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Temperature Fine Structure Near the Sea-Ice Margin of the Chukchi Sea

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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Temperature Fine Structure Near the Sea-Ice Margin of the Chukchi Sea

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Temperature fine structure with peak-to-peak fluctuations often exceeding 2°C is prevalent throughout the marginal sea-ice zone of the shallow Chukchi Sea in midsummer. It is normally found within 20–35 km outside of the ice and seldom farther than 5–10 km inside the ice margin. It has also been infrequently found more than 100 km south of the ice. Temperature and salinity fronts of all degrees of sharpness occur in the same general area, but the two types need not be coincident. Considerable variability in time and length scales of fine structure elements has been noted with persistences ranging from 2 hours or less to more than 20 hours and length scales ranging from 600 m to more than 20 km. While much of this variability is intrinsic, part can be accounted for by the inability to sample in the direction of flow and the relative motion between the sampling platform and fine structure element. Fine structure lenses are considerably longer parallel to the ice edge with similarity in temperature structure noted over distances of 80 and 100 km.

Introduction

In the vicinity of the marginal sea-ice zone (MIZ) of the Chukchi Sea in summer large-scale temperature fluctuations in the vertical, termed fine structure, are produced from the dynamic interaction of the various water masses present near the sea-ice margin. Following *Osborn and Cox* [1972] and other authors, we define fine structure as having a thickness scale of the order of meters. In earlier reports, before the nomenclature became well established, we called the same phenomenon mesostructure. Recent cruises to the MIZ using continuously profiling temperature-salinity instruments have shown some regularity amidst the temporal and spatial variability of the fine structure. It is the purpose of this paper to generalize upon the distribution of fine structure, its relation to the oceanographic processes in the area, and its causes.

Fine structure near the ice margin derived from bathythermograph observations in Nereus 1947 was first reported by *LaFond and Pritchard* [1952]. Little practical note of the phenomenon was taken until the advent of Project Mizpac 24 years later. The initial results of these studies were reported by *Garrison and Pence* [1973] and by *Paquette and Bourke* [1973]. The latter two authors (1974) also described the coastal current of northeastern Alaska, a warm high-speed flow important in the melting of ice and the subsequent generation of fine structure. Aspects of fine structure formation and its space-time distribution were investigated by *Corse* [1974] and *Karrer* [1975]. *Paquette and Bourke* [1976] further described the character and causes of fine structure formation. *Bourke and Paquette* [1977] evaluated the considerable effects of fine structure on acoustic propagation in the MIZ.

Other work with continuously profiling recorders has been done by the Applied Physics Laboratory, University of Washington, much of it from drifting ice floes [*Garrison et al.*, 1974; *Garrison and Becker*, 1975; *Garrison*, 1976]. Their measurements have been confined to the extreme northeastern part of the Chukchi Sea and a small portion of the Beaufort Sea north of Pt. Barrow. Some of their temperature profiles show weak to moderate fine structure, but in their measurements the phenomenon is ordinarily not so prevalent nor so intense as it is in the regions we have sampled.

Fine structure, of couse, is not confined to the Chukchi Sea. It presumably may occur anywhere in the oceans where there is a juxtaposition of two water masses. A number of examples were given at the recent *Chapman Conference on Oceanic Fronts* [1977]. Other examples illustrating fine structure with temperature excursions exceeding 1°C have been reported by *Gregg* [1975] in the California Current and by *Howe and Tait* [1972] in the Mediterranean outflow.

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Experimental Program

The authors have made five midsummer cruises to the marginal sea-ice zone of the Chukchi Sea, in 1971, 1972, 1974, 1975, and 1977. This paper reports on the first four of these, pertinent data for which are shown in Table 1. The region surveyed during these cruises is shown in Figure 1. The bottom contours show this to be a relatively shallow sea with a mean depth of approximately 45 m. The Barrow Canyon, the only major topographic feature of the region, is a deep passage which acts sporadically to couple middepth Arctic Ocean water with the shallow Chukchi Sea [*Coachman et al.*, 1975, pp. 123, 127; *Bourke and Paquette*, 1976]. Figures 2–5 show the station distribution for the four Mizpac cruises with each station coded to illustrate the intensity of fine structure, a coding discussed later in the text. (Mizpac is an acronym for Marginal Sea-Ice Zone, Pacific, a project of several years duration under the general direction of the Arctic Submarine Laboratory of the Naval Ocean Systems Center, San Diego, and concerned with acoustic and other environmental problems of submarine operations under ice.) Contours of the maximum temperature in the water column are also plotted for each cruise; generally, fine structure will be found north of the 4° isotherm. The position of the ice edge as observed from each station is shown for each cruise. This is not a synoptic description of the ice margin, but is one which correlates best with observed ice-dependent processes.

The 1971, 1972, and 1974 data were obtained with two models of the Plessey Model 9006 STD (salinity-temperature-depth recorder) standardized by means of the Nansen bottle just above the STD, near bottom. The data of 1975 were obtained with the portable digital CTD (conductivity-temperature-depth recorder) of APL-UW [*Becker*, 1975]. There were some complications, notably salinity spiking, which caused some reduction in accuracy in the upper portions of the water columns, in which salinity and temperature changed rapidly with depth. But in the deeper, slowly changing portions of the water column the instrument stabilities were demonstrated to be good and correction to an accuracy of ±0.02°C and ±0.05‰ at the 1-sigma level is believed to have been achieved.

