la mer de Sibérie orientale et dans la mer de Laptev.

РЕЗЮМЕ. *Распределение питательных микроэлементов в Восточно-Сибирском море и море Лаптевых летом 1963 года.* Исследования, проведенные летом 1963 г., показали, что определяющее влияние на распространение питательных микроэлементов в Восточно-Сибирском море и море Лаптевых оказывают летнее цветение фитопланктона, дыхательные процессы, сток Лены и различное происхождение вод с высоким содержанием соли в указанных морях.

INTRODUCTION

A few data are available on the distributions of salinity and temperature in the East Siberian and Laptev seas, but until now there have been no data on the distributions of micronutrients. In order to measure micronutrients and to make systematic observations of salinity and temperature, the U.S.C.G.C. *Northwind* occupied 140 oceanographic stations in the East Siberian and Laptev seas (Fig. 1) in the summer of 1963.

DESCRIPTION OF THE AREA

The East Siberian and Laptev seas are shallow (Fig. 2), but they tend to deepen gradually as the edge of the continental shelf is approached; the East Siberian Sea deepens towards the east.

The average precipitation in these seas is approximately 12 cm./year (U.S.

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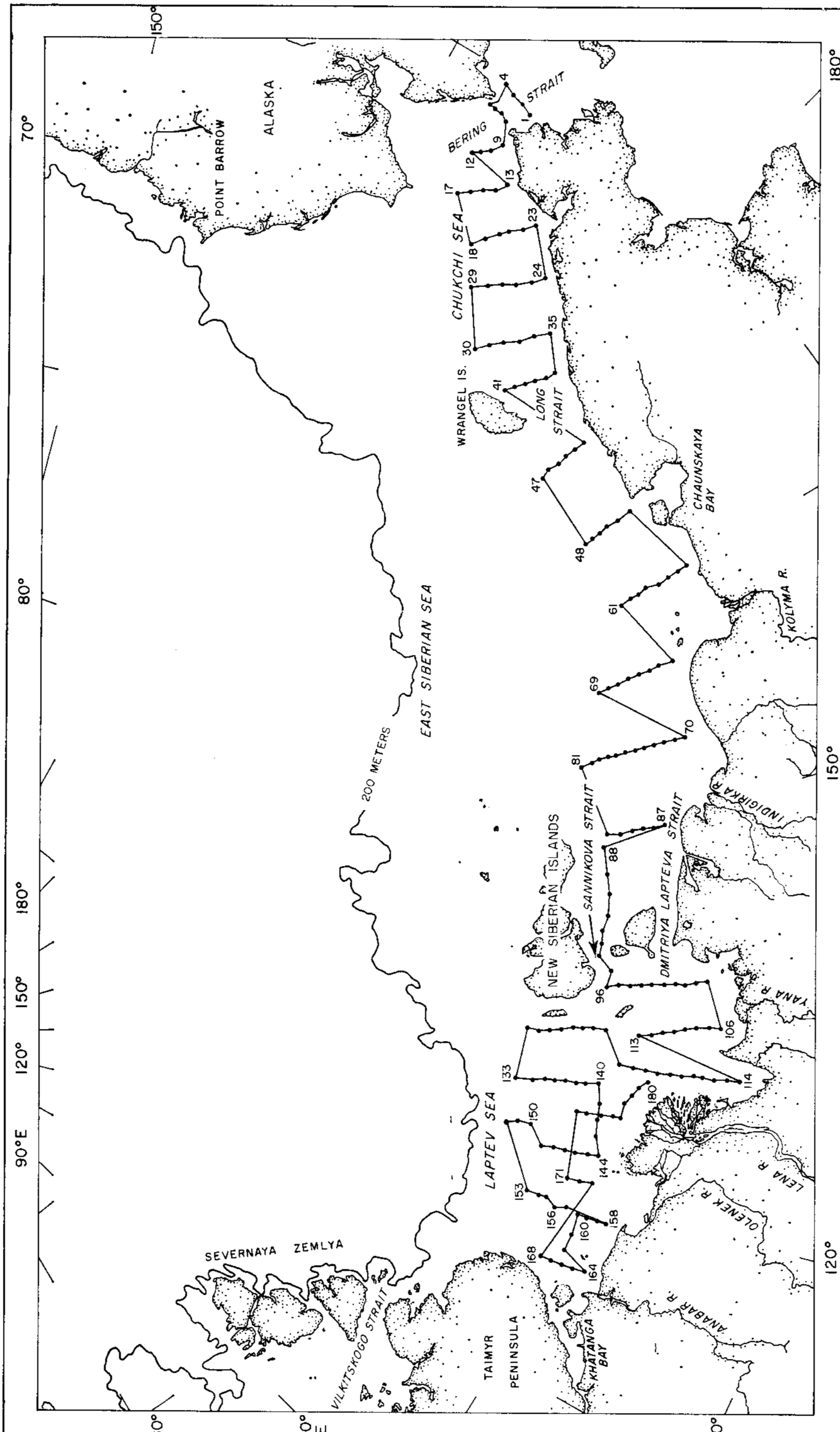

FIG. 1. Oceanographic stations occupied during the 1963 cruise of the U.S.C.G.C. *Northwind.*

Navy Hydrographic Office 1954), and the evaporation is approximately 33 per cent of the precipitation (Defant 1961). The excess precipitation should add about 50 km.^{3} of freshwater to the *Northwind* survey area each year.

Yearly runoff into the East Siberian Sea is approximately 250 km.^{3} and about 700 km.^{3} into the Laptev Sea (Antonov 1958). Some 85 to 95 per cent of this water is discharged between May and October (Zaykov 1936). The Kolyma and Indigirka rivers supply most of the runoff to the East Siberian Sea; the Lena River, discharging approximately 500 km.^{3}/year, is the largest river entering the Laptev Sea (Table 1).

TABLE 1. Approximate yearly discharge of the major rivers in the 1963 *Northwind* survey region.*

River	*Discharge (km.^{3}/year)*
Anabar	12
Indigirka	57
Khatanga	101
Kolyma	120
Lena	490
Olenek	35
Yana	31

*From L'vovich (1953)

Ice occurs in the East Siberian and Laptev seas throughout the year. About 2 m. of ice form during the winter, and the summer ice melt is approximately 1 m. (Sverdrup 1956). The difference between ice formation and ice melt apparently is compensated by a net drift of ice out of the region. The average thickness of the ice in the region traversed by the *Northwind* was approximately 1 m., but the ice cover and thickness vary widely. Figure 3 indicates the ice conditions encountered by the *Northwind*.

Because the rivers add heat to the region (Zaykov 1936) and tend to induce north-setting surface currents (Antonov 1957), they are important in reducing the near-shore ice cover in summer. Regions adjacent to outfalls were often ice free and there was a large area of open water near the Lena River Delta. The body of close-pack ice adjacent to the Taimyr Peninsula (Fig. 3) is called the Taimyr Ice Massif (Antonov 1957) and is a normal feature of the region in summer.

