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ABSTRACT

The continental shelf of the eastern Bering Sea (EBS) is highly productive, supporting some of the most valuable fin- and shellfish fisheries in the United States as well as large, local and migratory, populations of seabirds and marine mammals. Temperature and hydrographic structure are important components to the pelagic and epibenthic habitat that influence the distribution, behavior and inter-specific interactions of larger commercially and ecologically important species in the EBS. Since 1982, the Alaska Fisheries Science Center has collected depth-temperature data during their annual standardized bottom trawl survey (BTS) of the EBS. We describe the origination and post-survey processing of the data, and the procedures used to calculate statistics describing nominal temperature, mixed and transition layers, and stratification characteristics. We discuss the potential use of this data to identify larger scale domains and fronts and to calculate indices describing overall conditions encountered by the BTS. Changes in BTS timing and duration over the years are important to consider when interpreting any patterns. The statistics and indices resulting from the depth-temperature data provide a means to examine relationships between pelagic habitat characteristics and biological characteristics such as species composition, abundance and feeding habits.

CONTENTS

INTRODUCTION

The continental shelf of the eastern Bering Sea (EBS) is highly productive, supporting some of the most valuable fin- and shellfish fisheries in the United States as well as large, local and migratory, populations of seabirds and marine mammals. This capacity results from a combination of tremendous areal extent (the EBS continental shelf is larger than the state of California), high nutrient supply, long summer day length, and efficient transfer of energy through the food web to pelagic, benthic, and terrestrial communities.

Patterns in the timing and intensity of productivity, and patterns in the direction of energy flow through the system, are mediated by the seasonal development and progression of hydrographic conditions over the continental shelf (Hunt et al. 2002). The hydrographic structure during the spring-summer warming season over the EBS shelf is dynamic, representing an integration of both stratifying and mixing forces, and it has high inter-annual and spatial variability (Overland et al. 1999). The degree of stratification can directly affect nutrient transport and availability, phytoplankton and zooplankton production, larval fish survival, and interactions among individuals and groups of organisms (National Research Council 1996, Sarkar et al. 2005). Temperature and hydrographic structure are important components to the pelagic and epibenthic habitat that also influence the distribution, behavior, and interspecific interactions of larger commercially and ecologically important species in the EBS (Bailey 1989, Decker and Hunt 1996, Lang et al. 2000, Robson 2001, Sterling et al. 2004).

Although temperature and hydrographic structure are important factors in understanding the relationship of larger species to their pelagic habitat in the EBS, the use of hydrographic structure in analyses covering large areas has been limited. Typically, the distribution and biology of species have been examined with respect to hydrographic structure along transects (Lang et al. 2000, Coyle and Pinchuk 2002), but over the expanse of the continental shelf, abundances and distribution are correlated with surface temperature or bottom temperature (Francis and Bailey 1983, Kotwicki et al. 2005, Spencer 2008). In addition, surface temperatures, bottom temperatures and the distribution of the cold pool are used as environmental indicators in the EBS (Lauth 2007, Wang et al. 2007). These environmental indicators are based primarily on the data collected during the standardized bottom trawl survey (BTS) of the EBS continental shelf which has been performed every summer for more than 25 years (Acuna and Lauth 2008). The bottom temperatures were collected by bathythermographic devices that allow a depth-temperature profile to be obtained at each station. Although salinity was not recorded at these stations, temperature is the main determinant of density (Stabeno et al. 1999), and temperature data were found to provide the most complete and accurate description of the physical structure of the water column in areas over the EBS continental shelf (Kachel et al. 2002).

We describe methods for generating statistics of hydrographic structure (fish habitat) from depth-temperature data from the EBS BTS. We generally focused on the characteristics related to the "cold pool" and the strength of stratification or mixing of the water column because these characteristics are important to biological production and distribution in the EBS. The broad, shelf-wide coverage of these data should be complementary to the smaller-scale studies that have revealed so much about the atmospheric-oceanographic-biologic processes in this ecosystem. Our secondary objective was to integrate some of these characteristics over the entire survey area to provide annual survey indices of water conditions over the EBS shelf. These hydrographic statistics and indices describing pelagic habitat will be valuable to scientists for examining a variety of hypotheses regarding groundfish distribution, production, diet, and cannibalism in the EBS. We also discuss the interannual changes in timing and duration of the survey and how it affects the composite geographic distributions of large-scale features such as oceanographic domains and fronts across the EBS shelf as well as interannually comparable indices.

METHODS AND MATERIALS

Survey Data

The BTS of the EBS continental shelf is conducted annually by the Resource Assessment and Conservation Engineering (RACE) division of the Alaska Fisheries Science Center. The main purpose of the BTS is to collect biological data for estimating abundance and the age- and sex-composition of commercially important species of fish and crab for use in annual stock assessments (Wakabayashi et al. 1985). Bottom trawl tows are performed over a grid of stations in the EBS (Fig. 1) from late spring through mid-summer. The survey begins in eastern Bristol Bay with two vessels generally proceeding westward by column across the EBS shelf.

Paired depth-temperature data were routinely collected at each station during the BTS. The data from successful casts were recorded and entered into RACE division's central data processing system in one of two ways depending on the survey year. From 1982 through 1989 (on all vessels) and in 1990 on the chartered survey vessel *Ocean Hope 3,* depth-temperature traces were determined using expendable bathythermographs (XBT). Graph paper traces from XBT casts were later converted to depth-temperature data pairs through visual examination, especially transcribing inflection points to describe the depth-temperature profile. In 1990 on the RV *Alaska*, and from 1991 to 1992 on all vessels, the XBT graphical recordings were replaced by digital traces stored on a computer. Starting in 1993, digital bathythermograph recorders (BTR) were attached to the headrope of the trawl net in place of using XBTs. The data recorded during the downcast of the net, from the surface to the bottom, were selected for inclusion in the RACE database. In a few cases, however, the surface portion of the profile was excluded which resulted in the shallowest reading at a depth below 10 m in the RACE database.

We corrected anomalous depth-temperature pairs where possible. Frequency distributions of the depth at which particular temperatures and water column features occurred, suggested substantial anomalies in some of the profiles originally recorded on graph paper. The anomalies were traced back to a mismatch between the drum-gearing (which controls the advance-speed of the graph paper) and the scale on the graph paper. Consequently, depths were understated by a factor of 2.54 for some profiles in 1985, 1986, 1987, 1989, and 1990. For our analyses, we corrected the depth values and removed the depth-temperature data when they were deeper than the sea floor.

Data from graphically recorded profiles sometimes required the addition of data points for our analyses. In some years, temperature profiles start at the surface and in other years they start at a depth of 5 m. Profiles without a temperature record at 5 or 6 m were modified using interpolation between straddling points to estimate the temperature at the 5.5 m depth; this data point was added to the profile. We only used depth-temperature data points that were 5 m and deeper in our analyses. Some profiles did not have a bottom depth-temperature data point because only the deepest inflection point was recorded. A subsample of archived depth-temperature traces was examined to confirm that this was the case. To complete the depth-temperature profile, we appended the bottom depth-temperature record to the existing data in the profile by adding the gear depth and gear temperature when the gear depth (depth of the trawl headrope) was 5 m deeper than the existing deepest depth-temperature data pair. If the gear temperature was missing, then the temperature of the last inflection point was replicated at bottom depth. Unusual changes in temperature with depth were checked against the original depth-temperature traces from that station and neighboring stations to confirm or correct the data if possible. Profiles originally recorded on graph paper were described by relatively few data points compared to profiles recorded directly into computer memory.

Data recorded into computer memory had relatively high numbers of data points describing the depth-temperature profile at each station, and in most cases some data points were excluded. Depth-temperature data from depths shallower than 5.5 m were deleted to exclude data recorded while the net was towed near the surface in the turbulent wake and propeller-wash of the vessel prior to deployment to the bottom. Multiple temperature readings at the same depth were replaced by an average temperature value for that depth. Cursory examination of the resulting statistics indicated there were some profiles with unusually messy data or multiple profiles. These were corrected where possible, or they were culled from the available profiles for our analyses if the data were not correctable.

Depth-temperature profiles from the RACE database are also being archived at the Pacific Marine Environmental Laboratory (PMEL) from the 1994 BTS onward (Peggy Sullivan, NOAA PMEL, 23 September 2008, pers. comm.). At PMEL the temperature data are averaged within 1 m depth bins. Near-surface data are extrapolated to the top, and spurious points are removed. The data are visually inspected for reasonableness, especially the near-surface, bottom layer and mixed-layer values. These data are made available through two web interfaces at PMEL: http://www.epic.noaa.gov/epic/ewb/ and http://dapper.pmel.noaa.gov/dchart/ (Peggy Sullivan, NOAA PMEL, 23 September 2008, pers. comm.).

Water Column Characteristics

Three types of statistics were calculated on the resulting depth-temperature profiles. The first group of statistics describes nominal temperature characteristics. Maximum and minimum temperatures were listed for each profile, as well as the temperatures and associated depths for the top (usually 5.5 m depth) and bottom of each profile. The differences between top and bottom temperatures and between maximum and minimum temperatures were also calculated. Other nominal temperature statistics included description of the depth and thickness of the "cold pool" layer defined in two ways by: water ≤ 2°C and by water ≤ 0°C. The second group of statistics describes the mixed and transition layers, the average temperature of the surface and bottom mixed layers, and the average rate of temperature change (°C m^{-1}) within the transition layer (when one existed) occurring between the mixed surface and bottom layers. The third group of statistics describes the strength and depth of the maximum temperature gradient, or thermocline (the maximum rate of temperature decrease with depth, °C m^{-1}), in the depth-temperature profiles. These statistics are listed and described in more detail in Table 1.

Standardizing Procedures

To standardize the descriptive statistics between the two collection methods, the two types of data required different handling. The minimal number of data points transcribed from the graphical traces (1982-1990) required interpolation to locate the depths associated with particular temperature values. In contrast, the digitally recorded profiles (1990-2006) sometimes had data points too close together for the automated process to correctly locate the maximum thermocline (TC_{max}) based on comparison of the statistic (calculated from the raw data) and visual examination of the depth-temperature plot. Temperature readings were recorded to the nearest 0.1°C and depths were recorded to the nearest 0.1 m.