TABLE 1. Mizpac Cruise Summary

	1971	1972	1974	1975
Cruise dates	July 30–Aug. 20	July 31–Aug. 19	July 13–30	July 30–Aug. 14
Ship	USCGC *Northwind*	USCGC *Burton Island*	USCGC *Burton Island*	USCGC *Glacier*
Stations occupied	163	114	111	194
Instruments	Bissett-Berman 9006 STD	Bissett-Berman 9006, mod. 1, with 200-ft depth scale	Bissett-Berman 9006, mod. 1, with 200-ft depth scale	APL-UW portable CTD
Reference	*Paquette and Bourke* [1973] NPS-58PA73121A	*Paquette and Bourke* [1973] NPS-58PA73121A	*Paquette and Bourke* [1976] NPS-58PA76051	*Zuberbuhler and Roeder* [1976] NPS-58PA7609

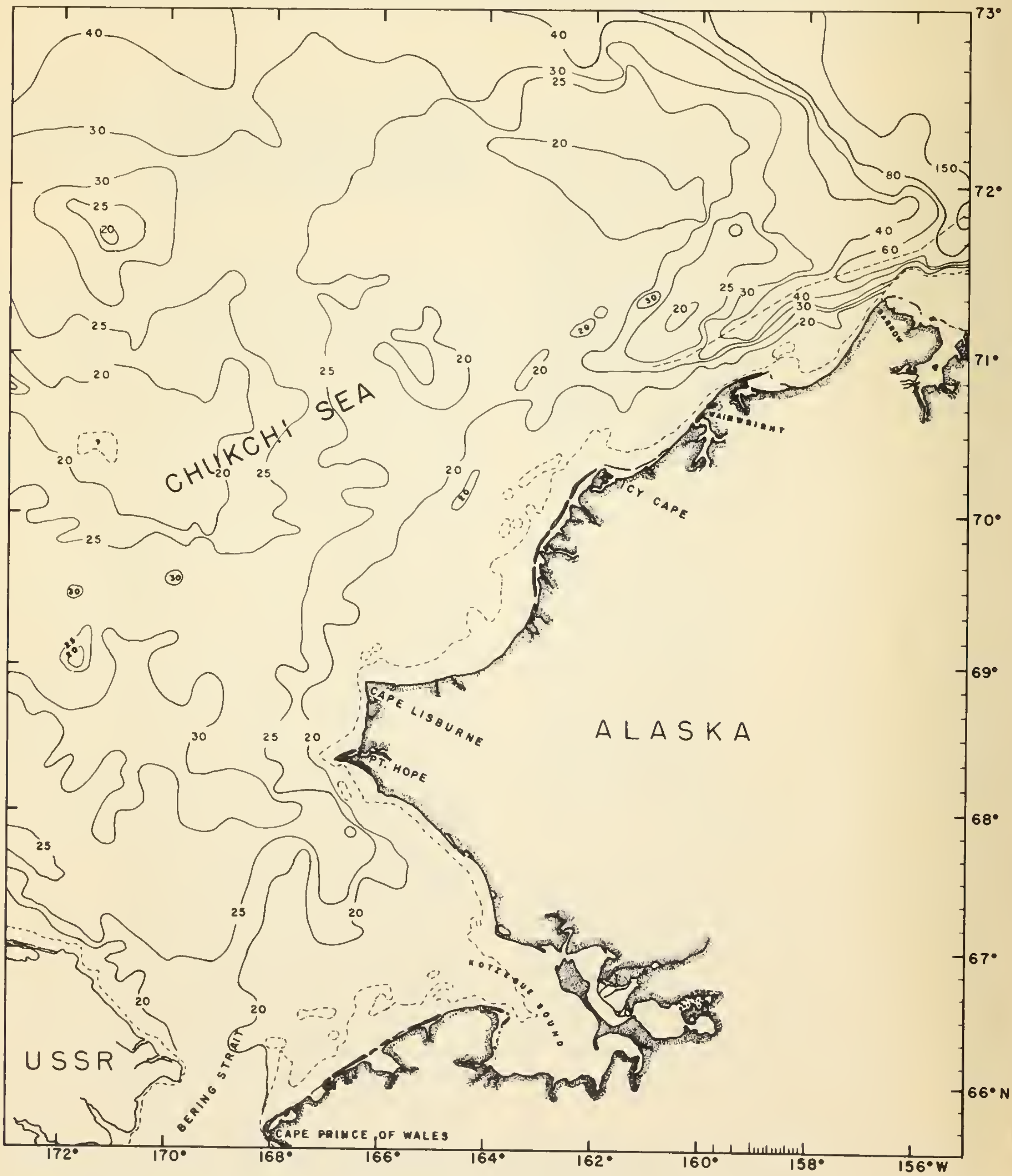

Fig. 1. A map of the Mizpac area. The dashed line in the upper right corner indicates the axis of the Barrow Canyon. Bottom contours are in fathoms (1 fm = 1.83 m).

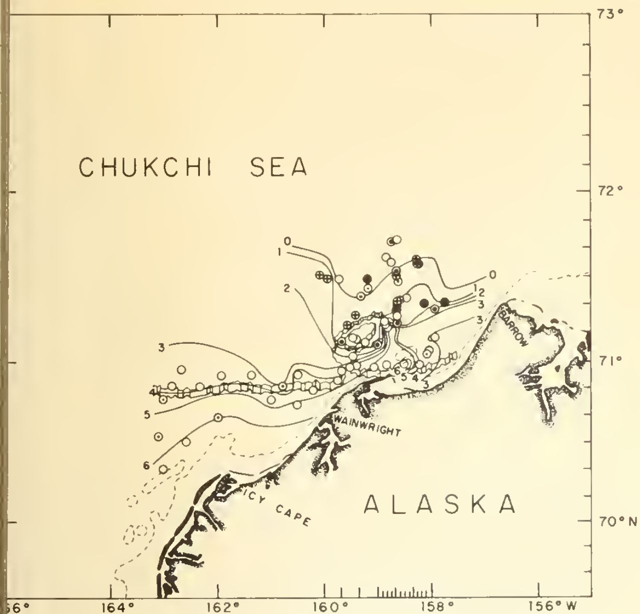

Fig. 2. A plot of the station distribution for the Mizpac 71 cruise howing the position of the ice edge and contours of the maximum emperature in the water column. Each station is coded to indicate the egree of fine structure: open circle, none present; circled dot, weak; ircled cross, moderate; solid circle, strong.

The temperature and salinity resolutions are better than 0.01 nit; the depth resolution is 0.3 m in 1971, better than 0.1 m in 972–1974 and about 0.3 m in 1975. There are no phenomena r identifications of water masses in this paper for which the nstrument accuracies are not entirely adequate.

