Hydrographic Structure Over the Continental Shelf of the Southeastern Bering Sea

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ABSTRACT

We synthesize recent work conducted over this exceptionally broad (~500 km) shelf which generally has only slow mean flow (≤2 cm/sec). Hydrographic structure is little influenced by this flow, but rather is formed primarily by boundary processes: tidal and wind stirring; buoyancy input from insolation, surface cooling, melting, freezing, and river runoff; and lateral exchange with the bordering oceanic water mass. Three distinct hydrographic domains can be defined using vertical structure to supplement temperature and salinity criteria. Inshore of the 50 m isobath, the coastal domain is vertically homogeneous and separated from the adjacent middle domain by a narrow (~10 km) front. Between the 50 m and 100 m isobaths, the middle domain tends toward a strongly stratified two-layered structure, and is separated from the adjacent outer domain by a weak front. Between the 100 m isobath and the shelf break (~170 m depth), the outer domain has surface and bottom mixed layers above and below a stratified interior. This interior has pronounced finestructure, as oceanic water intrudes shoreward from the weak haline front over the slope, and shelf water (middle domain) intrudes seaward across the 100 m isobath. These domains and their bordering fronts tend to persist through winter, although the absence of positive buoyancy often makes the middle shelf vertically homogeneous.

INTRODUCTION

We selected the title hydrographic "structure" rather than simply "hydrography" because we wish to emphasize the structure, or organization, inherent in the hydrographic distributions. This approach focuses on the shapes of vertical profiles, or rather classes of shapes (e.g., two-layered), rather than on values of temperature and salinity or their correlation (TS diagrams). Thus, we find a large region of the shelf where the temperature and salinity are vertically homogeneous throughout the year, although the values of temperature and salinity fluctuate over a wide range. We concentrate on the persistent vertical homogeneity and label this region a hydrographic domain. Because vertical profiles control the hydrostatic stability of the water column, and because stability influences vertical mixing, this approach is physically meaningful and useful.

We also concentrate on characteristics of small size, on what can be called the spatial variability. Thus the fronts that separate regions of uniform hydrographic structure (hydrographic domains) are discussed in some detail, as is the finestructure over the outer shelf. One front, for example, has a width of only 10 km and the finestructure has a typical vertical extent of 5 m. It is now possible to resolve such features as fronts and finestructure because samples are taken closer together than formerly.

Our emphasis on hydrographic structure and small spatial scales is not opposed to examination of TS properties or broader spatial scales, but complementary to it. Our description of the shelf hydrographic structure is more meaningful in considering shelf environment from a climatic point of view. We mostly ignore changes at intervals longer than annual, although interannual hydrographic variability is significant (e.g., Overland, Niebauer, and Ingraham, this volume). The major features that we discuss here, however, were observed both in 1976 (the winter of 1975-76 was exceptionally cold, with extensive ice cover) and in 1977 (the winter of 1976-77 was exceptionally mild, with reduced ice cover). Although altered by interannual changes, the features that we describe persist through these long-term variations.

Because mean flow over the shelf is small, changes in hydrographic properties can be straightforwardly attributed to local processes rather than to advection. For instance, cold temperatures in the lower layer of the middle shelf persist throughout summer (Fig. 4-4). This was once believed to be evidence of mean flow from the northern shelf, but in fact the cold temperatures are caused by local processes: heat loss at the sea surface and complete vertical mixing during winter, followed by the establishment of strong stratification during spring and summer. This stratification insulates the lower layer from downward heat transfer. Especially over the inner two-thirds of the shelf, important characteristics of the hydrography can be explained by local phenomena and advective effects are unimportant.

We complete the introduction by briefly discussing the oceanographic setting, reviewing previous work, and discussing the data. Then we define the hydrographic structure by discussing salient characteristics: domains, fronts, finestructure, winter structure, and river plumes. We then discuss some processes that affect the hydrographic structure: stirring and buoyancy addition, heat and salt transport, and upwelling. Finally we discuss and speculate about aspects of the hydrographic structure.

Setting

The southeastern continental shelf is bordered by the Alaska Peninsula, the Alaska mainland, and a line running southwest from Nunivak Island to the Pribilof Islands and thence following the shelf break southeastward to Unimak Pass. Waters above the shelf receive an annual excess of precipitation over evaporation, as well as freshwater runoff from numerous rivers. Estimating precipitation either from Jacobs (1951) or from station data reported by Brower et al. (1977), and evaporation from Jacobs, a net of about 1 percent of the volume of water over the southeastern shelf is added annually by precipitation minus evaporation.[1] An additional 1 percent is added by river runoff, principally from the Kuskokwim and Kvichak (1,500 to 2,000 m^3/sec average discharge from all rivers: Roden 1967, Favorite et al. 1976). In winter, ice covers over 50 percent of the shelf, initially appearing inshore in November, often expanding to cover more than 80 percent of the shelf by March, and rapidly disappearing between late April and early June (Favorite et al. 1976, Muench and Ahlnäs, 1976). Ice appears to form near shore and is blown southward during the freezing season (see McNutt and Pease, this volume). Current meter records show that most of the horizontal kinetic energy of the shelf water is tidal: 60-95 percent of the variance in records 9-332 days long was tidal (see Kinder and Schumacher, Chapter 5). Vector mean speeds ($\leqslant$2 cm/sec) were one order of magnitude lower than tidal speeds ($\sim$20 cm/sec).

[1] Using recent precipitation estimates by Reed and Elliott (1979) would increaase this to nearly 2 percent. Reed and Elliott state, however, that their estimates may be inaccurate in the subarctic Pacific.

Historical review

There has been considerable Japanese, Soviet, and American work done on this shelf. Results of this work have been effectively summarized (Ohtani 1973, Takenouti and Ohtani 1974, Arsenev 1967, Dodimead et al. 1963, and Favorite et al. 1976), and this brief review places more recent results in perspective.

Takenouti and Ohtani (1974) discussed waters above the shelf, which they realized were separated from ocean waters by a "discontinuous zone" (cf. Kinder and Coachman 1978). They further reported that the cold (<1.0 C) water near the bottom in the middle shelf (cf. Fig. 4-4) was not advected from the Gulf of Anadyr as Kitano (1970) believed, but was formed *in situ* in winter and insulated by strong stratification in summer. Their proposed classification of water masses over the southeastern shelf has been modified by recent findings. Takenouti and Ohtani defined a CW (coastal water) region by its low salinity, but we have found that at the end of winter the salinity may be higher there than in the adjacent convective area (CA—roughly corresponding to our middle domain). Furthermore, the Alaskan Stream (AS) region near the shelf break is misnamed—direct connection with the westward-flowing Alaskan Stream, which exists south of the Alaska Pennisula and Aleutian Islands, is not proved. At the same time, our map of hydrographic domains (Fig. 4-1) is congruent with theirs, and builds upon their insights.

Ohtani (1973) discussed the southeastern shelf in more detail. He mentioned the thermal front that forms between the middle and coastal domains (cf. Fig. 4-6 and Schumacher et al. 1979), and correctly suggested the importance of tidal stirring in forming this front. Ohtani also emphasized vertical stratification in defining shelf water masses, and dwelt less on arbitrary temperature and salinity limits. Again, net inflow of Alaskan Stream water is more tenuous than Ohtani suggested; properties are certainly exchanged

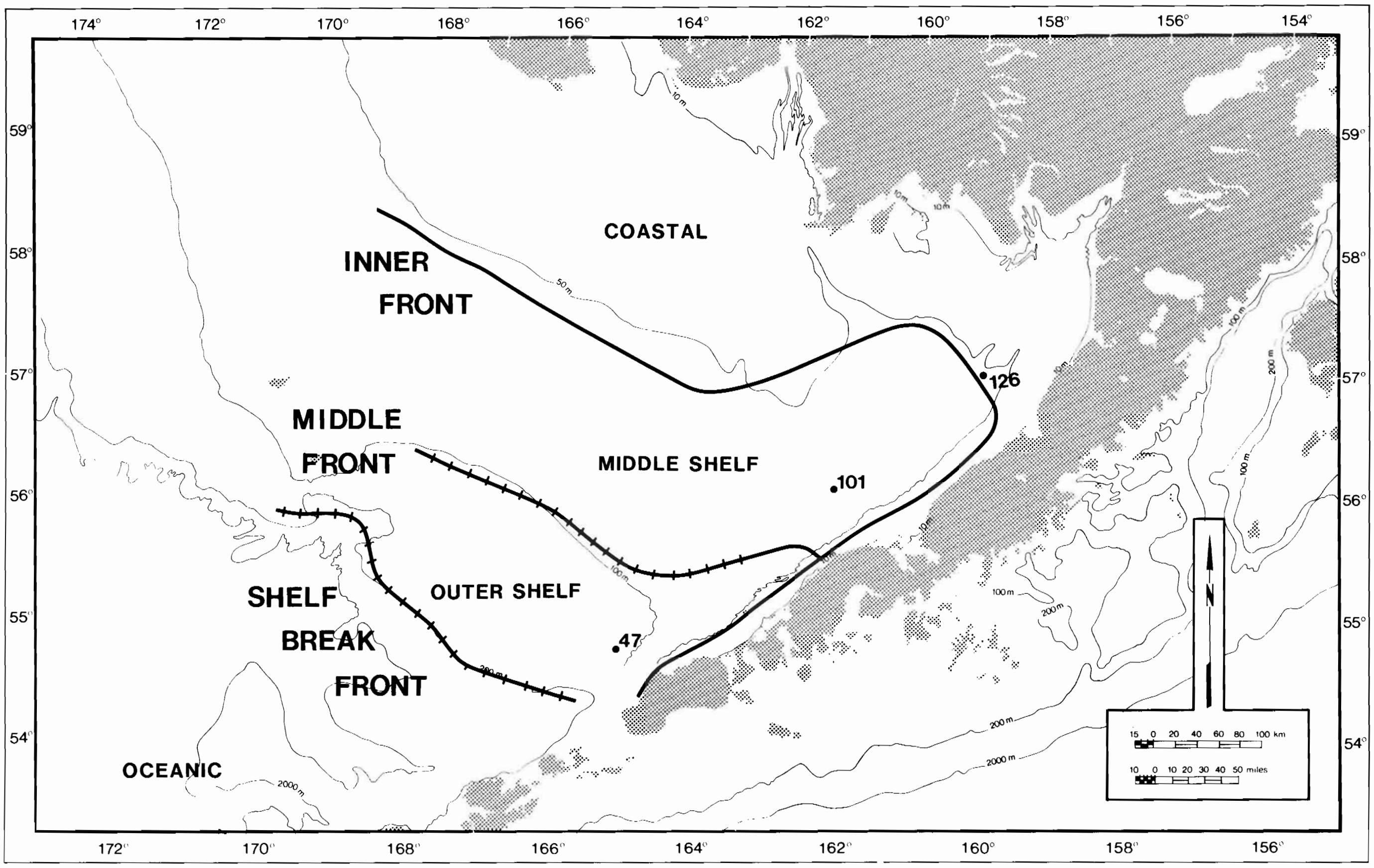

Figure 4-1. Approximate boundaries separating the three shelf (coastal, middle, outer) and the oceanic hydrographic domains. The boundaries are three fronts: inner, middle, and shelf break. These fronts roughly coincide with the 50 m isobath, the 100 m isobath, and the 200 m isobath (shelf break). Profiles from the numbered stations appear in Fig. 4-2.

through the eastern Aleutian passes by vigorous tidal currents, but the net flux of water is not known, and is probably small in any case because of small cross-sectional area (Favorite 1967).[2]

Arsenev (1967) wrote about water masses and currents of the entire Bering Sea, using many sources, but highlighting Soviet work. He discussed the importance of water mass transformation by freshwater runoff, insolation, cooling, melting, and freezing. He also recognized the separation of oceanic and shelf waters, but virtually ignored the southeastern shelf in favor of the western shelf, especially the Gulf of Anadyr.

