TECHNICAL REPORT

OCEANOGRAPHIC SURVEY RESULTS
KARA SEA
SUMMER AND FALL 1965

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ABSTRACT

NAVOCEANO made a survey of the Kara Sea during the summer and fall of 1965.

Data were collected at 163 oceanographic Nansen stations and included serial-depth temperature, salinity, dissolved oxygen, nitrogen, pH, reactive phosphorus, and reactive silicate measurements.

Six major water masses were found in the Kara Sea: Continental Runoff, Atlantic Water, Arctic Water, Residual Water, Inflow from the Laptev Sea, and Arctic Bottom Water.

Atlantic Water is brought into the Kara Sea both as a deep estuarine inflow from the Arctic Ocean compensating for the outflow of shallower Continental Runoff and as a relatively shallow inflow from the Barents Sea. This estuarine movement from the Arctic Ocean raises the core depth of the Atlantic Water from 300 to 150 meters where it then mixes with the inflow from the Barents Sea and Continental Runoff. The movement of Atlantic Water across the Barents Sea and into the Kara Sea has largely been ignored by American oceanographers.

Arctic Water is formed in the shallow peripheral seas adjacent to the Arctic Ocean, e.g., the Kara Sea, by mixing of Continental Runoff with the saline Atlantic Water. Salinity and density increase as ice forms during the winter.

Residual Water was found in the deeper areas of the East Novaya Zemlya Trough. This water, formed by cooling and gradual sinking, had the coldest temperatures found on the survey.

Arctic Bottom Water was found in the deepest portions of the Svyataya Anna and Voronin Troughs. It, like Atlantic Water, also is probably brought into the areas as a countercurrent to the outflowing Continental Runoff.

Reactive silicate was an interesting new parameter for examining Continental Runoff; noted especially were anomalously high measurements recorded north of Ostrov Vize. Other parameters which proved valuable in the study of water masses were pH and reactive phosphorus.

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FOREWORD

The Naval Oceanographic Office conducted an extensive oceanographic survey in the Kara Sea during the summer and fall of 1965. Data from 163 ocean stations provided information which allowed a detailed analysis of the marine environment. The major emphasis of this technical report is on the water masses which either enter or originate in the Kara Sea.

A handwritten signature in dark ink, appearing to read "T. K. Treadwell".

T. K. TREADWELL
Captain, U.S. Navy
Commander

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I. INTRODUCTION

A. A Brief History of Exploration of the Kara Sea.

William Barents made the first known survey of the Kara Sea in 1594. Later, with the urging of Peter the Great in the early 1700's, the Great Northern Expedition of 1733 to 1743 succeeded in mapping the northern coast of Asia and Europe. Economic reasons, rather than scientific, were the primary motivation for these early explorations as attempts were made to find a water route over the top of Eurasia between the eastern and western civilizations (Gordienko, 1961). In 1763, Mikhail Lomonosov wrote the first significant scientific work on this area, "Brief Account of Travels in the Northern Seas." The Swedish explorer N.A.E. Nordenskjold made the first passage from the Barents Sea to the Pacific Ocean in 1878 and established the Northeast Passage. Nordenskjold also explored the Kara Sea in 1875 and 1876 and published the first accurate chart of the area.

In 1893, the Norwegian oceanographer Fridtjof Nansen crossed the Kara Sea in the historic voyage of the FRAM (Nansen, 1902).

The U.S.S.R. has undertaken an extensive oceanographic program in the arctic peripheral seas; however, the data collected on these surveys are not readily available to western scientists.

B. Narrative of the Survey.

The Naval Oceanographic Office (NAVOCEANO) conducted an extensive oceanographic survey of the Kara Sea during the summer and fall of 1965. The survey was performed aboard U.S. Coast Guard Cutter NORTHWIND (WAGB 282) (Photo 1) by ten NAVOCEANO scientists. The author was chief scientist. This study of the Kara Sea is only a small part of a continuing survey effort by NAVOCEANO in a relatively unexplored and strategic area. Figure 1 denotes the NAVOCEANO Arctic surveys from 1961 through 1965 and includes the Kara Sea survey.

In addition to the oceanographic program aboard NORTHWIND, Dr. N. Ostenso, two graduate students, and one technician from the University of Wisconsin conducted a geomagnetic and gravity program. Their program was coordinated closely with the total effort.

Owing to the paucity of available information and the relative inaccessibility of the survey area (Fig. 2), an effort was made to canvass the scientific community before the survey to provide as much needed data as time allowed.

Underway radioisotope water sampling began on 18 July en route from Copenhagen, Denmark, to the Kara Sea, and oceanographic station work started in the Kara Sea on 25 July. A temporary halt was called on 5 August and a damaged starboard shaft was replaced while the ship

FIGURE 1. NAVOCEANO Arctic Surveys from 1961 through 1965

PHOTO 1. USCGC NORTHWIND (WAGB 282)

was drydocked in Newcastle, England. On 10 September, radioisotope water sampling was continued, and oceanographic stations were occupied from 12 September to 2 October. A track of the survey is presented in Figure 3.

C. Ice Conditions in the Survey Area.

Oceanographic operations in the Kara Sea were not hampered greatly by ice (Fig. 4). Close ice, found along the east coast of Novaya Zemlya, apparently was due to prevailing winds (Photo 2). When NORTHWIND returned to the area following the import period, almost all the ice had disappeared. Permanent arctic pack ice was not encountered until NORTHWIND had penetrated north of Severnaya Zemlya. The northernmost line of stations was taken in and just south of this pack. Along

FIGURE 2. Chart Showing Relative Inaccessibility of Kara Sea

FIGURE 3. Track of NORTHWIND, July-October 1965

FIGURE 4. Ice Conditions of the Survey Area

PHOTO 2. Close Ice

this line, grease ice and pancake ice were encountered, and at 80°E , the ice increased to close pack. However, the existence of polynyas permitted oceanographic stations to be taken. Close pack also was found along the southeast and southern coasts of Franz Josef Land.

