Physical Oceanography in the Arctic Ocean: 1968

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INTRODUCTION

Three years ago I reviewed our knowledge of the physical regime of the Arctic Ocean (Coachman 1968). Briefly, the Ocean may be thought of as composed of two layers of different density: a light, relatively thin (~ 200 m.) and well-mixed top layer overlying a large thick mass of water of extremely uniform salinity, and hence density. In cold seawater, the density is largely determined by the salinity. Superimposed on this regime is a three-layer temperature regime.

The surface layer is cold, being at or near freezing. Frequently there is a temperature minimum near the bottom of the surface layer (~ 150 to 200 m. depth), and within the Canada Basin a slight temperature maximum is found at 75 to 100 m. depth owing to the intrusion of Bering Sea water. The intermediate layer, Atlantic water, is above 0°C., and below this layer (> 1000 m.) occurs the large mass of bottom water which has extremely uniform temperatures below 0°C. but definitely above freezing.

The general picture of the water masses is drawn from 70 years of oceanographic data collection. The Naval Arctic Research Laboratory, in its support of drifting stations and other scientific work on the pack ice, has provided the basic support for the United States contribution to physical oceanographic studies of the central Arctic Ocean.

There are still enormous gaps in our knowledge. The Arctic Ocean is probably no less complex than any of the world oceans, but its ranges of property values are less and hence the complexities are reflected as smaller variations of the values in space and time.

The spatial coverage of even the mean temperature and salinity fields in the water is very spotty; hence our knowledge of the water masses and their interactions is poor, particularly in regard to the quantities involved. This comes about because we have been for the most part restricted to analysing samples from drifting stations, and these stations drift only along certain defined paths. Furthermore, we do not have anything like a synoptic picture of the distributions of these variables. Therefore, our picture of the distributions does not represent the fields in the ocean at a particular time, and in fact may not properly represent the mean fields of temperature and salinity.

The field of motion is much less well known than is the distribution of the water masses. This stems in part from the fact that the motion field has much more "noise" in it than does the temperature field, for example. Also, the measurements we have been able to get suffer from the limitation of being made from a

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moving platform, which causes two problems. One is that the platform motion must be subtracted from the measurements to find water motion, and positioning of the ice with sufficient accuracy and frequency to allow a reasonable separation of ice and water motions has been possible only very recently. The other problem is that inherently time and space variations cannot be separated when the measuring point continually changes position. We have practically no information on spatial variations of Arctic Ocean currents today, but the experiments outlined later are aimed at this problem.

NARL'S CONTRIBUTION TO PHYSICAL OCEANOGRAPHIC STUDIES

An important contribution by NARL is their willingness to support drifting stations. Without this support, our knowledge of the physical character of the ocean would not even be at the present level. If this support were to cease now, there would virtually be no United States physical oceanographic research in the Arctic Ocean.

The most significant particular contributions in the last 20 years can be summarized as follows:

1) We have been able routinely to collect hydrographic data for a number of years from the Canada Basin. Continuation of this data-collection will allow us in the near future, I believe, to analyse for long-term trends in the characteristics of the water masses. Climatic variations can be reflected in small changes in the t and S of ocean water, as has been documented for example for the Greenland Sea (Aagaard 1968) and deep Labrador fjords (Nutt and Coachman 1956).

2) The support of "Ski Jump" in 1951-52 (Worthington 1953) which has been the only U.S. counterpart of the Soviet High-Latitude Air Expeditions. This expedition, even though limited in scope, produced very useful results from the oceanographic viewpoint. Stations were occupied near the central part of the Beaufort Sea gyre which are still the only data we have from this area.

3) The current measurements obtained from ARLIS II while it drifted out of the Arctic Ocean with the East Greenland Current provided significant new ideas about this western boundary current of a subpolar gyre (Aagaard and Coachman 1968a, b). New concepts of the circulation in the Greenland Sea and exchange with the Arctic Ocean were generated by the observations.

4) The recently developed capability of precise and frequent position-fixing of Fletcher's Ice Island, T-3, now permits good direct measurement of the horizontal currents in the deep Arctic Ocean. The initial results from the first series of these direct current measurements are presented below.

