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Distribution of maturing *Illex illecebrosus* Relative to the Shelf-Slope Water Front of the Northeastern United States

by

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ABSTRACT

Preliminary analyses of the association of Illex illecebrosus with the shelf-slope front were conducted. Information for the location of maturing Illex was obtained from catch per trawl data, standardized to kg per minute, as reported by United States Foreign Fishery Observers, from distant-water fisheries off the northeastern USA. Location of the shelf-slope front was determined from satellite infrared imagery data and charts.

INTRODUCTION

The short-finned or summer squid, Illex illecebrosus, is one of three species of the Ommastrephidae family found in the Northwest Atlantic. It has been observed as far north as Greenland, and south to Florida, with commercial concentrations from Newfoundland to Virginia, especially inshore in shallow waters during the summer. Illex undergo seasonal migrations with shoreward movements during the summer related to feeding, and offshore movements in late autumn toward spawning grounds which have not yet been identified. It is presumed that spawning, for the entire stock, occurs in deep waters off the shelf edge, south of the Chesapeake Bay, primarily in the northern edge of the Gulf Stream, and that eggs and larvae are transported from the spawning sites along the Gulf Stream - Slope water interface (Hatanaka, et al. 1984).

Illex have been taken in commercial fisheries off the USA and Canada since the early 1900's, and catches since the mid-1970's have been quite significant. However, great fluctuations occur in the annual availability of Illex. Understanding the factors associated with these fluctuations is important to the management of this stock. The present study investigates the influence of the shelf-slope front, a prominent oceanographic feature found in the vicinity of the outer continental shelf, on the distribution of Illex.

THE FISHERY

Initially Illex was taken only incidentally to other directed fisheries, especially inshore during the summer, and catches off each country averaged less than 500 t. However, beginning in the early 1960's, with the increase in effort applied by the distant-water fleet, catches increased rapidly. By 1973 annual catches exceeded 25,000 t and the International Commission for the Northwest Atlantic Fisheries (ICNAF) had established a pre-emptive quota of 71,000 t (for all squid taken in the area, including Loligo pealei and Illex illecebrosus), to take effect in 1974. This quota was designed to prevent overexploitation of these stocks before their population dynamics were more fully understood. In 1976, separate quotas were established for each species with a 55,000 t quota for Illex apportioned, 25,000 t for the waters off Canada (ICNAF areas 3+4) and 30,000 t to the area off the USA.

In early 1977, with the adoption of Extended Jurisdiction by the USA and Canada, management of the Illex fishery off each country became the responsibility of each coastal nation. The Illex quota off the USA has been maintained at 30,000 t (except in 1977 when it was set at 35,000 t), while the quota off Canada (under advice from the Northwest Atlantic Fisheries Organization, NAFO, ICNAF's successor) was increased, first to 100,000 t in 1978, then to 120,000 t for 1979, and to 150,000 t in 1980. This final quota of 150,000 t has been maintained off

Canada, since 1980.

Catches off the USA have averaged about 19,000 t (1972-83), and ranged from a peak of 25,000 t in 1976 and 1977, down to 15,000 t in 1983. Catches off Canada averaged about 44,000 t (1972-83) and ranged from a high of 162,000 t in 1979 down to 400 t in 1983.

The fishery occurs primarily during the summer months (July-September), in all areas, although Illex are also taken during the Loligo fishery and throughout the year off the USA. In general, the fishery begins in late June-July off the USA and in mid to late July off Canada, but depends on the timing of migration in any given year. Off the USA, since Extended Jurisdiction, the distant-water-fleet has been restricted to fishing within "windows" as depicted in fig. 1, with no fishing permitted between April 1 and June 15.

Illex occurs over a broad range of temperatures, from about 0° C to 15°C, with peak occurrence at 7° - 13° C (Roper and Lu, 1979). It is assumed that variability in the availability to the fishery is associated with differences in water temperature. If an association is found between the location of Illex catches and the proximity of specific water masses, we may be able to account for some of the annual variability in availability.