D. Survey Accomplishments.

A total of 163 oceanographic Nansen stations was occupied in the Kara Sea and adjoining Barents Sea (Fig. 5). At these stations, 1,814 serial-depth temperature, salinity, dissolved oxygen, nitrogen, and pH observations were obtained. In addition, 1,797 water samples were frozen and returned to NAVOCEANO for determination of reactive phosphorus and reactive silicate concentrations. Also, bathythermograph lowerings were made at 161 stations, 18 samples were taken in a program of continuous air sampling, 25 nanoplankton samples were obtained, 6 plankton tows were taken while drifting on station, 35 thirty-gallon water samples were collected for gamma-radiation analysis, 48 bottom sediment grab samples were collected, and 95 gravity cores were taken in areas of water depth in excess of 200 meters. A special piston corer (Photo 3) was used to obtain six cores. These cores were collected

FIGURE 5. Oceanographic Station Locations in the Kara Sea. Stations 160 through 163 were located in the Barents Sea and are not included in this figure.

PHOTO 3. Modified Piston Corer

for gamma-radiation analysis of the surface layers. A total of 12,000 miles of bathymetric profiles was recorded in the Kara Sea and adjoining sea areas. These records will be used to revise present charts of the area. Subbottom configuration was plotted along much of the ship's track. The core and subbottom profiling data will be discussed in

separate reports. Two deep current stations were occupied, and five shallow water areas were surveyed bathymetrically.

E. Observational and Analytical Techniques.

Serial-depth observations were made from the surface to the bottom at all stations with a single cast of 13 or 14 Nansen bottles until loss of a cast at station 143 necessitated a second cast at some stations. The tin-lined Nansen bottles carried two and sometimes three protected reversing thermometers. At depths in excess of 200 meters, two protected thermometers and one unprotected thermometer were used. Due to the shallow water and the close proximity of ice, the wire angle of the Nansen cast usually was less than 5 degrees. On the shallow stations where an appreciable wire angle was encountered, depth calculations were made by multiplying the cosine of the wire angle by the wire out. Thermometers were allowed at least 6 minutes to come to equilibrium before reversal. A check was kept of thermometer performance, and when paired thermometers consistently failed to agree by at least 0.02°C , one thermometer of the pair was interchanged with a thermometer of another pair. This interchanging allowed determinations of thermometer accuracy. Approximately 88 percent of the paired thermometer readings agreed to within 0.02°C . Table I groups the temperature differences between paired thermometers and gives the number of readings in each group.

TABLE I. Thermometer Performance

0.00-0.02°C	0.03-0.04°C	One Thermometer Accepted	Greater than 0.04°C or a Malfunction
3,092	168	200	62

Water samples were drawn and examined for dissolved oxygen and nitrogen content using a modified Fisher Gas Partitioner (Photo 4) equipped with an integrating recorder (Sullivan, 1963).

A Beckman Model 76 expanded scale pH meter was used for pH determinations.

Salinity samples were analyzed aboard ship using induction-type salinometers. Difficulties were encountered with the salinometers, and as a check, salinity samples collected after station 57 were returned to NAVOCEANO for a second analysis. This check did not produce the anticipated precision, and the best claim for this cruise is $\pm 0.10\text{‰}$. However, with the marked variations of salinity with depth due to the large amounts of runoff from the Ob and Yenisey Rivers, the salinity problems have not materially affected the results of the survey.

PHOTO 4. Modified Fisher Gas Partitioner

Water samples were frozen and returned to NAVOCEANO for reactive phosphorus and reactive silicate analyses. The methods of Murphy and Riley (1962) and Strickland and Parsons (1965) were used for these analyses.

Bathythermograph lowerings were taken by ship's personnel using a mechanical BT.

Plankton samples were taken while drifting on station and were preserved in an aqueous solution of formaldehyde and returned to Dr. N. Anderson of NAVOCEANO.

The continuous air sampling program consisted of mounting a pump on the flying bridge and drawing air through a filter. The filter was changed every 3 days and stored for return to Dr. J. H. Harley of the Health and Safety Laboratory, U.S. Atomic Energy Commission.

Nannoplankton samples were collected for Dr. A. McIntyre of the Lamont Geological Observatory for electronic microscopic analysis. Surface water samples initially were sieved through a wire mesh to remove all coarse material and then were pumped through a very fine filter. The filters were stored and at the end of the survey forwarded to Lamont Geological Observatory for analysis.

In shallow areas, 30-gallon water samples for gamma-radiation analysis were collected while the ship was underway. These samples were drawn through the ship's fire main system after first flushing the fire main for 30 minutes. In the deeper trench areas, the gamma-radiation samples were taken while the ship was lying-to using a Bodman bottle (Photo 5) at 100-meter depth intervals. To indicate possible

PHOTO 5. Bodman Bottle

pretrips, a Nansen bottle was placed directly above the Bodman bottle, and salinities of the two samples were compared. The Bodman bottle samples were stored in 15-gallon containers and returned to Dr. Anderson.

The six core samples obtained with the special piston corer were frozen immediately after they were collected and were forwarded to Dr. Anderson for radiological examination at the end of the survey.

The 95 Kullenberg gravity cores, averaging about 1 to 2 meters in length and 5 centimeters in diameter, were collected in plastic (Tulox) liners, wrapped with Saran Wrap, and covered with a thick layer of wax. These cores were divided between the University of Wisconsin and NAVOCEANO. The cores, when opened at NAVOCEANO 3 to 4 months later, had suffered very little desiccation. They were analyzed for specific gravity, moisture content, organic carbonates, bulk density, porosity, lithology, and grain size.

The 48 bottom grab samples were taken using either a Shipek grab or a weighted orange peel bucket sampler. These samples were divided between the University of Wisconsin and the Smithsonian Institution. The Smithsonian Institution samples were preserved with dilute alcohol and sealed in pint jars for foraminiferal examination.

Two current stations were taken in the Kara Sea. The first, while examining a shoal area, was of 4 hours duration. The second was taken for 24 hours to obtain information for a full tidal cycle. The current meter used (Photo 6) was a Hydro Products Model 460 current speed sensor (Savonius rotor type) and Model 465A current direction sensor. Both sensors were connected to deck readout modules and Rustrak recorders.

Continuous bathymetric profiling was done along the entire track of the survey using an Alden Precision Graphic Recorder (PGR) Model 418. At half-hour intervals, the PGR record was annotated with the date and time.

Using a Giffit transceiver in conjunction with the PGR, a continuous subbottom profile was recorded along with the bathymetry for much of the track of the NORTHWIND. Bottom penetration was possible due to the variable pulse length of the transceiver and the shallow depths of the survey area.