CURRENT INVESTIGATIONS — TWO SCALES OF ICE-WATER MOTION

Long-term trends

There have been a number of drifting stations in the last 20 years in the Canada Basin for which reliable positions are available. The drift tracks of those

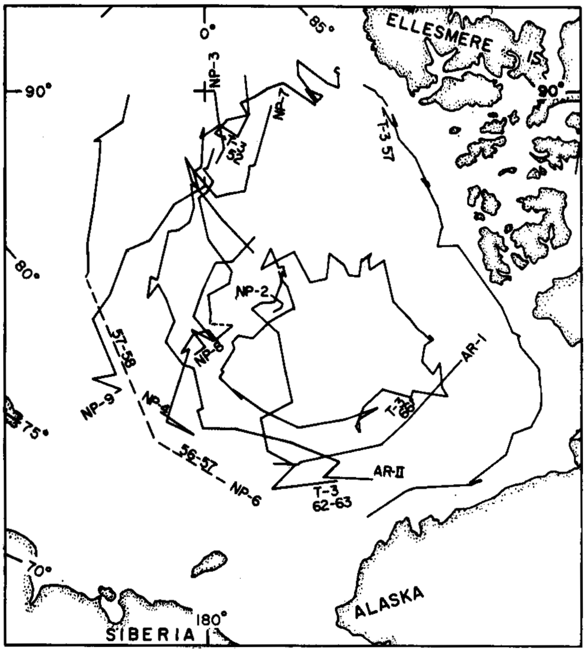

FIG. 1. Ice station drift tracks in the Canadian Basin constructed from segments of net monthly drift. Track of NP-6 is broken as monthly data are not available.

for which positions at the end of each month were available are shown in Fig. 1. Each track is composed of segments of net monthly movement. The tracks define clearly the well-known Beaufort gyre circulation. The centre of the gyre, 80°N. and 140°W., coincides with the centre of the mean atmospheric pressure anticyclone (Felzenbaum, from Campbell 1965).

The day-to-day drift of ice stations has been observed to be quite erratic (see, for example, Fig. 5). To analyse for possible long-term trends the vagaries of the motion were suppressed by using the net monthly displacements. There is a very definite directional preference to the long-term motion for various locations, resulting in the anti-cyclonic gyral pattern of the mean atmospheric pressure field. The inevitable conclusion is that, over the long term, the winds associated with the mean atmospheric pressure field drive the ice in a similar pattern.

As the atmospheric pressure field will vary in intensity over months and years, the speed of ice drift in the gyre can also be expected to vary similarly. However, the speed variations may be different in different parts of the gyre owing to differences in atmospheric pressure gradients, and to time and space variations in the large frictional resistance (Campbell 1965) in the ice cover.

A first attempt to define seasonal and long-term variations in the ice drift was made as follows. All drifts west of 140°W., which are in general directed to the west and north, were separated from those taking place farther east. These segments are identified as being in the Transpolar Drift Stream, while those east of 140°W., where the drifts are predominantly east to west along the Canadian Arctic Archipelago, are in the eastern Beaufort gyre.

The mean monthly drift speeds grouped by months and their standard deviations for the two drift areas are presented in Fig. 2a. The conclusions are:

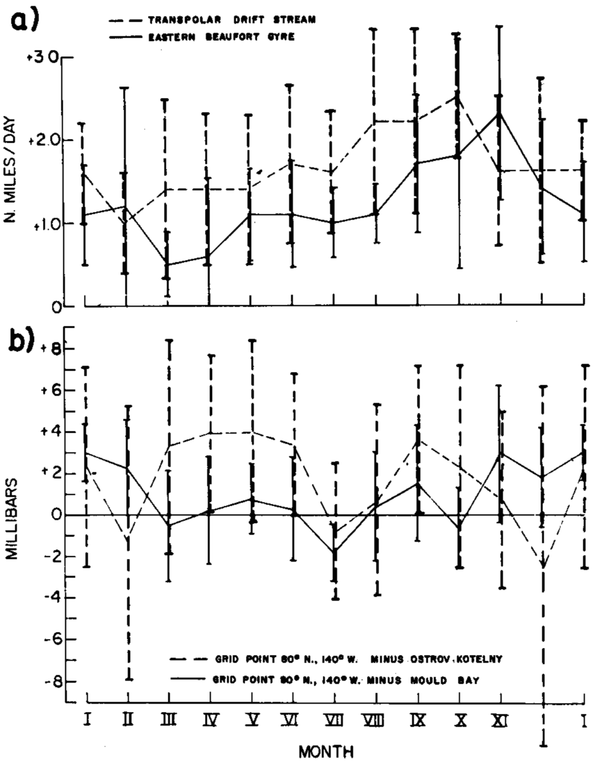

FIG. 2. a) Mean monthly drift speeds and b) mean monthly surface atmospheric pressure gradients, by months, and for the two sides of the Beaufort gyre. Monthly means are connected to show trends, and ± one standard deviation is indicated.