Because of factors such as fluctuations in river runoff and annual and seasonal variations in air temperatures and the wind regime, steady-state currents, salinities, and temperatures are not even approximated in the region. Time-series stations indicate that conditions in the surface layers can change significantly even in a few hours (Table 2), and so wide fluctuations in the currents in the area are to be expected. According to Sverdrup (1929), there are no permanent currents on the North Siberian Shelf. Gorbunov (1957) stated that water transport through Long Strait is governed by the prevailing winds, and Chirikhin (1932) presented data indicating that the currents in Dmitriya Lapteva Strait also change with the wind direction. Nevertheless, certain current systems appear to be more or less permanent. A northerly surface current in the eastern Laptev Sea and a southerly

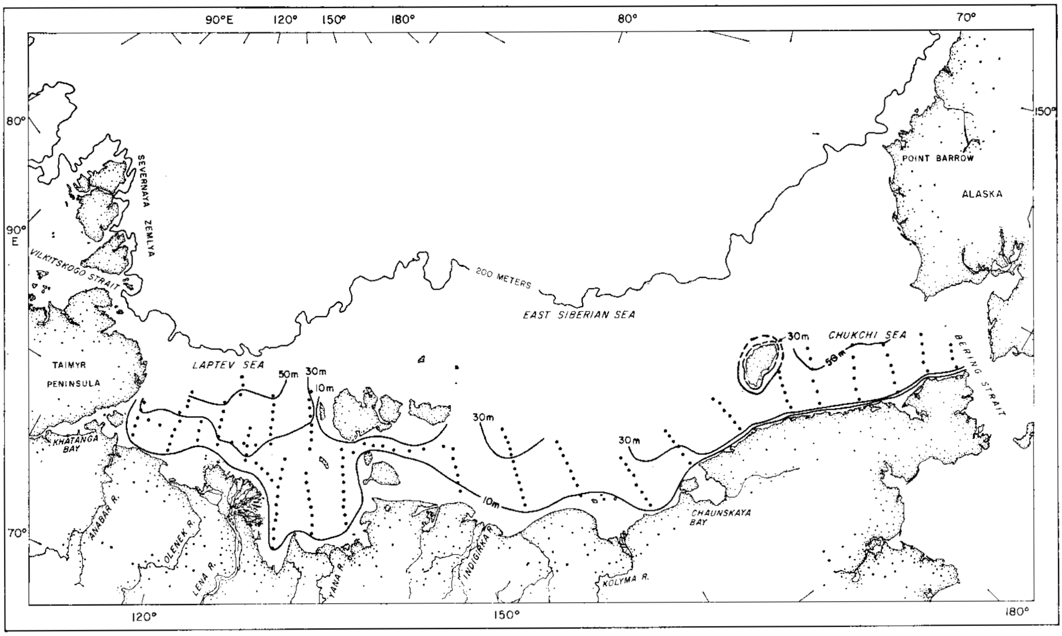

FIG. 2. Bathymetry of the region compiled from the depths observed at the oceanographic stations.

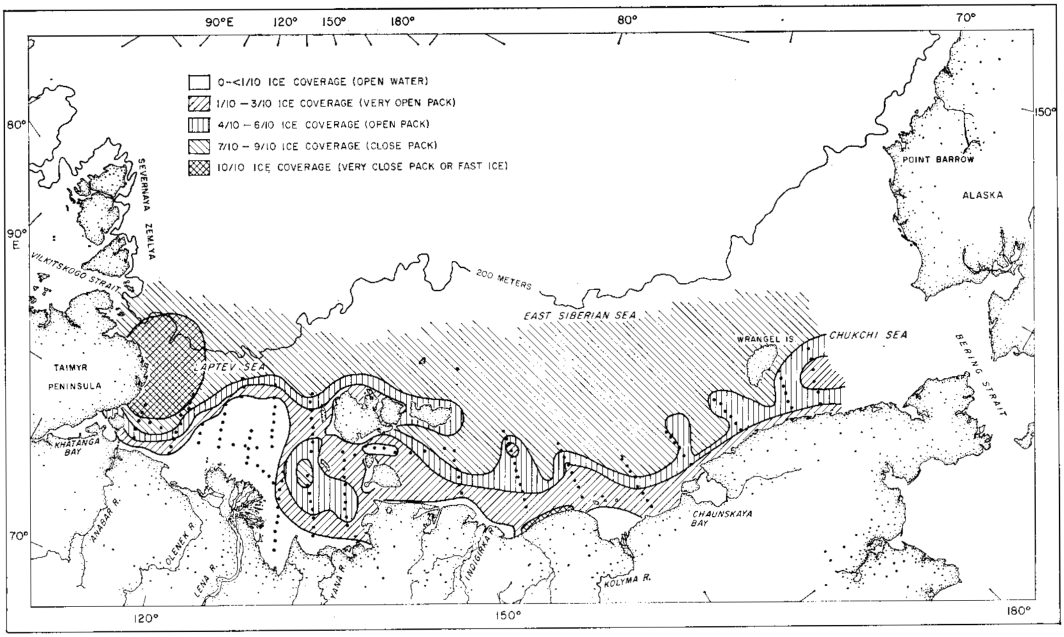

FIG. 3. Ice conditions encountered during the *Northwind* cruise.

TABLE 2. Short term variations in water properties in the survey region.

Cruise	*Location*	*Date*	*Hour*	*Depth*	*S‰*	*T°C.*
Polarnaya	73°00′N	19 Aug.	2230	0 m.	14.52	3.00
Zvezda 1927*	140°10′E			14 m.	20.41	0.55
		20 Aug.	0330	0 m.	14.96	1.80
				14 m.	19.67	0.75
			1030	0 m.	15.41	1.89
				14 m.	18.40	1.15
Northwind	74°32 N	2 Sept.	1400	0 m.	21.89	0.48
1963	127°05′E			27 m.	33.72	—1.78
	74°31′N	10 Sept.	0800	0 m.	12.46	1.08
	127°18′E			27 m.	33.40	—1.78
Burton	70°46′N	19 July	1300	0 m.	17.80	0.32
Island 1964**	164°15′E			18 m.	28.72	—1.34
		20 July	2100	0 m.	17.28	1.44
				18 m.	29.66	—1.36

*From Chirikhin (1932).
**U.S. Naval Oceanographic Cruise PG-010.

compensation current in its western reaches have been mentioned by a number of authors, including Vize (1926) and Antonov (1957). The *Northwind* data also indicate a north-setting surface current in the eastern part of the sea and a south-setting compensation current parallel to the Taimyr Peninsula. The south-setting current could be responsible, in part, for the perpetuation of the Taimyr Ice Massif. These currents appear to be normal summer features of the region. Antonov (1957) stated that currents in the East Siberian Sea appear to be weaker and more unstable than those in the Laptev Sea.