Ship positioning was unusually accurate due to the installation of a Satellite Navigational System (SRN-9) designed by the Applied Physics Laboratory, Johns Hopkins University. The accuracy of this system was about 500 feet.

F. Data Analysis and Presentation.

Oceanographic station data were checked, coded, and forwarded to the National Oceanographic Data Center (NODC). Machine computations

PHOTO 6. Hydro Products Current Meter

produced sigma-t, dynamic depth and specific volume anomalies, and sound velocity values at observed and standard depths.

Although the figures in this report were prepared from manually computed standard depth values, the discrepancies engendered by machine and manual computations are insignificant.

Map views depicting salinity and temperature distributions were prepared for depths of 0, 10, 25, 50, and 100 meters. Reactive phosphorus, reactive silicate, and pH concentrations at 10 meters were chosen because this depth seemed to best depict Continental Runoff. A map view and a cross section of temperature and salinity, based on Wüst's Core Method, were prepared in an attempt to trace the deep Atlantic Water movement into the Kara Sea. Map views delineating bottom topography and ice conditions are presented. The topographic data were primarily obtained from sonic depth soundings taken on oceanographic stations. The ice map was modified from the map contained in the Cruise Report of the NORTHWIND (NORTHWIND, 1965).

Temperature versus salinity (T-S) plots were drawn for four of the longer cross sections, and a T-S plot was drawn to show the presence of various water masses in different geographical areas.

Temporal variations were observed from data obtained at stations reoccupied after a 6-week time lapse and by various data parameters observed at the 24-hour current station.

Fifty cross sections are presented in the appendix, the majority of which are of temperature and salinity.

II. OCEANOGRAPHY OF THE KARA SEA

A. General.

1. Physical Setting. The Kara Sea is a shallow sea enclosed by the Franz Josef, Severnaya Zemlya, and Novaya Zemlya island groups; the Russian mainland on the southeast; the Barents Sea on the west; and the Arctic Ocean on the north (see Fig. 2). The sea is approximately 1,300km in length and has an area of 883,000km², an average depth of 118m, and a volume of 104,000km³. The Kara Sea overlies a portion of the Asian continental shelf; consequently, in only three areas do depths exceed 200 meters (Fig. 6). One of these deep areas, the East Novaya Zemlya Trough, lies along the eastern coast of Novaya Zemlya and is a miniaturized deep sea trench complete with outer ridge development (Johnson and Milligan, 1967). The two other deep areas, the Syvataya Anna Trough and the Voronin Trough located between the Franz Josef Land and Severnaya Zemlya Island groups, have the same geomorphological history as the East Novaya Zemlya Trough; these troughs deepen to the north and provide ingress for deep Atlantic Water which has transited the Arctic Ocean. They also provide egress of Kara Sea surface waters into the Arctic Basin. The deepest depths found in the Kara Sea area are in excess of 600 meters where the Syvataya Anna Trough incises the continental slope. A majority of the observed depths of the Kara Sea are less than 100 meters, and a definite shoaling trend extends northward from the Ob and Yenisey Rivers to the plateau between the Syvataya Anna and Voronin Troughs. It is not likely that this plateau was formed depositionally as shown

FIGURE 6. Bottom Topography of the Survey Area. Contours are Based on Sonic Depths at each Station

by the rough traces on the PCR record; however, the presence of a smooth trace in the western portion is evidence of deposition of particulate matter carried by the large rivers emptying into the Kara Sea.

2. Description of Rivers Emptying Into the Kara Sea. Some of the major Siberian rivers empty into the Kara Sea (Table II). This

TABLE II. Siberian Rivers Emptying Into the Kara Sea and Vicinity (After L'vovich, 1953)

RIVER	LENGTH (km)	Drainage Area (km ²)	Annual Discharge (km ³)
TAYMYR	600	72,000	20
PYASINA	820	192,000	80
YENISEY	3,354	2,599,000	548
TAZ	779	108,000	47
PUR	256	67,000	29
OB	3,676	2,485,000	394
PECHORA	1,790	327,000	129

outpouring of warm waters, which occurs mainly during the summer months and amounts to approximately 1,100km³/yr, entrains and mixes with vastly more water to form a brackish water type that overlies heavier and colder water. According to Antonov (1958), 213,000km³/yr flow into the Arctic Ocean from all sources. Eighty-three percent of this volume comes from the Atlantic Ocean as a submarine current traveling between Greenland and Spitsbergen. Continental Runoff constitutes approximately 0.5 percent of the water entering the Arctic Ocean. Nevertheless, the small amount of Continental Runoff exerts far greater influence on the currents and Arctic Basin water masses than the volume of runoff would indicate.

Temporal changes in the water are seen by noting changes at stations which were reoccupied after a 6-week interval (Fig. 7). At stations 37 and 59, which were near the mouths of the Ob and Yenisey Rivers, surface salinity values increased from August to September. Conversely, stations farther away from the river mouths showed decreased surface salinity values in the same time span. These variations illustrate the extreme changeability of surface salinity in this area. Figure 7 also shows that below about 30 meters, the salinity values did not change significantly during the 6-week period. This consistency in salinity of the deeper waters indicates that the variations were primarily due to runoff and winds.

3. A Description of Water Masses Found in the Kara Sea. There are six major water masses that either originate in the Kara Sea

FIGURE 7. Temporal Changes at Certain Locations

or enter the Kara Sea from adjacent areas. These water masses are seen on T-S diagrams (Fig. 8). The near vertical sigma-t lines on these T-S diagrams demonstrate that density of most Kara Sea waters is controlled principally by salinity.

FIGURE 8. Temperature-Salinity Curves for Selected Stations

The six water masses are as follows:

a. Continental Runoff. Relatively warm, fresh water that originates from the Ob and Yenisey Rivers. This water was found at station 36 from the surface to 10 meters.

b. Atlantic Water. Relatively warm, saline water entering the Kara Sea through:

(1) The Barents Sea between Novaya Zemlya and Franz Josef Land. This water was observed at stations 53 and 156 and had a temperature of approximately 0°C and a salinity of 34 ‰ at depths of 15 and 18 meters, respectively.