1) Ice drifts faster in the Transpolar Drift Stream than it does along the Canadian islands, by about ½ n. mi./day.;

2) A marked increase in speed occurs in summer or fall. The surge occurs in late summer in the transpolar stream, but not until late fall in the eastern part of the gyre.

As a crude approximation to the surface atmospheric pressure gradients, which must be instrumental in driving the system, mean monthly atmospheric pressure gradients across the east and west sides of the gyre were compiled and treated in a manner identical to the drift data (Fig. 2b.).

For the eastern side, the pressure difference was the mean monthly value for grid point 80°N., 140°W. minus the mean monthly value reported for Mould Bay. For the transpolar side, 80°N., 140°W. minus Ostrov Kotelny was used.

The atmospheric pressure gradient variations agree qualitatively with the drift speed variations in that:

1) The pressure gradient across the eastern side of the gyre is less than across the transpolar drift stream;

2) There is an increase in late summer or fall with the same phase shift between the transpolar and eastern Beaufort sides as observed in the drift speeds.

In addition, there is a marked increase in late winter-spring in the magnitude of the atmospheric surface pressure gradient across the transpolar drift stream which apparently is not reflected in a corresponding increase in drift speed. This

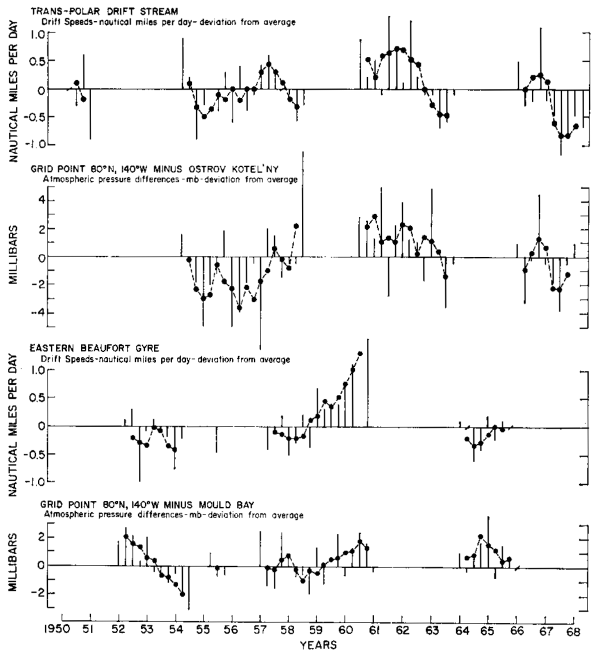

FIG 3. The transpolar drift data and eastern Beaufort data, deviations of drift speeds (above) and atmospheric pressure gradients (below) from the monthly averages, averaged by seasons. Trends are indicated by 3-point running means. Vertical lines are quarterly averages. Seasons indicated are winter (December through February), spring (March through May), summer (June through August), and fall (September through November.

might be attributed to the fact that in winter the ice cover is tighter and heavier and undoubtedly there is a much greater frictional resistance within the pack.

To examine the data for longer term trends, the spatial separation was maintained, the mean monthly speeds averaged by quarters, and then the seasonal variation removed by examining deviations from the quarterly average. The residuals are plotted in Fig 3, which show whether the stations were drifting slower or faster than normal for the location and season. To illuminate trends, three-point running means are also plotted. Below each segment of drift data the comparable atmospheric pressure gradient data, treated identically, are plotted. The conclusions are:

1) There are definitely times when the ice drift has been significantly faster and slower than the average. In the period 1959-62 drift speeds were greater than one-half nautical mile per day faster than normal; recently, beginning in 1967, drifts have been more than one-half mile per day slower than normal;

2) The speed variations are positively correlated with intensity in the appropriate mean atmospheric pressure gradients.