Dodimead et al. (1963) and Favorite et al. (1976) summarized the regional oceanography of the North Pacific, including the Bering Sea. Dodimead et al. (1963) included an appendix on Bristol Bay, and noted several features that have been elaborated only recently. They reported the inner front that separates the coastal and middle domains as a sharp boundary (cf. Schumacher et al. 1979), and also reported "marked changes" near the shelf break that correspond to the weak haline front there (cf. Kinder and Coachman 1978, Coachman and Charnell 1979). They also noted the patch of cold surface water within Bristol Bay, which they attributed to upwelling. Favorite et al. (1976) showed three domains across the shelf: shelf edge, mid-shelf, and West Alaska Coast (their Fig. 33). Their geographical boundaries nearly coincided with the three domains that we describe in the next section, but they were apparently based on TS relations (cf. Ingraham, this volume). Favorite et al. (1976) also discussed the frontal zone over the slope.

Thus, many of the features that we now recognize as important components of the hydrographic structure of the shelf were reported previously. Among these features are the front over the slope and the inner front farther inshore, the division of shelf waters into distinct domains, and the possible upwell-

[2] Favorite (personal communication 1979) has pointed out that the distribution of a temperature maximum along the eastern Bering Sea continental slope suggests net inflow to the Bering Sea through passes west of Unimak Pass between 170° W and 172° W.

ing in Bristol Bay. We now know more details and understand these features better, but it is clear that our progress has benefited from these earlier works.

Data

From August 1975 to February 1978, hydrographic casts were made with profiling instruments: STD (salinity, temperature, depth), CTD (conductivity, temperature, depth), or XBT (expendable bathythermograph). Covering all months from February to October, these 1,064 STD and CTD casts are biased towards summer (Table 4-1), but this bias is not a serious limitation because of adequate coverage in February.

The STD and CTD data were calibrated by a water sample, normally taken at the bottom during alternate casts. Calibration temperatures were determined by reversing thermometer, salinity by portable induction salinometer. We claim an accuracy of ±0.02 C and ±0.02°/oo. The XBT profiles were calibrated against nearby CTD casts, and we claim ±0.1 C. The unusual data processing necessary to examine details of finestructure in vertical profiles of salinity is discussed elsewhere (Coachman and Charnell 1979).

TABLE 4-1

Summary of STD and CTD data

MONTH	NUMBER OF CASTS
February	117
March	65
April	34
May	159
June	213
July	122
August	152
September	184
October	18
TOTAL	1064

These casts were taken during the period August 1975 to February 1978.

HYDROGRAPHIC STRUCTURE

Three hydrographic domains

We have divided the shelf into three structural domains, called the coastal, middle, and outer domains (Fig. 4-1). These domains are nearly congruent with geographical boundaries previously defined by water masses (e.g., Favorite et al. 1976), and are approximately separated by the 50 m isobath, the 100 m isobath, and the shelf break (close to the 200 m isobath). Our structural domains broaden the criteria previously used for defining the shelf water masses, emphasizing the potential for stratification of the water column (Table 4-2; also cf. Fig 24 in Coachman and Charnell 1979). These domains are most prominent in summer, but are also discernible during the other seasons. Lying seaward of the outer domain, and separated from it by a weak haline front (shelf break front), is the oceanic domain. The oceanic domain completes our scheme, but it is outside the geographic focus of this chapter (Sayles et al. 1979 concentrate on the water overlying the deep basins).

Defining water masses is most useful where temperature and salinity vary slowly at a location (e.g., no surface cooling), or where significant mean advection makes water masses useful in tracing flow. Thus tracing water masses has usefully revealed mean flows in the deep ocean. On this shelf, however, great changes in water mass properties occur annually (Coachman and Charnell 1979, Kinder et al. 1978), and there is little mean flow. Moreover, seemingly reasonable temperature-salinity parameters may prove deceptive. For example, a criterion previously used to describe coastal water has been its low salinity (Takenouti and Ohtani 1974, Favorite et al. 1976), but we now know that during early spring the coastal domain may be more saline than the adjacent middle shelf water (Kinder 1977).

To overcome some of these ambiguities, we have added vertical structure to the criteria. Instead of water mass, we use the word domain, favored by Dodimead et al. (1963), to connote broader criteria than simple temperature-salinity correlations. These domains are geographic entities; energy balances forming vertical structure are closely tied to local geography, so that the domains are also nearly fixed geographically (see *Stirring and buoyancy addition* in the next section of this chapter).

During the summer, vertical structural criteria permit easy separation of the shelf into three domains: homogeneous (coastal), two-layered (middle), and stratified interior (outer; see Table 4-2). These categories are insensitive to particular values of temperature and salinity which vary from year to year (see Niebauer, Chapter 3, for variations of sea surface temperature, and Ingraham, this volume, for interannual hydrographic variations), but depend on the influence of buoyancy input, which

TABLE 4-2

Hydrographic domains in summer

	Coastal	Middle	Outer
Vertical structure	homogeneous	two-layer	surface mixed layer stratified interior bottom mixed layer finestructure
Stratification	very low	very high	moderate
Depth	<50 m thickness of bottom (tidal) mixed layer	50 m ⩽ depth <100 m thickness of surface + bottom mixed layer	⩾100 m > surface + bottom mixed layers, thus an interior region exists
Temperature	very warm in late summer (efficient heat transfer throughout water column) (~ 8 to 12 C)	very cold bottom temperature throughout summer (vertical heat transfer impeded by stratification) (~ −1 to 3 C)	moderate (~ 3 to 6 C)
Salinity	generally low (<31.5°/oo), but may be relatively high following winter (>32°/oo: brine drainage during freezing)	moderately low (~ 31.5°/oo)	high (>32°/oo)
Influences	river runoff freezing	melting	adjacent water overlying deep basin; Bering Slope Current

This table emphasizes summer conditions, when the domains are most clearly established and when our data are most extensive. These domains remain useful throughout the year: see the section in this chapter on winter structure.

tends to stratify the water column, and tidal stirring, which tends to mix the water column.

An example of each domain from early autumn 1976 (Fig. 4-2) illustrates the three structures. Station 126, in about 50 m of water, is nearly homogeneous in both temperature and salinity, while station 101, in about 70 m of water, is strongly two-layered with vertical temperature and salinity differences of 4 C and 0.4°/oo. In still deeper water, station 47 has a surface layer, a bottom layer (not completely mixed), and a stratified interior. Many stations in the outer domain display strong finestructure in temperature and salinity (Coachman and Charnell 1977, 1979; Kinder 1977; Kinder et al. 1978), but we smoothed the profiles in Fig. 4-2 to emphasize larger-scale features.

A companion view of these domains is shown by plotting vertical temperature differences across the shelf in early autumn 1976 (Fig. 4-3). Shoreward of the 50 m isobath, this difference was generally ⩽1 C, while between the 50 and 100 m isobaths it commonly exceeded 7 C. Nearer the shelf break,

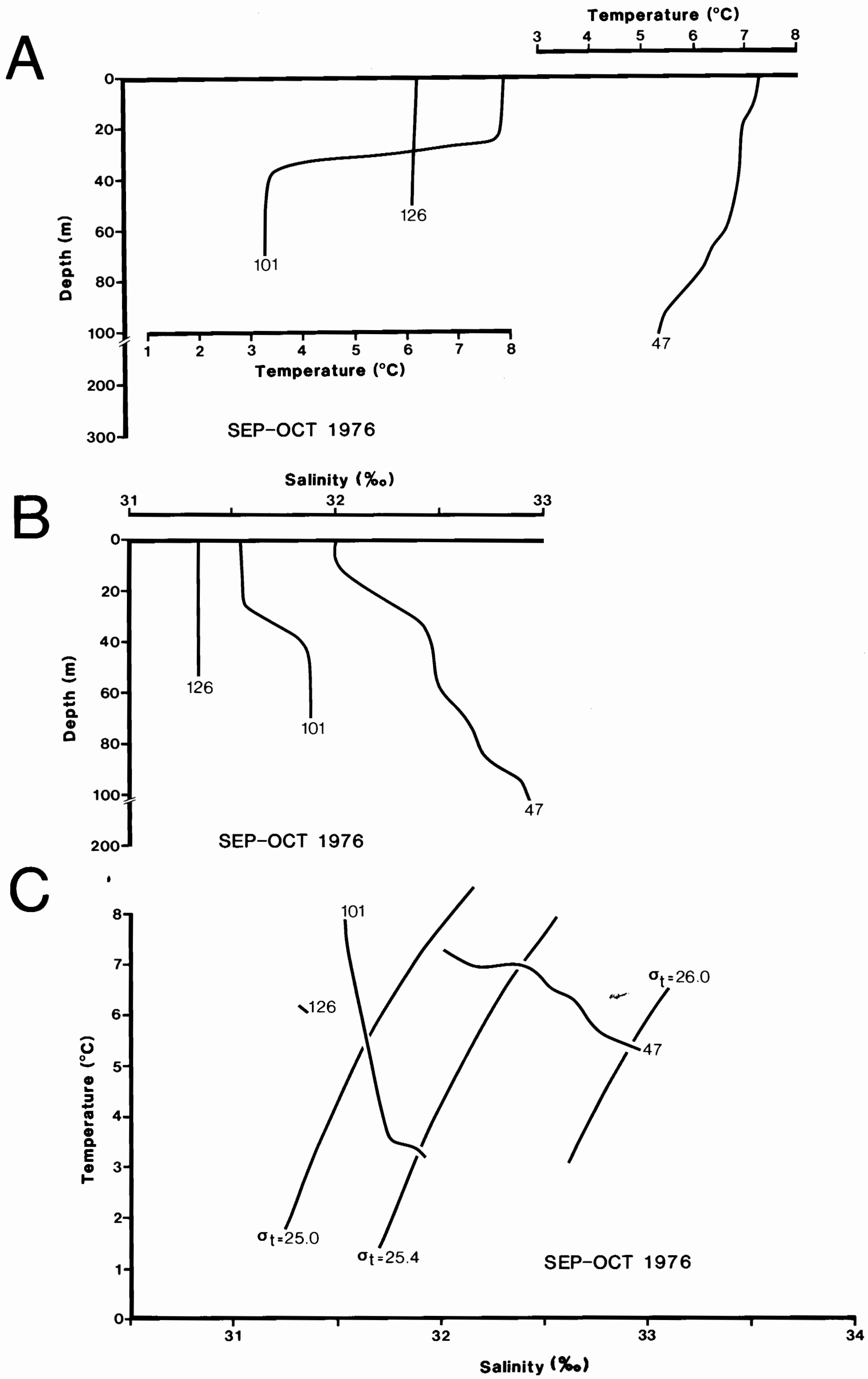

Figure 4-2. Typical stations from autumn 1976 illustrating the three domains. Coastal (homogeneous), station 126; middle (two-layered), station 101 ; outer (stratified interior), station 47 (see Table 4-2 for domain characteristics). (A) Temperature (°C). (B) Salinity (°/oo). (C) Temperature-salinity (°C, °/oo). Station locations are shown in Fig. 4-1.