The question of static density instability associated with temperature inversions, such as those suggested by *Coachman and Charnell* [1977], is impossible to resolve. Whether or not there is instability depends upon how much of the mostly or entirely spurious salinity spike is real. We have experimented with spike removal techniques [*Paquette and Bourke*, 1978] and find that the simple method of *Scarlet* [1975] applied to the STD is inadequate when the spikes are large. More complex methods which were applied to the CDT are reasonably successful only if the response constants of the conductivity cell are taken to be somewhat variable and are subjectively adjusted in individual cases or groups of cases to minimize the spike. Under the circumstances we do not believe that the question can be resolved by present computational methods when instruments with such long response constants are used.

ICE BEHAVIOR

Ice normally covers the Chukchi Sea from November to June, and then melts back fairly rapidly in an irregular fashion to a northern limit of about 72°N latitude, achieved in mid-September [*U.S. Naval Oceanographic Office*, 1958]. As the ice begins to recede from north of Bering Strait, melting initially proceeds at a faster rate in the central part of the Chukchi Sea than in areas near shore. By August a shore lead along the northwestern Alaskan coast is developed and a large bight typically has opened out to the NNW in the direction of Wrangel I (71°N, 169°W). Between these two ice-free regions the ice usually projects farther south to latitudes in the vicinity of 70°N in early August. All of the Mizpac cruises have worked near this southward projection and to the northeast along the shore lead. We believe that these two ice-free areas are produced mainly by melting from the heat supplied by the

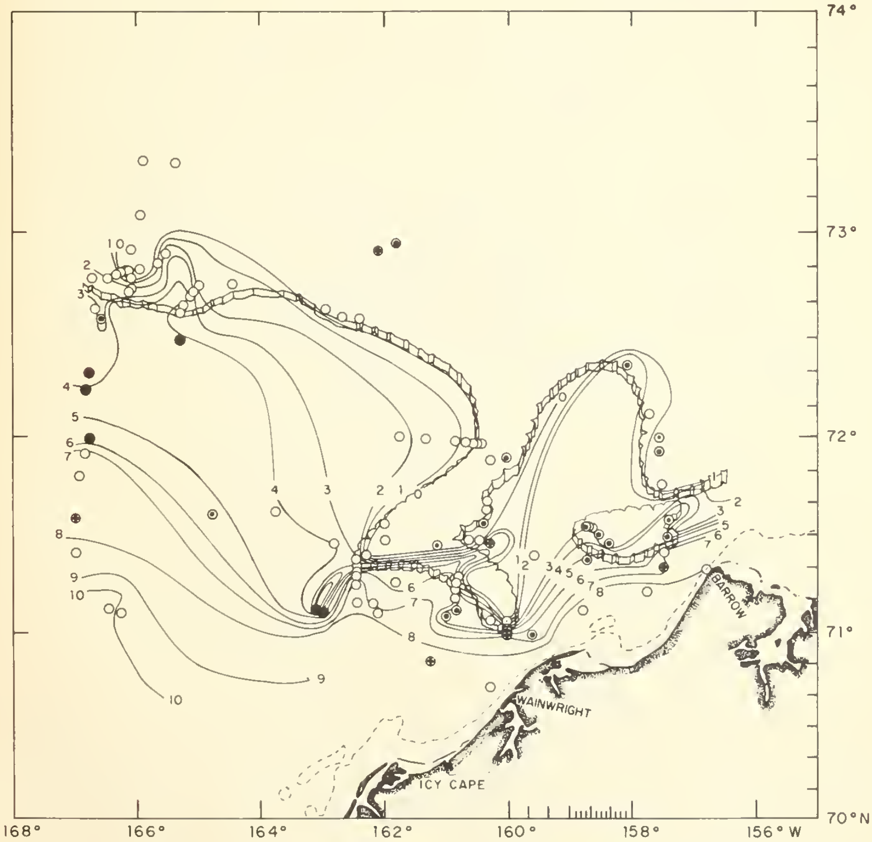

Fig. 3. Station distribution for the Mizpac 72 cruise. Contours and symbols are the same as in Figure 2.

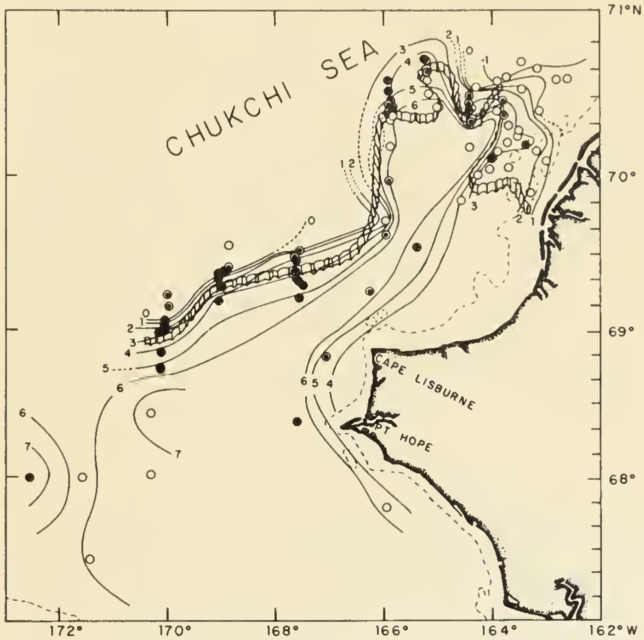

Fig. 4. Station distribution for the Mizpac 74 cruise. Contours and symbols are the same as in Figure 2.

relatively warm water flowing northward from Bering Strait which, evidently, has bifurcated into two streams. The amount of heat in the northward flowing water is of the right magnitude to do the melting, as was shown by *Paquette and Bourke* [1976]. It also may be shown that insolation falling directly o the southern fringes of the ice pack is only 0.1–0.2 as great as necessary to account for the observed rate of recession. Henc melting is concentrated at the line of contact of the warr southerly water and the ice, producing cold melt water whic contributes strongly to front formation and probably to othe phenomena occurring near the ice.