For data recorded directly into computer memory (1990-2006), two procedures, “averaging” and “weeding” of the data, were used to increase the distance between consecutive points, and the results were compared. Averaging consisted of taking the average temperature and the average depth of the data in each 1 m bin throughout the depth-temperature profiles. Weeding consisted of sub-sampling the depth-temperature data pairs and keeping the data pair that occurred closest to the whole meter in each 1 m bin. When data pairs occurred equidistant from the whole meter (e.g., 10.8 m and 11.2 m), the deeper reading was used. TC_{max} values were located in the depth-temperature data-pairs resulting from averaging and from weeding at each station. A scatter-plot of the TC_{max} values based on averaging and weeding was examined. The difference in thermocline depths between the two methods was plotted against the difference in thermocline strength between the two methods. When differences in thermocline strength were ± 0.25°C m^{-1} or more, we examined the original data plots and raw data of the depth-temperature profile to understand the discrepancies.

Annual Survey Indices

Indices based on the profile statistics were calculated for the standard survey area (1982-2006) and for the extended survey area (1987-2006) (Fig. 1). Each survey index is listed and described in detail in Table 2. We compensated for the interannual variability in the number of stations with depth-temperature profiles by weighting each profile by the area of the Thiessen polygon (Burrough 1991) – an area determined by the location of the surrounding stations that also have depth-temperature profiles. Indices for average bottom temperature, volume of the cold pool, volume and average temperature of the surface mixed layer, volume and average thermocline of the transition layer, and the average TC_{max} were calculated. We examined the correlation between some of these indices during the 1982-2006 (six strata) period that we would expect to have a relationship based on oceanographic processes in the EBS. Because these indices are influenced by variation in the timing of the survey, the start, end, mean, and median annual Julian Day of the survey were also calculated. We examined the variation in timing and duration of the BTS for patterns or trends that could influence interpretation of the survey indices as a time series.

Seasonal Variation

Finally, we illustrate the dynamic nature of the annual warming period by comparing the depth-temperature profiles from some stations that were repeated after the standard survey was completed in 1999. Patterns in the seasonal warming and stratification of the water column in a particular area are indicative of the stratifying and mixing forces described above as well as advection of water into the area (Kachel et al. 2002, Luchin et al. 1999, Stabeno et al. 2002). The major change between the pairs of depth-temperature profiles, with respect to the amount of time that has passed between them, is described to illustrate the potential usefulness of preserving depth-temperature profiles acquired before and after the main BTS.

RESULTS

Water Column Characteristics

The number of depth-temperature profiles used in this exercise ranged from 175 in 1983 to 371 in 2006 and averaged 325 profiles per year (Table 3). Temperature profiles over the inner shelf (bottom depth ≤ 50 m) tended to be fairly simple, being either fully mixed or displaying surface stratification (Fig. 2). Profiles over the middle shelf (50 m < bottom depth ≤ 100 m) were often more complex, with multiple thermoclines (temperature gradients of decreasing temperature with increasing depth) or influence by the cold pool, especially in northern locations (Fig. 3). Profiles over the outer shelf (100 m < bottom depth ≤ 200 m) seemed to have greater variability within and among years, sometimes having multiple thermoclines, reverse thermoclines (temperature gradients of increasing temperature with increasing depth) or influence from the cold pool in mid-water (Fig. 4). Figures 2-4 also illustrate the difference in number of data points between the transcribed (1982-1990) and the digitally recorded (1990-2006) depth-temperature profiles. For comparison, Table 4 provides some of the statistics calculated for each of the profiles in Figures 2-4. The entire set of statistics calculated from each depth-temperature profile can be accessed online; http://www.afsc.noaa.gov/RACE/groundfish/survey_data/ebswater.htm.

Standardizing Procedures

The different data recording methods affected the results of the subsequent calculations of the thermocline characteristics. The depth of the TC_{max} in the 1982-1990 profiles appeared to have a similar frequency distribution as the 1990-2006 profiles (Fig.

5), but the frequency distribution of the strength of the TC_{max} in the 1982-1990 profiles (Fig. 5) showed a higher frequency of weak thermoclines. This probably resulted from averaging relatively small changes in temperature over larger ranges of depth in the 1982-1990 transcribed data when fewer depth-temperature data points were available.

The frequency distribution of layer thickness appears similar between the 1982-1990 data and the 1990-2006 data for both the top and bottom layers (Fig. 6) even though about 0.1% of the 1990-2006 depth-temperature profiles began at depths ≥ 10.0 m. It follows then that the midlayer slope, calculated by dividing the temperature difference between the top and bottom layers by the distance between them, would also appear very similar between the two time periods (Fig. 6). Data points transcribed from paper traces recorded in the 1982-1990 period were sometimes limited to inflection points in the profile, thus it is not surprising that the description of layers would be similar from both time periods.

Thinning of the data points in profiles in 1990-2006 improved the automated selection of TC_{max} based on visual inspection of the calculated statistics and plots of the raw data. Temperature readings were recorded in the database to the nearest 0.1°C, and as the descent of the BTR or XBT slows with increasing depth, the distance between readings can decrease (see Figs. 2-4) to where rounding to the nearest 0.1°C can artificially create a substantial thermocline (a change in temperature with depth). For example, a very small change in actual temperature can cause the recorded temperature to change by 0.1°C due to rounding, and if this occurs between readings that are 0.2 m apart, then a slope of 0.5°C m^{-1} is calculated. In the automated selection process, this value would be chosen as the TC_{max} (and the depth of the TC_{max}) even if the water column was well-mixed, or even if there was a 2.0°C change in temperature over a 4.1 m interval (giving 0.49°C m^{-1}) somewhere else in the water column. Both averaging and weeding of the raw data appeared to improve the overall accuracy of locating TC_{max} in the water column, but the results occasionally differed between the methods (Fig. 7). Most of the 5,591 points are on or very near the diagonal line which represents general agreement between the calculated TC_{max} after the data points were thinned. There is a tendency for more points to fall below this diagonal, indicating that the method of averaging tends to yield a lower estimate of the TC_{max} more often than the other way around. Visual inspection of the depth-temperature profiles, where the agreement was poorest between the location of TC_{max} from the two data-thinning methods, indicated that the method of weeding tended to locate the visually correct depth and value of the TC_{max} slightly more often.

The difference in TC_{max} calculated from averaged and weeded data was plotted against the difference in the depth associated with the TC_{max} for each station from the 1990-2006 profiles (Fig. 8). The horizontal spread in points indicates differences in the calculated strength of TC_{max} and the vertical spread in points indicates differences in the depth where TC_{max} was calculated to be the strongest. Visual inspection of the profiles associated with the horizontal spread indicated they had strong stratification (so the method of thinning had little influence on the depth where the strongest stratification was found). Visual inspection of the profiles associated with the vertical spread indicated they had very weak stratification (so the method of thinning had a large influence on where the strongest stratification was found in each profile).

Annual Survey Indices

The survey indices provide shelf-wide indications of nominal temperatures, stratification, and mixing characteristics encountered during the spring-summer BTS of the EBS (Tables 2, 5, 6). Average Water Column Temperature is an indicator of the heat content in the region. Top Layer Volume is an indicator of the amount of surface mixing, but it includes fully mixed water columns that occur in shallower water, so the sub-category of Fully Mixed Volume is also provided (Table 2). Stratification indicators include Transition Layer Volume, Average TC_{max}, and Average Transition Layer Slope. These indices are calculated for the extended survey area covered since 1987 (Table 5) and the standard survey area covered since 1982 (Table 6). Anomalies of Volume of °C ≤ 2, Top Layer Volume, Average TC_{max}, and Average Transition Layer Slope are shown for the standard survey area (Fig. 9). All the annual survey indices described in Table 2 can be found online; http://www.afsc.noaa.gov/RACE/groundfish/survey_data/ebswater.htm.

Interannual variation in winter cooling of the water over the EBS continental shelf and the spring-summer processes affecting warming, mixing, and stratification suggest relationships that should be reflected in these indices. We found a negative correlation

($r = -0.637$, $P < 0.001$) between the cold pool, Volume of °C ≤ 2, and the Top Layer Temperature index. Also, when the Top Layer Volume is larger, the Top Layer Temperature tends to be lower ($r = -0.611$, $P < 0.002$).

Analysis of the time trend in the timing of the survey each year indicates a statistically non-significant tendency towards an earlier survey start date but a significant relationship indicating an earlier completion date over time - the Start Day ($r = -0.260$, $P > 0.2$) and End Day ($r = -0.692$, $P < 0.001$) are negatively correlated with the Survey Year. In the period 1982-1992 the last day of the survey appeared to be later (range = annual Julian Day 211-232) than in the period 1993-2006 (range = annual Julian Day 192-210), so we compared the average duration of the survey from these two time periods (Fig. 10). We found the later period to have a significantly shorter survey duration (10.5 fewer days; $P < 0.0005$; Mann-Whitney test) (Zar 1984).

Seasonal Progression

In 1999, some stations were first surveyed in late May then repeated in late July, providing us with an example of the dynamic changes occurring during the spring-summer warming period. Four of these stations were chosen (Fig. 1: C-8, E-12, I-9, I-13) to illustrate changes in the temperature profile that occurred between May and July (Fig. 11). In an area that was nearly fully mixed in both May and July (I-13; thin, solid line), the temperature increased from less than 0°C to just over 3°C. The other three stations also became much warmer, but shifted from mild to substantial stratification. For example, at the deepest station shown (C-8; dots), the temperature below 30 m increased by about 0.75°C while the surface layer temperature increased by about 4.5°C.

DISCUSSION

The hydrographic structure during the spring-summer warming season over the EBS shelf is dynamic, representing an integration of both stratifying and mixing forces, and it has high inter-annual and spatial variability (Overland et al. 1999). Stratifying forces include terrestrial run-off (reducing the salinity and density of the surface layer), insolation (warming and reducing the density of the surface layer), and spring melting of sea ice (which contributes to formation of a dense "cold pool" of water ≤ 2°C near the bottom (Takenouti and Ohtani 1974)). Mixing forces include wind events (deepening the surface layer, mixing heat downward and nutrients upward) and tidal currents (primarily thickening the bottom layer). The interaction and spring progression of these forces are directly and indirectly dependent on atmospheric conditions (Kachel et al. 2002, Stabeno et al. 2007) which are affected by climate change (Grebmeier et al. 2006, Stabeno et al. 2007).

The degree of stratification can directly affect nutrient transport and availability, phytoplankton and zooplankton production, larval fish survival, and interactions among individuals and groups of organisms (National Research Council 1996, Sarkar et al. 2005). The spring phytoplankton bloom usually depletes the nutrients available in the euphotic zone over the continental shelf and stratification below this zone creates a barrier to nutrient transport into the surface layer (Kachel et al. 2002). Wind events of sufficient magnitude can break through the barrier and supply added nutrients to the euphotic zone for phytoplankton production (Kachel et al. 2002, Sambroto et al. 1986, Stabeno et al. 2001). Geographic and temporal patterns in phytoplankton (primary) production affect zooplankton (secondary) production (Coyle and Pinchuk 2002), and hydrographic structure affects species distributions (Coyle and Pinchuk 2002, 2005) and overall localized abundance of zooplankton (Coyle and Cooney 1993).