SHELF-SLOPE FRONT

A distinct Oceanographic feature is commonly found in the vicinity of the outer continental shelf, frequently within the "windows" authorized for foreign vessels fishing for Illex squid off the northeastern USA. This feature has been generally described by Ingham, et. al (1982) as follows:

"The shelf-slope front is located over or near the outer edge of the continental shelf, separating less saline and usually cooler shelf water from the slope water which lies offshore. The front is continuous from Cape Hatteras to Georges Bank and is present throughout the year. The shelf-slope front extends from the surface to the bottom, typically touching bottom at depths between 75 and 100 m and slopes seaward, with the surface intersection situated about 25 to 55 km offshore from the bottom contact (Beardsley and Flagg 1976).

The horizontal salinity gradient across the shelf-slope front is typically 1 to 2 ppt over 10 to 15 km and near-bottom temperature gradients are about 2-4 C throughout the year, but can be as much as 8 C (Bowman and Wunderlich 1977). Temperature contrasts across the front at the surface normally are about 4 to 6 C, but are much less intense from late June to September as the summer thermocline and a warm surface mixed layer cuts across the front (Bowman and Wunderlich 1977). The vertical temperature and salinity structure within the front can develop complex patterns because of inter-leaving of shelf and slope waters in the form of offshore extrusions of "cold pool" water at mid-depth, intrusions of slope water onto the shelf along the bottom and exchanges of surface waters. Gordon and Aikman (1981) hypothesized that considerable transfer of salt occurs from slope water to shelf water across this front during the summer stratification season. During this period the horizontal density gradient is minimal across the front facilitating the transfer of about half the salt required annually to balance fresh water inflow.

Examination of sea surface temperature patterns has shown that the front exhibits large wavelike motions of 100 km or more, propagating at speeds of about 5 cm/sec (Gunn 1978; Halliwell 1978). Robinson, et. al. (1974) found meanders along the front on scales of tens of kilometers with displacement speeds of 5 to 20 cm/sec. Such variations in the frontal position have been attributed to a dynamic response to atmospheric forcing (Stommel and Leetma 1972; Csanady 1973; Flagg and Beardsley 1978), Gulf stream meandering (Wright 1976), to the passage of warm core rings through the slope water (Beardsley and Flagg 1976; Celone and Chamberlin 1980) and because of destabilization of the front resulting from river discharge into the shelf water (Ketchum and Keen 1955; Ketchum and Corwin 1964).

Wind stress may be another cause of the offshore movement of the shelf-slope front due to Ekman transport (Boicourt and Hacker 1976; Beardsley and Flagg 1976) or interference with the normal momentum balance of the front in a direction parallel to the front, thus causing geostrophic adjustment normal to the front (Csanady 1978). Warm core Gulf Stream rings may also cause seaward extensions of the shelf/slope front due to the rings' currents (Morgan and Bishop 1977). Local baroclinic instability of the front over steep topography could be another factor affecting its movement (Flagg and Beardsley 1978).

Cresswell (1967) reported on the presence of detached parcels of shelf water within the slope water, which he believed had separated from the front by "calving", and Wright (1976) concluded that the detachment of such parcels, along with seaward excursions of the front, may account for most of the exchange required for salt balance of the shelf waters. The highly variable location of the shelf-slope front from Cape Hatteras to Georges Bank has been examined from weekly interpretations of surface thermal patterns using satellite-derived infrared imagery beginning in 1973 (Ingham 1976). Gunn (1979) compiled five-year means of these records and found that the mean position of the surface front remains close to the location of the 200 m isobath and variability averages about 50 km around the mean position. Hilland and Armstrong (1980) examined this five-year compilaton and described seasonal tendencies to the front's position, finding the front to be located more offshore during the first half of the year (maximum excursion in February to April) and more shoreward during the latter half of the year (extreme incursions in July to September). For the period of record for these analyses (1974-79), the most anomalous offshore excursion occurred in 1978 when the front generally was positioned distinctly offshore of normal (up to 150 km off southern New England) during spring and summer (Hilland and Armstrong 1980). This record excursion of the front in 1978 may have resulted from increased advection of shelf water from the east (Chamberlin 1978) or from a total absence of warm core rings in the slope water (Hilland and Armstrong 1980)."