There was a well-developed thermal "front" at all depths to the west of Wrangel Island (Figs. 4 and 5) when the 1963 *Northwind* stations were occupied, indicating that a branch of the warm Bering Strait inflow was setting north in this region.

U.S. Navy Hydrographic Office (1954) charts indicate that tides in the East Siberian and Laptev seas are weak, and that the surface currents in the straits connecting the East Siberian and Laptev seas and in the near-shore parts of the East Siberian Sea usually set east during the warmer months. However, the charts are based on few data.

METHODS AND DATA

The oceanographic phase of the 1963 *Northwind* cruise lasted from 7 August to 10 September. Water samples were collected in Nansen bottles. The distance between bottles seldom exceeded 5 m., and the deepest sample at each station was usually collected within 5 m. of the bottom. The data from the cruise have been published in U.S. Coast Guard Oceanographic Report No. 6 (U.S. Coast Guard Oceanographic Unit 1965).

Some of the salinities were determined with a salinity bridge of the type described by Paquette (1958) and some with a Hytech Model 620 Induction Salinometer. Temperatures were obtained from standard oceanographic reversing thermometers. Colorimetric determinations were made using a Beckman Model DU spectrophotometer and the methods of Mullin and Riley (1955*a,b*) for nitrates and reactive silicates, and of Murphy and Riley (1962) for reactive

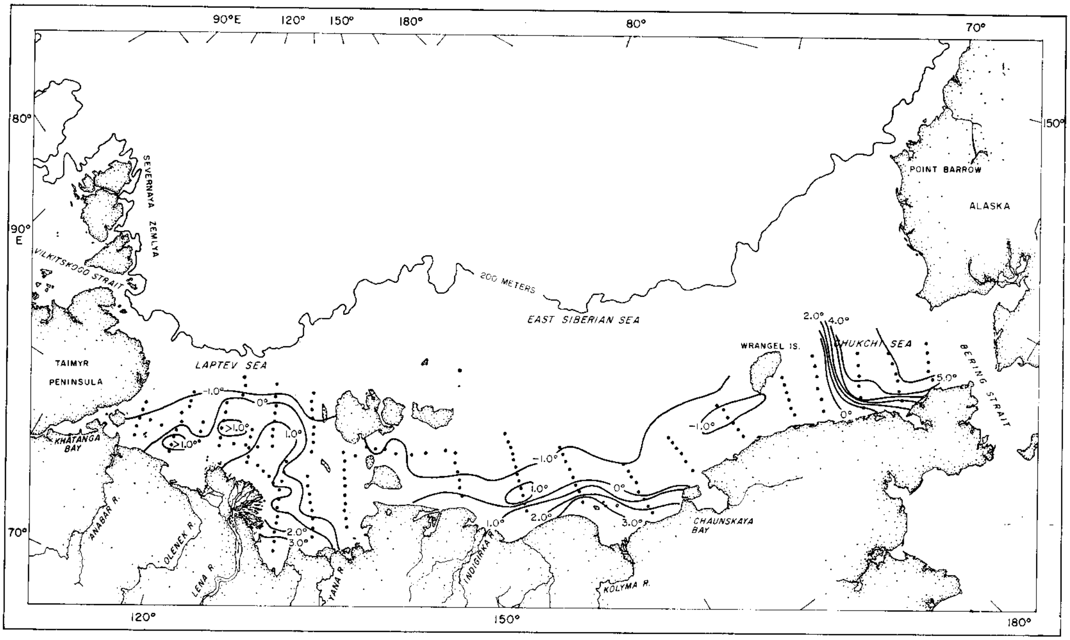

FIG. 4. Horizontal distribution of temperature, in °C., at 2 m.

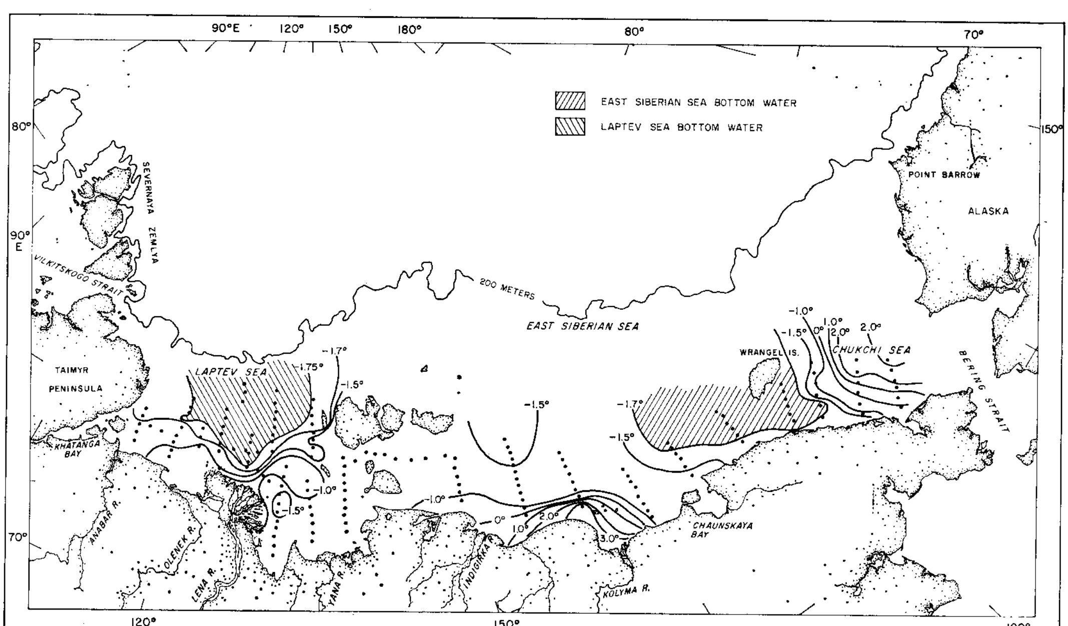

FIG. 5. Horizontal distribution of temperature, in °C., in the bottom waters.

phosphates.

The reactive phosphate concentrations of freshly drawn samples were determined at sea. Nitrate, reactive silicate, and reactive phosphate determinations were later carried out ashore using samples that had been frozen in polyethylene bottles immediately after collection. When the difference between the phosphate concentration from a frozen sample and that determined at sea was greater than the limit of reproducibility for the phosphate method described by Strickland and Parsons (1960), the micronutrient result from the frozen sample was rejected.

The distribution of variables in the bottom waters, as shown here, has generally been based on the deepest sample collected at each station. However, when the data were unreliable, the next deepest sample has been used.

SALINITY AND TEMPERATURE DISTRIBUTIONS

The salinity in the region varied between 2 and 34‰ (Figs. 6 and 7), but because of the presence of ice, the temperatures were fairly uniform (4 to -2°C.) and usually close to the freezing point (Figs. 4 and 5). The waters were generally highly stratified, and at some stations the salinity increase from the surface to the bottom was more than 20‰. Because of the large amount of runoff, and because the rate at which ice melts increases towards the shore, the distribution of salinity in sections perpendicular to the coasts usually resembled the salinity distribution of an estuary, with a marked halocline deepening as the coast was approached.