Clearly, there are long-term variations in the ice motion which are related to variations in atmospheric pressure. More detailed research along these lines may well lead to better predictions of ice drift.

Ice and water motion during summer, 1967

During the summer of 1967 the satellite navigation system provided numerous fixes of T-3's position to about ±0.3 nautical mile. Three current meters, at 150, 500, 1300 m. depth, recorded relative water motion at 10-minute intervals over nearly 110 days. This is one of the longest series of deep-ocean current mea-

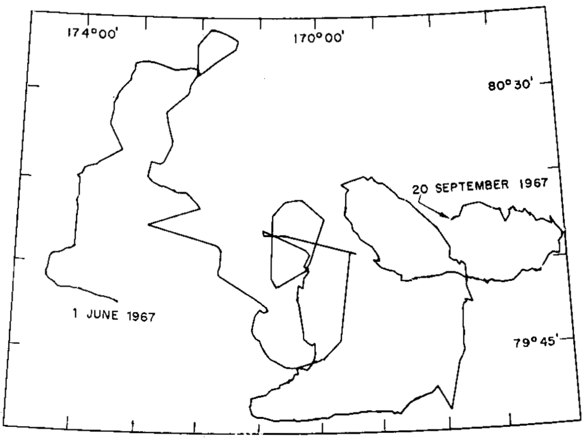

FIG. 4. The track of T-3 between 1 June and 20 September 1967, as determined by satellite navigation. The 1 June position is in lower left, the 20 September position in middle right.

surements that have been obtained anywhere, and considerable information about Arctic Ocean currents in the three water masses and their time variations are in the record.

To convert the relative measurements to actual water motion, the movement of T-3 had to be analysed as thoroughly as possible. Fig. 4 shows the track of T-3 for the 110 day-period. Fixes were examined sequentially in time; those that gave positions of less than 0.3 n. mile (the presumed error) from the previous one were averaged in space and time with each previous fix to generate a new position. By this technique we feel the track has been smoothed as much as possible without reducing the resolution.

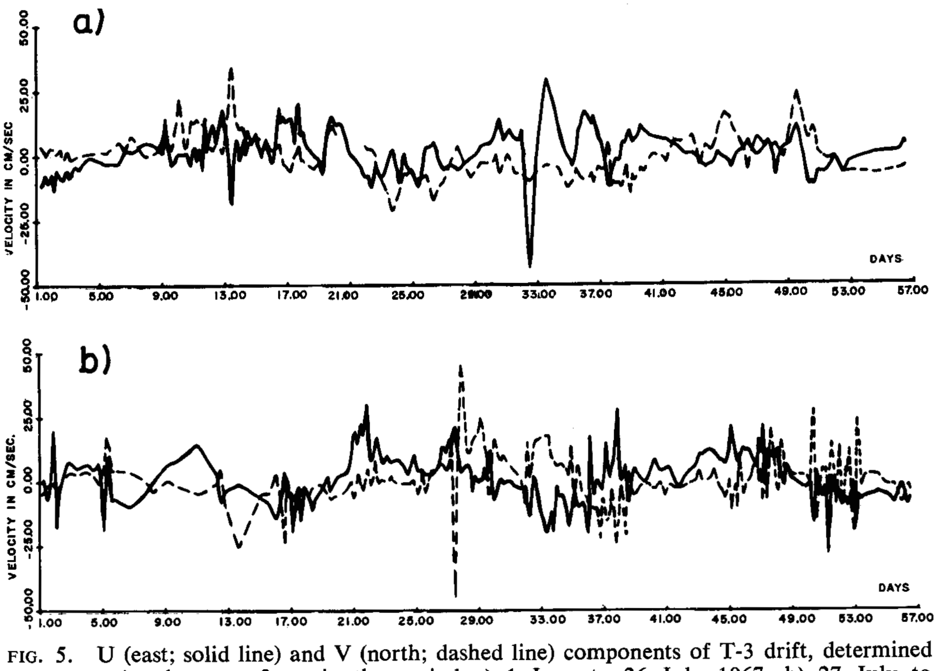

FIG. 5. U (east; solid line) and V (north; dashed line) components of T-3 drift, determined as net motion between fixes, in the period a) 1 June to 26 July 1967, b) 27 July to 20 September 1967.