Examples of the vertical temperature structure of the shelf-slope front during stratified periods (late spring-summer, fig. 2) and unstratified periods (autumn-early spring, fig. 3) show that it extends to the bottom on the outer shelf and upper slope, influencing the thermal habitat throughout the water column. The differences in temperature between the water masses are large enough and the horizontal temperature gradients are strong enough to influence the distribution of nektonic organisms preferring the temperature range of one mass or the other. An additional influence the front exerts on the distribution of nektonic organisms, including squid, is the accumulation of prey organisms along the front, which is the consequence of the fact that fronts involve convergence of surface water masses, necessary to maintain the strong horizontal gradients characteristic of fronts. In light of these factors, it is reasonable to expect the shelf-slope front to influence the distribution of Illex squid.

METHODS AND MATERIALS

In order to test the hypothesis that the shelf-slope front influences the distribution of adult Illex, we compared the positions and catch rates (kg/min) in the directed foreign fishery with the location of the front. The catch data were obtained from the logs kept by the NMFS Foreign Fishery Observers, and the frontal locations were determined by plotting trawl start positions on 'Oceanographic Analysis' charts (fig. 4) produced from satellite infrared imagery three times per week by the USA National Weather Service and National Environmental Satellite Service during fishing periods in 1980 and 1981.

Fishery Data

The NMFS Foreign Fishery Observer Program was established in 1977 to provide coverage of the distant-water-fleet vessels fishing in the USA Fishery Economic Zone, established under the Fishery Conservation and Management Act of 1976. Observers are deployed aboard foreign vessels for periods up to three weeks, during which time, along with other duties, they collect fisheries and biological data for the Northeast Fisheries Center. These data include a trawl log for each trawl completed during their deployment. These logs contain information to identify the observer's trip, the vessel, and the exact location and time of the trawl (starting and ending latitude, longitude, depth, and time), surface and bottom temperatures (when available), and details of the catch, in weight (kg) per species. A random subsample of trawl data for the summers (June-August) and autumns (September-December) of 1980, 1981 and 1982 were used in this study.

Oceanographic Data

Satellite-borne infrared radiometers provide a means of obtaining frequent synoptic views of the location of the shelf-slope front along its full extent from Georges Bank to Cape Hatteras, or at least those portions not obscured by clouds. Admittedly, the location of the surface trace of the front, which is seen by the satellite sensors, is not the same as the bottom trace, but the location of the surface trace certainly provides an indication of its proximity.

The infrared radiance data from the Advanced Very High Resolution Radiometers (AVHRR) on polar-orbiting satellites are processed by the U.S. National Earth Satellite Service into grey-scale imagery or digital, computer-ready formats. The imagery is used by staff scientists to produce the Oceanographic Analysis charts (fig. 4) made widely available three times each week. The digital data are held in archives and copies are made available to requesting scientists for further processing or analysis.

Analysis of Relationship between Front location data and *Illex* catch rate data

The first stage of this study involved analysis of data from autumn 1980 and 1981 and summer 1981. Each trawl location from the observer logs was hand-plotted on the Oceanographic Analysis chart closest in time to the trawl time, and distances between the trawl start positions and the shelf-slope front were estimated (to the nearest 5 nautical miles) from the charts. Data sets of paired values were constructed by listing the catch rate (kg/min) for each trawl with the estimated distance (nautical miles) between the trawl position and the shelf-slope front. A total of 1361 data pairs were obtained this way: 717 for autumn 1980, 317 for autumn 1981, and 327 for summer 1980. These three data sets were subjected to descriptive statistical analyses and graphical portrayals, in search for relationships between catch rate and proximity of the shelf-slope front.