The ice edge is exceedingly variable both in space and tim It can be compressed or attenuated by variable winds an currents and melted by warm streams. These latter ar strongly influenced by the variable heat advection in the flo through Bering Strait, river flows, general weather conditio and cloudiness which influences the warming of the water b insolation.

OCEANOGRAPHY AND FRONTS NEAR THE ICE MARGIN

The warm waters which lead to the formation of fronts an fine structure near the ice enter the Chukchi Sea from Berin Strait, where they already have considerable warmth. In sum mer within Bering Strait the waters are only weakly horizon tally stratified, grading from 10°C or more and 30‰ or less i the extreme eastern surface to about 2°C and over 33‰ in th western bottom [*Coachman et al.*, 1975]. A few tens of kilome ters north of the center of Bering Strait there is a rather abrup change to a regime having a warm upper layer with tempe atures of 6° to 10°C in midsummer and salinities less tha 31‰. We believe we interpret *Coachman et al.* [1975] correctl in assuming this water to come from the eastern filaments c Bering Strait with some contribution from the waters of Ko

Fig. 5. Stations distribution for the Mizpac 75 cruise. Contours and symbols are the same as in Figure 2.

ebue Sound (see Figure 1). There must also be some addiional warming by insolation. Near the ice the salinity dereases to less than 30‰ due to ice melt. This warm layer overs much of the central Chukchi Sea, appears to have ontinuity with the waters of Kotzebue Sound in the east, and xtends to within 100 km of the Russian Coast. The upper ayer is between 5 and 15 m thick and often is separated from he underlying layer by an exceedingly sharp thermocline with gradient as great as 7°C/m. This water, flowing northward, s a dominant factor in the melting of the ice in summer.

When the water reaches the ice, the heat in the warm upper ayer is rapidly diminished due to melting of the sea ice. As a esult of the melting, a near-surface temperature and salinity ront is found everywhere along the ice margin; it represents he abrupt termination of the heat carried by the northward lowing surface waters upon coming in contact with the ice. The strength of the near-surface front undoubtedly varies with he diffuseness of the ice edge and the rate of northward heat ransport by the warm southern water.

There are temperature fronts also in the lower layer between slightly warm southern water coming north from Bering Strait and a cold saline northern water near or under the ice. These fronts vary from sharp vertically oriented fronts to more liffuse frontal zones of the order of 50 km from front to back. The diffuse fronts often contain fine structure. In this latter ase the two waters which interleave seem not to be the cold vinter bottom water and the typical Bering Sea water, waters vhich are present at the extreme ends of the frontal zone. They ire, rather, of compositions transitional between the two exremes. We find the fronts most often within a few tens of ilometers south of the ice edge. Some are so closely associated vith the ice edge that the association seems unlikely to be ccidental.

L. K. Coachman (personal communication, 1978) suggests hat since the ice is melted principally by the northward flowng warm water, the front between southern water and the cold vater resident under the ice will automatically be near the ice dge. This assumes that the flows of the upper and lower layers of southern water are closely coupled, whereas the direct curent measurements described by *Coachman et al.* [1975] seem o indicate that the coupling is only fairly good. We think there nay be some dynamic process going on under the ice margin vhich tends to partially mix the parent waters, both horizonally and vertically, along the line of retreat of the ice, thus eaving identifiable northern water only behind the ice edge. To date we have been unable to prove either hypothesis.

There is notable fine structure also at distances to more than 00 km south of the ice, as will be seen in Figures 2–5. These ases may actually be relatively more numerous than shown because our tendency to explore mainly near the ice biases the lata in favor of near-ice phenomena. These occurrences of fine tructure must inherently indicate the presence of fronts of greater or lesser intensity. Whether these are secondary fronts between the diverse waters available in the Chukchi Sea or vhether they are phenomena generated by an ice front and left behind when the ice is quickly pushed northward by the wind s presently unclear.

An example of the frontal features, near the ice can be seen n the temperature-salinity cross section developed from a line of closely spaced stations taken in 1974 aligned more or less orthogonally to the ice edge (Figure 6). These are the stations along about 170°W in Figure 4. About half of the many ice margin crossings which have been made have the general characteristics of Figure 6 but vary exceedingly in detail.

In cases like Figure 6 the temperature gradient between the inflowing upper layer and the waters below is sharp and there is a relatively large bolus of low-salinity melt water near the ice. This suggests that the flow of warm surface water toward the ice is rapid. Fine structure commonly occurs in this situation. It is, of course, possible that ice moving relative to the water can be an equivalent causative factor. In some of the other cases the isopleths are much less distorted, the property gradients are more moderate, the bolus of melt water is less marked, and fine structure is generally absent or weak. This suggests a weaker component of warm water flow toward the ice. Yet the degeneration of the typically sharp thermocline indicates that vertical mixing has taken place. Turbulent mixing must have been caused by at least moderate velocities but the diminished volume of melt water suggests that the inflow of warm water must be nearly parallel to rather than normal to the ice edge. In a few cases the frontal surfaces are nearly vertical, the temperature gradient through the front is large and the front is maintained through most of the bottom layer. There is little evidence of melt water even when the front and the ice are nearly coincident. The lack of mixing between the two frontal waters indicates that the flow necessary to maintain the front against dissipative processes must be a weak shear between them.

Fine Structure

Description and Intensity

The temperature fine structure found in the MIZ is extreme compared to that found in other frontal zones in the ocean. Extremes of temperature excursion exceeding 2°C peak-to-peak are fairly common. These excursions are larger, in these cold northern waters, than those observed in more temperate waters probably because the density of seawater at low temperatures is only slightly affected by temperature. Thus temperature inversions are little inhibited by the associated density inversion when temperatures are low. Some examples of fine structure from a temperature time series carried out from a drifting ship about 40 km south of the ice in Mizpac 75 are shown in Figure 7. Tongues of water, more than 1.5°C warmer than than the surrounding water, are seen apparently to grow, fractionate, decay, and sometimes reform. Such a description implies that the ship drifts with the fine structure element, an assumption which may not be true, as will be seen in a following section. This activity takes place below the strong thermocline. The upper warm layer in Figure 7 shows an absence of any structure, but this is not always the case.