The track of T-3 took many twists and turns during the summer, and looks like the other drift tracks I have examined. When mean velocities between fixes are calculated and plotted as U (east) and V (north) components (Fig. 5), certain cyclical patterns appear. In both components there is a fairly long period of speed variation so that about four cycles are covered by the record, a periodicity of about 3 weeks. The higher frequency oscillations do not show as well, so the records were filtered.

Cut-off and band-pass filters were used to produce Fig. 6. The upper plot is of all periodicities longer than 10 days. The oscillations with a period of 2 to 3 weeks and speed changes of ½ knot are obvious. A phase shift between U and V shows contra-solem rotation, and this variation, then, corresponds to the cyclonic whorls in the drift track (Fig. 5).

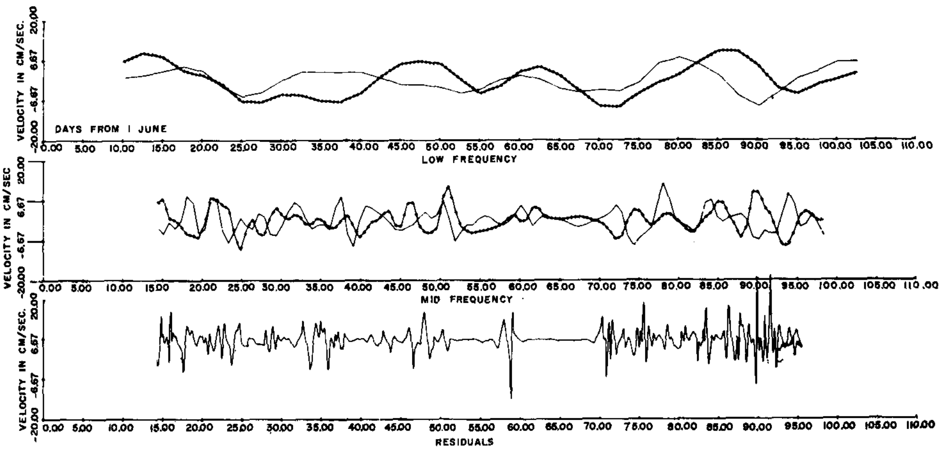

FIG. 6. The data of Fig. 5 filtered such that periodicities greater than 10 days (upper), between 3 and 10 days (middle) and less than 3 days (lower) are exposed. U component is light line, V component is heavy line with dots. Lower plot shows U component only.

In the middle plot of Fig. 6 the components are filtered to leave oscillations with periods of between 3 and 10 days. There is a definite oscillation with a period of about 3 days and amplitude of nearly the same magnitude as that of the long-period oscillation. The phasing between U and V components is quite erratic, and therefore this oscillation is not associated with a regular repeating phenomenon such as a wave.

The causes of the long term and 3 day oscillations most probably are in certain atmospheric phenomena. A cycle repeating every 2 to 3 weeks suggests to me the period for Rossby waves to pass a given location. These, in turn, guide the cyclone tracks, which might have effects lasting 3 days.

The residual after filtering (Fig. 6, lower) shows the seemingly erratic motion remaining, very much like "noise." An unsuccessful attempt was made to isolate diurnal motion, but the scarcity of fixes probably precludes positive identification of frequencies of one cycle per day and higher. In any event, the magnitude of the residual was relatively small and therefore the major portion of the ice motion is variable with periods of 3 days or more.