(2) The two deep trenches between Franz Josef Land and Severnaya Zemlya. This water has a temperature of approximately 1°C and a salinity of 34.8 ‰ and was observed at a depth of 200 meters at station 114 and at 181 meters at station 156.

(3) The straits in the lower Kara Sea. A minor inflow of a less saline, colder Atlantic Water. (This water was noted by

Nansen (1902).) Atlantic Water flowing through the straits in the lower Kara Sea was evidenced by water warmer than 0°C in the southernmost line of stations.

c. Arctic Water. A salinity of 33.5 to 34.5‰ and a temperature of less than -1.5°C . This water mass is well developed at a depth of 50 to 75 meters in a number of areas, e.g., stations 114, 1, and 156.

d. Residual Water. Cold, highly saline, dense water found in the isolated deeps of the East Novaya Zemlya Trough (200 to 300 meters at station 1).

e. Water entering from the Laptev Sea. Below 20 meters at stations 89 and 90. This water had a temperature range of -1.2° to -1.4°C , and a salinity range of 32.7 to 34.4‰.

f. Arctic Bottom Water. The densest of the water masses found in the Kara Sea with salinities of 34.8‰ and temperatures approaching -1°C . This water mass moves up the slopes of the trenches which incise the continental slope. Arctic Bottom Water was observed at stations 114 and 156 at depths of 600 and 317 meters, respectively.

4. The Wüst Core Method for Water Mass Determination. Wüst (1964) attempted to trace water types based on maximum or minimum values of either temperature, salinity, or oxygen "...the spatial spreading and mixing of the water types from their point sources cannot be deduced from the normal temperature, salinity and oxygen charts plotted for horizontal levels...because the core layers of the various water types rise and fall. Therefore, they are only fragmentarily manifested in such horizontal charts...". The method used in this NORTHWIND study consisted of drawing a chart of the maximum temperature values of the survey (Fig. 9). A vertical section of temperature was then constructed along an axis of spreading of warm water (Inset of Fig. 9). Due to shallow depths, no attempt was made to calculate potential temperatures.

Examination of the water masses by the Wüst Core Method shows the influx of Atlantic Water through the Svyataya Anna and Voronin Troughs. Using the 0°C isotherm as the boundary of the Atlantic Water, the slope of this rising water mass parallels the slope of the bottom. The cold water mass found at a depth of 50 meters is the Polar Water described by Nansen (1902), or in more recent terminology, Arctic Surface Water described by Coachman and Barnes (1962). Figure 9 also shows the relatively warm shallow Atlantic Water brought into the Kara Sea from the Barents Sea. Station 156 (Fig. 9) shows Continental Runoff at the surface, cold Arctic Water at 50 meters, relatively warm, rising Atlantic Water at 200 meters, and Bottom Water near the bottom. Station 156 also shows (Fig. 8) that mixing of surface water and Arctic Water at 46 meters could not form Atlantic Water at 18 meters because the water at 18 meters does not lie on a straight line between Continental Runoff and Arctic Water.

FIGURE 9. Water Mass Determination Using the Wüst Core Method

5. Current Data. Two current stations were occupied on this survey. The first was a 4-hour station which was occupied during an extensive shoal survey in the central Kara Sea. The second was a 24-hour station located 30 miles west of the western entrance to Proliv Vilkitskogo. Table III lists the bottom current data obtained on the second current station. The bottom current at this station

TABLE III. Bottom Current Data at 24-Hour Station

TIME Z	CURRENT SPD. kn.	CURRENT DIRECT. °T.	TIME Z	CURRENT SPD. kn.	CURRENT DIRECT. °T.
17/1630	0.08	---	30	0.16	225
45	0.00	---	45	0.18	225
1700	0.06	310	0500	0.12	225
15	0.02	---	15	0.06	225
30	0.20	270	30	0.10	225
45	0.30	265	45	0.16	225
1800	0.24	245	0600	0.16	225
15	0.10	240	15	0.12	225
30	0.32	240	30	0.20	225
45	0.14	245	45	0.28	225
1900	0.12	225	0700	0.10	225
15	0.10	225	15	0.14	225
30	0.06	225	30	0.30	225
45	0.06	225	45	0.20	225
2000	0.10	225	0800	0.24	225
15	0.02	225	15	0.20	225
30	0.10	225	30	0.24	225
45	0.12	225	45	0.26	225
2100	0.10	225	0900	0.20	225
15	0.10	225	15	0.18	225
30	0.20	225	30	0.16	225
45	0.14	225	45	0.18	225
2200	0.28	225	1000	0.12	225
15	0.14	225	15	0.18	225
30	0.24	230	30	0.10	230
45	0.12	225	45	0.18	220
2300	0.14	225	1100	0.12	225
15	0.12	230	15	0.08	225
30	0.10	230	30	0.10	225
45	0.12	230	45	0.08	230
18/0000	0.10	225	1200	0.04	225
15	0.02	225	15	0.04	260
30	0.10	225	30	0.14	260
45	0.14	230	45	0.08	245
0100	0.12	230	1300	0.04	245
15	0.14	230	15	0.04	270
30	0.18	230	30	---	---
45	0.14	230	45	0.02	---
0200	0.12	225	1400	0.04	310
15	0.16	225	15	0.02	---
30	0.13	225	30	0.04	310
45	0.24	225	45	0.02	---
0300	0.20	225	1500	0.04	270
15	0.22	225	15	0.04	260
30	0.18	225	30	0.02	260
45	0.14	225	45	0.08	255
0400	0.08	225	1600	0.10	255
15	0.08	225	15	0.12	225

set slightly south of west and had a range of 0 to 0.3 knot with an average speed of 0.2 knot. At the same time that subsurface currents were being measured, surface currents were estimated by plotting the tracks of icebergs. The surface current measured in this manner set slightly north of west and had an average speed of 0.5 knot. A 15-knot wind from 130°T undoubtedly was responsible for much of the surface water movement, and rather than long term wind patterns,

local winds east of Proliv Vilkitskogo likely were responsible for the movement of water through this shallow strait.

The water movement and the resultant changes in water characteristics are shown in Figure 10. The variations in values of observed properties seem to have occurred mostly above 25 meters with salinity least affected. These observations indicate that above 25 meters the surface layers east of the strait have values that correspond closely in salinity to those west of the pass. However, in the other parameters measured, e.g., reactive silicate, reactive phosphorus, and pH, the waters differ markedly.