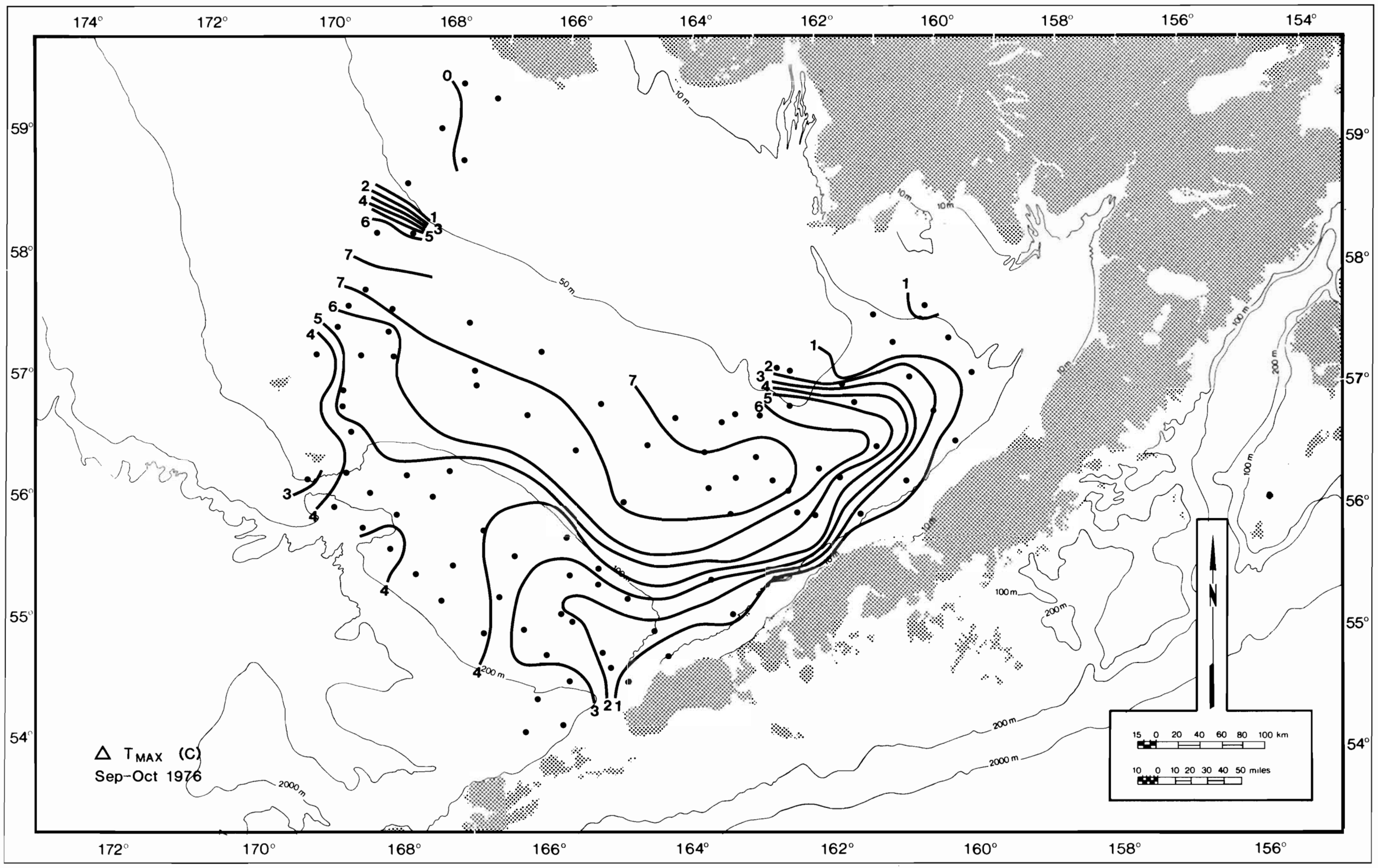

Figure 4-3. Maximum vertical temperature difference, surface minus deep (° C). The largest differences are in the middle domain, and the smallest in the coastal domain (cf. Fig. 4-1).

intermediate values near 4 C were found. A plot of bottom temperature in autumn 1976 (Fig. 4-4) illustrates the strong insulating effect on the stratification displayed in Fig. 4-3. Even in September, cold temperatures (<0 C) remained from the preceding winter, isolated by the very strong two-layered stratification in the middle domain. In contrast, the coastal domain was well mixed and bottom temperatures exceeded 9 C. In the deeper water of the outer domain bottom temperatures were intermediate, generally 3-6 C. Obviously, stratification is important to an understanding of the shelf.

Using stratification as an adjunct to water mass analysis is valuable, but Coachman and Charnell (1979) also used the traditional method successfully. They defined a shelf water mass found in the middle domain, and an oceanic ("Alaska Stream/Bering Sea") water mass found above the continental slope (Fig. 4-5). They were then able to explain much of the structure of the outer domain in terms of the lateral mixing along isopycnal surfaces between the shelf and oceanic water masses. The shelf water mass was always less saline and, below 30 m, colder than the adjacent oceanic water. In spite of annual and interannual variations, there exist throughout the year two water masses, one cold and fresh and the other warm and saline, in juxtaposition along the outer shelf. One important evidence of the interaction of these water masses, finestructure in vertical profiles, is discussed below in a separate section.

A combination of categorizing by vertical structure and by traditional water mass techniques is more useful than either used separately. For examining the shelf alone, structural categories are most distinct, but for understanding interaction with waters overlying the deep basin, water mass analysis is useful. As Coachman and Charnell (1979) implied, these two views are interdependent.

Fronts

The four hydrographic domains (coastal, middle, outer, and oceanic) are separated by three fronts. The front separating the coastal and middle domain is much narrower than the domains themselves, and so is legitimately called a front. The other two transitions are much broader relative to their adjoining

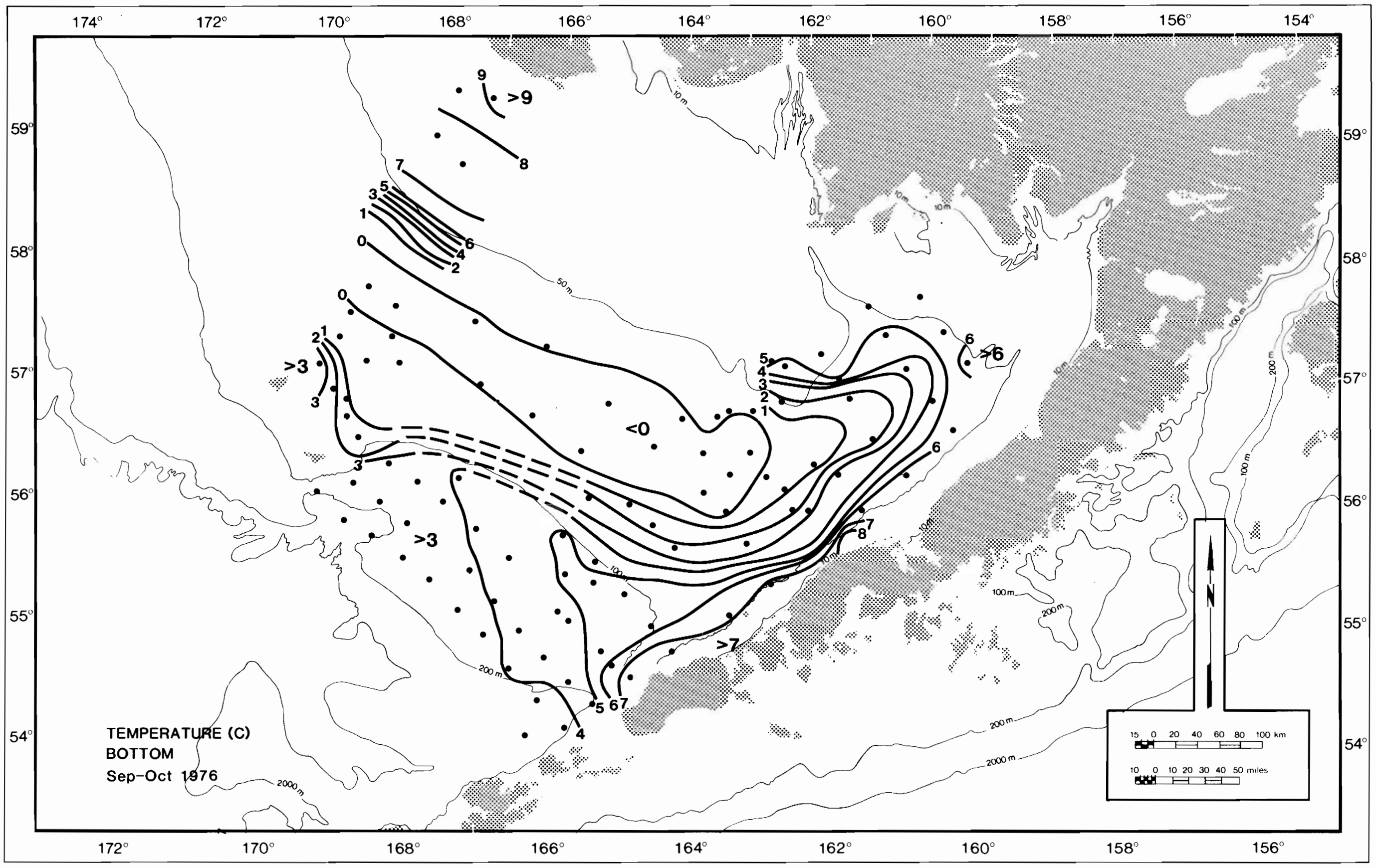

Figure 4-4. Bottom temperature (°C), late September and early October 1976. Even in autumn, low temperatures persist in the bottom layer of the middle domain.

domains, but since they have been called fronts (e.g., by Iverson et al. 1980), we adopt this usage also. Proceeding seaward, we label these fronts as inner, middle, and shelf break (Fig. 4-1).