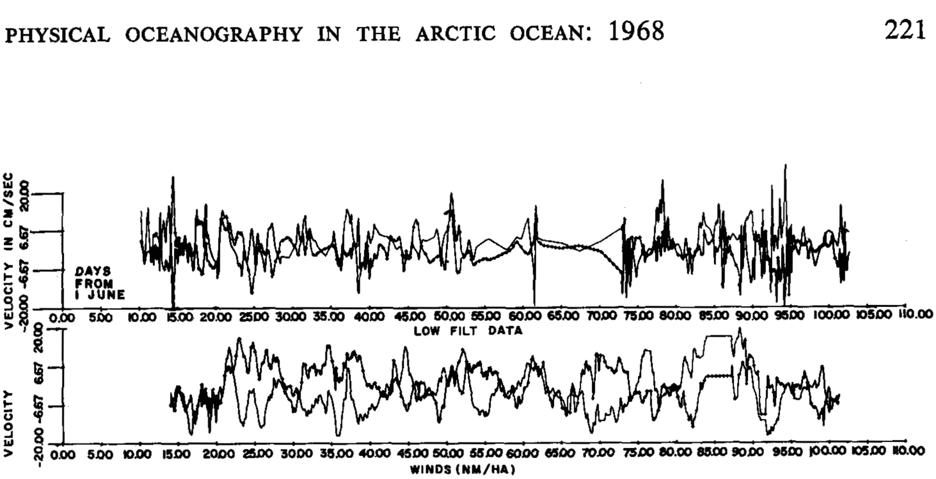

FIG. 7. Upper: U (light line) and V (heavy line with crosses) components of T-3 drift, from which oscillations with periods longer than 10 days have been subtracted. Lower: three-hour averages of winds recorded on T-3. U and V components marked as above.

The island motion and the local wind regime do not seem to be particularly related (Fig. 7), at least over short periods of time. This result is similar to analyses I had done previously (unpublished) which showed little correlation between ice station drift and winds for periods up to one week. On the other hand, Hunkins (personal communication) reported he has had some success in correlating drift and wind. Undoubtedly, the average large-scale ice drift patterns are wind-driven, but a detailed understanding of the coupling between ice and wind, sufficient for forecasting ice movement, awaits much more extensive research.

A preliminary feeling for the water motion measured under T-3 may be had from Fig. 8. Here are plotted the relative currents (U and V components) at 3 levels, 150 m. (in the pycnocline), 500 m. (core of Atlantic layer) and 1300 m. (in the bottom water), for a portion of the record. The following points may be noted:

1) The flow is quite similar in the three water masses. Since there is little shear in the water column, the dominant mode of motion is barotropic;

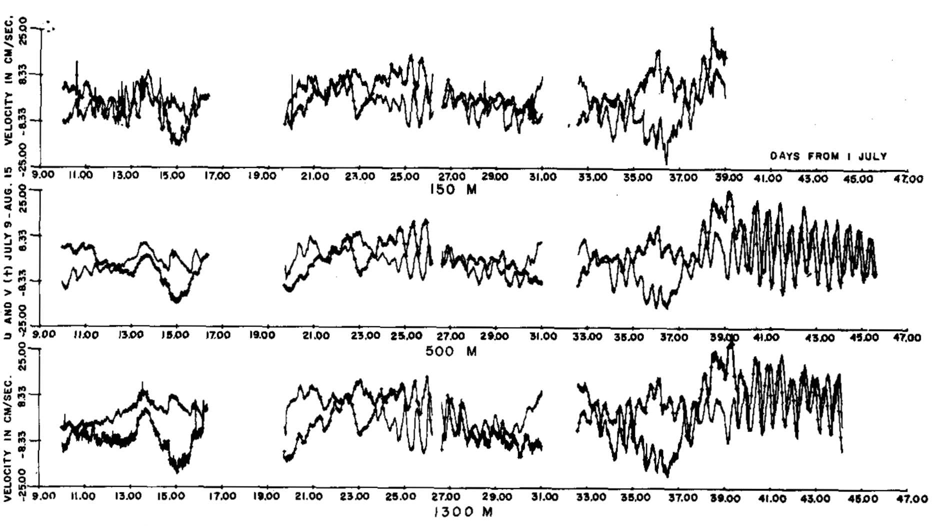

FIG. 8. Relative currents recorded under T-3 at three depths between 9 July and 15 August 1967. U (line) and V (line with +) are three-hour averages of the 10-minute recordings.

2) Island motion would also be reflected in the record because these are relative measurements. There is a long-term period variation in this record, a period of 2 to 3 weeks, which is probably the island motion noted above;

3) There is a very marked oscillation of approximately semidiurnal period. The phase shift between U and V of approximately 60° indicates cum sole rotation; we are undoubtedly measuring an inertial or semidiurnal tidal oscillation in the water, and it would appear that this wave provides the dominant magnitudes of flow, ±⅓ knot.