There were considerable inaccuracies in plotting the trawl positions on the Oceanographic Analysis charts and estimating the distances to the front, because of the scale (1 mm=5.7 nm) involved, because of small errors made in the preparation of the charts, and because of changes in the front after the day represented by each chart. In an effort to eliminate these inaccuracies and to perform a more precise test of the hypothesis, we selected clear-sky periods in the satellite infrared data record for 1982, during which observer catch records were available, and determined the distances from the shelf-slope front from the satellite data collected on the days of the trawls, only. These distance measurements were made by displaying high resolution (about 1 Km) processed digital data (atmospheric and geographic corrections applied) on an image display monitor. Each image was enhanced to identify clearly the surface thermal trace of the shelf-slope front. Trawl positions were plotted on each relevant image while still on the monitor screen, and the distance between each trawl position and the front was calculated using a routine in the image-processing computer (fig. 5). The image analyses were performed at the University of Rhode Island's Oceanographic Remote Sensing Laboratory. Image processing software was developed and has been maintained by O. Brown, R. Evans, J. Brown, and A. Li at the University of Miami.

RESULTS

In the initial analysis, there appeared to be an influence on squid distribution in the autumn data, but none in the summer, so we concentrated on the autumn data subsequently. As portrayed in fig.s 6, 7, and 8, the percentage of "high" catch rates (one standard deviation above the mean) near the front was much larger than the percentage of time spent fishing there, as follows:

- in September-December 1980 (717 trawls), 46.9% of the trawls were begun within 10 nautical miles of the front, but 82.8% of the high catch rates were experienced there.

- in October-December 1981 (317 trawls), 63.7% of the trawls were begun within 10 nautical miles of the front, but 92.3% of the high catch rates were experienced there.

- in October-December 1982 (57 trawls, analysed with satellite data) 29.8% of the trawls were begun between 10 and 16 Km (5.4 and 8.6 nautical miles), but 100% of the high catch rates were experienced there.

In 1980 and 1981 in the autumn fishery over 50% of the high catch rates were experienced about 5 nautical miles ($\pm$ 2.5 nautical miles) from the front, as evident in fig.s 6 and 7, and a similar grouping was found n the smaller data set analysed for 1982.

It is evident from these results that in the autumn of the three years adult Illex squid were not uniformly distributed laterally in the vicinity of the shelf-slope front in the area occupied by the fishery, approximately 36°N - 40°N, in the allowed "windows" (fig. 1). Instead, they appear to have been more abundant within 10 nautical miles of the front.

DISCUSSION

Although the results of this study have not been conclusive, they were encouraging enough to stimulate us to conduct further analyses on other data sets and to pursue other hypotheses. For example, we need to determine if high catch rates were distributed preferentially on either the shelf side or the slope side of the shelf-slope front. Also, we need to consider in detail the possible influence of bathymetry on the distribution of high catch rates; in the small data set we analysed for autumn 1982 all of the high catch rates were located within 4 Km of the 200 m isobath. Biases in the fishery data due to restrictions in the areas where fishing is permitted and due to fishing practices associated with where *Illex* are expected to be, would also have to be considered more thoroughly in future analyses.

The analyses presented here are preliminary but they demonstrate a potential for using satellite imagery data inconjunction with fishery data to explain changes in local availability of *Illex* to the fishery. These data sets may also be useful for studying associations of other species with various oceanographic features. Techniques for such analyses, developed during this study, should be applicable to any future studies.

ACKNOWLEDGEMENTS

Dr. J.L. Chamberlin deserves credit for giving us the central concept for this study. For at least two years before his recent retirement, he suggested that someone should utilize the observer data from the foreign squid fishery, along with the satellite data base, to determine if either the shelf-slope front or the warm core Gulf Stream rings influence the distribution of *Illex* squid. He saw that both oceanographic features reach to the sea floor on the outer continental shelf and upper slope, which provides the potential to influence the distribution of nektonic organisms throughout the water column.