Temperature and hydrographic structure are important components to the pelagic and epi-benthic habitat that also influence the distribution, behavior, and interspecific interactions of larger commercially and ecologically important species in the EBS. The summer cold pool extends the distribution of Arctic species southward over the EBS continental shelf while limiting the northward distribution of subarctic species (Mueter and Litzow 2008). Walleye pollock (*Theragra chalcogramma*), a nodal species in the EBS food web, have long been known to exhibit markedly decreased abundance in the cold pool (Francis and Bailey 1983). Flathead sole (*Hippoglossoides* sp.) and rock sole (*Lepidopsetta* sp.) tend to be located further northwest in warm years relative to cold years (Spencer 2008). The cold pool also affects the geographic overlap, and thus predation mortality, between predatory Pacific cod (*Gadus macrocephalus*) and juvenile snow crab (*Chionoecetes opilio*) (Livingston 1989). Stratification of the water column has been proposed as a factor affecting rates of cannibalism, a significant population structuring process, by walleye pollock in the eastern Bering Sea (Bailey 1989, Dwyer et al. 1987). Hydrographic features, such as fronts between stratified and thoroughly mixed-water columns, can provide enhanced feeding conditions for fish and birds (Coyle and Cooney 1993, Decker and Hunt 1996, Lang et al. 2000). Foraging patterns of northern fur seals (*Callorhinus ursinus*) and Steller sea lions (*Eumetopias jubatus*) also correspond with hydrographic features such as fronts and thermoclines (Robson 2001, Sterling et al. 2004).

The statistics calculated in this study were targeted to describe the larger features of each depth-temperature profile. While these may be very rough characteristics from an oceanographic point of view, these do provide information at each location about the hydrographic habitat that influences commercially and ecologically important species in the EBS. The characteristics of each depth-temperature profile during the spring-summer warming season represent an integration of the preceding seasonal events over the EBS shelf and localized influences of mixing and stratifying forces. The BTS occurs during a very dynamic warming period (Kotwicki et al. 2005, Luchin et al. 1999) with inter-annual fluctuations linked to atmospheric forces described by the El Niño-Southern Oscillation, the Pacific-North American index, and the Aleutian Low index (Niebauer 1988). However, much of the variability within the Bering Sea environment results from localized forcing (Stabeno et al. 1999).

Several modifications of the BTS depth-temperature data were required to describe water column structure at each station. Surface points and bottom points had to be added to some of the depth-temperature profiles that were transcribed from graph paper traces (1982-1990). In most cases these were interpolated from the existing data or appended from other tables in the RACE database. We also discovered and corrected problems with the depth scale on some original graph paper traces. Depth-temperature data logged directly into computer memory (1990-2006) also required some modification before calculating the descriptive statistics. Data shallower than 5.5 m were excluded to avoid the influence of turbulent propeller-wash and the data were thinned to more correctly locate TC_{max}. Thinning was necessary because some depth-temperature points were less than 1 m apart and a "recorded" change in temperature of 0.1°C created a relatively high TC_{max} value (°C m^{-1}) that was not near the actual thermocline in the depth-temperature profile. The recorded change in temperature from one depth to the next can be more than the actual change in temperature due to rounding. This problem could be alleviated by recording temperatures in the RACE database to the nearest 0.01°C rather than the nearest 0.1°C.

Statistics calculated from data after averaging or weeding were not always in agreement, and when these profiles were examined, weeding of the data (subsampling by taking the depth-temperature data nearest to the midpoint of each 1 m bin) seemed to be slightly better at locating true inflection points in the profile. Weeding inflated the value of TC_{max} more often than averaging, but averaging tended to deflate the value of TC_{max} a lot more than weeding. Weeding is the method we chose because it seemed to perform slightly better and it subsampled actual data points rather than creating new data points in each 1 m bin. The profiles where weeding and averaging resulted in different locations for TC_{max} generally were well-mixed or had very small changes in temperature with depth (similar to K-7, 1996 in Fig. 2), but occasionally they had multiple thermoclines of similar strength (similar to N-22, 1991 in Fig. 3).

We provided several measures of stratification because a single measure of stratification did not capture the complexity observed among the depth-temperature profiles. Stratification can be very sharp, having a very high °C m^{-1} value, but with very little nominal temperature change between the adjacent layers. In the other extreme, a large change in temperature can occur gradually over a wide depth range. We calculated statistics that describe surface, bottom, and transition layers, as well as the thermoclines occurring in discrete depth ranges to provide additional information to TC_{max} about the vertical structure at each station.

Differences in the methods of data recording appear to affect the values of TC_{max} that were calculated (Fig. 5) but not the statistics that described the layers (Fig. 6). The data transcribed from graph paper (1982-1990) have much less detail than digitally recorded data (1990-2006). After correcting the depths for transcribed profiles in 1985, 1986, 1987, 1989, and 1990, the distribution of the depth of TC_{max} appeared similar to that from the data recorded directly into computer memory, but the distribution of maximum thermocline strength had a higher frequency of weak thermoclines. We attributed this to having fewer data points describing the temperature-depth profile, thus changes in temperature were averaged across larger changes in depth. The distribution of top layer thickness, bottom layer thickness and transition layer slope is very similar between the two time-periods, so we believe the method of data recording had little effect at the scale of these water column characteristics.

Using these descriptive statistics to identify oceanographic domains encountered during the BTS shows promise even though the profiles are highly variable. The hydrographic structure across the EBS shelf is generally considered to consist of three well-defined domains (National Research Council 1996). An inner front, or inner transition zone (Kachel et al. 2002), separates the coastal domain of well-mixed water from the stratified, two-layered waters of the middle domain. A middle front, approximately coincident with the 80 to 100 m isobath, separates the two-layered, middle domain from the multi-layered, outer domain. In the outer domain, the surface layer and bottom layer are separated by an intermediate zone that can have a variety of thermal patterns rather than a single thermocline. The outer domain extends from the middle front to the shelf break front which approximately coincides with the 170 m isobath (National Research Council 1996). Automating the classification of the depth-temperature profiles into these idealized domains and yielding spatially coherent water masses is problematic due to the high variability across the EBS shelf, the duration of the survey, and the intervening time between adjacent stations. However, preliminary results indicate the coastal domain, and possibly the inner front (or transition zone) can be identified with these depth-temperature profiles. The distinction between the middle domain (two-layered water columns) and outer domain (three- or multi-layered water columns) will require experimentation with somewhat subjective criteria (Nancy B. Kachel, NOAA PMEL, 20 March 2008, pers. comm.) perhaps using the Transition Layer Thickness.

When examining geographical patterns in water column characteristics, researchers must remain cognizant of the fact that these data are not collected synoptically across the survey expanse (the BTS is usually conducted over an 8- or 9-week period) and the timing of the survey can vary somewhat due to weather, vessel capability, and scheduling constraints. The observed increase in surface temperature from east to west across the shelf that occurs in most years probably reflects the progression of summer warming that occurs during the BTS (Goddard 2000). Even so, maps of surface and bottom temperatures are compiled from the survey data to show temperature anomalies (Lauth 2007) and the distribution of the cold pool (Wang et al. 2007). These are useful because, while there is variability in timing, the BTS is repeated over the same areas during the same season year-after-year.

The full extent of the cold pool may not be captured by examining bottom temperatures alone. In Figure 4 (N-29, 1998), we see an example of a layer of very cold water occurring in midwater that would not be considered part of the cold pool if only bottom temperatures were examined. The increase in temperature with increasing depth below a layer of very cold water is indicative of "dichothermal" water as described by Kitani (1972) and occurs primarily in the northeast portion of the EBS Basin (Ohtani et al. 1972). While the mid-water occurrence of the cold pool might be limited in extent, it influences the vertical distribution of walleye pollock that occur above and below this feature and avoid crossing it (Taina Honkalehto, NOAA Alaska Fisheries Science Center, 14 June 2006, pers. comm.).

The relationships among some annual survey indices appear to be consistent with the seasonal oceanographic dynamics in the EBS. Each winter, the amount of ice-cover determines the thermal properties of the quasi-homogenous layer over the EBS continental shelf (Luchin et al. 1999, Stabeno et al. 2007). Although the seasonal warming, mixing, and stratification differ interannually, we found the thermal conditions between the top layer and the volume of the cold pool were correlated. This illustrates how important the winter ice-cover is to the following summer's thermal conditions, even in surface waters, over the EBS shelf. The negative correlation between the volume and temperature indices of the top layer is explained by seasonal surface heating and mixing of that heat through the volume of the top layer of water (which mixes top to bottom in the shallow, coastal domain) (Kachel et al. 2002). In general, as the volume of the top layer increases through mixing, the surface heat is dispersed through a larger amount of cold water, and the average temperature throughout the top layer decreases.

The annual survey indices provide indications of the average nominal temperatures, stratification and mixing characteristics encountered during each BTS, but due to differences in survey timing they should not be considered to represent a robust time-series. Since 1993, the survey has been completed in about 10.5 fewer days on average than in previous years (Fig. 10). This corresponds to the first year that fishing vessels contracted to conduct the survey were required to exceed 120 feet in length. The larger vessels can continue survey operations in weather that would hinder some of the smaller vessels used during 1982-1992, and they may require less time re-supplying fuel, water or food. We did not examine the effect of other factors on survey duration such as the northern extent of the survey, special shallow stations and additional tows required when high densities of crab are encountered. Accounting for these factors would probably result in even faster completion of the survey since 1993.

To achieve a robust time-series, correcting for differences in survey timing should probably be made at each station before re-calculating the statistics for the entire survey area. There are two reasons for this. First, the Start Day of the BTS, while trending slightly earlier over the years ($r = -0.260$, $P > 0.200$), has changed little relative to the End Day over the years ($r = -0.692$, $P < 0.001$), evident by the overall faster completion of the BTS since 1993 (Fig. 10). Thus, the primarily shallow stations in Bristol Bay, where the survey starts, were sampled within a narrower range of seasonal advancement over the years than those stations in the northeastern portion of the BTS area, where the survey ends. Second, the advance of the seasonal shifts taking place may occur rapidly in some areas (and in some statistics) and slowly or not at all in other areas (and in other statistics). For example, the changes in bottom temperature, surface temperature and stratification are different among the stations re-sampled in 1999 (Fig. 11). Properly corrected, indices from the depth-temperature profiles have the potential to inform investigations and discussions about changes in warming, stratification, and ecological consequences due to climate change.