B. Continental Runoff.

Continental Runoff is evident in all Arctic Ocean studies. Nansen (1902) stated that Continental Runoff "...is the chief factor in forming the layer of North Polar Water with low salinity, covering the sea that was transversed by the Fram...". Coachman and Barnes (1962), in their study of the surface water of the Eurasian Basin, noted that most of the fresh water was spread along the Siberian Coast before entering the Arctic Ocean. Antonov (1958) points out that the concentration of river discharge into the Kara and Laptev Seas creates an intensive summer runoff movement of surface waters directed mainly towards the north and east. Antonov gives the volume of yearly discharge from the Kara Sea Basin as $1,428 \text{ km}^3$ (this figure includes the Pechora River) which is more than one-half of the total annual Continental Runoff ($2,685 \text{ km}^3$) into the Arctic Ocean.

In Figure 11, the 0°C contour indicates the extent of Continental Runoff emptying into the Kara Sea. The warm waters spread almost directly north from the river mouths across the Kara Sea to north of 80°N . Surface movement in a southwesterly direction was indicated by high temperatures along the southeast coast of Novaya Zemlya. Due to the 6-week interval between the two phases of the survey, no attempt was made to join surface contours of the separate phases.

FIGURE 10. Changes in Various Parameters at 24-Hour Anchor Station Located Near the Western Entrance to Proliv Vilkitskogo

FIGURE 11. Surface Temperature Distribution

The surface isohalines (Fig. 12) show much the same picture as the surface isotherms. The distribution of surface salinity shows Continental Runoff extending north of 80°N and the movement of low salinity water towards the northern tip of Novaya Zemlya with a south-western component along the island. Figure 13, taken from Vize (1933), shows certain features that correspond closely to the NORTHWIND data. The movement of surface waters towards the small island of Ostrov Vize, which lies between the Franz Josef Land and Severnaya Zemlya Islands chains, is shown in both Figure 12 and Figure 13.

The depth of 10 meters, as compared to the surface, better indicates movement of surface water because this depth is not obscured by melting ice and other transient features. The 10-meter isotherms presented in Figure 14 show high temperature values along the southeastern coast of Novaya Zemlya due to the southwestern component of movement observed in the surface values. High temperature values in the southwestern end of the Kara Sea may be due to water movement through the Kara Strait from the Pechora River. Nansen (1902) noted "...eastward flowing surface currents may be formed through the Kara Strait, as observed by Krusenstern in 1860 and Sidoroff in 1869...".

At a depth of 10 meters, the warm lobe of water extending north of Ostrov Vize is apparent; however, the orientation of the warm water influx at this depth is both east-west and north-east. This unusual feature will be discussed later. Salinity distribution at 10 meters (Fig. 15) indicates the movement of river runoff to be primarily directed to the north with some movement southwestward along the coast of Novaya Zemlya. Dissolved silicate concentration (Fig. 16) also shows Continental Runoff moving in a northerly direction. Dissolved silicate values were in excess of $34\text{ }\mu\text{g-at/l}$ at the mouths of the Ob and Yenisey Rivers. High dissolved silicate values were found in the lee of Ostrov Vize.

Phytoplankton biomass distribution found during the 1934 SEDOV Expedition (Zenkevitch, 1963) (Fig. 17) also shows anomalously high values existing north of Ostrov Vize.

With both dissolved silicate and salinity, a marked variance exists between the influx from the rivers and from other sources such as the influx of Atlantic Water. The pH isopleths (Fig. 18) are not as useable as the others in defining the movement of Continental Runoff; however, pH clearly indicates movement corresponding to that of the other parameters, i.e., the low values are related to the Continental Runoff and the high values are related to Atlantic Water moving eastward past the tip of Novaya Zemlya. The reactive phosphorus distribution (Fig. 19) neither supports nor detracts from the pattern established by the other parameters. A feature indicated on all of the 10-meter distribution figures is the lobe of warm, fresh water moving northward from the Ob River mouth.

FIGURE 12. Surface Salinity Distribution

FIGURE 13. Surface Salinity Distribution - Taken from Vize (1933)

Cross sections, Figures A-2 through A-23 (Appendix), show in sectional view the water types present in the Kara Sea. The surface water runoff is particularly well depicted in sections A-A' (Fig. A-2) through M-M' (Fig. A-14). In the sections lying between Novaya Zemlya and the Siberian Coast, the runoff is found at very shallow depths. This pattern remains true until section H-H' (Fig. A-9) where the 0°C isotherm dips steeply at station 42. This abrupt dip probably has a number of causes rather than being due primarily to river runoff, e.g., the surface movement of Atlantic Water around the tip of Novaya Zemlya and the estuarine effect as deep Atlantic Water, sections J-J' (Fig. A-11) and V-V' (Fig. A-23), moves into the Kara Sea from the Arctic Ocean to compensate for the outflow of surface waters. Based on older and less complete data, Coachman and Barnes (1962) went into some detail in reporting on this estuarine effect "...Dynamics similar to those in estuaries develop over the edge of the continental shelf and in the canyons; the surface water moves off the shelf and the deeper water moves toward the shelf and up the canyons where it attains depths considerably shallower than it occupies in the

FIGURE 14. Temperature Distribution at 10 Meters

FIGURE 15. Salinity Distribution at 10 Meters

FIGURE 16. Dissolved Silicate Distribution at 10 Meters

FIGURE 17. Phytoplankton Biomass Distribution Found During the 1934 SEDOV Expedition

FIGURE 18. Distribution of pH at 10 Meters

FIGURE 19. Reactive Phosphorus Distribution at 10 Meters

deep-water basin...". Defant (1961) discusses the fact that river water flowing into the sea gives rise to compensation currents along the river bed "...the outflow of river water in the estuary was accompanied by an inflow of sea water in the lower layers... .

C. Atlantic Water.

1. General. Waters originating in the Gulf Stream flow northward along the Norwegian Coast. A division of this Atlantic Water occurs between Bear Island and northern Norway where the flow approaches the submarine slope at the entrance to the Barents Sea. Here, some of the water in the shallow layers enters the Barents Sea under the influence of Coriolis force, and despite many offshoots and countercurrents, some Atlantic Water rounds the northern tip of Novaya Zemlya and enters the Kara Sea. The majority of flow, however, does not enter the Barents Sea but continues northward and enters the Arctic Basin between Greenland and Spitsbergen. In the Arctic Basin, the mass of this water flows eastward along the continental slope at depths between 200 and 900 meters. In transit, the water is modified so that when it reaches the Kara Sea it retains about 40 percent of its original characteristics (Coachman, 1962).

