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Fisheries Oceanography of the Southeastern Bering Sea Shelf — Misconceptions and Perspective 1986

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FISHERIES OCEANOGRAPHY OF THE SOUTHEASTERN BERING SEA SHELF - MISCONCEPTIONS AND PERSPECTIVE 1986

by

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ABSTRACT

A major increase in the collection of physical oceanographic data on the southeastern Bering Sea shelf since 1975 has improved our understanding of the physical environment, and has led to hypotheses relating features of the physical environment to the distribution and abundance of biota. The present state of knowledge in the field of fisheries oceanography (interactions between biological resources and their marine environment) is reviewed, summarized, and compared to the state of knowledge of fisheries oceanography as presented by Favorite et al. (1977 and summarized by Favorite (1981) and Favorite and Laevastu (1981). Several conceptual problems are discussed and suggestions for future research are offered.

I. INTRODUCTION

A major interdisciplinary study of fisheries oceanography of the eastern Bering Sea, funded by the Outer Continental Shelf Environmental Assessment Program (OCSEAP) was implemented in the latter part of the 1970's. Historical information was combined with data acquired during the study and published in 1981 in a 2-volume book, The Eastern Bering Sea: Oceanography and Resources (D.W. Hood and J.A. Calder, eds.), a comprehensive summary of the biological resources and abiotic environment of the eastern Bering Sea and their interrelationships. In the ensuing years, numerous eastern Bering Sea field studies in both fisheries and physical oceanography greatly expanded the detailed knowledge in both fields; however, fisheries oceanography (i.e., the study of the interactions of the biological and abiotic systems) in the eastern Bering Sea was largely ignored. Recent attempts to combine fisheries and oceanographic studies have resulted in certain misconceptions which we will discuss.

As physical oceanographers working closely with fisheries biologists, we are well aware of the different conceptual approaches to problems inherent in the two fields. In particular, time and space scales important to fisheries biologists are often quite different from those studied by physical oceanographers. Scientists in each field, when attempting to simplify, may actually present information which is misleading if not fully understood. We have attempted to bridge these conceptual gaps and to present those areas of physical oceanography most applicable to the study of fisheries biology.

II. BACKGROUND

Historical studies in fisheries oceanography

Favorite (1981) presented an historical review of fisheries oceanography studies in the eastern Bering Sea. He restricted his definition of fisheries oceanography to controlled interdisciplinary research as opposed to random application of environmental data to fisheries studies. Favorite et al. (1977) synthesized observations of eastern Bering Sea fisheries and physical oceanography from the point of view of potential relationships between the two. The following summarizes the effects of the three most commonly measured physical variables, temperature, salinity, and currents, on fisheries resources, as presented in this latter paper.

a. Temperature

Laboratory research has shown that fish have upper and lower limits to the temperatures in which they can live. Such limits may differ greatly between species, or for various developmental stages of a particular species. Temperature effects metabolic rate, growth rate, and egg and larval development rates as well as fecundity and egg viability. Temperature may affect the development of sexual products and thereby modify the timing of spawning. Temperature may act as a cue to fish migrations or may affect swimming speeds and therefore the speed of migrations. Avoidance of temperature extremes may alter fish distribution patterns.

b. Salinity

The effects of salinity on most adult marine fish species are much less pronounced than those of temperature, since adult fish are able to maintain their internal salt balance through osmoregulation while their internal temperature approximates that of their surroundings. However, osmoregulation requires an output of energy and adult fish may therefore avoid salinity extremes.

Laboratory studies have shown relationships between salinity and egg survival and development: survival tends to be highest when the salinity of the environment is similar to that of the internal salinity of the egg; survival at very low salinities is lower than survival at higher salinities. Salinity affects water density and thereby affects the vertical distribution of eggs. Most commercially important eastern Bering Sea marine fish species cannot reproduce at very low salinities. The young of many species live in lower salinity waters than the adults (this is, however, more likely a response to food availability and/or avoidance of predation).

c. Currents

Currents may transport eggs and larvae away from spawning grounds or may retain eggs and larvae near the spawning grounds through eddy motions. Currents may be used by fish as directional signals for migrations, or as a form of locomotion during migrations. In particular, certain flatfish have been shown to utilize tidal currents for migrations by leaving the bottom and entering the water column to be transported by a strong tidal current, then returning to the bottom at the change of tide.

Recent studies in fisheries oceanography

Interest in cooperative fisheries oceanography studies in the eastern Bering Sea has recently revived, encouraged mainly by three factors: the federal Fisheries Oceanography Cooperative Initiative (FOCI), the merger in 1981 of the Department of Oceanography and the School of Fisheries at the University of Washington, and the 1982-83 El Nino. A preliminary cooperative effort between the Pacific Marine Environmental Laboratory (PMEL) and the Northwest and Alaska Fisheries Center (NWAFC) resulted in the development of an online acquisition system for existing eastern Bering Sea fisheries and oceanography data.