The inner front separates the homogeneous coastal domain from the two-layered middle domain. It was hinted at by Dodimead et al. (1963), and noted by Muench (1976) farther north. Schumacher et al. (1979) have called it a structural front, to stress the separation of two vertical structures or marked change of stratification rather than the separation of two water masses. The front is about 10 km wide and generally follows the 50 m isobath (Fig. 4-1). Approaching shallower water from the middle domain, isotherms, isohalines, and isopycnals all spread from the thin thermocline, halocline, and pycnocline over the middle shelf (Fig. 4-6). Within 10 km the vertical hydrographic structure changes from distinctly two-layered to nearly homogeneous. Away from the front, within the strongly stratified middle domain, the thickness of the bottom mixed layer (as judged by nearly isothermal and isohaline profiles) is nearly 50 m, about the same as the total water depth where the front is found. In general, we find that over the middle shelf the bottom mixed layer is ~50 m thick, the surface mixed layer is 15-20 m thick, and the front occurs where the water depth approximately equals the thickness of the bottom mixed layer (i.e., 50 m); the strongest stratification occurs where the sum of the bottom and surface mixed layer thickness equals the water depth (i.e., 20 m + 50 m = 70 m).

During winter, the middle and coastal domains are nearly vertically homogeneous following surface cooling, freezing, and vigorous wind stirring in fall and winter (but see our section on winter structure for an important exception). Frontogenesis occurs with the addition of meltwater during the ice breakup in spring. As this initial stratification forms, it is reinforced by insolation, so that later in summer thermal stratification is primarily responsible for vertical density differences. Schumacher et al. (1979), Kinder (1977), and Kinder et al. (1978) reported details of this front, and Simpson and

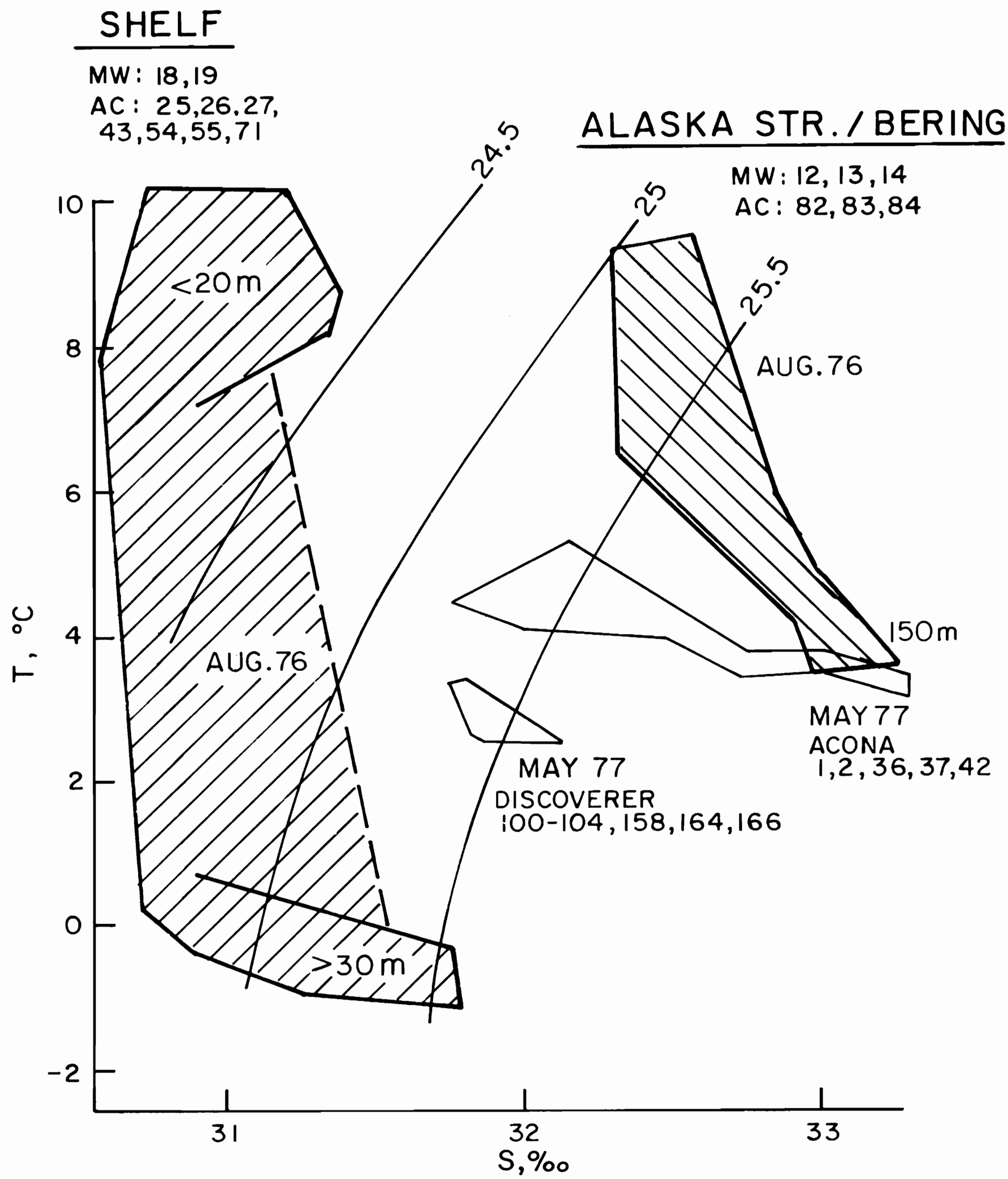

Figure 4-5. Temperature-salinity correlations, middle domain (SHELF) and oceanic domain (ALASKA STR./BERING). Envelopes drawn from data gathered in August 1976 and May 1977 illustrate the warmer and saltier oceanic water at the same density as the cooler and fresher shelf water, and interleaving occurs across the outer domain. (From Coachman and Charnell 1979.)

Pingree (1978) summarized features of similar fronts over the European continental shelf.

The shelf break and middle fronts are less clearly describable. Overlying the continental slope, the shelf break front separates the oceanic domain from the outer domain, but the width of this front is similar to that of the outer domain. Similarly, the middle front which divides the middle and outer domains near the 100 m isobath (Fig. 4-1) is broad and ill-defined compared to the inner front. Nevertheless, the shelf break and middle fronts are both real and important components of the hydrographic structure.

Kinder and Coachman (1978) described the shelf break front and recognized its essentially haline character. The front is revealed by a change in the horizontal salinity gradient (from nearly zero over the deep basin to about 4×10^{-3} g/kg/km over the outer

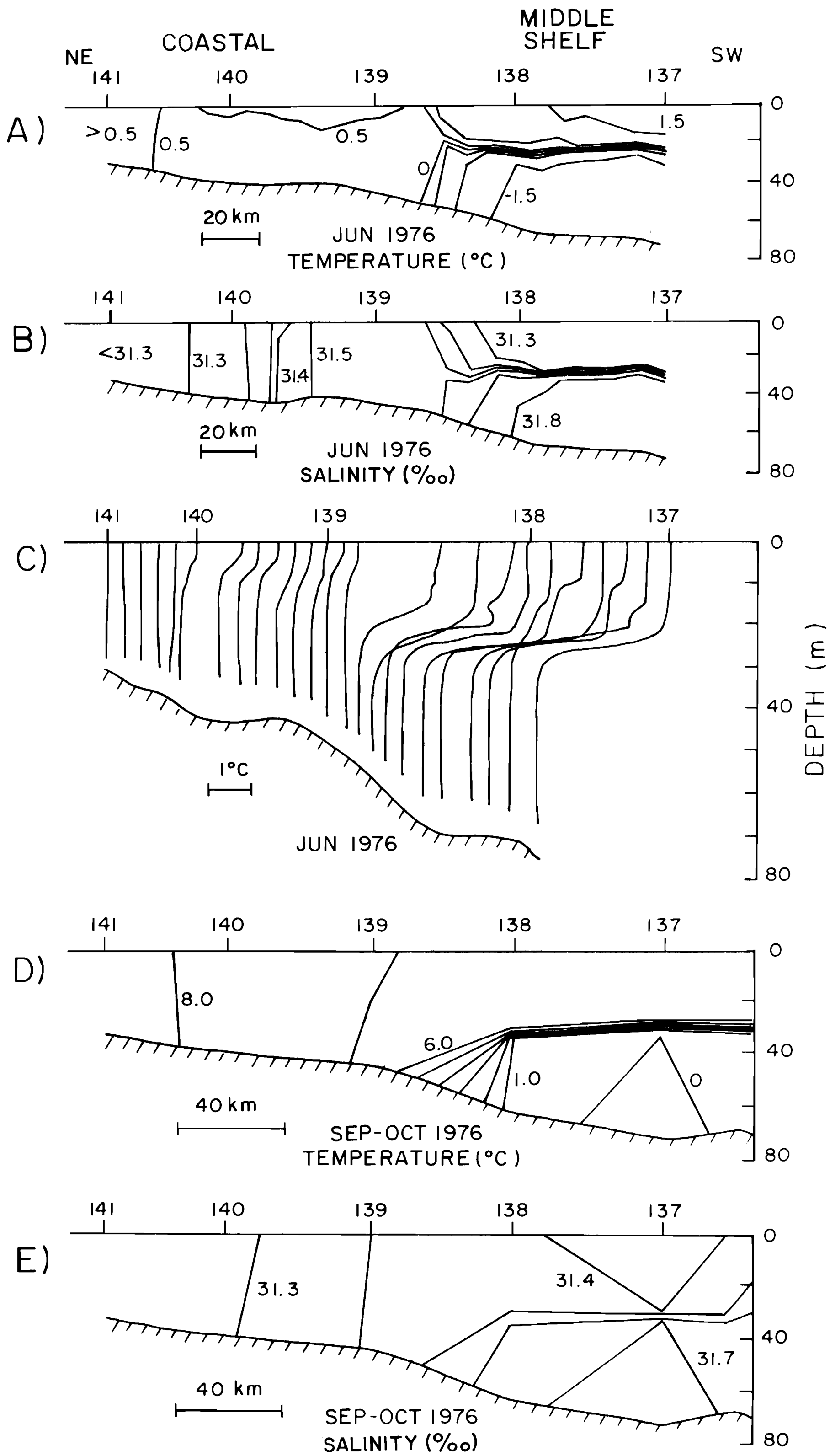

Figure 4-6. The structural (inner) front separating the coastal and middle domains. This line was between Nunivak Island and the Pribilof Islands. (A, B) Temperature and salinity cross sections, and (C) sequential temperature profiles from June 1976. The sections are based on stations separated by about 10 km. (D, E) The same section based on widely spaced CTD stations in autumn 1976. (From Schumacher et al. 1979.)

shelf), by isopycnals extending from the shelf to intersect the sea surface above the slope, and by isolines downwarped beneath the front. Available winter data show that this front persists throughout the year.