The large body of relatively warm, low-salinity water spreading northward from the eastern shores of the Laptev Sea (Figs. 4 and 6) was a major feature of the region and apparently arose mainly from the Lena River outflow.

A relatively uniform bottom water mass was observed near Wrangel Island. Its salinity ranged from 32.30 to 33.39‰ and its temperature from -1.71 to -1.80°C. For convenience, this will be called East Siberian Sea Bottom Water. Another relatively uniform bottom water mass was observed at many of the more northerly stations in the Laptev Sea. This will be referred to as Laptev Sea Bottom Water and includes waters in the Laptev Sea with salinities between 32.70 and 33.86‰ and temperatures between -1.75 and -1.83°C. (Figs. 5 and 7).

The salinity and temperature characteristics of the remaining waters in the East Siberian and Laptev seas varied widely, but their properties could almost always be accounted for by assuming that they were mixtures of runoff (salinity $\gtrsim$ 0‰, temperature $>$3°C.), ice melt (salinity $\gtrsim$ 3‰, temperature $<$0°C.), and either East Siberian Sea Bottom Water or Laptev Sea Bottom Water. No distinct intermediate water mass was observed in the East Siberian and Laptev seas in 1963.

Naming the above water masses is merely a convenience and is not meant to imply that these water masses are permanent features. The characteristics of the bottom waters might well change from year to year.

MICRONUTRIENT DISTRIBUTIONS

Figures 8 to 13 show the observed micronutrient distributions. The concentrations in the surface layers were usually much lower than those in the bottom

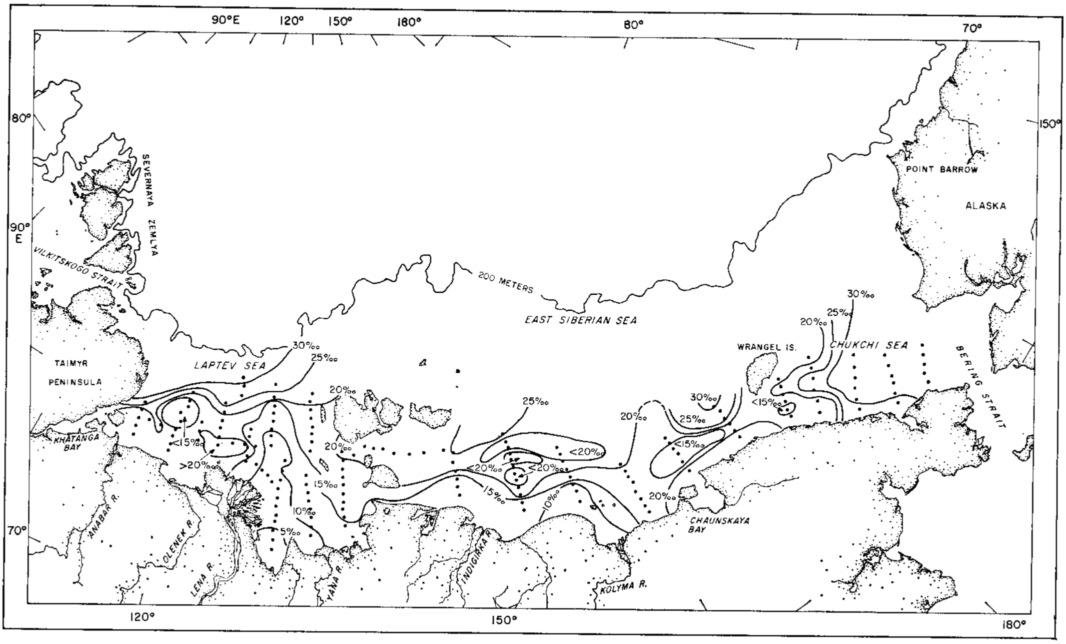

FIG. 6. Horizontal distribution of salinity, in ‰, at 2 m.

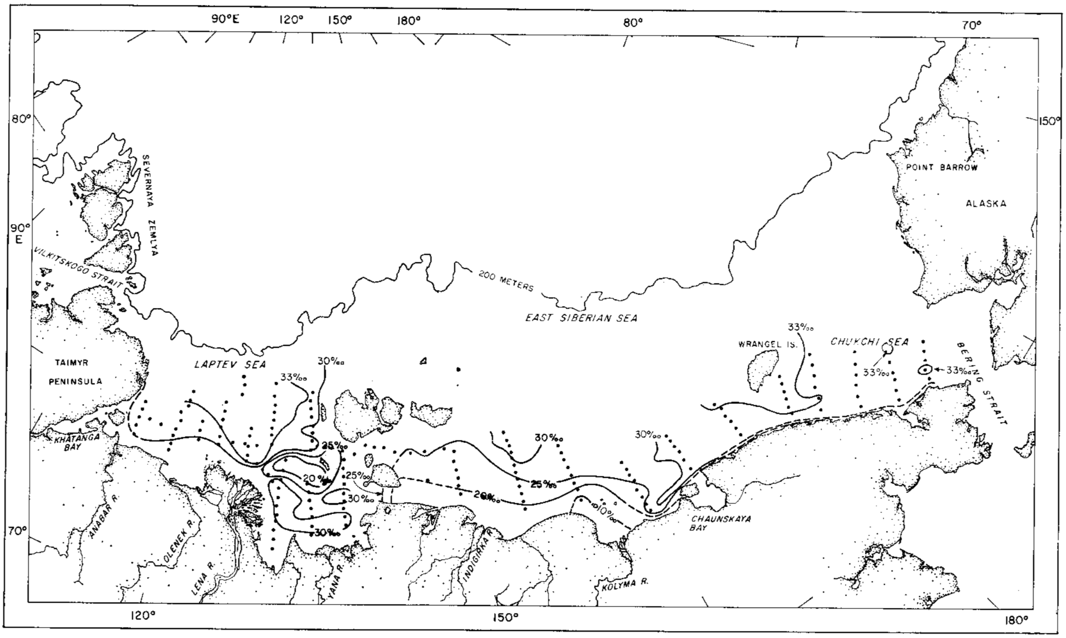

FIG. 7. Horizontal distribution of salinity, in ‰, in the bottom waters.