Fine structure in the MIZ has remarkable variety. Because of this variety we have attempted to find meaningful categorizations of the structure. Perhaps the most important property to categorize is intensity. We have used as a measure of intensity the maximum peak-to-peak temperature fluctuation in the profile, omitting the near-surface temperature maximum to be described later. This measure thus give less weight to a profile with several small perturbations than to one with a single large one. It is also possible that where the vertical temperature gradient is small the temperature anomaly of an intrusion may be a poor indicator of the physical size of the intrusion. If one is interested in size, a possible alternative would be to normalize the intensity by dividing by the vertical temperature gradient. However, at the present stage of understanding, more complex representations seem unjustified. Based on the maximum peak-to-peak fluctuation we have

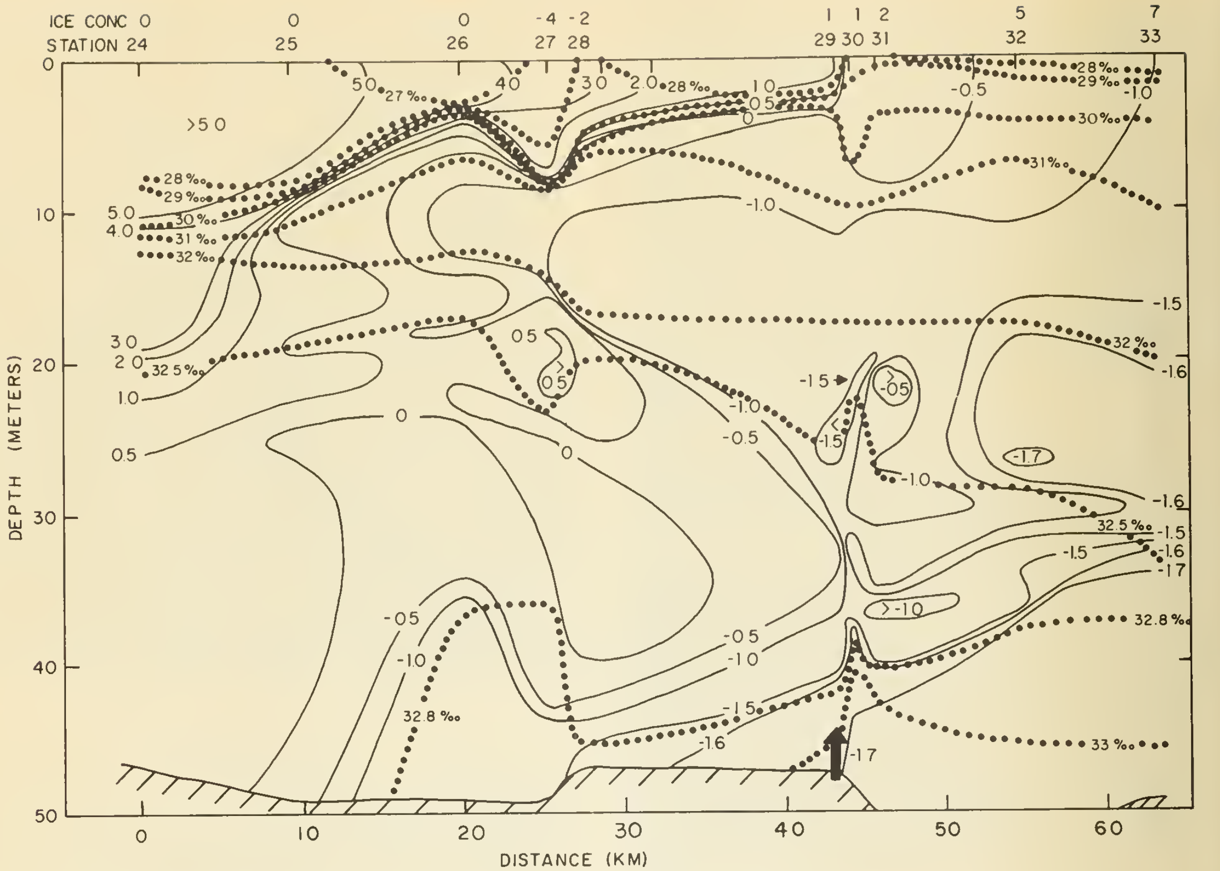

Fig. 6. Temperature and salinity cross section from the westernmost line of closely spaced stations taken in Mizpac 74, oriented approximately S-N. The approximate position of the ice front is denoted by the arrow. The ice concentration is in oktas (eighths) with values less than 1 okta preceded by a minus sign to indicate concentrations in negative powers of ten. Note that the salinity field is closely representative also of the density field at these low temperatures and relatively large salinity gradients.

classified intensities as weak, moderate, or strong. The occurrence of weak structure, with an excursion of 0.2°C–0.5°C, is indicated in Figures 2–5 as a circle with a central dot; moderate structure, with excursion 0.5°C to 1.0°C, is indicated by a circle with a cross; strong structure, with excursion greater than 1°C, is indicated by a solid circle. An open circle indicates fluctuations of less than 0.2°C.

Categorization by Depth

The next property to be considered is the depth of the feature in the water column. We have separated fine structure into two categories, shallow and deep, reasoning that the processes forming fine structure above the thermocline are likely to be so complicated by active melting of ice and stirring by ice keels as to be basically different from those in or below the thermocline. In this we follow *Zuberbuhler and Roeder* [1976] with the difference that we classify fine structure within the thermocline as deep rather than shallow. Earlier systems of separation of the two types by specific density surfaces, by *Corse* [1974] and *Karrer* [1975], were found inappropriate by *Zuberbuhler and Roeder* [1976] as more data accumulated.