Coachman and Charnell (1979) and Coachman (1978) examined this region in more detail, and described this transition zone as two broad fronts, one over the slope and one farther inshore near the 100 m isobath. Between these two transitions, each of which has a large horizontal salinity gradient ($\sim 10 \times 10^{-3}$ g/kg/km), is a region of very small gradient (Fig. 4-7). The transition near the shelf break corresponds to the front described by Kinder and Coachman (1978), while the inner transition corresponds to the middle front separating the middle and outer domains (Fig. 4-1).

At different times when examined by different distributions, these broad transitions do appear truly frontal. For instance Coachman and Charnell (1979) showed a mean cross-shelf temperature section for August 1976 that clearly showed a thermal front near the 100 m isobath, and Coachman (1978) showed strong evidence of a front delineated by particulate and chlorophyll *a* concentrations in April 1978. Over the slope Kinder and Coachman (1978) showed a shallow weak-density front in an August 1972 section, and we show a weak-salinity front from February 1978 (Fig. 4-9). Kinder and Coachman (1978) also showed large dissolved phosphate and nitrate gradients across the shelf break front in July 1974. Both the middle and shelf break fronts generally appear broad and therefore weak, but occasionally they are manifest as sharp fronts in various properties. The shelf break front, however, can always be detected as a weak front in salinity.

Finestructure and density inversions

Finestructure, the layering of vertical profiles on scales from 1 to 25 m (Fig. 4-8), is a salient feature of the outer domain (Table 4-2). The distribution of the finestructure and the mixing physics associated with it are clues to understanding cross-shelf fluxes.

Horizontal distributions of the occurrence of finestructure over the shelf showed that it was common between the shelf break and the 100 m isobath, and occurred elsewhere only rarely. During

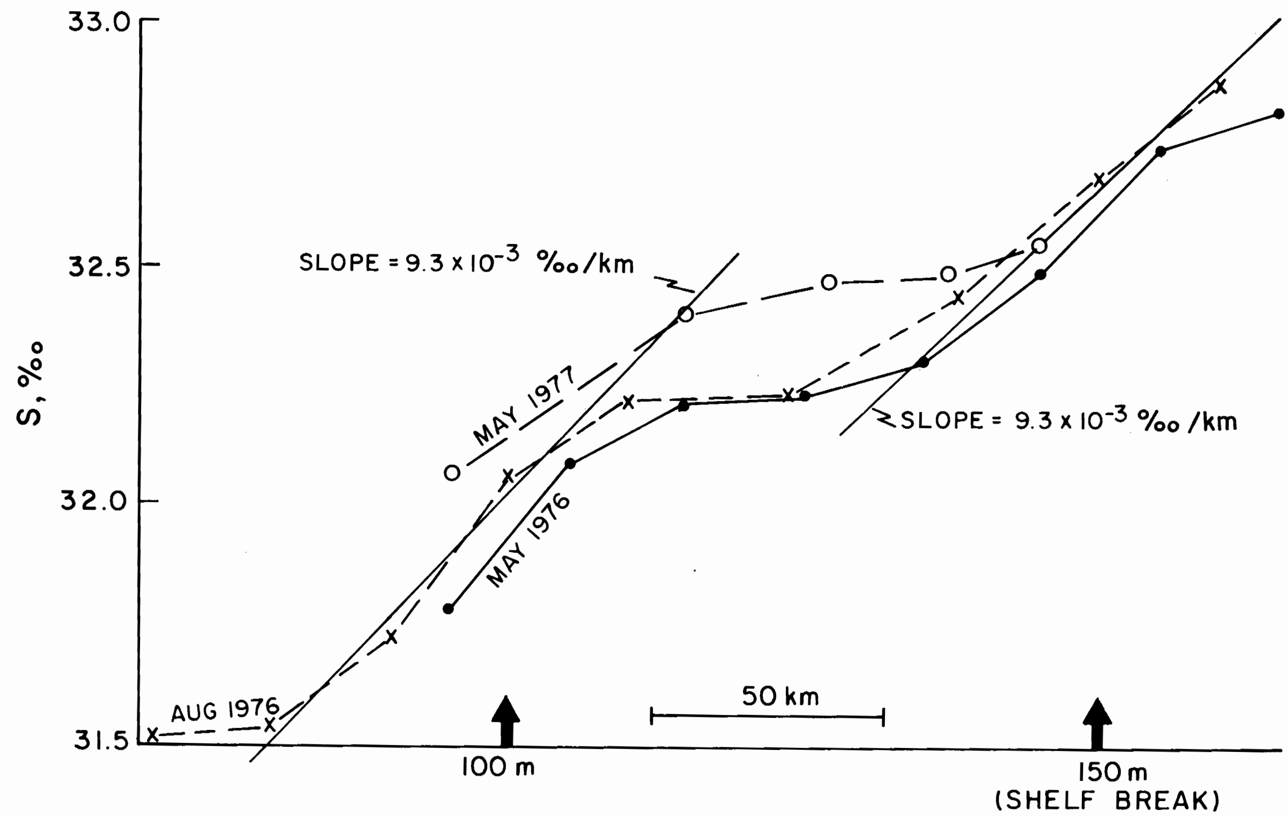

Figure 4-7. Vertically (0-100 m) and horizontally (along-isobath) averaged sections across the shelf from May 1976, August 1976, and May 1977. Transitions in the salinity gradient mark the 100 m isobath (middle-outer domains; middle front) and the shelf break (outer-oceanic domains; shelf break front). (From Coachman and Charnell 1979.)

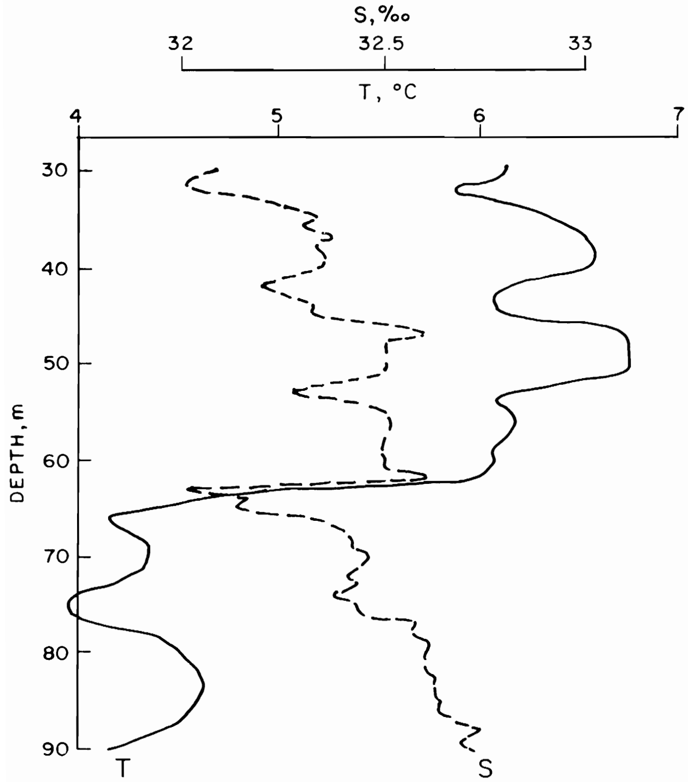

Figure 4-8. A superb example of temperature and salinity finestructure in August 1976. Finestructure, although often less pronounced than this, was present at most outer domain stations. (From Coachman and Charnell 1979.)

1976, a year when the shelf was surveyed extensively, finestructure in the outer domain was reported in March (Coachman and Charnell 1977), in June (Kinder 1977), in August (Coachman and Charnell 1979), and in September-October (Kinder et al. 1978). Only a few stations with finestructure were reported outside the outer domain (e.g., Kinder 1977, Fig. 22), and data from 1977 and 1978 also conform to these distributions. As Coachman and Charnell (1979) discussed, the finestructure occurs in the interior of the water column, below the surface mixed layer and above the bottom mixed layer.

Within this interior region, warmer and saltier oceanic water intrudes shoreward while cooler and fresher shelf water intrudes seaward. As interpreted by Coachman and Charnell (1977, 1979), the outer domain is a region of lateral (i.e., cross-flow, and here also cross-isobath) water mass interaction with interleaving of water masses occurring at finestructure scales. Such interleaving, when water masses of similar density but differing temperature and salinity values mutually intrude, has been observed in many other locations (e.g., see *J. Geophys. Res.* 83(C6) 1978). Occurrence of finestructure throughout the outer domain, best documented in 1976 (a year with extensive ice cover and late ice breakup) but also observed in 1977 and 1978, implies that finestructure is an inherent part of mixing across the outer domain. An essential stage in mixing large masses of water is the reduction of the spatial scale of identifiable water parcels, until a scale is eventually reached at which molecular diffusion is effective. As the spatial scales decrease, spatial gradients increase, as does the surface area of the boundary, and so mixing progresses. Interleaving on finestructure scales is the initial scale reduction. While finestructure features are only a few meters in vertical extent, they apparently extend horizontally for tens of kilometers. In both March and August 1976, Coachman and Charnell (1977, 1979) traced temperature-salinity correlations within layers for distances of about 100 km.

One startling result of Coachman and Charnell's work was the discovery of a static instability in a layer about 10 m thick in March 1976 and many smaller-scale instabilities of a few meters' thickness in summer. The larger instability was clearly resolved by the instrumentation used (standard CTD vertical profiling system), and had an apparent lifetime of about one week. They speculated that it was formed by interaction between strong winds and the seasonal ice cover. The smaller instabilities were poorly resolved by the standard CTD profilers used, but Postmentier and Houghton (1978) measured nearly identical features over the oceanographically similar slope region south of New England using a higher-resolution profiler. Both Coachman and Charnell (1979) and Postmentier and Houghton (1978) invoked differential diffusion of temperature and salt to explain the smaller instabilities. Because heat diffuses more rapidly than salt at molecular scales (it is easier to transfer energy than mass), adjacent layers of water can become convectively unstable on small scales, either through salt fingers (warm and saline water overlying cool and fresh water) or through double diffusion (cool and fresh water above warm and saline water). In the outer domain, the conditions for salt fingers exist at the lower interface of shoreward-intruding basin water, while the conditions for double diffusion exist at the upper interface.