We now have similar current records from 1968 and 1969 to analyse. However, a more thorough analysis of these records plus many more will be required before we can say very much about the flow regime obtaining in the Arctic Ocean. The regime is complex, as with all of the World Ocean, and we have a variety of periodic and aperiodic phenomena to contend with. It is clear, though, that our techniques, reliable recording current meters together with frequent satellite navigation fixes, are finally producing data from which some progress can be made in describing the water motions and variations.

PHYSICAL OCEANOGRAPHY INTO THE FUTURE

The principal physical oceanographic problems in the Arctic Ocean may be summarized:

1) The ice and water motions and variations, and relation to the driving forces. Here are included questions about the frictional coupling between ice and water, how the ice cover deforms under the normal stress field, and the movement of the Atlantic and bottom waters; and

2) The exchange of heat with the atmosphere. Here are included questions about the role of leads vis-a-vis ice in heat-energy exchange across the surface, and how the heat from the Atlantic layer is passed upward through the Arctic water.

The survey stage of oceanography is essentially passed. Today, oceanographic field work should be undertaken as experiments to test hypotheses or models, for example, specific studies to attack aspects of the major problems outlined above. In our present efforts from T-3, where we are strictly limited geographically and synoptically, we try to concentrate on those experiments for which an "ice island without satellite station capability" (cf. Coachman 1968) is particularly suited.

Physical oceanography in the Arctic Ocean today is being conducted in a manner essentially the same as that of Nansen 70 years ago. That is, we still place a station in the ice cover and measure when convenient with Nansen bottle and reversing thermometer. In this same period of time, logistic and scientific hardware has been enormously improved. For example, the nuclear submarine and the C-130 aircraft for long range and quasi-synoptic operations, and helicopters, Otters and hovercraft for smaller-scale operations have all proved to be operable in the Arctic. Scientific instruments of improved accuracy such as the STD meter, recording current meters and satellite navigation devices have only begun to be used. The next step is the use to a greater extent of all the modern oceanographic and support equipment in the conduct of specific experiments.

The major observational gap, as indicated, is in spatial deployment of synoptic measurements. I propose a series of experiments, from simple to more complex, in which water properties and currents would be measured using the most modern equipment, and supported by the best modern equipment and technology. These experiments are aimed primarily at problem (1) above, but when meteorological and other observations are included they also provide information aimed at problem (2) above. The experiments are:

1) During summer 1969 pairs of recording current meters have been suspended from T-3 on opposite sides of the island, a separation of 5 km. A long-time series, together with as many satellite navigation fixes as possible, should allow definition of the spatial coherence of the currents on a horizontal scale of 5 km.;

2) The next larger scale of experiment, which was proposed for execution during spring in both 1968 and 1969 but has not been undertaken because of inadequate logistic support, we call the "geostrophic experiment." A triangular array of 3 temporary stations would be established at 15 km. distance around T-3, and supported and positioned by NARL Cessna aircraft. Recording current meters would be suspended under T-3, and at the satellite stations hydrographic casts would be made every 4 hours synoptically for a week or so. We should be able to estimate from the results the validity of the geostrophic approximation for Arctic Ocean currents; a similar experiment in other oceans would require four ships;

3) The next largest scale of experiment that has been proposed is an ice-deformation study, mentioned by Untersteiner (pp. 195-99). A triangular array of manned stations would be occupied for one month in the spring of 1970. T-3 would be one, with satellite navigation fixing capability, and the other two would be about 150 km. distant and within range of the precise position-fixing capability provided by the Polar Continental Shelf Project. Synoptic hydrographic and current measurements would be made from the stations;

4) The grand-scale experiment would be similar, but extended to cover the Arctic Ocean. Three to six manned stations, equipped with STD and recording current meters, would monitor the detailed time variations in water properties and currents. Additional spatial coverage could be obtained through unmanned stations; these could be positioned and the data remotely collected using the IRLS subsystem of the Nimbus satellite. Finally, synoptic surveys over the basin four times yearly would be achieved utilizing a nuclear submarine specifically equipped for the conduct of physical oceanographic measurements. Appropriate meteorological and other measurements would of course also be made. This experiment, even though expensive, would produce a more comprehensive picture of an ocean system at much less cost than can be envisaged for any other ocean.

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