The amount of summer heating of the surface layer is not fully captured by the BTS survey data due to its timing. The depth-temperature profiles illustrated in Figure 11 occurred in the cold year of 1999, when the survey was conducted about 10 days earlier than average (Table 6; Mean Julian Day). While the temperature had increased a considerable amount between May and July, maximum surface temperatures generally occur in August and September over the EBS shelf (Luchin et al. 1999). In several years, portions of the survey area have been re-sampled later in the summer, but the temperature profile data are not yet available in RACE division's central data processing system. We believe these data, especially acquired over several years, would be valuable information in understanding the pattern of summer warming as a complement to oceanographic research being conducted each year.

Weather events can quickly change the hydrographic structure over the EBS shelf (Kachel et al. 2002). In the BTS depth-temperature profiles, there can sometimes be a separation of days or more than a week between neighboring stations. In the intervening period of time, a storm, or other atmospheric event could have a great effect on the depth-temperature profile. This provides opportunities to examine physical changes that occur in the water column as a result of weather during the intervening period.

Consideration of pelagic habitat as a linking feature between physical forcing, trophic production, and the distribution and health of populations of larger animals (fish, shellfish, marine birds, and mammals) is increasing. The BTS depth-temperature profile information provides a means to examine the hydrographic structure over the expanse of the EBS continental shelf over a period of many years. It provides coverage that encompasses the depth-associated domains across the shelf as well as domains occurring along isobaths (Kachel et al. 2002, Stabeno et al. 2002). While not synoptic, the depth-temperature profiles were collected concurrently with biological information on a wide variety of species by the BTS. Comparisons of biological data – species composition and abundance, food habits, etc. – with hydrographic, pelagic habitat characteristics can now be accomplished. More recently, collection of light attenuation profiles and zooplankton sampling have been added to the BTS survey. Examination of a variety of hypothesized relationships between physical factors and biological interactions, as well as examining the data for currently undescribed relationships should now be possible.

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Table 1.--Statistics calculated from depth-temperature profiles to describe water column characteristics of the eastern Bering Sea over the continental shelf.

Water Column Descriptors	Units	Description of the Calculations
Nominal Temperature Characteristics		
Top Temperature	°C	Temperature at shallowest depth
Top Depth	m	Shallowest data-point
Bottom Temperature	°C	Temperature at deepest depth
Bottom Depth	m	Deepest data-point
Top – Bottom Temperature	°C	Top minus Bottom Temperature
Maximum Temperature	°C	Highest temperature
Minimum Temperature	°C	Lowest temperature
Temperature Range	°C	Maximum minus Minimum Temperature
2°C and colder		
Minimum Depth	m	Shallowest 2°C or colder data-point
Maximum Depth	m	Deepest 2°C or colder data-point
Thickness	m	Maximum minus Minimum 2°C Depth
0°C and colder		
Minimum Depth	m	Shallowest 0°C or colder data-point
Maximum Depth	m	Deepest 0°C or colder data-point
Thickness	m	Maximum minus Minimum 0°C Depth
Layer Characteristics		
Top Layer Depth	m	Deepest of contiguous points within 1°C of the Top Temperature
Top Layer Temperature	°C	Average temperature of the top layer
Bottom Layer Depth	m	Shallowest of contiguous points within 1°C of the Bottom Temperature
Bottom Layer Temperature	°C	Average temperature of the bottom layer
Transition Layer Thickness	m	Bottom layer depth minus top layer depth
Transition Layer Slope	°C m^{-1}	Where Transition Layer Thickness > 0 m, (Top Layer Temperature minus Bottom Layer Temperature) / (Transition Layer Thickness)

Table 1.--Continued.

Water Column Descriptors	Units	Description of the Calculations
Thermocline Characteristics		
Entire water column		
Maximum Decrease Rate	°C m^{-1}	Maximum decrease in temperature with increasing depth (TC_{max})
Maximum Decrease Depth	m	Depth of Maximum Decrease Rate
Maximum Increase Rate	°C m^{-1}	Maximum increase in temperature with increasing depth
Maximum Increase Depth	m	Depth of Maximum Increase Rate
Depth ranges: 5.5-30 m, 30-75 m, and 75 m-bottom		
Maximum Decrease Rate	°C m^{-1}	Maximum decrease in temperature with increasing depth
Maximum Decrease Depth	m	Depth of Maximum Decrease Rate

Table 2.--Description of the indices of spring-summer water column characteristics encountered during each year's AFSC bottom trawl survey, within the standard survey area in 1982-2006, and within the extended survey area in 1987-2006.

Indices	Units	Description of the Calculations
Average of Bottom Temperature	°C	Average weighted by the area of the Thiessen polygon
Average of Top Layer Temperature	°C	Average weighted by the area of the Thiessen polygon
Average of Water Column Temperature	°C	Average of the average water column temperature weighted by the area of the Thiessen polygon
Volume of 2°C and Colder	km^3	Sum of the volume at each station (2°C Thickness × area of Thiessen polygon)
Volume of 0°C and Colder	km^3	Sum of the volume at each station (0°C Thickness × area of Thiessen polygon)
Volume of Top Layer	km^3	Sum of the volume at each station (Top Layer Depth × Thiessen polygon)
Volume of Fully Mixed	km^3	The portion of the Volume of Top Layer where temperatures throughout the water column are within 1°C of the Top Temperature
Volume of Transition Layer	km^3	Sum of the volume at each station (Transition Thickness × Thiessen polygon)
Average of Maximum Decrease Rate	°C m^{-1}	Average weighted by the area of the Thiessen polygon
Average of Transition Layer Slope	°C m^{-1}	Average weighted by the area of the Thiessen polygon
Start Day	day	Julian Day of first profile each year
End Day	day	Julian Day of last profile each year
Mean Day	day	Average Julian Day of the profiles
Median Day	day	Median Julian Day of the profiles

Table 3.--Number of useable depth-temperature profiles from the standardized AFSC bottom trawl survey of the eastern Bering Sea continental shelf in each year.

Survey Year	Number of Station Profiles
1982	319
1983	175
1984	324
1985	300
1986	335
1987	327
1988	368
1989	338
1990	217
1991	259
1992	297
1993	333
1994	287
1995	320
1996	361
1997	355
1998	345
1999	348
2000	345
2001	359
2002	364
2003	369
2004	363
2005	346
2006	371

Table 4.--Some descriptive statistics of the depth-temperature profiles depicted in Figures 2-4. Corresponding profiles can be identified by their alpha-numeric station designation and survey year.

Station	K-07	K-07	N-01	N-01	G-04	G-04	N-22	N-22		C-02	C-02	N-29	N-29
Survey Year	1982	1996	1987	1994	1986	2001	1985	1991		1987	1994	1983	1998
Thickness of °C ≤ 2 (m)								46					62
Top Layer													
Temperature (°C)	3.59	4.02	2.45	2.57	3.81	5.74	4.37	8.28		6.39	6.14	8.88	7.18
Depth (m)	9.6	39.9	38.0	36.4	11.1	45 14.4	28.3	14.0		37.1	17.7	18.1	16.9
Transition Layer													
Thickness (m)	0.3	-34.3	-32.5	-30.6	14.9	7.3	4.5	16.0		1.4	6.6	15.6	28.8
Slope (°C m^{-1})	5.09				0.22	0.37	1.25	0.57		1.39	0.34	0.45	0.18
Bottom Layer													
Temperature	2.11	4.02	2.45	2.57	0.56	3.02	-1.27	-0.78	84	4.43	3.92	1.88	2.04
Depth	9.9	5.6	5.5	5.8	25.9	21.7	32.8	30.0		38.5	24.3	33.7	45.7
Max. Decrease													
Rate (°C m^{-1})	0.25	0.07	0.09	0.06	0.30	0.28	0.95	1.72		0.20	0.23	2.07	1.05
Depth	9.3	7.6	7.9	11.4	10.0	20.8	32.9	29.5		39.0	16.6	21.5	21.2
Max. Increase	43												
Rate												0.05	0.58
Depth						7.8						61.5	43.1
Max. Decrease (5-30 m)													
Rate	0.25	0.07	0.09	0.06	0.30	0.28	0.01 0.95	1.72		0.10	0.23	2.07	1.05
Depth	9.3	7.6	7.9	11.4	10.0	20.8	52.5 29.3	29.5		23.5	16.6	21.5	21.2
Max. Decrease (30-75 m)									0.05				
Rate						0.09	0.95	0.35	81.8		0.12	0.06	0.62
Depth						65.1	32.9	30.5			38.1	35.5	31.7
Max. Decrease (> 75 m)													
Rate									0.20				
									39.0	88.5			85.6
Depth													

0.05

Table 5.--Selected annual indices generated from the extended survey area for the period 1987-2006. Descriptions of all the indices are in Table 2, and all of the indices can be found at http://www.afsc.noaa.gov/RACE/groundfish/survey_data/ebswater.htm.

Survey Year	Mean Julian Day	Bottom Avg.°C	°C ≤ 2 Volume km^3	Water Column Avg.°C	Top Layer km^3	Top Layer Avg.°C	Maximum Thermocline Avg.°C m^{-1}	Transition Layer Avg.°C m^{-1}
1987	181	3.05	5,700	4.02	12,883	5.86	0.65	0.85
1988	183	2.19	10,754	3.30	9,198	5.85	0.81	0.64
1989	185	2.85	5,918	2.79	8,838	6.53	0.54	0.61
1990	183	2.24	12,203	3.07	8,182	6.73	1.06	0.63
1991	196	2.46	11,978	3.32	7,831	7.38	1.15	0.61
1992	189	1.78	12,623	3.15	10,165	6.07	0.79	0.48
1993	181	2.93	6,923	4.02	9,984	6.71	0.56	0.41
1994	176	1.49	16,039	2.20	9,412	4.80	0.83	0.56
1995	175	1.56	15,210	2.60	9,154	5.60	0.68	0.51
1996	185	3.28	3,747	4.45	13,532	6.27	0.46	0.38
1997	181	2.62	8,674	3.61	7,217	7.08	0.84	0.49
1998	187	3.14	8,225	3.59	7,769	6.68	0.75	0.40
1999	166	0.68	20,626	1.58	11,314	3.29	0.64	0.46
2000	174	1.98	11,952	3.02	9,407	5.36	0.61	0.43
2001	176	2.41	7,861	3.43	10,629	5.10	0.64	0.56
2002	177	3.03	5,633	3.86	8,708	6.30	0.62	0.41
2003	180	3.67	2,071	4.73	9,557	7.33	0.81	0.62
2004	182	3.21	4,760	4.22	7,189	7.83	1.17	0.72
2005	178	3.29	4,340	4.33	8,204	7.07	1.09	0.46
2006	177	1.70	14,087	2.68	8,402	5.22	1.06	0.70

Table 6.--Selected annual indices generated from the standard survey area for the period 1982-2006. Descriptions of all the indices are in Table 2, and all of the indices can be found at http://www.afsc.noaa.gov/RACE/groundfish/survey_data/ebswater.htm.