2. Inflow from the Barents Sea. Off the northern tip of Novaya Zemlya, the Atlantic Water which has transited the Barents Sea continues eastward and enters the Kara Sea as shown by the 10-meter isopleths in Figures 14, 15, and 16.

Temperature and dissolved silicate in sections V-V' (Fig. A-23) also show Atlantic Water entering the Kara Sea at station 42 at a depth of less than 50 meters. Since Continental Runoff and Atlantic Water from the Arctic Basin were found to have high dissolved silicate values, the shallower, low dissolved silicate water at station 42 probably is Atlantic Water.

Using the data from section V-V', a T-S diagram (Fig. 20) was constructed to further delineate the various water masses. At station 42, a temperature inversion existed in the upper layers. This inversion was produced by Continental Runoff overriding warmer Atlantic Water brought into the area across the Barents Sea. The influence of dilute runoff is apparent at most stations. At stations 154, 147, and 143, for example, the highly saline, relatively warm, shallow water mass from the Barents Sea mixed with both a cooler, lower salinity Continental Runoff from one direction and a cold, highly saline Arctic Water from the Arctic Basin. At stations 42 and 53, Arctic Water was not encountered because of intense mixing in this area.

Temperature and salinity map views (Figs. 21 through 26) also depict the influx of Atlantic Water into the Kara Sea via the Barents Sea. Isotherms at 25, 50, and 100 meters (Figs. 21, 22, and 23) show an east-west orientation, indicating an influx of water from the

FIGURE 20. Temperature/Salinity Diagram for a Selected Line of Stations (Cross Section V-V', see Figure A-1)

west. These figures also show three small vortices which commonly form when friction arises from overlying and underlying strata moving in different directions (Nansen, 1902). These vortices facilitate mixing of water masses.

Isohalines at 25 meters (Fig. 24) turn northward, corresponding to a similar pattern of isohalines at shallower depths. These high salinity values indicate that appreciable flow into the Kara Sea is from the Barents Sea. At 50 meters (Fig. 25) and at 100 meters (Fig. 26), the 34.5‰ isohaline also shows that high salinity water enters the Kara Sea from the west, moves past the tip of Novaya Zemlya, and then turns northward.

3. Inflow from the Arctic Ocean. Atlantic Water enters the Kara Sea from the Arctic Ocean via the Svyataya Anna and Voronin Troughs with the major flow passing through the deeper Svyataya Anna Trough. Five cross sections, O-O', P-P', Q-Q', R-R', and S-S' (Figs. A-16 through A-20) show the penetration of Atlantic Water into the Kara Sea via the two troughs. The 0°C isotherm shows that Atlantic Water fills most of the Svyataya Anna Trough but does not fill the Voronin Trough, despite the trough's sufficient depth. The salinity, and therefore density, is essentially the same in both troughs. However, the Voronin Trough does not appear to receive as much Atlantic Water because either there exists some peculiar circulation patterns or

FIGURE 21. Temperature Distribution at 25 Meters

FIGURE 22. Temperature Distribution at 50 Meters

FIGURE 23. Temperature Distribution at 100 Meters

FIGURE 24. Salinity Distribution at 25 Meters

FIGURE 25. Salinity Distribution at 50 Meters

FIGURE 26. Salinity Distribution at 100 Meters

Atlantic Water which enters is modified by cooling as it moves to the surface. In effect then, a water mass of similar characteristics is present in both troughs with a sigma-t of 28, a salinity close to 35 ‰, but with a temperature below 0°C in the Voronin Trough and slightly above 0°C in the Svyataya Anna Trough.

Cross sections O-O', P-P', Q-Q', R-R', and S-S' (Figs. A-16 through A-20) also show that the Atlantic Water entering the Kara Sea through the Svyataya Anna Trough hugs the western side of the trough. This feature probably is attributable to Coriolis force deflecting the water to the right as it moves southward in the troughs.

In cross sections Q-Q', R-R', and S-S' (Figs. A-18 through A-20), the isotherms and isohalines are seen to slope upward. This upward slope is attributable to geostrophic balance which would tend to elevate the eastern edge of the Atlantic Water.

Cross section V-V' (Fig. A-23) shows the extent of southern penetration of Atlantic Water and shows the movement of water up the slope of the Svyataya Anna Trough. Coachman and Barnes (1962) describe this inflow as an estuarine effect as deeper waters are carried up the slope compensating for the outflow of surface waters. This description was based on a Russian cross section located 20 miles west of and almost parallel to cross section V-V'.

Both cross section J-J' (Fig. A-11) and Figure 27 show this estuarine effect of Atlantic Water and the mixing and warming of the cold upper

FIGURE 27. Temperature/Salinity Diagram for a Selected Line of Stations (Cross Section J-J', see Figure A-1)

waters. The Atlantic Water core entering the Kara Sea through the two troughs rises from a depth of 300 meters to a depth of 150 meters within 50 nautical miles as it encounters the continental shelf. Above 150 meters, Atlantic Water loses its distinguishing characteristics by admixture with other waters.

D. Arctic Water.

The primary source of Arctic Water found in the Arctic Basin is Continental Runoff from the Arctic Ocean's peripheral seas (Cross section 0-0', Fig. A-16). Coachman (1962) divided Arctic Water into the following three sublayers: The shallow layer (0 to 25-50 meters), a relatively dilute, generally cold layer formed primarily by summer melting of pack ice; the subsurface layer (25-50 to 100 meters), a cold layer which increases in salinity with depth (33-34 ‰); and the mixed layer (100 to 200 meters), a layer with increased temperatures and a slight increase in salinity marking the approach to the Atlantic Water core at 300 meters.

Coachman (1962) refers to these sublayers as Surface Water, and Nansen (1902) refers to them as North Polar Water. The temperature/salinity relationship is such that the water mass must be advected into the Arctic Basin from some outlying area. The NORTHWIND survey has allowed a re-examination of the questions of where the water originates and what waters mix.