Winter structure

The discussion of hydrographic domains and fronts mostly reflects summer conditions, but winter conditions are more interesting than might be expected. In winter, waters above most of the shelf usually are vertically homogeneous, with two exceptions. In the outer domain warmer (but more saline and therefore denser) water from the oceanic domain intrudes beneath cooler and fresher shelf water, thus maintaining stratification. Elsewhere, low-salinity water from melting ice may stratify water that was well mixed during autumn and winter (by wind stirring and surface cooling).

A cross section taken from southeast of the Pribilofs toward Cape Newenham in February 1978 (Fig. 4-9) illustrated intrusion of the basin water. Between the shelf break and the 100 m isobath (i.e., outer domain) water warmer than 3.5 C and saltier than 32.5‰ intruded beneath shelf water which was both colder and fresher. Inshore of the 100 m isobath the water column was well mixed, colder (<2.5 C) and fresher (<32.25‰). Data from several stations with similar profiles, saltier and warmer near the bottom, were also taken near the Pribilof Islands during April and May 1978, and Coachman and Charnell (1977) showed data with this character taken in March 1976. There is sufficient coverage of the outer domain during late winter and early spring to suggest that cold and fresh shelf water overlies warmer and more saline basin water, and that this domain remains stratified during winter.

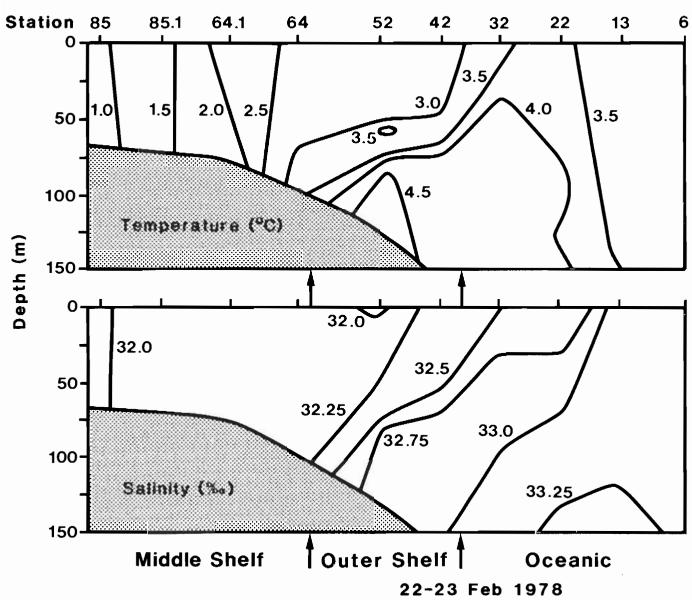

Figure 4-9. Temperature (°C) and salinity (‰) across the shelf in February 1978. This section is from southeast of the Pribilofs toward Cape Newenham. In the outer domain the deeper water is warmer, but more saline and therefore denser, than the shallower water.

Melting ice in the middle shelf can also cause stratification during the winter, but inshore within the coastal domain mechanical stirring keeps the water column well mixed. In February 1978 we observed (by satellite imagery, see Fig. 5-11, Chapter 5) that ice near Nunivak Island moved about 100 km southeast, into an area previously free of ice. About ten days later we measured hydrographic properties near this ice, which was melting. Away from the ice (~20 km), sea surface temperatures were near 0 C, and temperature profiles were vertically homogeneous (Fig. 4-10). Within the ice (where water depths exceeded 50 m), however, the water column was stratified in two layers. In the shallow layer temperatures were near freezing (~−1.73 C) and the salinity was lower than in the homogeneous water.

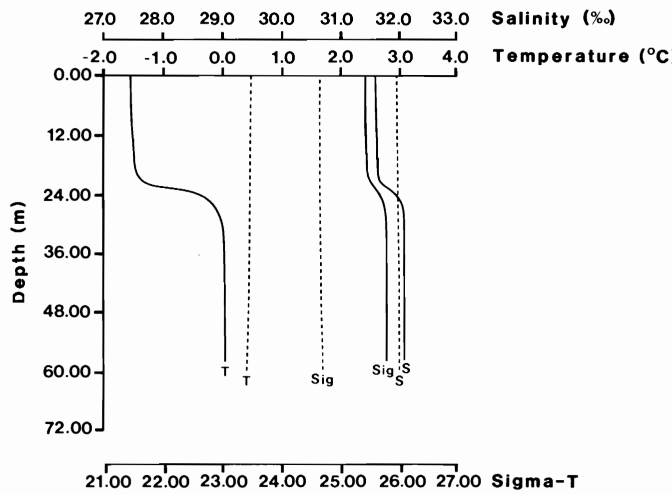

Figure 4-10. Temperature (°C), salinity (‰), and density (kg/m^3) profiles near the ice edge in February 1978. Dashed profiles were typical away (>20 km) from the ice or where water depth was less than about 50 m. Solid profiles were typical near the ice where water depth exceeded 50 m.

Below the weak pycnocline, salinity and temperature were similar to values away from the ice. The decrease of temperature and salinity probably resulted from ice melting, about 30 cm of ice for Fig. 4-10. The transition between two-layered and homogeneous conditions occurred near the 50 m isobath, as in summer. Inshore of the 50 m isobath, the water column was homogeneous with or without ice.

We do not know how persistent this winter stratification is, but we suspect that the weak stratification found in water deeper than 50 m was fragile, dependent in part on the continued presence of ice. Once the upper layer cools to the freezing point, ice stops melting. As stirring erodes the pycnocline, however, heat remaining in the bottom layer is mixed upward, presumably melting ice and adding light meltwater. The continued presence of ice above a stratified water column in winter apparently favors continued stratification, suppressing wind stirring, limiting surface heat loss, and maintaining a reservoir of potential meltwater. The question of whether ice cover generally affects the hydrographic structure over the middle shelf in winter and to what extent this structure in turn influences the resulting stratification during the ice-free season remains unanswered, but the ice may be important through the following summer. It is clear that the eventual melting of ice in spring is important in stratifying the middle shelf domain (Schumacher et al. 1979).

River plumes

The local effects of river discharge have received little attention because most oceanographic data have been collected away from the coast. Satellite images and sparse hydrographic data suggest that river plumes (defined, say, by salinity lower than 25^o/oo) remain near shore, flowing anticlockwise around Bristol Bay, and leaving the southeastern shelf to the north (much of this water may flow through Etolin Strait, inshore of Nunivak Island). Large discharges of fresh water can stratify the water column in the coastal domain, and may form fronts (see Garvine and Monk 1974 for a description of the frontal plume of the Connecticut River in Long Island Sound).

Straty (1977) reported observations made in Bristol Bay during 1966. He traced the anticlockwise nearshore flow of river water around Bristol Bay using dye, drift cards, and salinity measurements. He reported no fronts associated with the Naknek, Kvichak, Egegik, and Ugashik rivers, probably because of vigorous tidal stirring in the shallow (less than 20 m) bay. Conditions may be similar in Kuskokwim Bay farther west, but we have no data there. The direct effects of the river discharges appear to remain within a few tens of kilometers of the coast, providing an inshore boundary of the coastal domain.

PROCESSES THAT AFFECT THE HYDROGRAPHIC STRUCTURE

Many processes can form, alter, or erase features of the hydrographic structure. We have grouped such processes into three somewhat arbitrary categories. First we discuss the addition of heat and salt and their transport across the shelf, processes which directly transform water masses. Next we focus on the interplay of mechanical stirring and buoyancy addition. These processes determine the stratification, a key element of the structure and a strong influence on the transport. Finally, we speculate on the possibility of upwelling, which may affect the hydrographic distributions in Bristol Bay.

Heat and salt transport

Transformations of water masses on this shelf occur locally through the addition of heat and salt. Because of cooling and heating at the surface, evaporation and precipitation, and freezing and melting, relatively large fluxes of heat and salt occur at the sea surface. To a lesser extent horizontal mixing and river runoff at lateral boundaries influence temperature and salinity. Because of the low mean flow on the shelf, and because of the shelf's great width, water mass properties are more likely to result from local phenomena (e.g., insolation and melting) than from advection. Great changes occur annually in the flux of heat and salt at shelf boundaries, so that water masses vary annually also.

In the middle and coastal domains the change in heat content of the water is primarily balanced by heat transfer through the sea surface; horizontal advection and horizontal turbulent diffusion are much smaller. Reed (1978) calculated a heat budget for an area (1° lat. × 2° long.) of the middle domain for summer 1976. The local rate of heat change was balanced over the summer by net surface exchange within 10 percent (excellent agreement for such budgets). During the summer, most of this surface exchange was radiative, but by early fall evaporation was important. Over the fall, winter, and early spring, the terms incorporating phase changes (evaporation, freezing, and melting) share importance with radiation terms. The net surface exchange retains its importance, however: Coachman and Charnell (1979) found a high correlation ($r = -0.96$, $n = 12$) between mean lower-layer temperatures in June over the middle shelf and degree-days of frost for the preceding winters. Reed's (1978) results can probably be extrapolated into the coastal domain also. Although the vertical heat distribution differs there (Fig. 4-2), the horizontal terms and surface exchanges are probably similar.

In the outer domain, however, horizontal terms apparently are more significant. Since mean flow is 2-10 cm/sec, advection cannot be ignored, and lateral exchange, as evidenced by finestructure, may be even more important. The strong annual cycle which Coachman and Charnell (1979) showed for this region—approximately the seaward half of the shelf waters and those over the slope—was caused by surface exchange. Below the surface mixed layer, however, they showed large-amplitude finestructure (Coachman and Charnell 1977, 1979), with warmer shoreward intrusions originating in the oceanic domain and colder seaward intrusions originating over the shelf (Fig. 4-8). These lateral interleavings are strong evidence of lateral exchanges of heat and salt, with the shelf water (colder and fresher) gaining heat and salt.

Various attempts have been made to estimate the horizontal heat flux in terms of a bulk heat conductivity such that the turbulent horizontal heat flux is given by:

$$\rho C_p \; K_h \; \frac{\partial T}{\partial X} \qquad (J \; m^{-2}/sec)$$

ρ = density of water (kg/m³),

C_p = heat capacity (J/kg/°C),

$\frac{\partial T}{\partial X}$ = horizontal temperature gradient (°C/m),

and

K_h = horizontal conductivity ($m^2/sec = 10^4 \; cm^2/sec$).