Survey Year	Mean Julian Day	Bottom Avg.°C	°C ≤ 2 Volume km^3	Water Column Avg.°C	Top Layer km^3	Top Layer Avg.°C	Maximum Thermocline Avg.°C m^{-1}	Transition Layer Avg.°C m^{-1}
1982	181	2.26	6,669	3.41	10,581	4.93	0.36	0.49
1983	183	3.03	8,302	3.82	5,534	7.74	0.79	0.60
1984	190	2.36	9,330	3.60	8,245	6.98	1.05	1.04
1985	195	2.44	9,897	3.39	8,877	5.98	0.74	0.79
1986	181	1.88	10,484	3.07	11,799	5.06	0.51	0.63
1987	180	3.21	3,654	4.17	11,890	5.85	0.65	0.89
1988	182	2.39	8,704	3.47	8,720	5.90	0.74	0.64
1989	184	2.98	4,537	3.86	8,490	6.37	0.51	0.62
1990	182	2.42	9,712	3.24	7,742	6.63	0.93	0.60
1991	195	2.70	9,683	3.52	7,424	7.20	1.03	0.58
1992	188	1.94	10,594	3.27	9,634	5.96	0.78	0.49
1993	180	3.11	5,194	4.16	9,691	6.57	0.53	0.41
1994	174	1.66	13,907	2.33	8,958	4.69	0.80	0.57
1995	175	1.72	13,121	2.76	8,749	5.52	0.63	0.51
1996	183	3.44	2,757	4.52	12,927	6.15	0.44	0.38
1997	179	2.76	7,074	3.71	6,956	7.01	0.83	0.51
1998	186	3.30	6,208	3.75	7,502	6.60	0.69	0.41
1999	165	0.78	18,266	1.72	11,157	3.09	0.56	0.46
2000	173	2.16	9,949	3.16	9,043	5.26	0.57	0.42
2001	175	2.56	6,090	3.54	10,183	5.03	0.62	0.58
2002	176	3.23	3,791	4.02	8,344	6.26	0.59	0.41
2003	179	3.82	1,230	4.83	9,108	7.25	0.80	0.64

Table 6.--Continued.

Survey Year	Mean Julian Day	Bottom Avg.°C	°C ≤ 2 Volume km^3	Water Column Avg.°C	Top Layer km^3	Top Layer Avg.°C	Maximum Thermocline Avg.°C m^{-1}	Transition Layer Avg.°C m^{-1}
2004	181	3.41	3,142	4.36	6,996	7.65	1.13	0.75
2005	177	3.49	2,747	4.49	7,790	7.02	0.99	0.47
2006	175	1.87	12,031	2.83	7,962	5.11	0.99	0.70

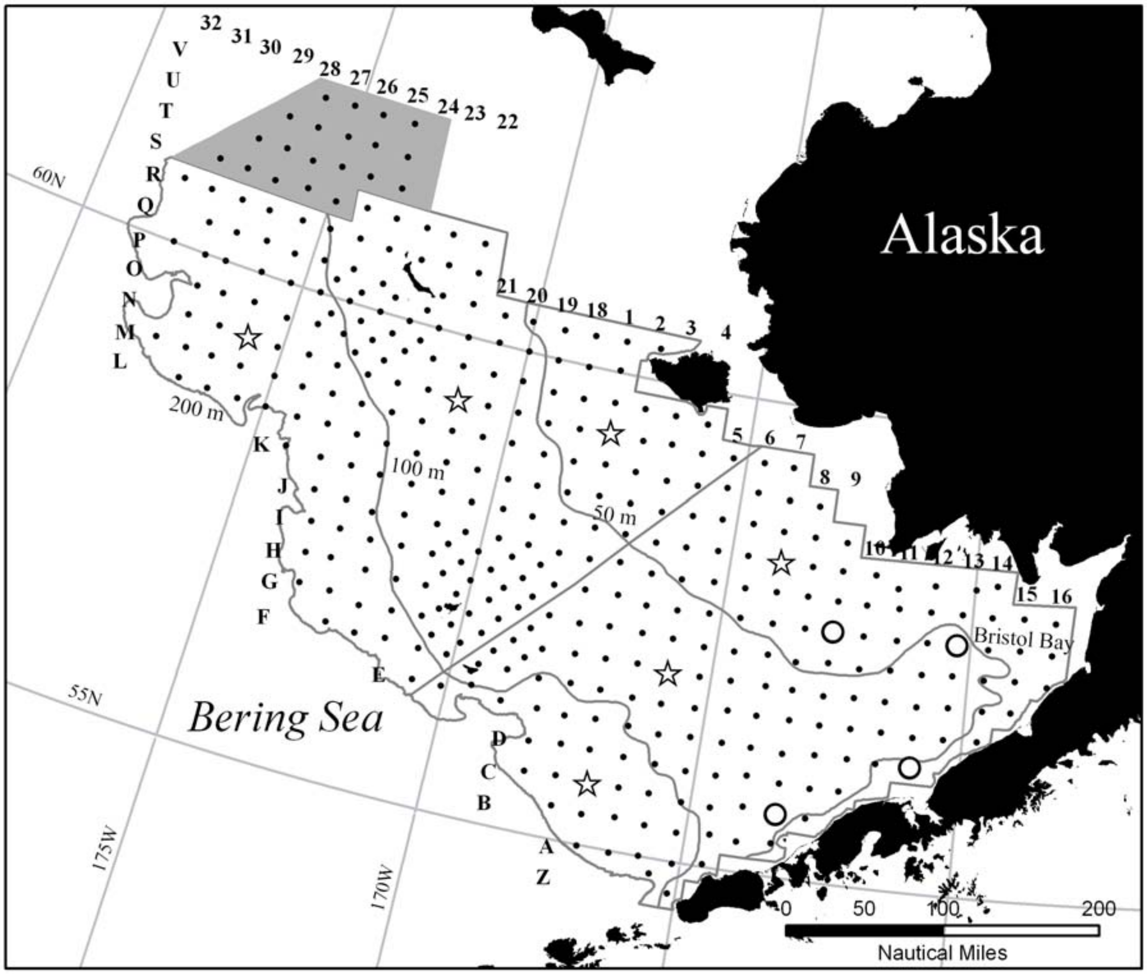


Figure 1.--Map of the AFSC survey area over the eastern Bering Sea continental shelf showing the grid of stations, the six strata of the standard survey area, and the additional northern stratum (shaded) that completes the extended survey area. Stars indicate the location of the stations illustrated in Figures 2-4 which are individually identified by their row (letter) and column (number) coordinates on the survey grid. Circles indicate the location of the stations illustrated in Figure 10 which are individually identified by their row (letter) and column (number) coordinates on the survey grid.

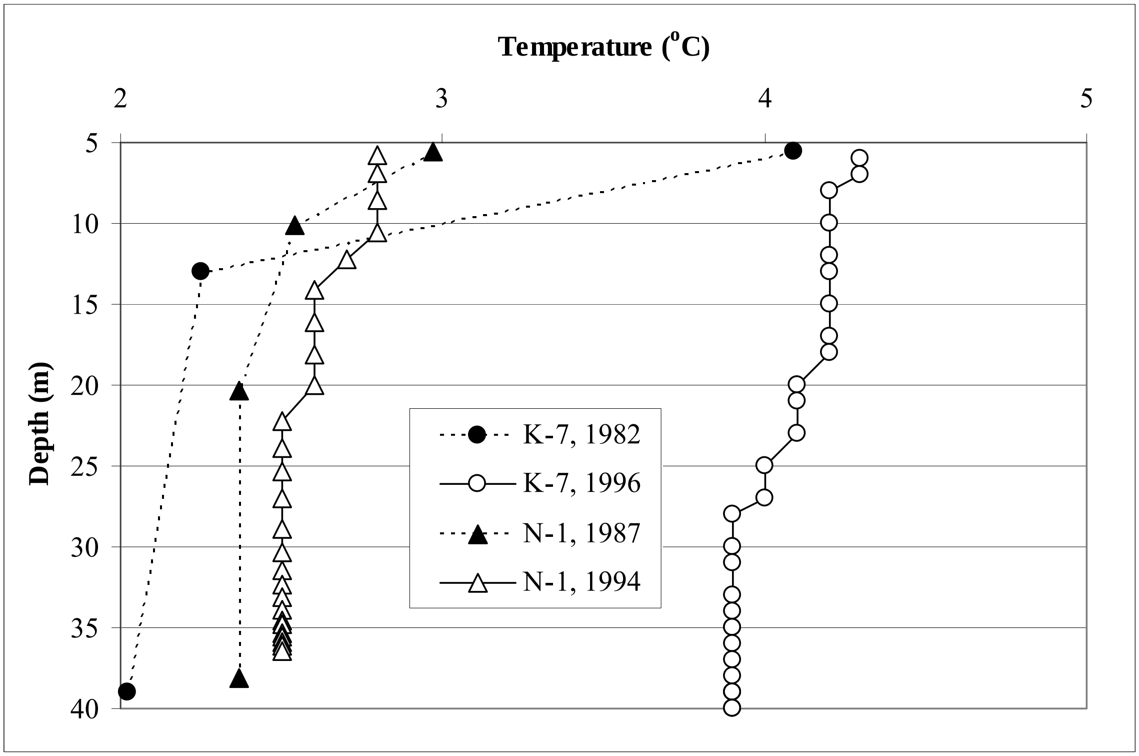


Figure 2.--Inner shelf (bottom depth ≤ 50 m) depth-temperature profiles from the southern and northern portion of the survey area from the 1982-1990 and the 1990-2006 data. See Figure 1 for station locations (stars). Statistics associated with these profiles are presented in Table 4.