Several interdisciplinary conferences and workshops were spawned by this renewed interest, including a fisheries oceanography workshop at Lake Wilderness, Washington and a workshop on walleye pollock and its ecosystem held in Seattle, Washington, both in May 1983. A review of the published proceedings of these two workshops[1/] brought to our attention some of the misconceptions which will be discussed in Section III.

Recent studies in physical oceanography

Physical oceanographic observations in the eastern Bering Sea, particularly over the southeastern Bering Sea shelf, have increased enormously since 1975 due largely to two major programs: OCSEAP and PROBES (Processes and Resources of the Bering Sea Shelf). Measurements of temperature, salinity (or conductivity) and other parameters have been augmented by extensive direct current measurements, often of several months duration. These recent observations have been discussed in numerous publications (e.g., Schumacher et al. 1979, Kinder and Schumacher 1981a and 1981a, Coachman et al. 1980, Schumacher and Kinder 1983,

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1/ From Year to Year (W.S. Wooster, ed.) and Proceedings of the Workshop on Walleye Pollock and its Ecosystem in the Eastern Bering Sea (D.H. Ito, ed.).

Schumacher 1984), where the following scenario of circulation over the southeastern Bering Sea shelf is consistently presented. Misconceptions arising from the application of this environmental picture to fisheries problems will be discussed in the next section.

The southeastern Bering Sea shelf (Fig. 1) is defined as the area bounded by the Aleutian Islands, the west coast of Alaska, a line running from Nunivak Island to the Pribilof Islands, and the shelfbreak near the 200 m isobath (Schumacher and Kinder 1983). The physical oceanography of the area is presented (e.g., Schumacher 1984, Schumacher and Kinder 1983, Coachman et al. 1980) as consisting of three distinct oceanographic domains identified by different characteristics of the hydrography and of the low-frequency circulation and corresponding roughly to three geographical regions defined by bathymetry.

The inner shelf (depth less than 50 m) is characterized by slow (1-5 cm s^{-1}) northwestward mean flow and lack of vertical stratification. The middle shelf lies between the 50 and 100 m isobaths where vector-mean flow is statistically insignificant and vertical structure is generally 2-layered. The outer shelf (from 100 m depth to the shelf break) is characterized by vector-mean northwestward flow (1-10 cm s^{-1}), 3-layer vertical stratification and lack of ice cover throughout the year. These three oceanographic regimes over the shelf are bounded by fronts (Coachman et al. 1980, Schumacher et al. 1979, Kinder and Coachman 1978). A "structural" front near the 50 m isobath separates the well-mixed inner shelf from the 2-layer middle shelf. The middle front occurs near the 100 m isobath and divides the middle and outer shelf domains. The shelf break front coincides with the shelf break and separates shelf waters from deeper oceanic waters.