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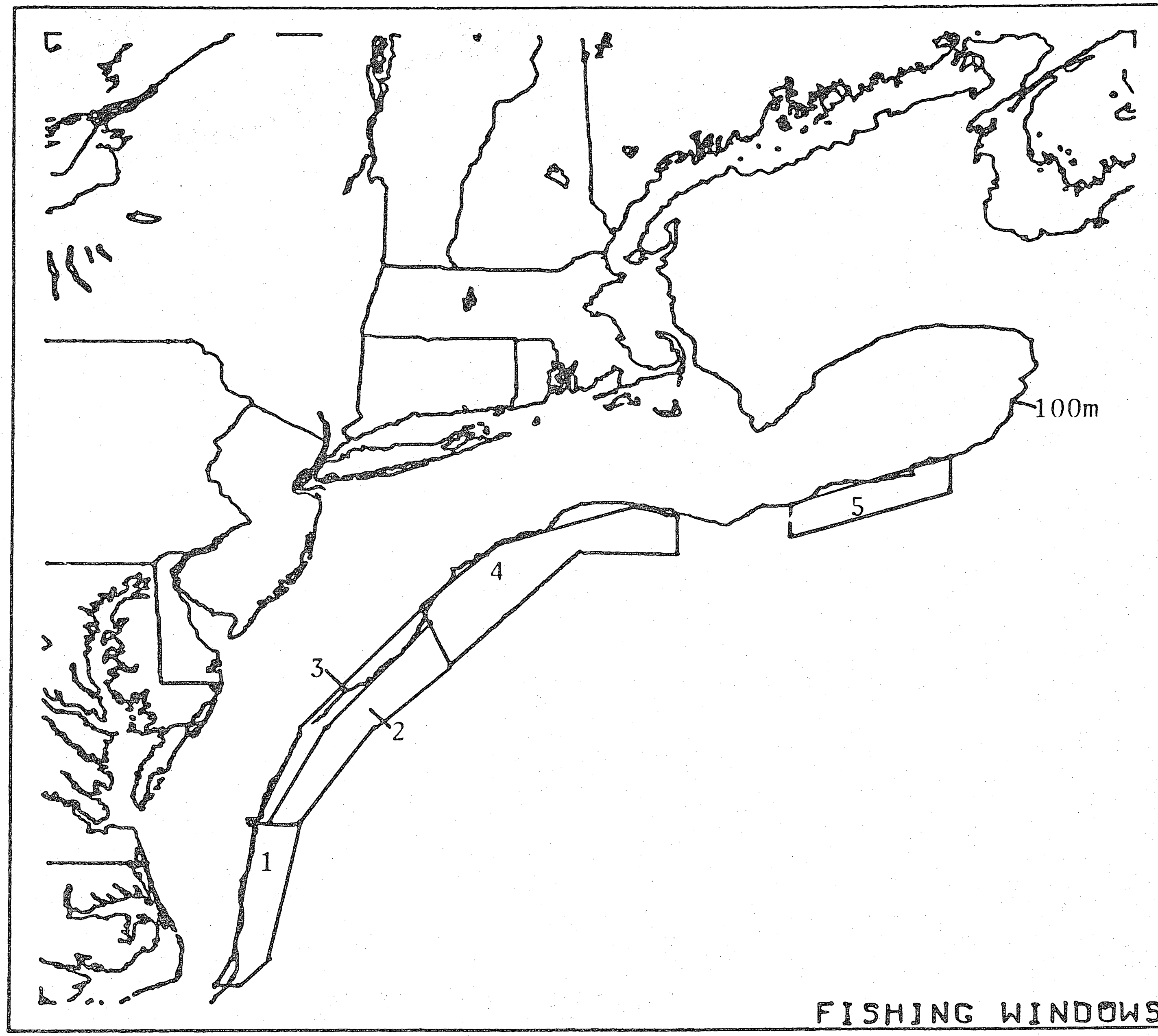


Figure 1. Areas of the Northwest Atlantic, off the USA, which are open to foreign fishing during authorized fishing seasons.