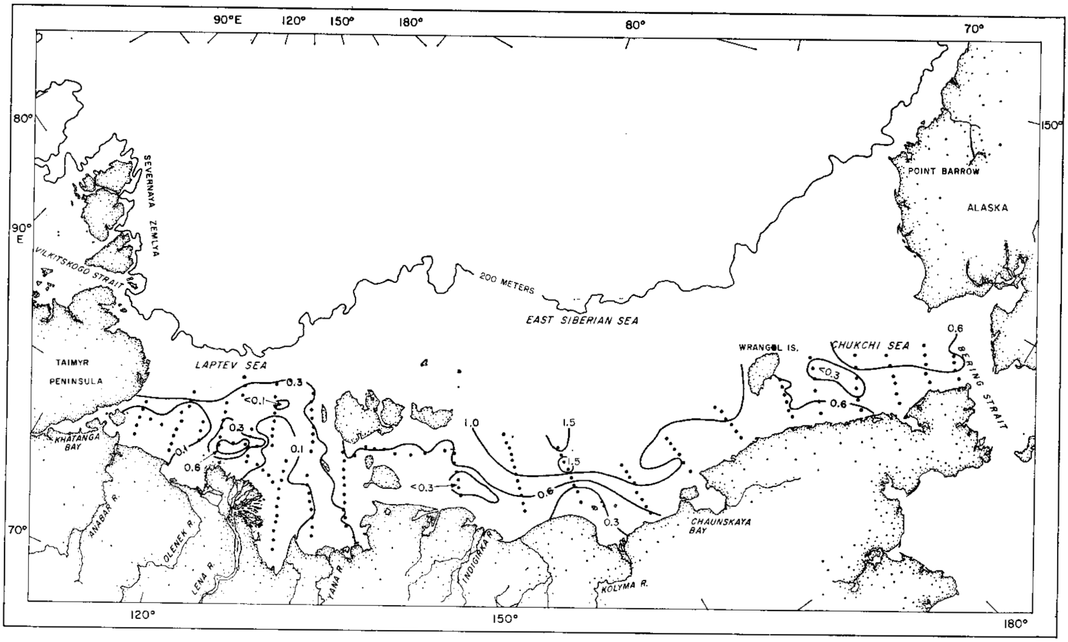

FIG. 8. Horizontal distribution of reactive phosphate, in μg-at./litre, at 2-3 m.

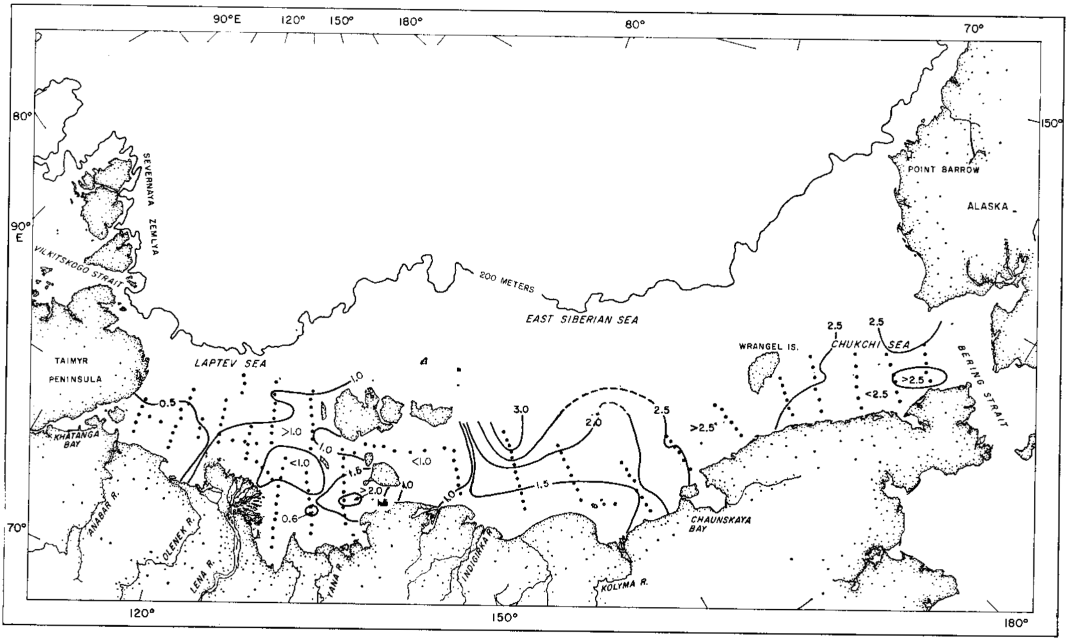

FIG. 9. Horizontal distribution of reactive phosphate, in μg-at./litre, in the bottom waters.

waters. At a given depth, phosphate concentrations in the East Siberian Sea were usually much higher than those in the Laptev Sea, whereas silicate concentrations in the East Siberian Sea Bottom Water were significantly higher than those in the Laptev Sea Bottom Water. Phosphate concentrations in the East Siberian Sea were usually much higher than in the Laptev Sea (Fig. 14). The highest nitrate: phosphate ratios in the East Siberian Sea were often in the surface waters near Sannikova Strait, and phosphate concentrations in the Laptev Sea near the strait were often higher than average for the Laptev Sea (Figs. 8 and 9), suggesting that waters from the East Siberian and Laptev seas mix in this region.

The micronutrient isopleths near the Lena Delta indicate that the river has an important effect on micronutrient distributions in the Laptev Sea. All of the micronutrient concentrations in the bottom waters and the nitrate and silicate concentrations in the surface waters increased as the delta was approached, while the surface phosphate concentrations decreased significantly. Near the eastern part of the mouth of the Kolyma River, the bottom waters were relatively rich in silicate.

DISCUSSION

Water from ice melt is probably poor in micronutrients, and some of the runoff waters in this region may be deficient in certain nutrients. Appreciable quantities of such waters may partially account for the relatively low micronutrient concentrations in the surface layers. However, with depth, there were sharp increases in micronutrients even when surface salinities were greater than 25‰ (Figs. 6 to 13), and the gradients were probably in large part brought about by the uptake of nutrients during the summer phytoplankton bloom in the surface layers (Anderson and Banse 1961). The intense stratification of the waters, their turbidity, and the presence of an ice cover should result in a shallow compensation depth, so that particulate matter does not have far to sink before it begins to decompose. Because these regions are so shallow, this may lead to an increase of nutrients in the bottom waters.

Silicate concentrations in the surface layer were almost always greater than 5 μg-at./litre (Fig. 10), but the concentrations of phosphate, or nitrate, or both, in the upper layers (Figs. 8 and 12) were often so low as to suggest nutrient limitation of phytoplankton production. In the surface layers of large parts of the East Siberian Sea, phosphate concentrations were high while nitrate concentrations were low, suggesting the possibility of nitrogen limitation. In the Laptev Sea near the Lena Delta, phosphate concentrations in the upper layers were often less than 0.1 μg-at./ litre, but nitrate concentrations in excess of 1.0 μg-at./litre were common, so there may have been differential nutrient depletion. The surface-layer phosphate and nitrate concentrations near the mouth of the Khatanga River were both quite low.