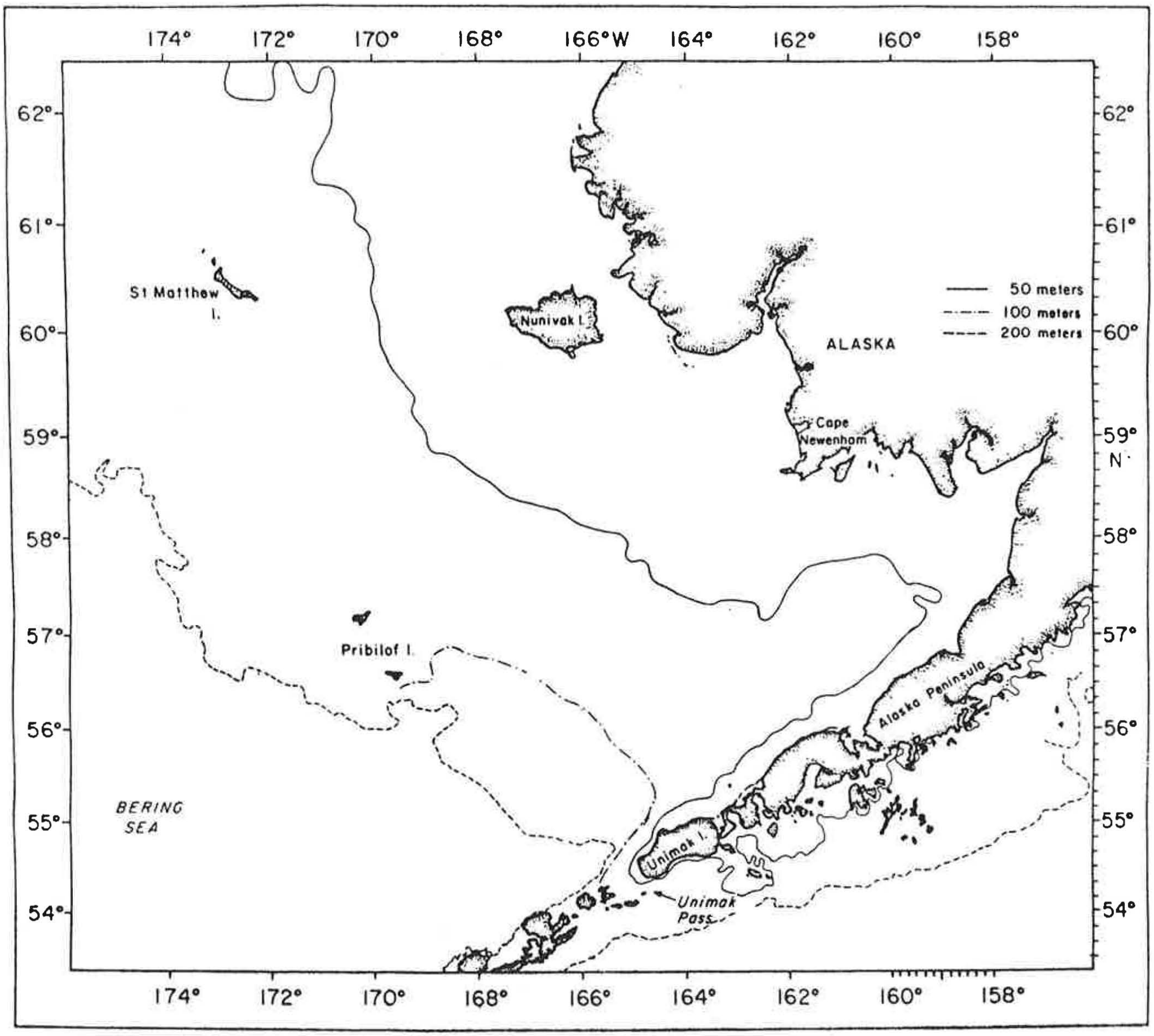

Fig. 1.--Southeastern Bering Sea shelf and bathymetry (m).

III CONCEPTUAL PROBLEMS

The physical oceanographic environment of the southeastern Bering Sea shelf as presented in the previous section differs from that which would actually be experienced by, say, a planktonic egg or a migrating fish, since mean conditions rarely if ever exist instantaneously in nature. It is noted that the above cited authors have often prefaced their discussions with comments on the limitations of the mean scenario; often, however, these limitations are ignored, and the above description is presented as the "typical" scenario of the region (Schumacher 1983). This has resulted in two major misconceptions: (1) that passively transported eggs would experience negligible net transport in the surface layer of the middle shelf (Lynde 1984, Francis and Bailey 1983), and (2) that fronts over the shelf affect biological processes (Coachman et al. 1980, Iverson et al. 1980). We would instead propose that (1) eggs spawned over the middle shelf could be passively transported hundreds of kilometers in surface waters before hatching, and (2) the transition areas between shelf regions which are referred to as fronts probably have much less effect on the biota than the oceanography of the regions themselves.

Our hypotheses do not contradict previous studies *per se*; in fact, we will often cite this literature to support our views. We propose, however, that a long-term, low-frequency description of the physical environment is inadequate for use over time and space scales of biological importance. We will emphasize features of the physical environment of the eastern Bering Sea shelf which are important at various time and space scales, and to reemphasize definitions already presented in the literature, not as an exercise in semantics, but to increase understanding and to remove misconceptions.

Time and space scales

A recent paper reviewed physical oceanographic measurements related to the study of fish migrations (Lynn 1984), pointing out the need to determine the "fields of motion over spatial and temporal scales that are pertinent to the migrations of a particular population of fish". We would extend this concept to include any behavioral processes which might be modified by the physical environment. That is, if a link between physical and biological processes is sought, those physical features which are important at the time and space scales of the biological processes should be examined. Scales of biological processes may differ among species or among various developmental stages of a species. For example, walleye pollock eggs and larvae are pelagic (within the upper 30 m of the water column); eggs hatch approximately 20 days after spawning and the larval stage continues a pelagic life. Eggs are therefore subject to passive transport by surface currents for about three weeks and larvae for at least two months. Most juvenile pollock appear to spend their first summer over the middle and inner shelf areas, in the upper 40 m of the water column, with a trend toward increased semidemersal behavior with increased age (Lynde 1984). Adults winter over the outer shelf and slope, then migrate shoreward to spawn in late winter or early spring (Smith 1981). Each developmental stage of pollock would thus encounter different spatial and temporal physical processes. Also, as described in Section 1, the same physical process will affect each developmental stage differently.