A complication in the classification arises due to a common near-surface feature called a 'nose.' Near the surface, cooling by ice can lead to the formation of a nose which may or may not have fine structure embedded. In Figure 8, station 85 from Mizpac 74 shows a typical nose, but in station 86 a cold intrusion is seen to break the nose into a two-pronged fork. We have not considered the nose itself as a fine structure element, but do include thinner fluctuations imbedded in t[h]
nose as shallow fine structure. In this paper the emphasis upon deep fine structure which is normally more intense, f[ar] more extensive, and more easily associated with causes.

The temperature profiles and cross sections show that most of the shallow Chukchi Sea deep structure is general[ly] found between 10- and 20-m depth. It is found at the shallow[er] depths when the structure is embedded in a sharp thermoclin[e], e.g., station 94 (1975) or station 40 (1972), Figure 9. Deep structure, i.e., that found between 20 and 30 m, usually occu[rs] in the layer below the thermocline, e.g., stations 76 (1975), (1971), 35 (1974), Figure 10. Examples of unusually de[ep] structure, i.e., temperature inflections below 30 m, are fair[ly] rare on the Chukchi Shelf, and in such cases the intensity usually weak. Stations 77 and 110 (1972), 31 (1974), and (1975) in Figure 11 are some of the few examples containi[ng] such structure. The rarity of such deep structure is perha[ps] associated with a lack of sufficient warmth at these depths create significant temperature inflections. Unusually de[ep] structure is more common in the deeper water of the Barr[ow] Canyon probably because the depth scale is effectively e[x]panded by the downhill flow to greater depths of Chukc[hi] Shelf bottom water which is denser, even in summer, th[an] water at the same depth in the Arctic Ocean.

Distribution of Fine Structure

It will be seen in Figures 2–5 that the fine structure is close[ly] associated with the ice margin. Where fine structure is found,

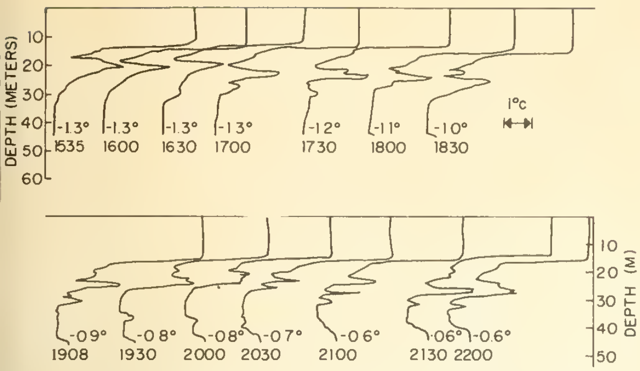

Fig. 7. Nested temperature profiles from part of a time series conducted in Mizpac 75 from a drifting ship about 40 km south of the ce. Fine structure is seen to grow, fractionate, decay, and sometimes eform. The indicated temperatures are bottom temperatures.

s usually within 20–35 km outside of the ice and seldom farther than 5–10 km inside the ice edge. Fine structure has also been found occasionally more than 100 km south of the ice, as was indicated in the previous section. Figure 12, which shows several profiles taken at varying distances behind the ice edge, demonstrates how rapidly fine structure and heat disappear behind the ice edge. A notable exception to this rule is an area WNW of Pt. Barrow where in 1971 structure was found 18–25 km behind the ice margin. Here, for reasons presently unclear, warm water seems to be finding its way westward from the main flow of warm water along the Alaskan Coast.

Considerable variability occurs from year to year. For example, Figure 3 in 1972 shows notably fewer cases of moderate to strong structure than in the other 3 years. This variability can be due to the same conditions which we have indicated to cause the year-to-year variability in the position of the ice edge.

There is little or no information in winter. In general, we expect little fine structure in shallow water under the winter ice because of the lack of temperature contrasts and the general convective overturn due to brine rejection during freezing. Even in summer, as was noted above, the water under the ice is usually cold and lacking fine structure a few kilometers behind the ice margin.

The four Mizpac cruises (Figures 2–5), all taken in midsummer, have found fine structure in many locations within the MIZ in the longitude band from 170°W to 156°W. Longitudes farther west were not explored but are probably similar to the surveyed area oceanographically and likely to contain fine structure. One exploration to the east of 156°W in the Beaufort Sea in 1971 was inconclusive due to inadequate sampling and instrumentation problems. However, temperature fronts have been found in that region and the potential for some fine structure formation therefore exists. Another unexplored zone which may contain fine structure is the water shoreward of the 10-fm (19 m) line which is avoided by deep-draft icebreakers.

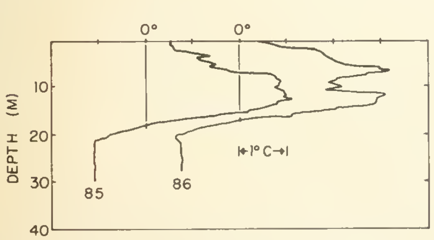

Fig. 8. Nested temperature profiles from stations 85 and 86, Mizpac 74. The profile from station 85 exhibits a typical 'nose,' while a cold intrusion is seen to break the 'nose' of station 86 into a two-pronged fork.

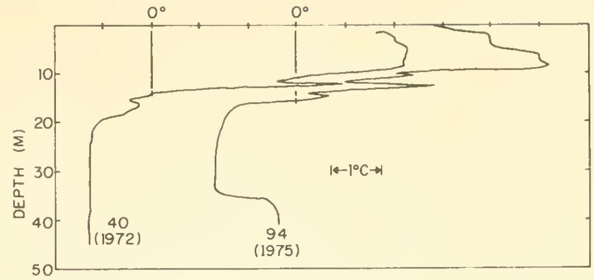

Fig. 9. Nested temperature profiles from stations 94 (Mizpac 75) and 40 (Mizpac 72) illustrating fine structure embedded in a sharp thermocline, typical of that found at about 10-m depth.

Fine structure was found as far south as 69°N in July 1974 when the ice was also that far south. In general, we would expect to find it even farther south earlier in the season up to a point where the turbulent velocities of water issuing from Bering Strait would cause too much mixing or to a time when the waters were too cold to provide the necessary temperature contrasts. Fine structure was found as far north as 72°N both near 167°W and near 157°W. The ice often is farther north than this in September (ca. 74°N), but we hesitate to predict the presence of fine structure so far north and so late in the summer both because the water then is cooling rapidly and the bottom is beginning to steepen at the edge of the continental slope, probably causing the bottom water to drain away.