Bottom water salinities greater than 30‰ were common near the Lena River Delta (Fig. 7), but the micronutrient concentrations of these waters were often more than twice those of the high-salinity waters to the north (Figs. 9, 11, and 13). All of the high-salinity waters in the Laptev Sea appear to have essentially

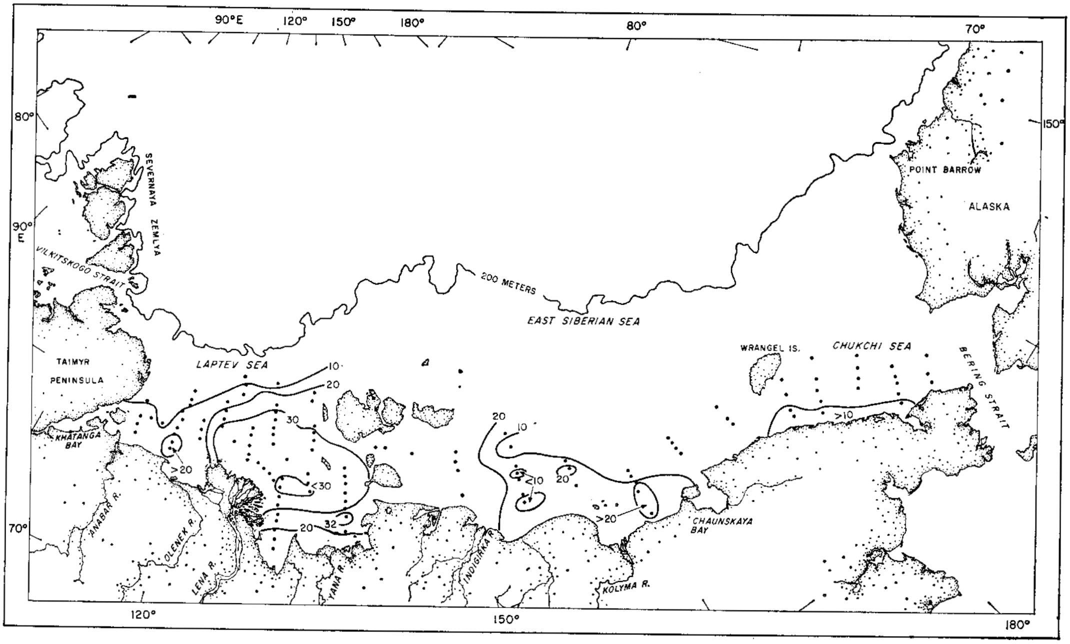

FIG. 10. Horizontal distribution of reactive silicate, in μg-at./litre, in the surface layers (0-5 m.).

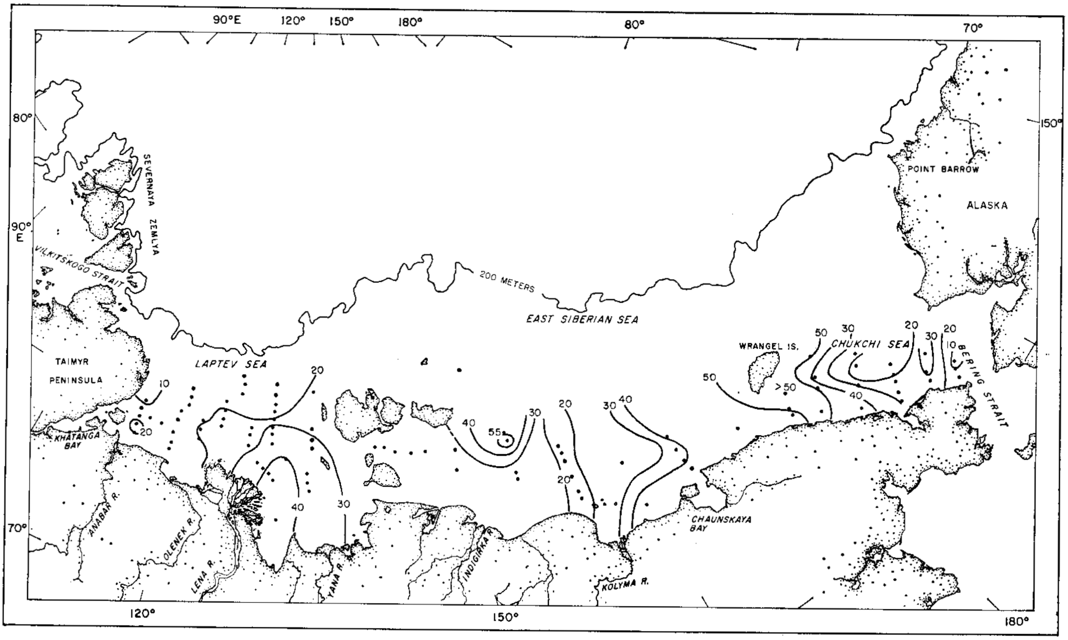

FIG. 11. Horizontal distribution of reactive silicate, in μg-at./litre, in the bottom waters.

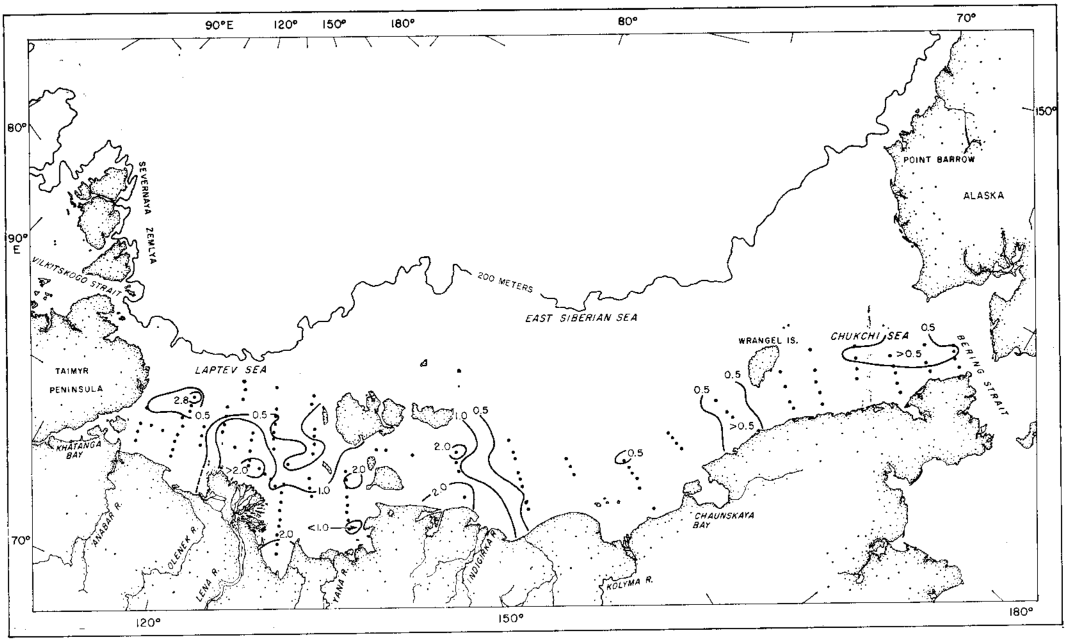

FIG. 12. Horizontal distribution of nitrate, in μg-at./litre, in the surface layers (0-5 m.).