Physical processes also occur at many time and space scales. The primary forces for currents over the southeastern Bering Sea are tides and winds (Coachman and Charnell 1979, Coachman et al. 1980, Kinder and Schumacher 1981b). Tidal currents are strong (on the order of 25 cm s^{-1}), but oscillatory. A particle's trajectory over one tidal cycle will be elliptical; since major tidal components are semidiurnal or diurnal, a particle driven strictly by the tide will be near where it began after a 24 hr period. Any displacement of a particle from its origin after a tidal cycle represents a net transport due to "residual" tidal currents (Lagrangian tidal currents). Wind forced motions are generally identified in current meter records as those motions with periods from 2 days to 2 weeks (Kinder and Schumacher 1981b, Schumacher and Kinder 1983). Intense winds from storms can drive sustained surface currents of over 20 cm s^{-1} for several days. Tides are modified by bathymetry and therefore vary over the shelf as do winds. Additional forcing mechanisms such as seasonal warming and cooling, ice cover and associated convective overturn, ice melting, precipitation, and river runoff modify temperature, salinity, and currents on time scales of days to months. Interannual fluctuations in physical parameters can be very large and variable over space (Ingraham 1981 and Ingraham 1983).

Limitations of the mean environmental picture

As previously mentioned, descriptions of the physical oceanography of the southeastern Bering Sea shelf as presented in Section II are often prefaced in the literature by a discussion of their limitations. In view of the variability in time and in space of both biological and physical processes, we will categorize the limitations in those terms.

a. Time scales

The environmental picture presented in Section II contains no time dependence. It is presented as a mean or typical scenario (Schumacher and Reed 1983). However, the hydrographic structure (i.e., well mixed inner shelf, 2-layer middle shelf, and 3-layer outer shelf separated by fronts) is primarily based on summer observations (Kinder and Schumacher 1980a, Coachman et al. 1980); during the winter, mid-shelf waters under ice cover are usually vertically homogeneous both in temperature and in salinity (Coachman and Charnell 1979). Effects of ice cover on mixing and temperature and salinity changes are not included in the mean scenario, nor are seasonal changes due to precipitation, runoff, and insolation. Hydrographic surveys carried out over several weeks are assumed synoptic (Kinder et al. 1977), although hydrographic fields over the shelf are known to be "highly variable" on scales of a few weeks (Kinder et al. 1980). Frontal features described as persistent throughout many seasons (Schumacher and Kinder 1982) are sometimes observed in salinity and sometimes in temperature (Schumacher et al. 1979).

The current velocities over the shelf as presented in Section II represent "vector means" of current water measurements which have been filtered to remove current fluctuations of 35-hour periods or less. Thus, all motions at or near tidal frequencies are ignored. Means are computed over variable record lengths (Schumacher and Kinder 1983, Kinder and Schumacher 1981b), so that fluctuations of longer periods (such as storm generated wind-driven flows) may average out.

b. Space scales

Between the coast and the shelf break the three separate hydrographic domains are associated with the three geographical areas separated by the 50 m and 100 m isobaths. Horizontal and vertical variability of parameters within each region have not been reported in detail and, as described above, temporal variability of domains is ignored. Although the inner front is apparently a legitimate "front", being much narrower than the domains it separates, the middle "front" is described as a much broader transition zone relative to its adjacent domains (Kinder and Schumacher 1981a). Fronts are sometimes observed in the surface layer and sometimes in bottom waters (Coachman et al. 1980).

Current meter measurements are Eulerian; that is, they represent flow past a fixed point in space. Particle trajectories (Lagrangian motion) cannot be extrapolated from isolated Eulerian measurements without detailed knowledge of adjacent spatial and temporal variability in the flow field.

IV. APPLICATION TO FISHERIES RESEARCH

We proposed two hypotheses in Section III: (1) pelagic eggs spawned over the middle shelf could be passively transported hundreds of kilometers before hatching, and (2) transition zones between different hydrographic domains which have been termed fronts probably have negligible effect on the biota. We will present our evidence to support these hypotheses, with the following qualifications. We are not attempting to prove that eggs will be transported hundreds of kilometers or that fronts never affect the biota. Instead, our major goal is to demonstrate that the physical oceanographic conditions most likely to affect the organisms over the southeastern Bering Sea shelf are those with small time and space scales which are therefore usually deleted from long term mean records.