One explanation of the anomalously high salinities found in the Surface Water in the Kara and Laptev Seas is intensive mixing of the saline Atlantic Water brought via the Svyataya Anna and Voronin Troughs with river effluent (Coachman, 1962)...this mixing results in the formation of the subsurface layer of Arctic Water at 25-50 to 100 meters which overlies the Arctic Basin. Another explanation for the high salinity is the sizeable amount of Atlantic Water entering the Kara Sea from the Barents Sea as discussed above. Zenkevitch (1963), on the other hand, states that the high salinity values can be attributed to the formation of ice in winter.

Examination of the northernmost line of stations allows study of this freezing process in action. It may be seen from the T-S plot (Fig. 28) that Arctic Water is being formed at the surface in this location. It should also be noted that the temperatures of the Arctic Water mass approximate the freezing point of sea water for those particular salinities.

The extent of Arctic Water in the Kara Sea can be determined by examining three temperature cross sections, J-J' (Fig. A-11), 0-0' (Fig. A-16), and V-V' (Fig. A-23). The core of Arctic Water in these sections will be considered to be the -1.5°C isotherm. This isotherm places the core at approximately 75 meters. The isotherms in section J-J' show the pinching out of the Arctic Water at station 77 as Arctic

FIGURE 28. Temperature/Salinity Diagram for a Selected Line of Stations (Cross Section O-O', see Figure A-1)

Water comes in contact with the warm, rising Atlantic Water, the surface runoff, and the inflow from the Barents Sea. Arctic Water is found at all stations between stations 140 and 77. At station 140, close to Franz Josef Land, the cold Arctic Water is overlain by warmer, less saline water which forces the Arctic Water to deeper depths. The T-S plots for section J-J' (Fig. 27) show these water masses in detail. The Arctic Water mass appears to form a tight locus of points with a salinity of 34.3‰ at stations 149, 152, and 154. The temperature isotherms of cross section O-O' (Fig. A-16) show a typical view of the Arctic Basin with the Arctic Water mass overlying the warmer Atlantic Water. The temperature isotherms of cross section V-V' (Fig. A-23) show Arctic Water extending almost to station 53 at a depth of 60 meters. The cold tongue of water at 20 meters at stations 31 and 41 closely resembles Arctic Water, but due to low salinity values, this water will not be considered as Arctic Water.

Arctic Water extends southward from the northernmost line of stations to the northern end of Novaya Zemlya. Eastward, this water mass pinches out as the water shoals and becomes warmer.

E. Residual Water.

A cold, residual water which was formed in previous winters is found in the East Novaya Zemlya Trough. This water is formed by

a gradual cooling and an increase in density which results in sinking. This water is depicted by a T-S diagram (Figure 29). **Residual Water** is exhibited at station 13 with a sigma-t of 28, a temperature of -1.75°C , and a salinity of 34.76‰ . The isolated nature of the East Novaya Zemlya Trough restricts mixing with other water; therefore, the coldest temperatures observed on this survey were found in this trough.

FIGURE 29. Temperature/Salinity Diagram for a Selected Line of Stations (Cross Section C-C', see Figure A-1)

F. Water from the Laptev Sea.

Current measurements at the western entrance to Proliv Vilkitskogo indicated a continuous inflow into the Kara Sea from the Laptev Sea. The surface current, measured by ice movement, averaged 0.5 knot, and the bottom current, measured by a current meter, averaged 0.2 knot with a range of 0 to 0.3 knot. Measurement of various parameters (Fig. 10) at the start and finish of the current station allowed an examination of this water; temperature at depth approached -1.4°C and salinity was 34.4‰ . A T-S plot (Fig. 8) shows that the bottom water at station 104 closely approximated that of station 90 indicating inflow of similar water north of Severnaya Zemlya. Also, Russian sources (Zenkevitch, 1963) suggest the Laptev Sea to be the origin of fauna found in Proliv Vilkitskogo. Zenkevitch also notes that the second route for the penetration of fauna from the central part of the Arctic Basin into the Kara Sea "...passes...through the northern deep part of the Laptev Sea and through the deep...Vilkitsky Strait [Proliv Vilkitskogo]...".

G. Arctic Bottom Water.

The deepest waters in the Svyataya Anna and Voronin Troughs is modified cold, saline Arctic Bottom Water. Coachman (1962) defines Arctic Bottom Water as having temperatures colder than 0°C and salinities between 34.93 and 34.99 ‰. The five east-west cross sections, 0-0' to S-S' (Figs. A-16 through A-20), show Arctic Bottom Water, with slightly lower salinity than that given by Coachman, to exist at the deepest depths in the troughs. In addition, the Arctic Bottom Water in both troughs is basically the same. The T-S plot of the northernmost line of stations (Fig. 28) shows that the Arctic Bottom Water at stations 107 and 108 has the same T-S characteristics as at stations 113 and 114.

The Arctic Bottom Water in the Svyataya Anna and Voronin Troughs is found at shallower depths than in the Arctic Ocean. The estuarine effect (Coachman, 1962) is probably responsible for the rising of this water mass although there might be some minor formation of bottom water at the heads of the Svyataya Anna and Voronin Troughs which would result in a northern flow counter to the above.

III. SUMMARY AND CONCLUSIONS

NAVOCEANO conducted an extensive oceanographic survey of the Kara Sea during the summer and fall of 1965. Examination of samples from 163 Nansen cast stations resulted in approximately 1,800 serial depth measurements for each of the parameters of temperature, salinity, dissolved oxygen, nitrogen, pH, reactive phosphorous, and reactive silicate.

Six water masses were found which either entered or were formed in the Kara Sea: Continental Runoff, Atlantic Water, Arctic Water, isolated remnants of previous year's water, water entering from the Laptev Sea, and Arctic Bottom Water. Atlantic Water was found entering the Kara Sea from both the Barents Sea and from the Arctic Ocean via the Svyataya Anna and Voronin Troughs.

Continental Runoff, principally from the Ob and Yenisey Rivers, was traced northeastward along the Siberian Coast. Continental Runoff also was observed to cross the Kara Sea towards Novaya Zemlya and then to move southward along the island. Another mass moved north from the Ob and Yenisey River mouths towards Ostrov Vize.