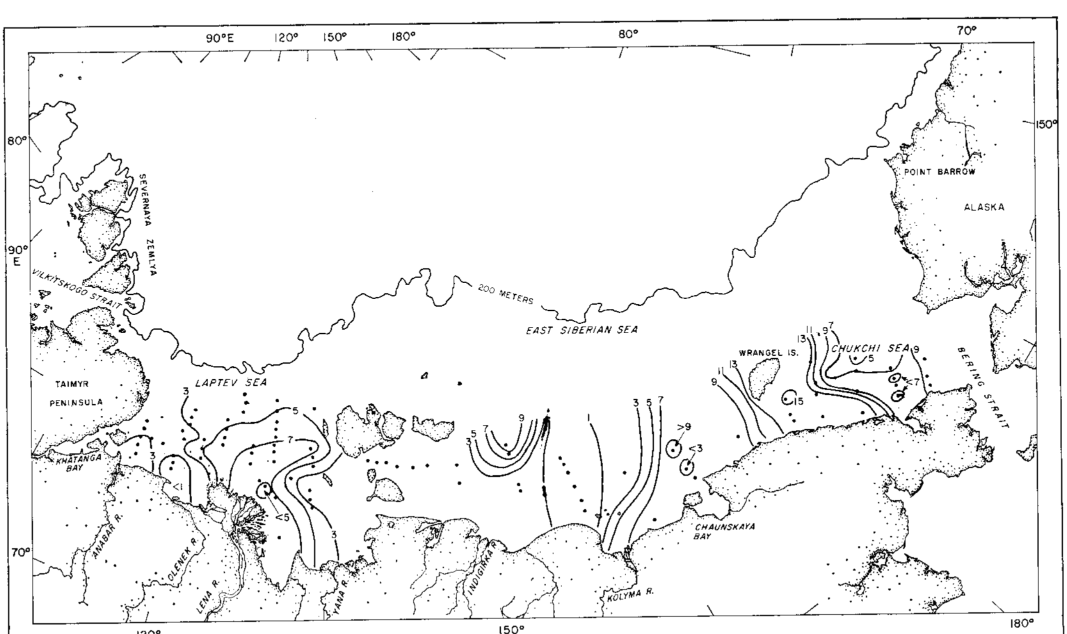

FIG. 13. Horizontal distribution of nitrate, in μg-at./litre, in the bottom waters.

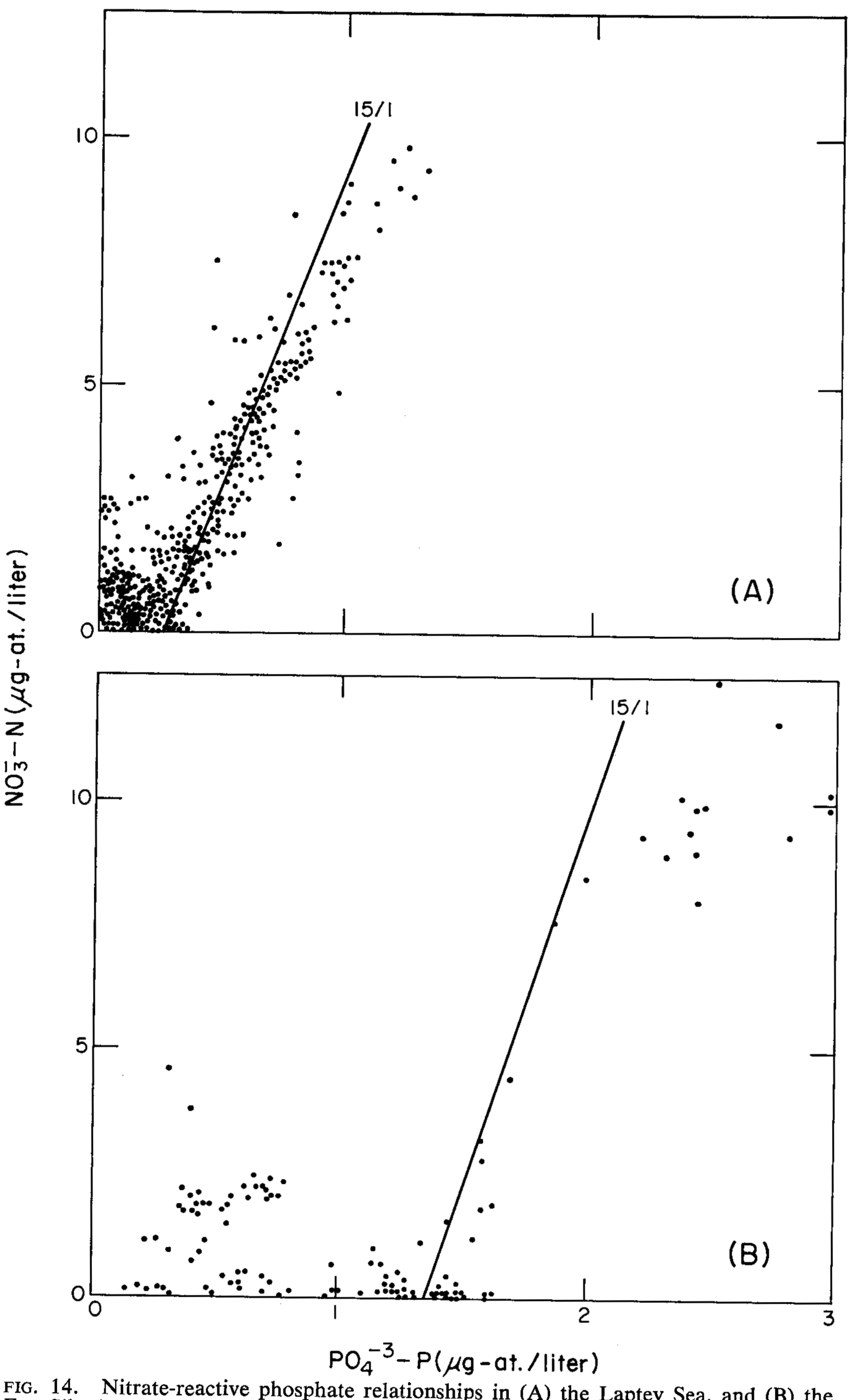

FIG. 14. Nitrate-reactive phosphate relationships in (A) the Laptev Sea, and (B) the East Siberian Sea. The lines representing the "normal" ΔN:ΔP ratio of 15:1 are included for comparison.

the same origin, so the differences in micronutrient concentrations cannot be attributed to different origins. The near-shore bottom waters with salinities greater than 30‰ could contain very little river water, so mixing of river water with high-salinity bottom water cannot explain the observed enrichment, which is probably caused mainly by an estuarine circulation induced by the outflow of the Lena and the decomposition of a "rain" of particulate matter.

A positive estuarine circulation will produce micronutrient distributions similar to those near the Lena Delta (Redfield, Ketchum, and Richards 1963). Currents were not measured, but the large outflow and the thermohaline structure in the Lena Delta region (Figs. 4 to 7) suggest such a system.