Temporal and Spatial Persistence

Estimates of the temporal persistence of individual fine structure elements have been obtained at various times by time-series measurements from drifting ships or drifting ice floes. The measurement of persistence from drifting platforms makes the assumption that the platform drifts with the fine structure. This is probably not true. If the platform moves away from the source of the fine structure, it will, in general, measure a shorter time than the actual persistence. This is the usual case. The conclusion is the same if the platform moves toward the source provided that it moves beyond the source. Therefore the actual persistences will be at least as long as the persistences measured by this technique. Some authors have computed lengths for fine structure elements from time series data by multiplying the apparent persistence time by the known rate of drift of the platform. This result will be seri-

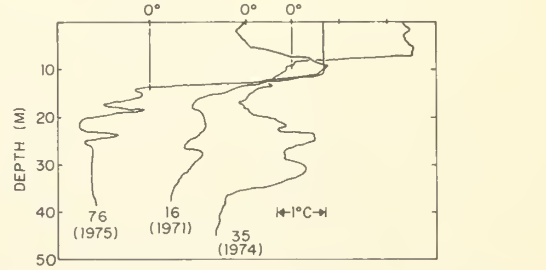

Fig. 10. Nested temperature profiles from stations 76 (Mizpac 75), 16 (Mizpac 71), and 35 (Mizpac 74) illustrating fine structure from the 20- to 30-m depth region, i.e., in the nearly isothermal layer below the thermocline.

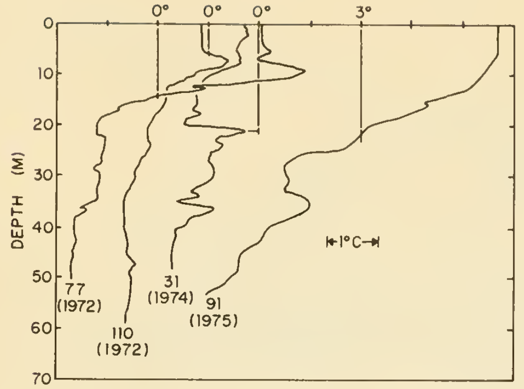

Fig. 11. Nested temperature profiles from stations 77 and 110 (Mizpac 72), 31 (Mizpac 74), and 91 (Mizpac 75), a few rare cases of the microstructure and fine structure found at depths greater than 30 m.

ously in error if the persistence is short compared to the time which should have been required to drift past the lens of fine structure.

Estimates of fine structure size have been obtained by noting the coherence of fine structure elements along lines of closely spaced stations. Evidence will shortly be presented showing that fine structure elements are elongated along the face of the generating front. Therefore a size measured along a line of closely spaced stations depends upon the orientation of the line. The apparent size may also be modified by the persistence if the time required to occupy the line of stations is larger than or comparable to the persistence.

The third factor to be considered relative to size and persistence is the amplitude of a temperature anomaly. Anomalies of small temperature amplitude are usually of small thickness. Therefore they may be expected to dissipate more quickly than large anomalies by the diffusion of heat. More important is the lack of temperature contrast with which to identify the small anomaly; it will disappear in the background fluctuations more quickly than will an anomaly of large amplitude. We have tended to concentrate on anomalies of large amplitude, in the vicinity of 1°C peak-to-peak.

With this preamble we proceed to cite such evidence of size

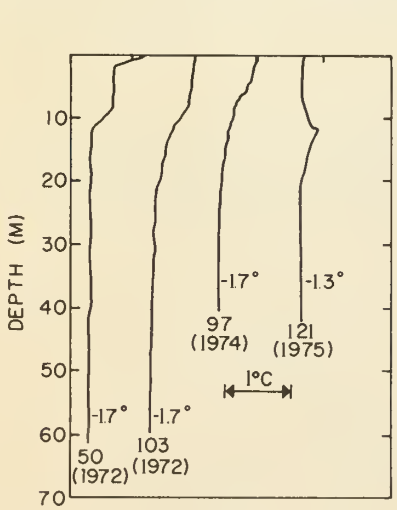

Fig. 12. Nested temperature profiles from stations 50 and 103 (Mizpac 72), 121 (Mizpac 75), and 97 (Mizpac 74), all well behind the ice edge, illustrating how rapidly fine structure and heat disappear. The indicated temperatures are bottom temperatures. Stations 50 and 103 are 74 km behind the ice edge, stations 121 and 97 are 80 and 22 km, respectively, behind the ice edge.

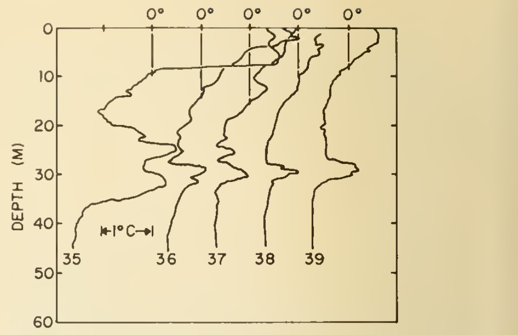

Fig. 13. Nested temperature profiles from stations 35–39 (Mizpa 74), separated by spacings of 7, 1, 3, and 2 km, illustrating the spatia correlation of the fine structure element near 30-m depth over a distance of 24 km.

and persistence as is available. The persistence of large anoma lies measured from a drifting ship was found by *Corse* [1974 to be 6 hours (drift rate unknown but probably approximatin 10 cm/s) and by *Zuberbuhler and Roeder* [1976] to be 4 hour while drifting at about 26 cm/s. In neither case is the velocit relative to the water known. From a drifting ice floe, *Garriso et al.* [1974] measured a persistence of about 2 hours fo anomalies approximating 0.2°–0.5°C peak-to-peak. Fron drift rates relative to the water of 7 and 18 cm/s in tw instances, they obtained lengths of 600 and 1300 m, respec tively. Longer coherence lengths may be seen in Figure 13 which shows a series of temperature profiles from stations 3 to 39 in 1974 (spacing 7, 1, 3, 2 km). There is good correlatio of the element near 30-m depth over a distance of 13 km traversed at an average speed of 64 cm/s for 5.6 hours. Tw parallel lines along the same front, stations 25–28, requirin 2.9 hours at an average speed of 250 cm/s gave a length of 2 km and stations 43–46 requiring 3.4 hours at an average spee of 106 cm/s, gave a length of 13 km. It should be noted tha these three groups of fine structure apparently emanated ap proximately at right angles from a long front to be describe shortly.