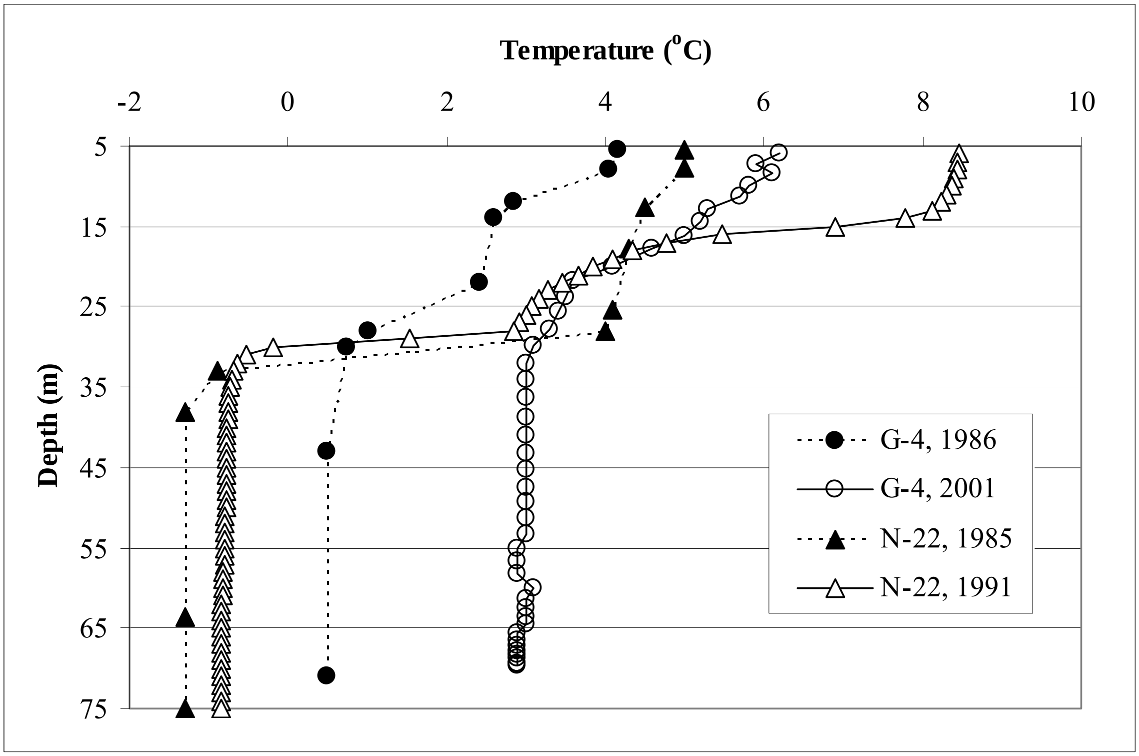


Figure 3.--Middle shelf (50 m < bottom depth ≤ 100 m) temperature profiles from the southern and northern portions of the survey area from the 1982-1990 and the 1990-2006 data. See Figure 1 for station locations (stars). Statistics associated with these profiles are presented in Table 4.

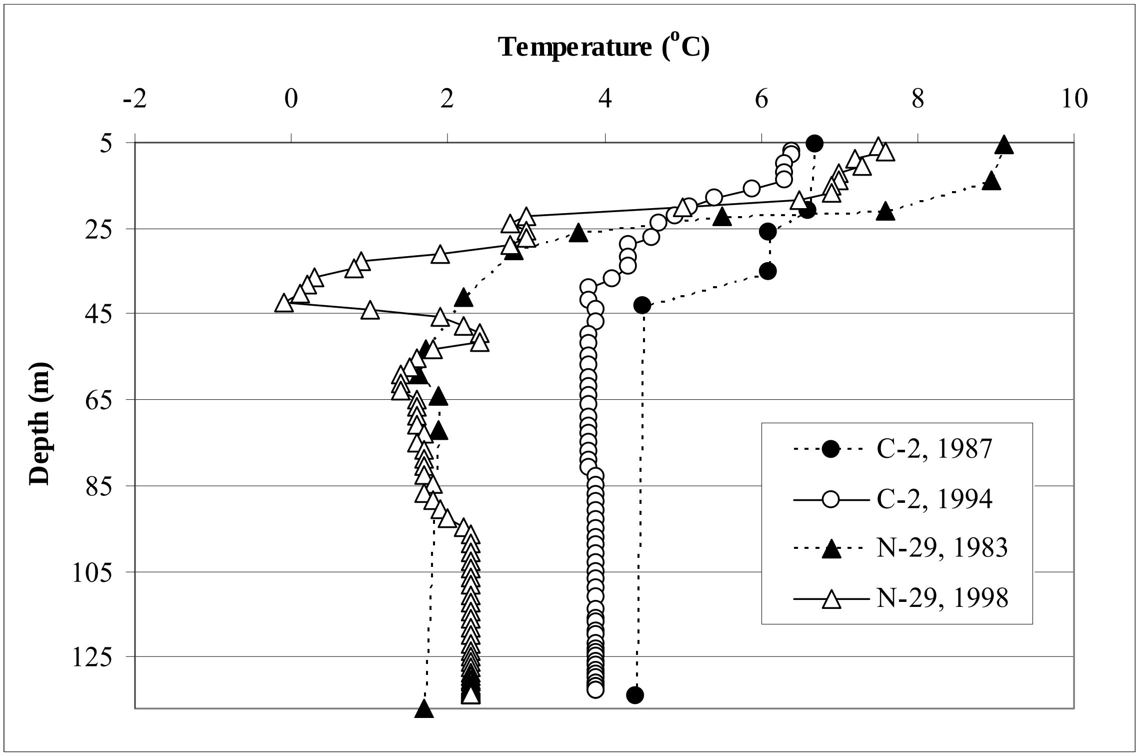
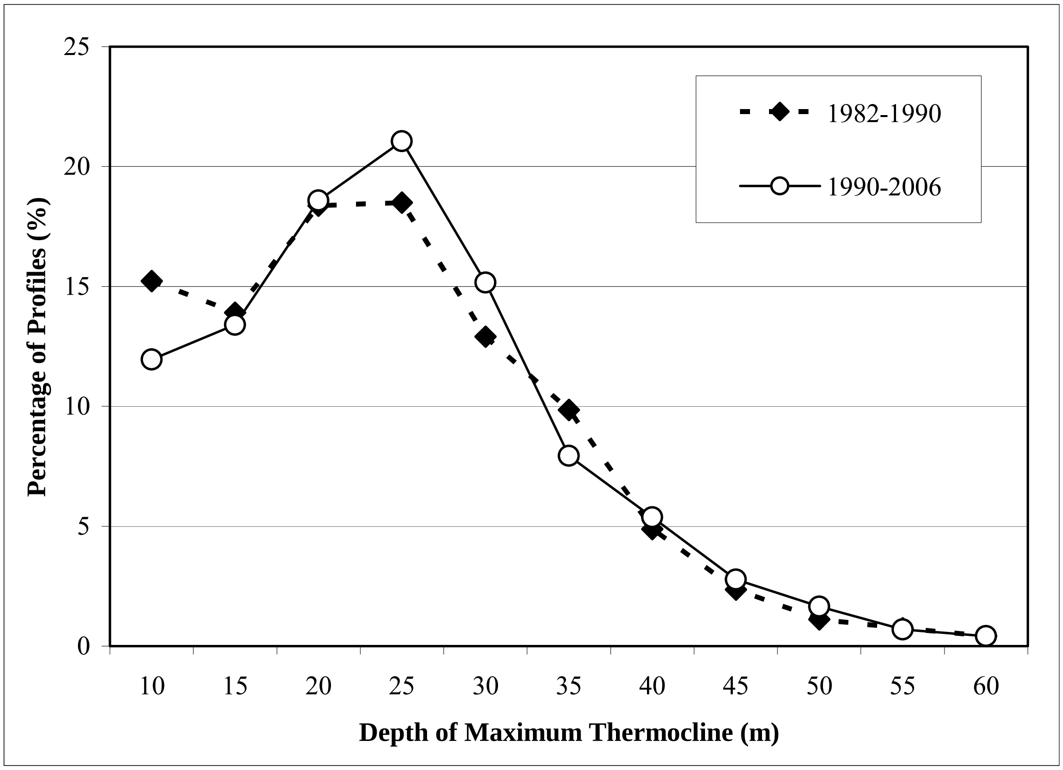


Figure 4.--Outer shelf (100 m < bottom depth ≤ 200 m) temperature profiles from the southern and northern portions of the survey area from the 1982-1990 and the 1990-2006 data. See Figure 1 for station locations (stars). Statistics associated with these profiles are presented in Table 4.