This is sometimes a poor approximation of the physical processes (which are hidden within K_h), and K_h is often not constant. Nevertheless, such estimates remain useful for modeling and estimating cross-shelf fluxes. Kinder et al. (1978) calculated a heat balance for the lower layer of the middle shelf over summer 1976 and estimated $K_h \sim 1.7 \times 10^6$ cm^2/sec ($=1.7 \times 10^2 \; m^2/sec$). They similarly estimated vertical conductivities in the middle shelf, and values ranged from 7×10^{-3} cm^2/sec to 5×10^{-1} cm^2/sec. Because of the strong stratification, the lowest values approached molecular diffusion ($\sim 1.4 \times 10^{-3}$ cm^2/sec). These estimates by Kinder et al. (1978) were probably maxima, since they assumed that all local change had been caused by one-dimensional diffusion, either vertical or horizontal. Coachman and Charnell (1979), applying a model proposed by Joyce (1977), estimated 2.8×10^6 cm^2/sec and 1×10^6 cm^2/sec for the middle and shelf break fronts and 20×10^6 cm^2/sec for the outer domain between fronts.

Kinder and Coachman (1978) calculated a salt budget for the entire shelf. Since fresh water is added annually at the coast by river runoff, and because precipitation exceeds evaporation over the Bering Sea, there must be a flux of salt shoreward to maintain the long-term mean salinity distribution. For the shelf as a whole, the largest term (>99 percent of salt flux) is advection: relatively saline water from the oceanic domain flows onto the western shelf to supply the Bering Strait outflow ($\sim 1.0 \times 10^6$ m^3/sec). Over the southeastern shelf, however, the salt balance is not advective (because of low mean flow). Kinder and Coachman (1978) estimated a diffusivity of 3×10^6 cm^2/sec for the cross-shelf salt flux. Calculating diffusivity for the middle domain over summer 1976, Kinder et al. (1978) obtained 1.1×10^6 cm^2/sec, using the same method as for thermal conductivity (the salt diffusion equation was analogous to that of heat).

Kinder and Coachman (1978) suggested that the cross-shelf salt flux was driven by the tides, as a "tidal diffusion," because most (~90 percent) of the kinetic energy over the shelf is tidal (Chapter 5, this volume). The tidal current, if appropriately correlated with salinity variations over the tidal cycle, could cause a significant flux of salt across the shelf. Coachman and Charnell (1979) showed, however, that in the outer domain lateral interleaving on vertical fine-structure scales is ubiquitous and represents cross-shelf mixing. Tidal diffusion still remains tenable for the middle and coastal domains, and the tides do contribute most of the turbulent energy (via the bottom frictional layer and velocity shear) within the outer domain.

Kinder et al. (1978) also reported another means of salt flux—ice transport. During the ice-covered part of the year, satellite imagery often shows open water south of east-west zonal coasts: south of St. Lawrence Island, south of Nunivak Island, and northern Kuskokwim Bay are typical examples (see Muench and Ahlnäs 1976 and chapters by McNutt and Pease, this volume). During the spring of 1976 (Kinder 1977) and to a lesser extent in 1977, water with elevated salinities (>32.5°/oo in June 1976) was found in Kuskokwim Bay. Our explanation is that ice freezing in Kuskokwim Bay is blown seaward, leaving behind the brine that drains during freezing. We do not know accurately the amount of ice exported from the coastal domain annually in this way, nor do we know the salinity of the exported ice. Kinder et al. (1978) estimated that this divergence of ice transport may account for a mean salt flux of 6 t/sec (1 t = 10^6 g) shoreward from the middle to the coastal domains. This is about 10 percent of the mean salt flux (50 t/sec) estimated by Kinder and Coachman (1978) for the southeastern shelf. As Coachman (1979) pointed out, this mechanism may be generally important at high latitudes; hypersaline water relict from the previous winter has been found not only in Kuskokwim Bay, but recently in Norton Sound (Chapter 6, this volume), Kotzebue Sound (Kinder et al. 1977), and lagoons adjoining the Beaufort Sea (Wiseman 1979). Since this mechanism causes a net freshening of the middle domain, it may partly explain the correlation that Coachman and Charnell (1979) reported between yearly mean temperatures and yearly mean salinities over the middle shelf: both cooling of the middle shelf waters and the export of ice from the coastal to the middle shelf domains may be causally related to severe (cold and windy) winters, when southward outbreaks of cold and dry continental air cause more ice formation (see Overland, Chapter 2, this volume).

Stirring and buoyancy addition

A water column is stably stratified if the density increases towards the bottom. During spring and summer, this stable water column usually prevails because lighter, more buoyant fluid is added at the surface (ice melting, precipitation, or freshwater runoff) or because the surface waters become less dense as a result of warming (insolation). Alternatively, the addition of dense water at the bottom (intrusion of oceanic-regime water onto the shelf) makes the surface waters more buoyant than the bottom waters (Fig. 4-9). Processes that tend to stratify the water column stably by decreasing the density of the near-surface, we call positive buoyancy additions. If dense water is added at the surface (brine drainage during freezing) or if the surface waters are made denser (radiative cooling or evaporation), then the water column becomes less stratified or less stable. If water becomes denser than that below it, then the water column is unstable and vertical mixing (overturn) occurs. We call processes that destabilize the water column negative buoyancy additions. By buoyancy addition we mean any change in water properties that alters the mean density of the water column (as distinguished from mechanical stirring that redistributes the density).

Mechanical stirring is an important process tending to mix the water column. Over this shelf, the main source of stirring is the tidal currents and a secondary source is the wind (Schumacher et al. 1979, Simpson and Pingree 1978). Most tidal stirring power (turbulence) is generated near the bottom, most wind stirring power (turbulence) at the surface. Thus, we attribute the surface mixed layer to wind stirring, and the bottom mixed layer to tidal stirring. Station 101 in Fig. 4-2 illustrates these two layers in which mechanical stirring is sufficient to keep temperature and salinity homogeneous over layers of 20 m or more thickness. At Station 126, stirring had overcome any stabilizing effects of positive buoyancy addition, and the entire (50 m) water column was well mixed (neutrally stable).

Another way of viewing these two tendencies is to consider the potential energy of two water columns. Consider the first, like Station 101, to consist of two layers, while the second, like Station 126, is completely mixed. If both columns have the same vertically averaged temperature, salinity, and thus density (assuming a linear equation of state), then all points from both stations fall on the same straight line on the TS plane; it is the vertical structure that differentiates between the two distributions. It requires mechanical work to mix the two-layered water column so that it looks like the homogeneous water column, because the center of mass of the well-mixed water column is higher than in the two-layer column. Over the Bering Sea shelf the primary source of this mixing energy is the tides.

When the cross section across the inner front was made in 1976 (Fig. 4-6) we found two water columns like those just described. The homogeneous water column on the coastal domain side of the front could have been made by completely mixing the water column on the middle domain side of the front. On the shoreward side of the front, the tidal stirring was just competent to overcome the buoyancy addition from melting ice and insolation; thus fresh water and heat were mixed throughout the water column. On the seaward side of the front, however, stirring was inadequate. A wind-stirred surface layer and a tidally stirred bottom layer met at a sharp pycnocline.

This interplay of buoyancy addition and stirring has some positive feedback. Stratification suppresses vertical mixing so that mixing is impeded after stratification forms, and as further buoyancy is added stratification increases. This added stratification further suppresses mixing, and so forth. This feedback helps explain why the transition between the coastal and middle domains is so sharp: stratification enhances stratification, and well-mixed structure likewise tends to persist. Over the middle shelf the surface mixed layer and the bottom mixed layers meet, making the vertical structure distinctly two-layered. The middle front, separating the middle and outer domains, marks the limit of the ability of the two homogeneous layers to encompass the entire water column. Seaward of this front, in the outer domain, an interior region exists between the two mixed layers. Finestructure exists only in this interior; elsewhere it would be vertically mixed by stirring. Table 4-3 emphasizes the roles of stirring and buoyancy addition in forming the hydrographic domains.

We can get a feeling for the reason why the domains are closely tied to the isobaths (50 m, 100 m, shelf break) by following the formalism of Simpson and Hunter (1974), who examined a front like our inner front near the British Isles. They compared the rates of addition of potential energy by insolation and by stirring.

For a two-layered water column, potential energy (V) addition rate is approximately:

$$\frac{dV}{dt} = \frac{\alpha Q g h}{2C\rho} \qquad (\text{J m}^{-2}/\text{sec}) \qquad (\text{J = Joule})$$

- α: a thermal expansion coefficient ($\text{kg}^\circ\text{C}^{-1}\,\text{m}^{-3}$)
- Q: insolation ($\text{J m}^{-2}/\text{sec}$)
- g: acceleration of gravity (m/sec^2)
- h: water depth (m)
- C: specific heat (J/kg/°C)
- ρ: density (kg/m^3)

The major annual change is in the insolation term (Q); other buoyancy terms (e.g., melting ice) could be added easily.

The turbulent energy available for stirring is simply:

$$\frac{dE}{dt} = k\,\rho\,U^3 \qquad (\text{J m}^{-2}/\text{sec})$$

where: k = drag coefficient, ρ = density (kg/m^3), and U^3 = mean of cubed speed (m^3/sec^3).

Most of this power (note that 1 J/sec = 1 watt) does not mix the water, but the relative amount (1 percent or so) that does go into mixing seems constant for a given flow regime (e.g., near the inner front).

We can see that the buoyancy addition term has small changes across the shelf in all of its terms but h, while in the stirring term U^3 changes across the shelf. The tidal current, U, is also a function of depth (h) and position on the shelf (Pearson et al., Chapter 8, this volume), so that both buoyancy addition and stirring are dependent on location. Although neither buoyancy addition nor stirring changes very rapidly at a given location, the tidal currents vary significantly over two-week cycles (fortnightly tide), winds vary, and buoyancy input changes diurnally and annually; but an important variation across the shelf can be seen by taking the ratio of dE/dt and dV/dt. The result is a constant times U^3/h; across the shelf, from the outer to the coastal domain, this changing ratio reflects the changing balance between buoyancy and stirring. Nearshore, since U^3 is large and h small, stirring prevails. Farther offshore, because U^3 decreases and h increases, stratification (given sufficient Q or other buoyancy source) prevails. We even found that this held in February 1978 when we took measurements in melting ice: seaward of the 50 m isobath the water column was two-layered, while shoreward of the 50 m isobath the column was well mixed (the 50 m isobath coincides with the inner front during summer). Thus the potential for stratification (expressed by U^3/h), is always present, requiring only sufficient buoyancy addition to be realized.

Our data do not reveal variability in frontal location, either on short time scales such as diurnal

TABLE 4-3

Stirring and buoyancy addition in the hydrographic domains

Coastal domain

Throughout the year tidal and wind stirring produce adequate mixing power to overcome normal sources of buoyancy: insolation, melting ice, and river runoff. Exceptions to this are probably short lived, except in river plumes within 10-20 km of the coast. (Water depth < thickness of tidal-mixed layer.)