These numbers illustrate very substantial differences in tim and space scales. Not only do the last three measurement indicate the presence of elements of the order of 20 km long but they cast into doubt the persistence times of 4–6 hour obtained from the time series measurements. It is unlikely tha the fine structure can have propagated at a speed greater tha 25 cm/s (0.9 km/h) in this area. To extend to 20 km, th

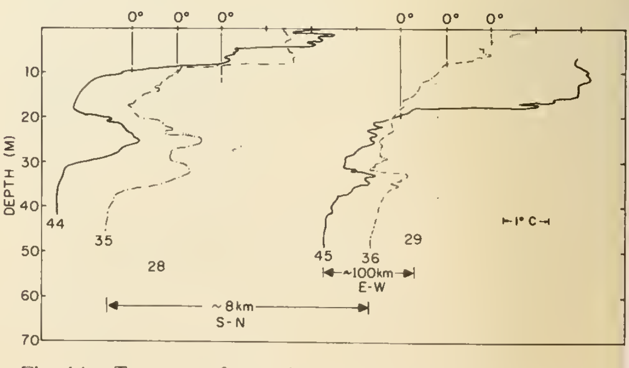

Fig. 14. Two sets of nested temperature profiles from the thre crossings in the western part of the 1974 Mizpac area illustrating th widespread similarity in processes creating fine structure over a di tance of 100 km. The curves have been shifted in depth to bring th major fine structure features into line. The amount of the shift may b judged by the fact that all profiles start at zero depth.

structure must have persisted for at least 22 hours. Another fact of interest is that in the last four of the five stations in Figure 13 the element near 30-m depth has scarcely changed at all during 4.1 hours. If the persistence were of the order of 6 hours, substantial degradation of the fine structure element would have been expected during the 4-hour period. Either of two conclusions may be drawn. Either the persistence times from drifting platforms cited above are too short and are indicators only of the length of the fine structure lens in the direction of the drift or persistence times can vary greatly, depending upon local factors such as turbulence and density gradient. In this connection we note the results of *Horne* [1978], who estimated persistence times of 31 hours as modeled by the double diffusive process in the warm waters of the Nova Scotia Slope Water Front. Using his formulas, diffusion rates in the cold Arctic waters should be about 130 times slower, resulting in unrealistically long times. Hence dissipation must be controlled predominantly by larger-scale turbulent processes.

In summary the persistence and length scales are seen to be highly variable. Persistence can range from as short as 2 hours to longer than 20 hours. Fine structure elements have been measured from 600 m to more than 20 km. This range of scale sizes appears to be entirely possible given the large variability in turbulent scale sizes thought to be associated with the marginal ice zone.

The three transects across the ice edge described above are part of a long front and provide evidence that fine structure elements can maintain spatial continuity over considerable distances parallel to the ice edge. The temperature profiles from three such lines taken in the western part of the 1974 Mizpac area, Figure 14, demonstrate the considerable similarity of structure found immediately outside and under the ice edge. Along this front at least 100 km long one may see thick warm intrusions at 20- to 30-m depth. Closer to the ice the intrusions have cooled and shrunk into a tongue. Although it is probably not justifiable to imply continuity of the large-scale interleaving phenomenon over the entire 100-km front, it is apparent that there must be widespread similarity in processes creating the fine structure. Therefore it is likely that the size of a lens of anomalous water is greater parallel to the front than normal to it. A similar example of fine structure similarity (not shown) over a distance of 80 km was found for a line of stations close to and parallel to the ice in 1975.

Causes of Fine Structure

The interleaving of two waters of different temperature-salinity structure which may occur when the two waters meet in a front is not an unexpected phenomenon. A layer from one may intrude into a zone in the other, where the temperatures are different but the densities the same, with no resistance from gravitational forces. However, there must be some driving force to cause the intrusion. We suggest that the driving force derives directly from local lateral pressure gradients causing shearing at the convergence or divergence of isopycnals. The general situation is illustrated schematically in Figure 15. The direction of motion will not necessarily be directly down the pressure gradient, as shown, but more or less transverse, depending on the degree of geostrophic balance attained. Many such situations are evident in the sections crossing the ice margin and in the general areas of fine structure formation. It is generally true that the regions of most active fine structure are also those in which the isopycnals are most distorted (i.e., the vertical density gradient is most variable).

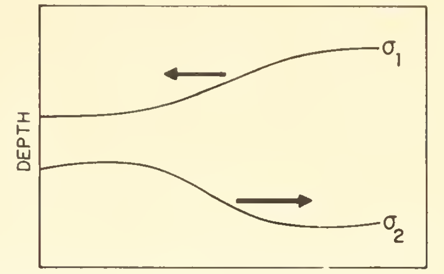

Fig. 15. Schematic of a portion of a vertical cross section in density showing a convergence/divergence of isopycnals and the directions of the resulting local lateral pressures which may lead to interleaving.

The question of the sources of the water which interleave may not be a simple one. Obviously, it is a middepth slightly warm southern water which interleaves with a middepth cold northern water. Both of these middepth waters are modified from parent water types to the north and south, each seemingly by an admixture of a water type which exists on the opposite side of the frontal zone from the parent water. At present, it is not possible to speculate about the mechanisms by which this is accomplished. The variability in the available cross sections and the paucity of adequate three-dimensional information makes a formulation of unequivocal explanations difficult.

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