A two-layered estuarine circulation might account for the bottom water enrichment, but it probably would not when either nutrient-rich offshore saline water or a source of particulate matter which could sink to the deeper layers and decompose there are absent. During summer, particulate matter could be introduced to the region by the rivers or by primary production in the surface layers, but the relative importance of these sources in introducing phosphate and nitrate cannot be evaluated. On the other hand, silicate concentrations in the bottom waters are so great near the Lena Delta that it is difficult to see how they could result primarily from the decomposition of phytoplankton.

According to Antonov (1957), offshore winds induce an estuarine circulation throughout the Laptev Sea during winter. Since at that time river outflow is low and no primary production can occur, the micronutrient gradients in the high-salinity bottom waters near the Lena Delta are probably at least partially destroyed during winter.

The near-surface micronutrient isopleths near the Lena Delta (Figs. 8, 10, and 12) indicate that the river adds silicate to the surface layers, and that the nitrate: phosphate ratio in the Lena River is greater than average for the Laptev Sea.

THE ORIGINS OF THE BOTTOM WATERS

Calculations indicate that the salinity of the surface waters throughout most of the survey region was so low that approximately 6 m. of ice would be required to increase it to that of the East Siberian Sea and Laptev Sea bottom waters. This is more ice than can be formed in these regions under present climatic conditions, so the bottom waters must be advected into the survey region.

Laptev Sea Bottom Water is probably a winter-formed mixture of surface and sub-surface waters from north of the Sea. Treshnikov (1959) has shown that winter surface salinities range from approximately 32.5 to 33.5‰ in the ocean directly north of the Laptev Sea, and Coachman and Barnes (1962) have shown that the layers from about 25 to 100 m. in this region have salinities of approximately 33.8 to 34.0‰. The surface waters must be close to freezing (≈ -1.80°C.) in winter, and Coachman and Barnes (1962) state that the sub-surface waters are also close to the freezing point. Thus, the temperatures and salinities of these layers are similar to those of the Laptev Sea Bottom Water.

The development of an estuarine circulation near the Lena Delta during summer and of offshore monsoonal winds during winter (Antonov 1957) in the Laptev

Sea would carry surface waters offshore and induce a sub-surface onshore current. Thus, offshore surface and sub-surface waters would probably sink and move onshore beneath the less dense waters moving away from the coasts.

Laptev Sea Bottom Water should consist primarily of water from the Atlantic Ocean, because the water balance of the Arctic Ocean and its surface currents as described by Coachman (1962) and the U.S. Navy Hydrographic Office (1954) indicate that little of the Bering Strait inflow could enter the northern Laptev Sea.

The near-freezing temperatures of the East Siberian Sea Bottom Water indicate that it too was formed near the surface during the winter. Coachman and Barnes (1961) state that the water flowing in through Bering Strait has salinities between 32.4 and 34.0‰ and temperatures near the freezing point, and calculations indicate that winter cooling of the summer inflow with the formation of 1 to 2 m. of ice would produce a water mass with salinity and temperature characteristics similar to those of the East Siberian Sea Bottom Water. Thus it is possible that before the 1963 *Northwind* cruise, some of the Pacific water flowing through Bering Strait entered the East Siberian Sea as relatively dense bottom water. If this was the case, the bottom waters near Wrangel Island must have experienced a net drift towards the west. The method of transport of water from Bering Strait to the East Siberian Sea cannot be completely defined, but Sverdrup (1929) indicated that a westerly sub-surface flow through Long Strait was likely; he concluded that an intermediate water which he encountered to the north of the *Northwind* survey region experienced a net drift towards the west. No direct measurements of bottom currents in this region are available for the winter months, but the drifts of the *Maud* (Sverdrup 1929) and the *Jeannette* (De Long 1884) and the results of a drift bottle experiment reported by Fleming and Heggarty (1962) indicate that the surface waters near Wrangel Island drift westward in winter and could transport high-salinity water flowing through Bering Strait to the East Siberian Sea, where it would sink beneath the low-salinity surface waters which occur there even in the winter (Sverdrup 1929, Treshnikov 1959).

The proposed origins of the two bottom waters cannot be definitely established, but the described mechanisms, if correct, could explain some of the observed micronutrient distributions in the two seas. For example, the phosphate concentrations in the North Atlantic Ocean are much lower than those in the North Pacific Ocean. Data from the Norwegian and Greenland seas (*Polyarnik* 1958 and *Edisto* 1963 and 1964 data are available from the National Oceanographic Data Center, Washington, D.C.) and from northeast of Wrangel Island (observed during the drift of *Alpha-2* [Gast 1960]) indicate that phosphate concentrations in the Atlantic water entering and circulating in the Arctic Ocean are only about 1.0 μg-at./litre whereas the deeper waters near Bering Strait contained about 2.0 μg-at./litre during the 1963 *Northwind* and 1964 *Burton Island* cruises (U.S. Naval Oceanographic Office Cruise PG-010).

Phosphate concentrations in the Laptev Sea Bottom Water farthest removed from the effects of the Lena River (Fig. 9) were similar to those found in the Atlantic inflow (0.7 to 1.0 μg-at./litre), whereas those in the East Siberian Sea Bottom Water were often between 2.5 and 3.0 μg-at./litre, slightly higher than the highest values encountered near Bering Strait. The relatively high phosphate concentrations found throughout the water column in the East Siberian Sea (Figs. 8 and 9) indicate that Bering Sea water may be a major component in this region.

Silicate concentrations in the high-salinity waters in the East Siberian Sea are considerably higher than those in the high-salinity waters in the Laptev Sea farthest removed from the Lena Delta (Fig. 11). This also suggests a large Pacific contribution to the East Siberian Sea, because the available data (*Alpha-2, Edisto* 1963 and 1964, *Northwind* 1963, and *Burton Island* 1964) show that the highest silicate concentrations in the Atlantic water flowing into the Arctic Ocean are considerably lower than the highest values found in the Bering Strait inflow.

Silicate concentrations in the high-salinity waters in the East Siberian Sea were also often somewhat higher than the highest ones in the Bering Strait inflow. This is not unreasonable, because the photic zone may extend to the bottom in a turbulent region such as Bering Strait, and the only micronutrient analyses available are from the summer months when photosynthesis may have temporarily reduced the micronutrient concentrations. The high-salinity waters in the East Siberian Sea, on the other hand, are in a region where marked stratification and frequent ice should cause the photic zone to be quite shallow. These two factors might also help to explain why maximum phosphate values in the East Siberian Sea were slightly higher than those in the Bering Strait region.

ACKNOWLEDGEMENTS

The data for this paper were collected during a cruise supported by the U.S. Coast Guard and the U.S. Naval Oceanographic Office. The authors received financial assistance from the Arctic Institute of North America under contractual arrangement with the Office of Naval Research [Nonr-477(37)]. We would like to thank Dr. C. A. Barnes and Dr. L. K. Coachman for their encouragement and advice.

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