Currents

"Mean" current velocities in each domain of the southeastern Bering Sea shelf have been determined mainly from low-pass filtered current meter measurements. The filter length used in the Bering Sea analyses is usually 35 hr (i.e., motions with periods less than 35 hours are removed). Residual tidal currents are therefore ignored, along with high frequency "noise" (random motions). Kinder and Schumacher (1981b) note that "mean flow is energetically two orders of magnitude smaller than tidal flow over much of the shelf, however, and mean circulation may not be the most important flow component in many situations".

The primary driving force of currents over the southeastern Bering Sea shelf is the tide. Tidal motions do not repeat themselves exactly and particles will be displaced from their points of origin after a complete tidal cycle. Residual tidal currents are caused by interactions of each tidal component with bathymetry, interactions among tidal components, and interactions between wind-forced and tidally-forced motions. Tides in the eastern Bering Sea have been modeled by Sündermann (1977) and others, as described by Mojfeld et al. 1984. Computed residual tidal currents due to interactions between the bathymetry and the M2 tide alone (Sündermann 1977) and between the bathymetry and each separate major tidal component (Mojfeld et al. 1984) were quite small (<1 cm s^{-1}). Residual currents due to interactions among tidal components are not known, and those caused by interactions with winds and tides have not been studied in the Bering Sea, but have been examined in some detail in the North Sea. Residual currents due to interactions between the mean annual wind stress and the M2 tide in the North Sea, computed by Maier-Reimer (1977), were on the order of 1-2 cm s^{-1}. These values are quite conservative since the M2 tidal component alone was used in the analysis, so that interactions among tidal components, or between other components and winds or bathymetry were not included in the model. Also, the instantaneous wind stress in the North Sea is much larger than the annual mean, so that current velocities were underestimated. Currents at tidal frequencies, therefore, are poorly understood and should not be neglected in the computation of circulation over the eastern Bering Sea. Particle displacement caused by these currents can only be resolved by using a model of the entire shelf (Mojfeld et al. 1984).

The second largest driving force of currents over the southeastern Bering Sea shelf is wind stress. Specifically, cyclonic storms passing over the area generate strong wind pulses of several days duration. Current meter measurements reflect the passage of such storms by "rotating vectors" (Schumacher 1984); i.e., strong currents in one direction for several days followed by a reversal in direction as the storm passes. When averaged over a sufficient record length, net current as recorded by the current meter will be near zero. The Eulerian reference frame of the current meter, however, does not truly reflect particle trajectories. Variability in wind forcing over the shelf will result in a net particle displacement or residual velocity. Also, the current meter record length determines the magnitude of the "mean" current. Storm-driven wind pulses of up to 10 days duration have resulted in anomalously large means in 6-month current meter records (Schumacher and Kinder 1983).

Storms occur frequently over the Bering Sea during both summer and winter, and appear in the low-frequency current meter measurements as strong (up to 30 cm s^{-1}), persistent (up to 10 days) flow in one direction. Kinder and Schumacher (1981b) cite several examples of such wind "events": mean flows of 20 cm s^{-1} for 4 days during January 1976, 15 cm s^{-1} for 5 days during January 1977, and over 30 cm s^{-1} for 30 hours in February 1977. If these Eulerian measurements could be equated to Lagrangian motions, they would represent net excursions of approximately 70 km in 4 days, 65 km in 5 days, and 32 km in 30 hours. As explained above, however, such an equivalence cannot be made without knowledge of spatial variations in forces and effects of higher frequency currents. Lagrangian motions can be closely approximated, however, by drifter measurements. A satellite-tracked drogued (17 m) drifter deployed in the vicinity of current meter moorings during summer 1976 responded to a storm by accelerating to over 20 cm s^{-1} and traversing over 75 km in 5 days. Near-surface current meters in the area recorded mean speeds of only 5-10 cm s^{-1} and biological fouling of the current meters was suspected (Kinder and Schumacher 1981b).

In general, then, passive transport of particles over the middle shelf for short periods of time cannot be assumed to be negligible. Francis and Bailey (1983), in comparing Soviet larval survey data from June 1982 and

NMFS 0-age acoustic survey data from August 1982, noted the suggestion of a rapid dispersal in the surface layer over the middle shelf since the region of maximum concentration is displaced between surveys (Fig. 2). Even a mean velocity of only 2.5 cm s^{-1} over the approximately 70 days of a pollock's pelagic stages would transport it over 150 km. As Coachman and Charnell (1979) point out, shelf flow is "driven primarily by winds and tides, while residual (longer-term) mean flows are insignificant in the transport of mass properties". Ten storms (usually lasting 2-5 days) were observed during 100-day current meter records in winter 1977, and strong storms are common in all seasons. Winds from only two such storms during a 3-week period could easily transport pelagic eggs a distance of over 100 km. The importance of storms in determining mean circulation patterns has not been studied in the Bering Sea; however, North Sea circulation models have shown that strong wind events of a few days duration during spring can statistically dominate mean annual surface transport (Sündermann, pers. comm., 1985).