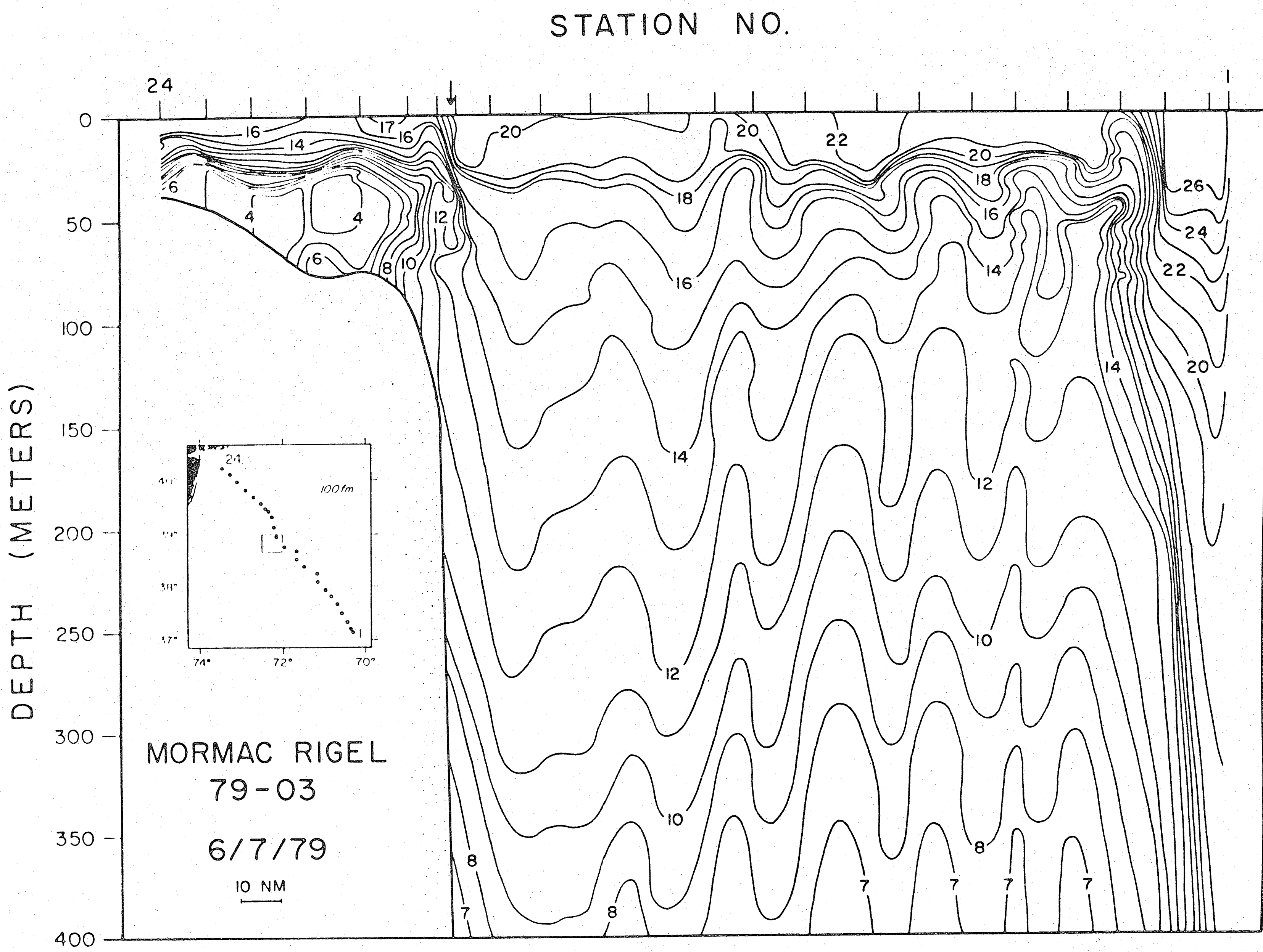


Fig. 2. Vertical section of water temperature (°C) obtained from an expendable bathythermograph transect conducted by a merchant ship-of-opportunity, the MORMAC RIGEL, on 7 June 1979.