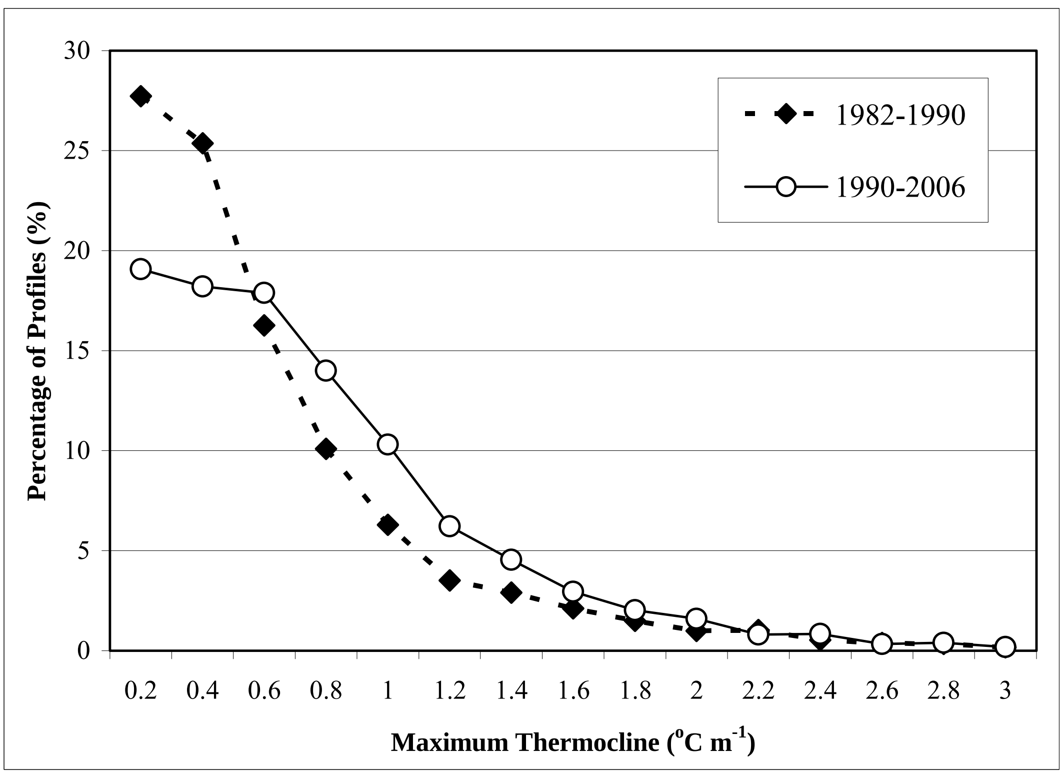
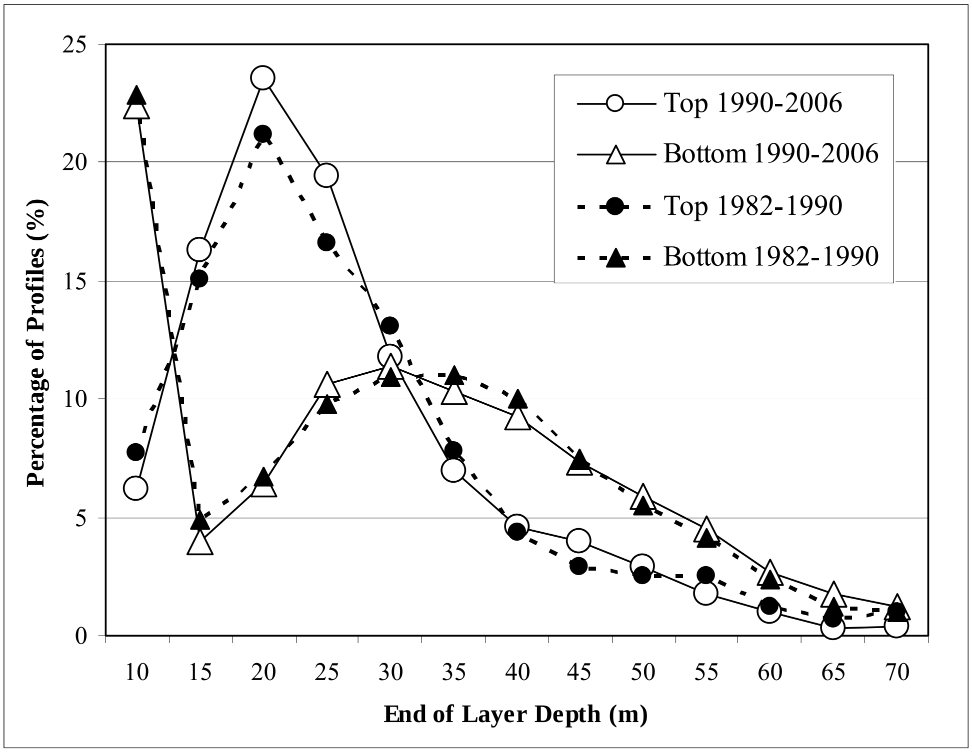


Figure 5.--Comparison of the frequency of the depth of the maximum thermocline (upper panel) and the strength of the maximum thermocline (lower panel) between 1982-1990 and 1990-2006 data.



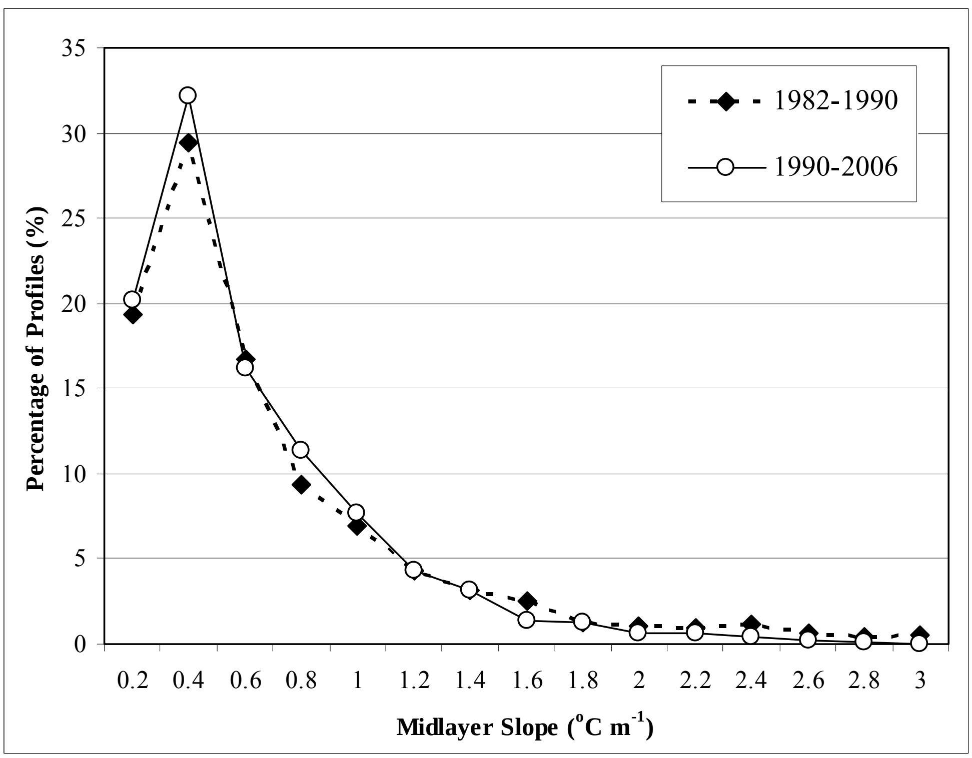


Figure 6.--Comparison of the frequency of the thickness of top layers and the thickness of bottom layers from 1982-1990 and 1990-2006 data (upper panel). And comparison of the frequency of the midlayer slope (°C m^{-1}) from 1982-1990 and 1990-2006 data (lower panel).

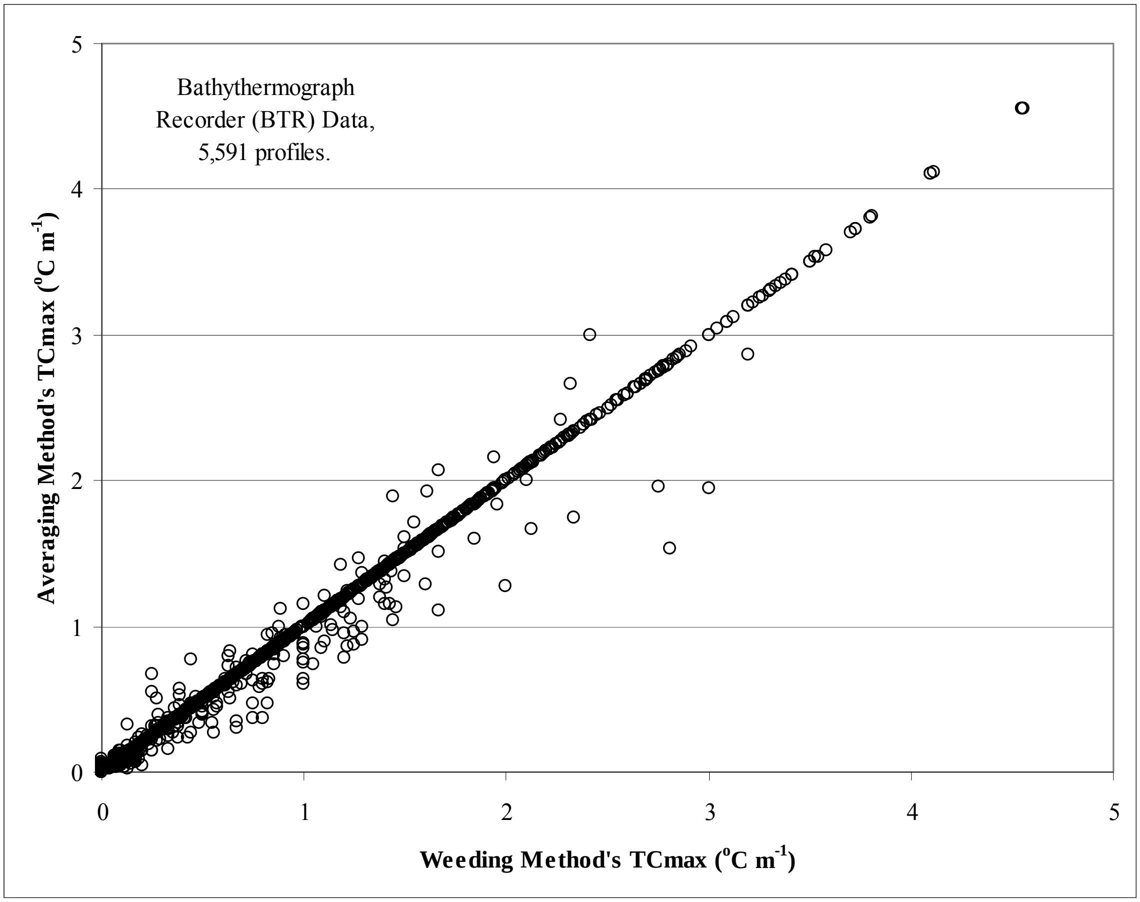


Figure 7.--Comparison of the maximum thermocline values (TC_{max}) calculated from 1990-2006 data that was thinned by averaging or by weeding in each 1 m depth bin. See Methods for a description of the data-thinning methods.