Fronts

Three "fronts" have been identified over the southeastern Bering Sea shelf: a "structural front" near the 50 m isobath which separates vertically mixed inner shelf waters from the middle shelf (Schumacher et al. 1979), a "shelf break front", or "slope front", separating oceanic waters from shelf waters (Kinder and Coachman 1978) and the "middle front", located near the 100 m isobath, separating the middle and outer shelf domains (Coachman and Charnell 1979). These fronts are characterized by horizontal changes in hydrographic structure. For example, when the

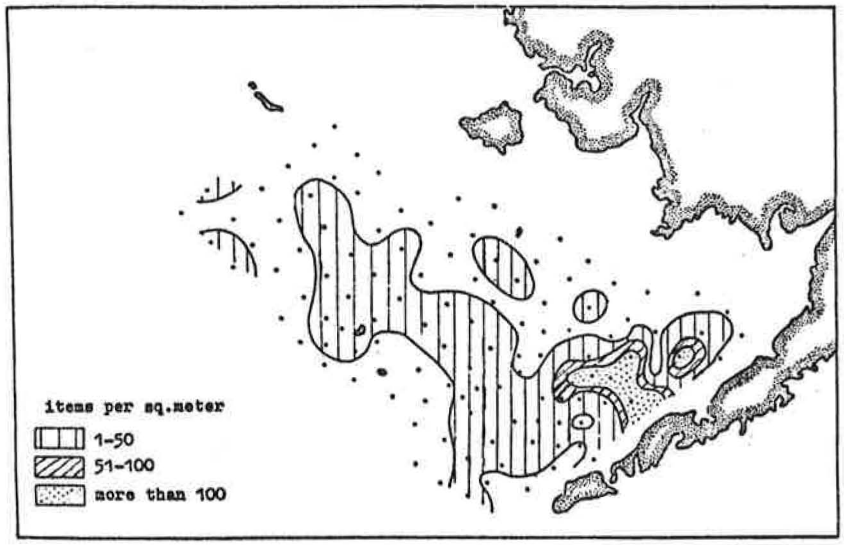

Fig. 2a.--Distribution of pollock larvae in June 1982 (from Francis and Bailey 1983).

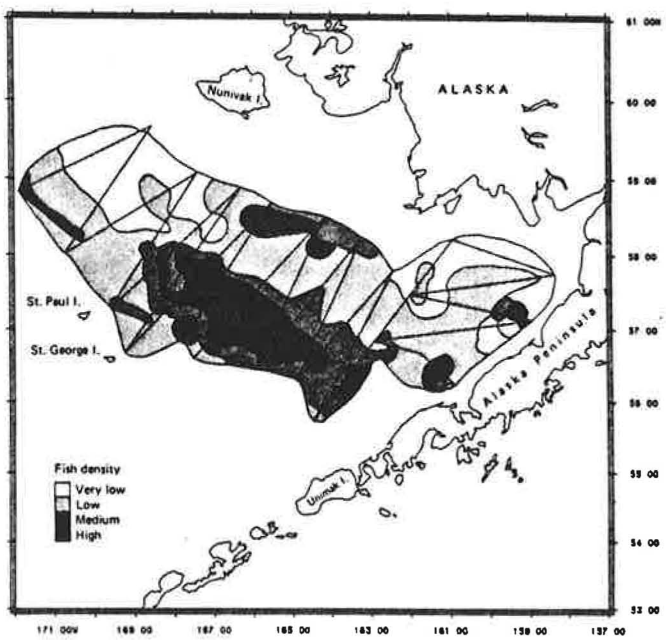

Fig. 2b.--Distribution of pollock juveniles in August 1982 (from Francis and Bailey 1983).

middle shelf is stratified and the inner shelf is well mixed, isotherms from the middle shelf will intersect the bottom at the transition between the two regions (Fig. 3, after Kinder and Schumacher 1981a).

A precise definition of the term "front" as it is used in the eastern Bering Sea oceanography is lacking. The above vague definition of "horizontal change in hydrographic structure" is at least consistent with observations. Coachman et al. (1980) define fronts as "regions of enhanced horizontal gradients of water properties", and present examples of fronts in salinity cross-sections. They go on to say, however, that the vertically-averaged salinity gradient of the inner front ($2x10^{-3}$gm $kg^{-1}km^{-1}$) is about equal to that over the middle shelf, and is an order of magnitude smaller than the salinity gradient over the inner shelf ($10x10^{-3}$gm $kg^{-1}km^{-1}$). That is, the vertically-averaged gradient of the front is less than or equal to the gradients of the adjacent domains. Also, the salinity gradients of the middle and shelf break fronts are about equal to that over the inner shelf. Stronger gradients can at times be seen in particular vertical levels in the fronts, but the level in which the front appears may change between seasons.