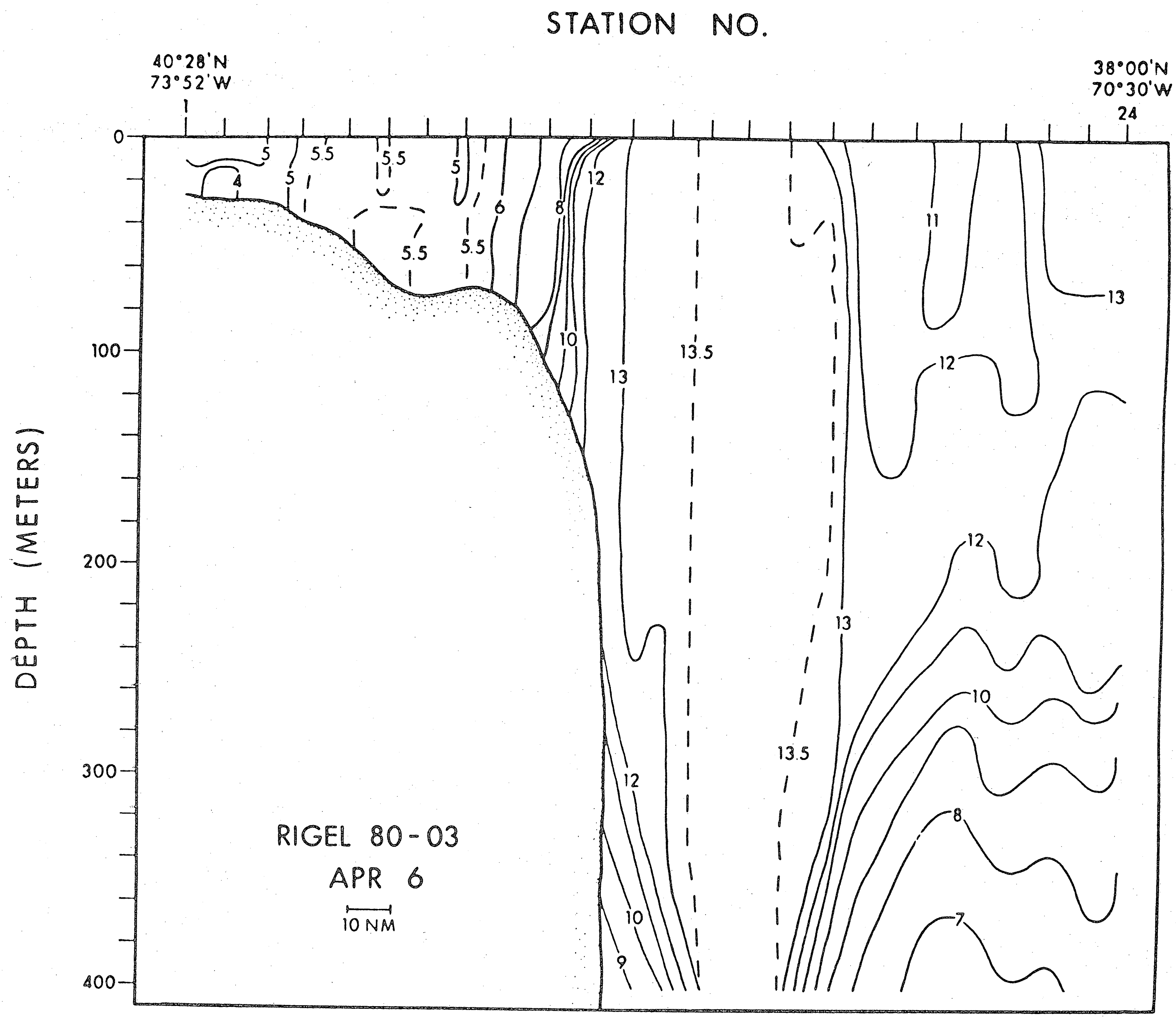


Fig. 3. Vertical section of water temperature (°C) obtained from an expendable bathythermograph transect conducted by a merchant ship-of-opportunity, the RIGEL, on 6 April 1980.