Middle domain

Tidal and wind stirring are inadequate to mix the entire water column during the high buoyancy-addition season (spring and summer). The vertical structure during that season is two-layered: a wind-stirred surface layer and a tidal-stirred bottom layer separated by a sharp pycnocline. During fall and winter, when buoyancy addition is usually negative, the vertical structure is uniform, but the potential for stratification remains. Melting ice can establish two-layered stratification, even in winter. (Water depth = thickness of tidal-mixed layer + thickness of wind-mixed layer.)

Outer domain

The surface mixed layers and bottom mixed layers do not meet; the pycnocline is weaker than in the middle domain and there is an interior region separating the mixed layers. Finestructure is ubiquitous within this stratified interior region. Even in winter, negative buoyancy and stirring are insufficient to mix the water column completely. More saline water from the oceanic regime makes the deep column denser than the surface waters, even if the surface waters are cooled to the freezing point. (Water depth > thickness of tidal-mixed layer + thickness of wind-mixed layer.)

See also our Table 4-2 and Figure 24 in Coachman and Charnell (1979).

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or fortnightly, or longer scales such as interannual. There is undoubtedly some variation in the location of fronts on many scales, but the inner front is tied closely to its mean position by the variation of U^3/h, and similar considerations probably affect the middle front's position also. Stirring and buoyancy addition form the vertical hydrographic structure within the coastal and middle domains, and modify the structure of the outer domain.

Upwelling

The cold surface patch observed in Bristol Bay during summer has been ascribed to upwelling. Myers (1976) documented the frequent occurrence of cooler surface water in Bristol Bay during spring and summer, and our own data also showed this (Kinder et al. 1978). Myers attributed this to upwelling forced by an Ekman convergence in the bottom boundary layer. This convergence was caused by a mean cyclonic flow that approximately follows the 50 m isobath.

Arguments based on hydrographic evidence from 1969-70 presented by Myers favored upwelling of water originating southwest of the cool surface patch rather than local vertical mixing, but the explanation of this upwelling was incomplete. The mean flow is only about 2 cm/sec, while tidal speeds are about 20 cm/sec (Chapter 5, this volume). Thus, the tidal kinetic energy is 100 times that of the mean flow, and tidal effects may be more important than the mean flow. For the Ekman convergence to work, water must be forced upward against stratification, rather than forced horizontally to the west or southwest (where there is no mean flow). Moreover, Myers hydrographically inferred that the source of upwelled water is southwest of Bristol Bay, but his proposed Ekman convergence requires a source to the east and north. A possible alternative, strong wind during summer, occurs too infrequently to account for this persistent feature. In the open ocean, with upper layers moving faster than lower layers, large (nearly geostrophic) cyclonic features are associated with isopycnals that dome upward; perhaps the mean flow does influence the observed distributions in Bristol Bay. A secondary circulation would then be necessary to maintain the density structure against tidal stirring and mixing. On the other hand, a combination of vertical mixing driven by tidal currents and freshening of inshore waters by river runoff could produce the observed hydrographic distributions. This seems more in harmony with processes over the remainder of the shelf, but is no more proved than the upwelling hypothesis.

In summary, cool surface water appears often in Bristol Bay during spring and summer, and Myers (1976) presented hydrographic evidence that this results from upwelling. Whether this persistent feature actually results from upwelling, from another dynamic response to the flow regime, or from vertical mixing, however, is not known.

DISCUSSION

Cross-shelf fluxes

On the basis of conservation of heat and salt, we have discussed some estimates of cross-shelf fluxes in terms of diffusion coefficients. Knowledge of these fluxes, and of the mechanisms driving them, is important for both conservative and non-conservative material, e.g., larvae, nutrients, plankton, and petroleum. Especially in summer, dispersion characteristics differ in the different domains. Vertical exchanges are severely damped in the strongly stratified middle domain, while complete vertical mixing occurs rapidly in the tidally stirred coastal domain. Dispersion also differs horizontally in the three domains. In the outer domain interleaving on finestructure scales is an important component of mixing processes, but no finestructure is found in the inner two domains. Mixing, although probably driven by the dominant tidal currents in both nearshore domains, differs between the middle and coastal domains. Over the two-layered middle shelf horizontal transport may differ markedly in each layer (e.g., a nearly estuarine two-layer flow), but this is unlikely in the vertically homogeneous coastal domain.

There is also a question of steadiness of these fluxes: how much do they vary and over what time scales? Coachman and Charnell (1979) estimated that the horizontal salt flux in the outer domain was three to four times greater than the fluxes at the shelf break and middle fronts. This implies a divergence (depletion) of salt transport near the shelf break and a convergence (accumulation) near the 100 m isobath—an imbalance which cannot persist over long periods without altering the observed long-term salinity distribution. There is some annual variation in fluxes, as the hydrographic structure, wind stress, and ice cover all change significantly over the year. The variability of these fluxes, and particularly their timing (or phasing) with respect to critical biological events, may be more important than the mean fluxes. As yet, we can only roughly estimate mean values, and we do not understand the processes that drive these fluxes.

Fronts

It is not clear whether the fronts separating the hydrographic domains are convergences or divergences—whether they enhance or inhibit mixing. These boundaries separate distinct hydrographic domains and probably dynamic ones, and they have large gradients in various properties. The methods of transport of passive properties, such as salt and nutrients, and of dynamic properties, such as momentum and vorticity, probably change across these fronts, and these changes are most clearly seen in the vertical hydrographic structure. Intuition suggests that fronts are convergences (James 1978), and that cross-frontal exchanges are impeded (e.g., methane distributions shown by Cline, this volume). A convergence throughout the depth and length of the inner front, for instance, seems unlikely; but neither observation nor modeling have answered the questions of convergence and cross-frontal mixing.

There is evidence of year-to-year (Coachman and Charnell 1979) and annual (Schumacher et al. 1979, Kinder and Coachman 1978, Coachman and Charnell 1979) variability of the fronts, and Schumacher et al. (1979) reported wavy features in satellite images of the inner front that imply more rapid variability. The longer-term fluctuations seem related to changes in atmospheric forcing (e.g., insolation, temperature, storms), and the wavy features may be frontal instability (inherent). Further understanding of these changes will probably add knowledge of variations in cross-shelf fluxes.

Role of ice

Ice, with strong annual and interannual variation, influences the hydrography of this shelf in several different ways. These effects are both local and shelf-wide.

Locally, ice affects the energy balance and vertical distributions of heat and salt. Ice cover effectively insulates the water and slows heat transfer (both radiative and conductive-convective), and ice covered with snow has high albedo, reflecting incoming short-wave radiation. Freezing and melting also alter the distribution of heat and salt. Ice acts as a buffer for temperature as changing heat balance alters the amount of ice present at nearly constant temperature. Local freezing and then melting causes a vertical redistribution of salt, so that a water column that has uniform salinity in fall may have haline stratification in spring.

Freezing and melting also influence shelf-wide distributions of heat and salt. Freezing nearshore and melting offshore transport both salt and heat shoreward. Waters offshore are cooled directly not only by the atmosphere, but by melting ice that originally formed nearer shore. Because these processes are forced by weather, changes in the winter weather are manifest in ice cover and therefore in the shelf hydrography.

Ice processes thus affect the shelf hydrographically in two ways: through melting and freezing, ice locally redistributes salt and heat in the water column, changing the vertical stratification; and it directly influences shelf-wide heat and salt budgets by acting as an insulating cover while transporting salt and heat.

SUMMARY

The southeastern shelf has a distinct hydrographic structure. Proceeding seaward from the coast in summer one encounters the vertically homogeneous coastal domain, the inner (structural) front, the two-layered middle domain, the middle front, the outer domain, the shelf break front, and finally the bordering oceanic domain (Fig. 4-11). These features can best be understood by considering these simplifications:

1. In the middle and coastal domains mean advection is negligible.

2. Water mass transformations occur locally, primarily through heat and salt transfer at the surface.

3. Vertical profiles are determined by the interplay of buoyancy addition and mechanical stirring, and in the outer domain also by lateral interleaving between shelf and oceanic waters.

4. Rates of buoyancy addition change annually, while stirring (primarily tidal) remains nearly constant with time and increases shoreward.

During winter, the separation into these domains is less clear, and the addition of negative buoyancy and stronger wind stirring move the boundary of vertical homogeneity seaward through the middle shelf. Even during this season, however, the potential for stratification like that in summer remains, and melting ice can provide sufficient buoyancy to stratify waters in the middle domain.

The hydrographic structure influences mixing, and the system of domains and fronts affects many distributions: e.g., salt, heat, momentum, vorticity, sediment, benthos, plankton, nutrients, fish, and pollutants. With few exceptions, we do not understand these effects, and in many cases we do not even know what the effects are. As we have suggested, some effects of salinity and temperature distributions and their interactions with the hydrographic structure are straightforward, but many others are not. Future studies of the shelf will have to consider the influence of hydrographic structure on many phenomena.

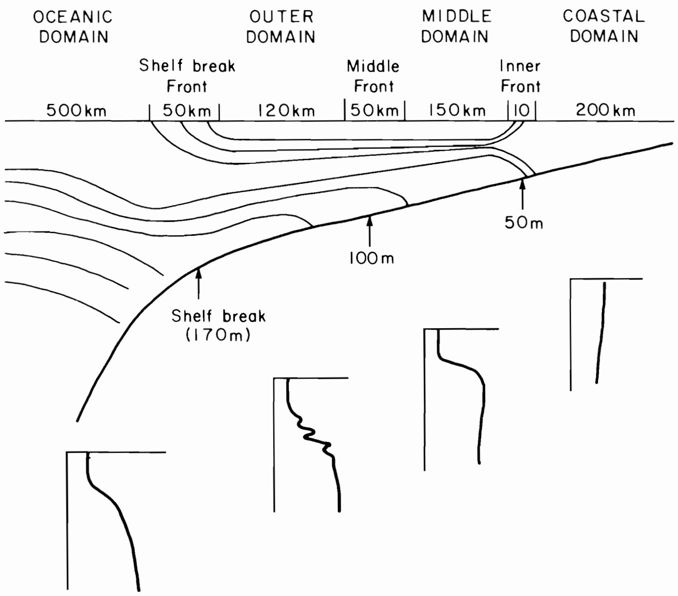

Figure 4-11. A schematic of the cross-shelf density structure illustrating the system of hydrographic domains separated by fronts. This picture represents summer conditions, when the structure is clearest. Vertical profiles are shown beneath each domain. See Tables 4-2 and 4-3 for a tabulation of domain properties.

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Bob Charnell was a coprincipal investigator on this project, and Pat Laird was frequently chief scientist on project cruises. Both were lost at sea off Hawaii in December 1978.

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