The shelf break front is described as essentially haline; "the thermal properties of the front are incidental" (Kinder and Coachman 1978). Such features are very common: "a transition zone where major water masses with diverse properties are in lateral juxtaposition is generally located along the outer edges of continental shelves" (Coachman and Charnell 1979); "no observed features of this front, nor our explanations of them, are unique to the Bering Sea" (Kinder and Coachman 1978). The middle front is

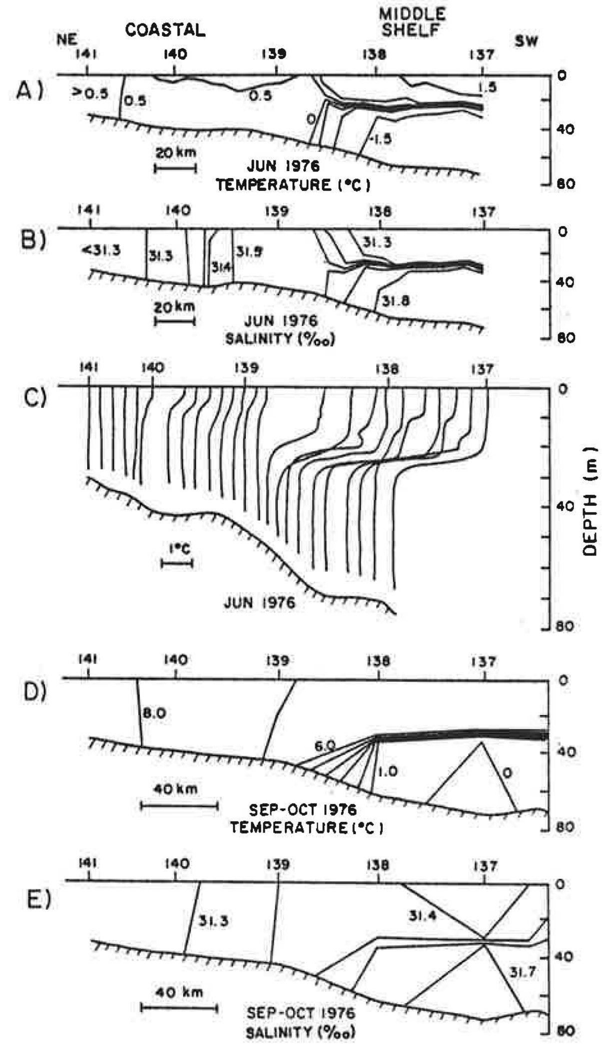

Fig. 3.--The structural (inner) front separating the coastal and middle domains. This line was between Nunivak Island and the Pribilof Islands. (A, B) Temperature and salinity cross sections, and (C) sequential temperature profiles from June 1976. The sections are based on stations separated by about 10 km. (D, E) The same section based on widely spaced CTD stations in autumn 1976. (From Schumacher et al. 1979.)

described as a broad, ill-defined transition area (Coachman and Charnell 1979, Kinder and Schumacher 1981a). The inner front is "legitimately called a front" (Kinder and Schumacher 1981a) since it is much narrower than the domains it separates; however, during the winter, water over the entire shelf out to 100 m has no stratification in either temperature or salinity (Coachman and Charnell 1979), and therefore the inner front does not exist at that time. The inner front forms during spring with the addition of fresh water from melting ice and a rising temperature from increased insolation; these processes initiate the two-layer structure in the mid-shelf domain. The horizontal gradient of vertical mean salinity changes sign over seasons, and the vertical structure of water properties is controlled by salinity in spring and by temperature in autumn (Schumacher et al. 1979).

We would conclude, then, that except during winter, three distinct hydrographic domains delineated by bathymetric changes are evident in the data. Three distinct regions in the eastern Bering Sea ("the shallows" to 25 fm (46 m) depth, "moderate depths" from 25-75 fm (46-137 m), and "deep water") were identified on the basis of temperature alone as early as 1880 on the voyage of the U.S.S. Yukon (Ingraham 1981). The divisions between domains may be gradual or may appear as abrupt gradients in one or more parameters over some depth range in the water column. We would hypothesize, however, that the regions of change (or "fronts") are less important, particularly from a biological standpoint, than the areas they separate, since the transition areas are usually broad, are variable in time and space, and are most evident as changes in salinity. In addition, salinity gradients within the transition zones may be no greater than those experienced by a fish while traversing the inner shelf. The transition zones may at times exhibit distinct temperature gradients, but the effects of such gradients on fish must be examined in the context of available empirical data on responses of particular fish species to temperature gradients.