Reactive silicate was a most interesting parameter for examining Continental Runoff. Runoff resulted in high reactive silicate measurements north of Ostrov Vize. These high values north of Ostrov Vize were also observed by the Russians in an earlier survey.

Atlantic Water enters the Kara Sea through the Svyataya Anna and Voronin Troughs as a subsurface counterflow to the outflowing

Continental Runoff. This flow results in the movement of relatively warm, saline water from a core depth of 300 meters at the arctic continental slope to perhaps 150 meters at the head of the two troughs where the water loses much of its distinguishing characteristics.

Atlantic Water also moves into the Kara Sea from the Barents Sea. Using T-S diagrams, this water was shown to mix with Continental Runoff and Arctic Water.

Arctic Water is believed to form in the shallow peripheral seas adjacent to the Arctic Ocean, e.g., the Kara Sea. Here, the saline Arctic Water is formed by the mixing of Continental Runoff and the saline Atlantic Water brought into the Kara Sea. The salinity, and therefore the density, is increased further in the winter with the formation of ice.

Isolated remnants of previous year's waters were found in the deeper areas of the East Novaya Zemlya Trough. This water is formed by cooling and gradual sinking. It is therefore understandable that here, at depth, were found the coldest temperatures of the survey.

Inflow from the Laptev Sea was recorded at the western entrance to Proliv Vilkitskogo both at the surface and near bottom. The water near the bottom is similar to waters at the same depth north of Severnaya Zemlya.

In the Kara Sea, Arctic Bottom Water is found at the deepest depths of the Svyataya Anna and Voronin Troughs and is probably brought into the area as a countercurrent to the outflowing Continental Runoff.

This survey has provided the much needed oceanographic data for study of the Kara Sea. The questions of where and under what conditions Arctic Water is formed have been re-examined. The addition of appreciable amounts of Atlantic Water via the Barents Sea to form this water is suggested.

The parameters of reactive silicate, pH, and, to a lesser extent, reactive phosphorus were valuable in distinguishing water masses.

The anomalously high reactive silicate values observed north of Ostrov Vize is a feature which warrants further study. This feature was observed 30 years earlier and is possibly a stable phenomenon. Another interesting feature observed on this survey is the hugging of Atlantic Water to the western side of the Svyataya Anna Trough caused by Coriolis Force.

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APPENDIX

CROSS SECTIONS

FIGURE A-1. Plan View of Cross Sections

FIGURE A-2. Cross Sections of Temperature and Salinity Along Line A-A'

FIGURE A-3. Cross Sections of Temperature and Salinity Along Line B-B'

FIGURE A-4. Cross Sections of Temperature and Salinity Along Line C-C'

FIGURE A-5. Cross Sections of Temperature and Salinity Along Line D-D'

FIGURE A-6. Cross Sections of Temperature and Salinity Along Line E-E'

FIGURE A-7. Cross Sections of Temperature and Salinity Along Line F-F'

FIGURE A-8. Cross Sections of Temperature and Salinity Along Line G-G'

FIGURE A-9. Cross Sections of Temperature and Salinity Along Line H-H'

FIGURE A-10. Cross Sections of Temperature and Salinity Along Line I-I'

FIGURE A-12. Cross Sections of Temperature and Salinity Along Line K-K'

FIGURE A-13. Cross Sections of Temperature and Salinity Along Line L-L'

FIGURE A-14. Cross Sections of Temperature and Salinity Along Line M-M'

FIGURE A-15. Cross Sections of Temperature and Salinity Along Line N-N'

FIGURE A-16. Cross Sections of Temperature, Salinity, Reactive Silicate, Reactive Phosphorus, and pH Along Line O-O'

FIGURE A-17. Cross Sections of Temperature and Salinity Along Line P-P'

FIGURE A-18. Cross Sections of Temperature and Salinity Along Line Q-Q'

FIGURE A-19. Cross Sections of Temperature and Salinity Along Line R-R'

FIGURE A-20. Cross Sections of Temperature and Salinity Along Line S-S'

FIGURE A-21. Cross Sections of Temperature and Salinity Along Line T-T'

FIGURE A-22. Cross Sections of Temperature and Salinity Along Line U-U'

FIGURE A-23. Cross Sections of Temperature, Salinity, Reactive Silicate, Reactive Phosphorus, and pH Along Line V-V'

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3. Water Masses
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13. ABSTRACT			
NAVOCEANO made a survey of the Kara Sea during the summer and fall of 1965.			
Data were collected at 163 oceanographic Nansen stations and included serial-depth temperature, salinity, dissolved oxygen, nitrogen, pH, reactive phosphorus, and reactive silicate measurements.			
Six major water masses were found in the Kara Sea: Continental Runoff, Atlantic Water, Arctic Water, Residual Water, Inflow from the Laptev Sea, and Arctic Bottom Water.			
Atlantic Water is brought into the Kara Sea both as a deep estuarine inflow from the Arctic Ocean compensating for the outflow of shallower Continental Runoff and as a relatively shallow inflow from the Barents Sea. This estuarine movement from the Arctic Ocean raises the core depth of the Atlantic Water from 300 to 150 meters where it then mixes with the inflow from the Barents Sea and Continental Runoff. The movement of Atlantic Water across the Barents Sea and into the Kara Sea has largely been ignored by American oceanographers.			
Arctic Water is formed in the shallow peripheral seas adjacent to the Arctic Ocean, e.g. the Kara Sea, by mixing of Continental Runoff with the saline Atlantic Water. Salinity and density increase as ice forms during the winter.			
Residual Water was found in the deeper areas of the East Novaya Zemlya Trough. This water, formed by cooling and gradual sinking, had the coldest temperatures found on the survey.			
Arctic Bottom Water was found in the deepest portions of the Svyataya Anna and Voronin Troughs. It, like Atlantic Water, also is probably brought into the areas as a countercurrent to the outflowing Continental Runoff.			

14.	KEY WORDS	LINK A		LINK B		LINK C	
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	<p>OCEANOGRAPHY KARA SEA WATER MASSES USCGC NORTHWIND (WAGB 282)</p>						
	<p>ABSTRACT (Cont'd)</p> <p>Reactive silicate was an interesting new parameter for examining Continental Runoff: noted especially were anomalously high measurements recorded north of Ostrov Vize. Other parameters which proved valuable in the study of water masses were pH and reactive phosphorus.</p>