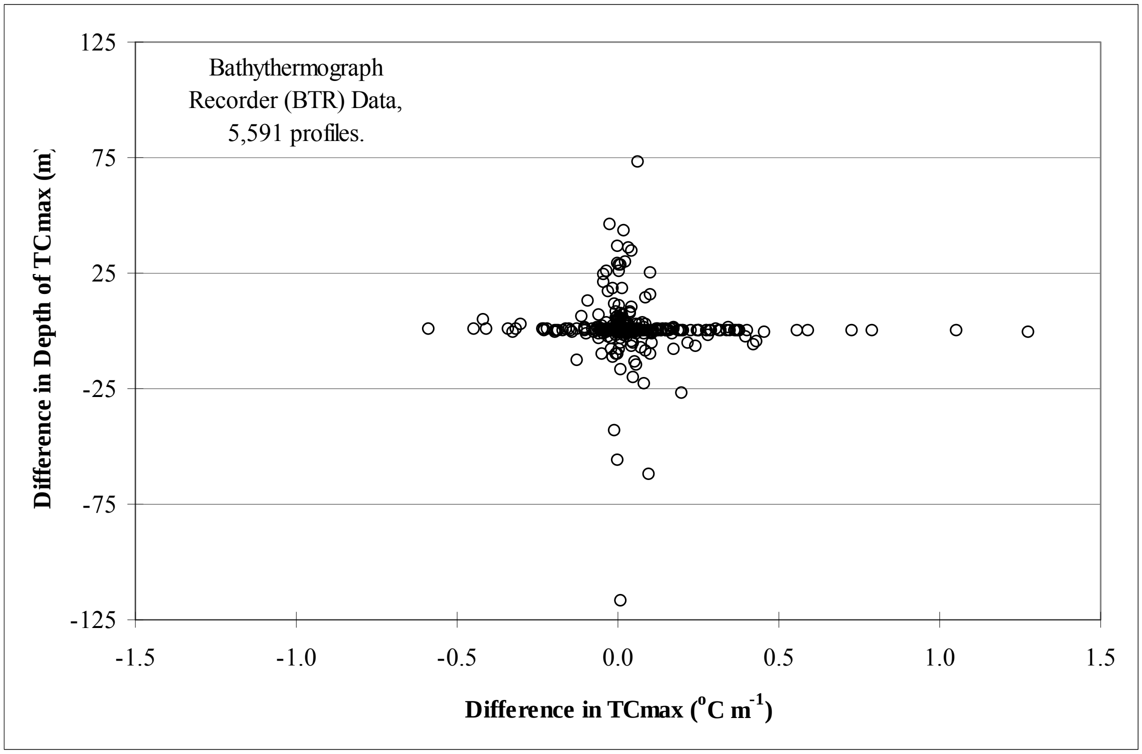


Figure 8.--Comparison of the difference in maximum thermocline values (TC_{max}) calculated from averaged and weeded data with the difference in the depth associated with the TC_{max} from each method of data thinning.

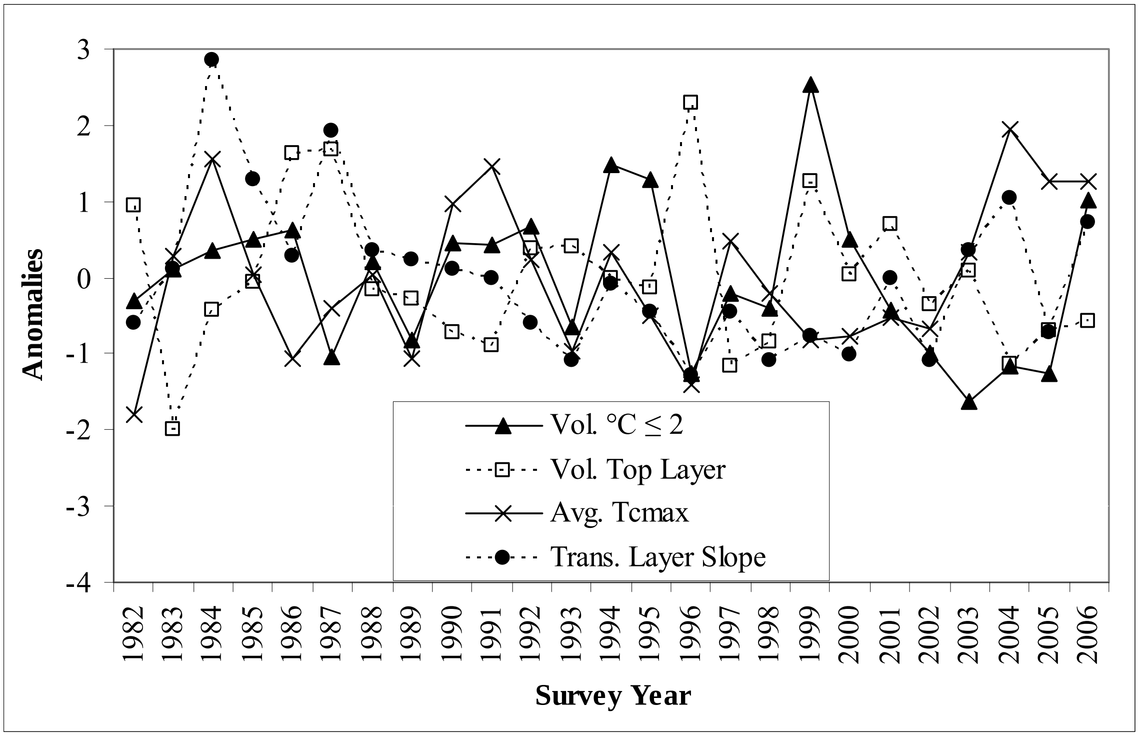


Figure 9.--Time series of some indices for the eastern Bering Sea presented as anomalies. The cold pool is represented by the volume of water with temperatures ≤ 2°C. Surface mixing is represented by the volume of the Top Layer. Stratification is represented by both the average of the TC_{max} and the average of the Transition Layer slope.

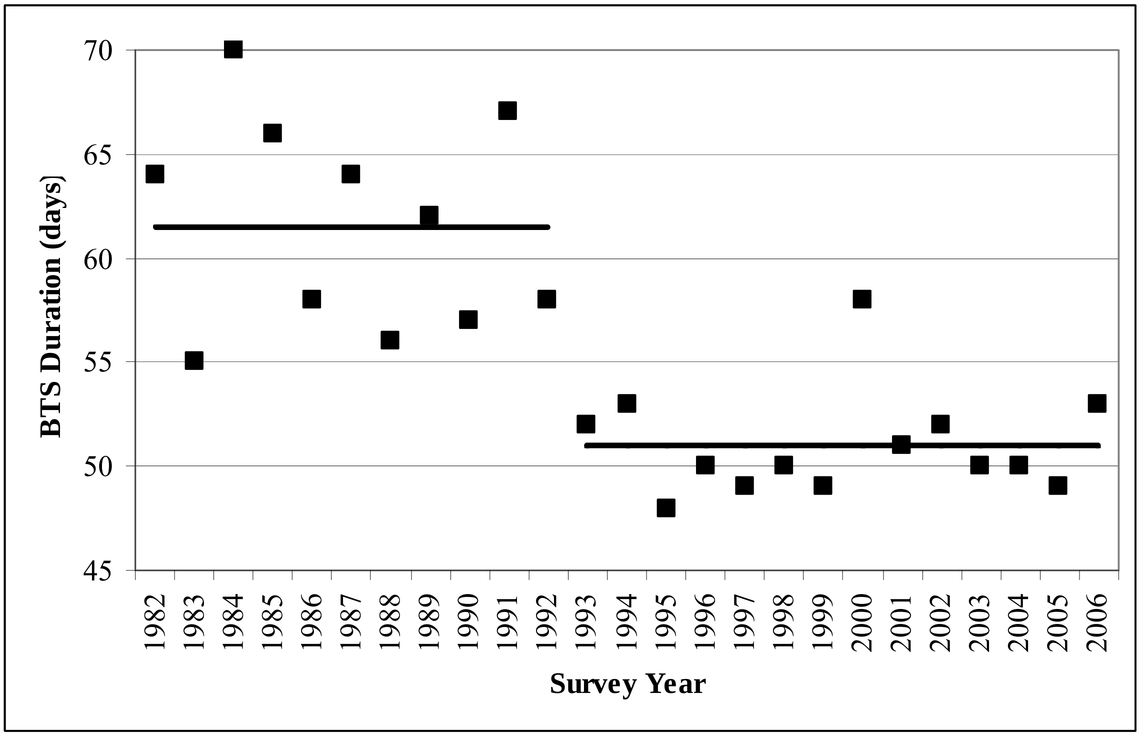


Figure 10.--Duration (End Day minus Start Day) of the AFSC bottom trawl survey (BTS) from 1982 through 2006.

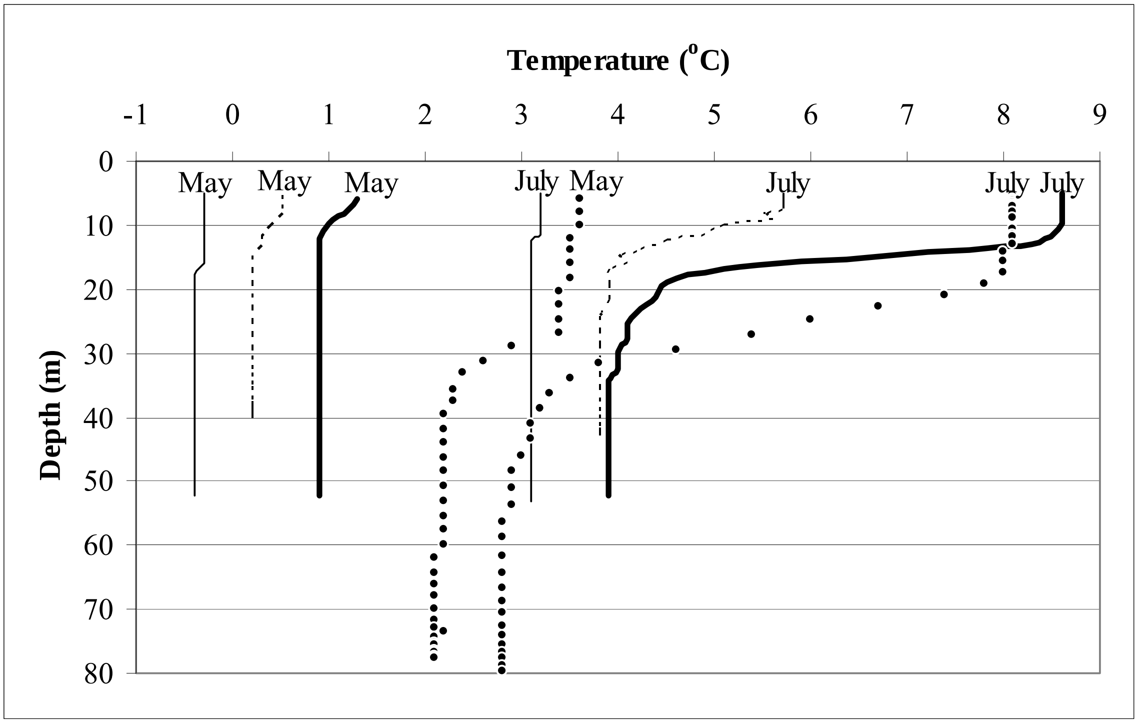


Figure 11.--Comparison of depth-temperature profiles at select stations taken during (May) and after (July) the EBS standard bottom trawl survey in 1999. The locations of stations I-13 (thin, solid line), I-9 (thin dashes), E-12 (thick, solid line), and C-8 (dots) are shown in Figure 1 and are individually identified by their row (letter) and column (number) coordinates on the survey grid.

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