We also question the unqualified use of the term "front" to describe the transition zones since it may be misleading. Although the term is commonly used by physical oceanographers to describe transition areas on continental shelves (e.g., Mooers 1978, Pietrafesa 1983), biologists are familiar with the connotation of a front as an area of high biological concentration, derived from the association with such oceanic frontal zones as the Antarctic Convergence and the Subpolar Front, areas of strong convergence. Frontal convergence in the eastern Bering Sea has been suggested (e.g., Coachman et al. 1980) but has never been substantiated by observations.

A recent paper by Iverson et al. (1980) explored the ecological role of fronts in the eastern Bering Sea. They hypothesized that faunal distributions are related to front locations. They presented evidence of three distinct regions over the shelf with different nutrient and chlorophyll concentrations. For example, highest concentrations of nitrate and of silicate occurred in bottom waters at depths greater than 100 m. Chlorophyll and particle counts had maxima over the middle shelf and minima over the outer shelf. Copepod species in the middle and inner shelf areas differed from those over the outer shelf. Transitions between these regions corresponded to front locations, which were evident as gradients in salinity but not in temperature. We could see no evidence in their figures, however, of any significance of the fronts themselves. They also suggested that fronts may partition demersal predators by isolating benthic food resources within the middle shelf, and cite as examples that yellowfin sole are "never found deeper than 100 m in the southeastern Bering Sea" and that "King crabs and tanner crabs are caught exclusively in the middle shelf zone of the southeastern Bering Sea". However, yellowfin sole catches are concentrated between 100 and 200 m depth in the southeastern shelf during winter; yellowfin sole annually migrate to the middle shelf from the deeper waters of the outer shelf and appear to alter their diet according to availability of prey (Bakkala 1981). During the summer yellowfin sole is also found in quantities in depths less than 50 m. Tanner crabs (C. bairdi) are consistently most abundant deeper than 100 m (Otto 1981).

It would seem, then, that the biological significance of the "fronts" is that they may aid the biologist in determining the boundaries (which fluctuate in time and space) between different physical environments. The effect of the physical environment on the biota, however, is as yet poorly understood.

V. DISCUSSION

For the most part, especially in the U.S., fisheries biologists and physical oceanographers depend on each other's expertise in their respective fields. Too often we oversimplify the unfamiliar. Fisheries oceanography would be far less complicated for the biologists if the ocean were static and predictable and much simpler on the oceanographer if all fish behaved similarly and predictably. Neither the behavior of the ocean nor the behavior of fish is completely understood. Fisheries oceanographers must understand the limitations in both fields and must examine the ocean from the point of view of the fish.

Some probable effects of the environment on the biota, summarized from Favorite et al. 1977, were presented in Section II. Temperature, currents, and to a lesser degree salinity, may affect eggs, larvae, or fish. Eggs and larvae are highly susceptible to the environment; they are also highly susceptible to predation. The relative magnitudes of these effects are unknown. The effect of egg and larval mortality on recruitment to the fishery is also not known. Adult fish are not passively affected by the environment. They can adapt to moderate changes in salinity through osmoregulation. They are much more directly affected by temperature, but little is known of how fish respond to temperature changes in the ocean. Temperature tolerances differ among species. Response to temperature changes must also differ: slow benthic migrators such as crabs would be far more likely to be directly affected by a sudden temperature gradient than a pelagic fish, which could change its vertical position in the water column by a few meters to avoid the cold. The magnitude of the temperature gradient required for reaction by a particular species of fish must be considered.

Effects of water motions differ for different life stages and between species. It must be stressed that low-frequency flow is not the same as mean flow. Currents vary with depth. Surface layers are dominated by wind forcing, which can be strong and persistent over time scales of days to weeks. Bottom waters are dominated by tidal currents, which fish may selectively use as an aid in migration. The entire shelf is affected by ice cover in winter and the effects of ice melting or forming in spring and autumn. Favorite and Laevastu (1981) presented monthly scenarios of probable environmental and biological events. All important features of the environment were included and fish were discussed according to species behavior and life stages. They pointed out gaps in knowledge at that time and asked several pertinent questions, such as what environmental stimulus (if any) triggers the autumnal seaward migration of flatfishes and crabs and whether the extensive seasonal NE-SW migrations of these species are aided by tidal transport, and what are the effects of spring storms on the pelagic larvae (and subsequent year class strength) of several species. Perhaps the study of fisheries oceanography in the eastern Bering Sea should continue from that standpoint, building on the historical studies and using new data to fill some of the gaps in knowledge and to answer some of the still unanswered questions.

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