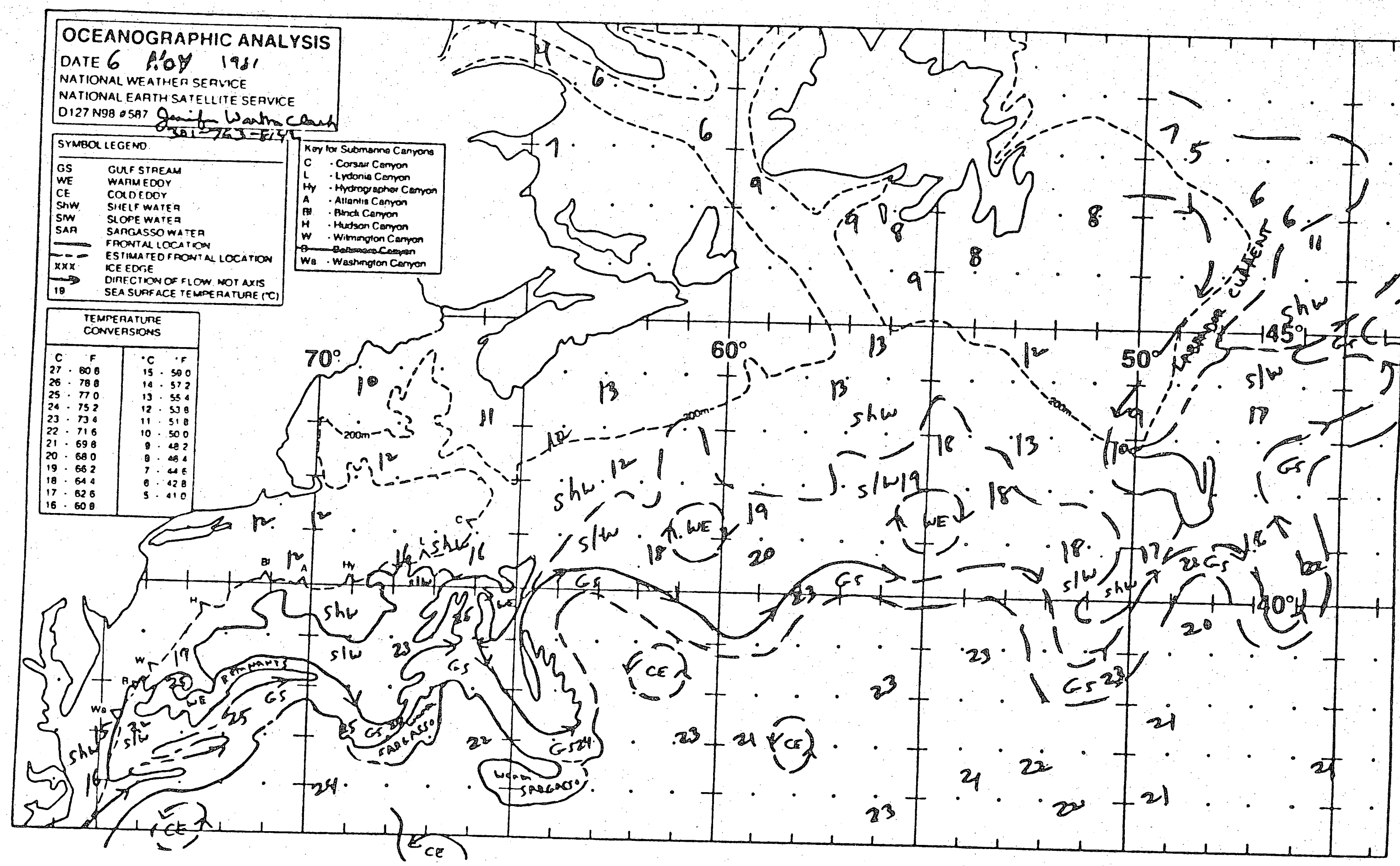


Figure 4. An example of the Oceanographic Analysis charts used to locate trawl positions relative to the shelf-slope front.

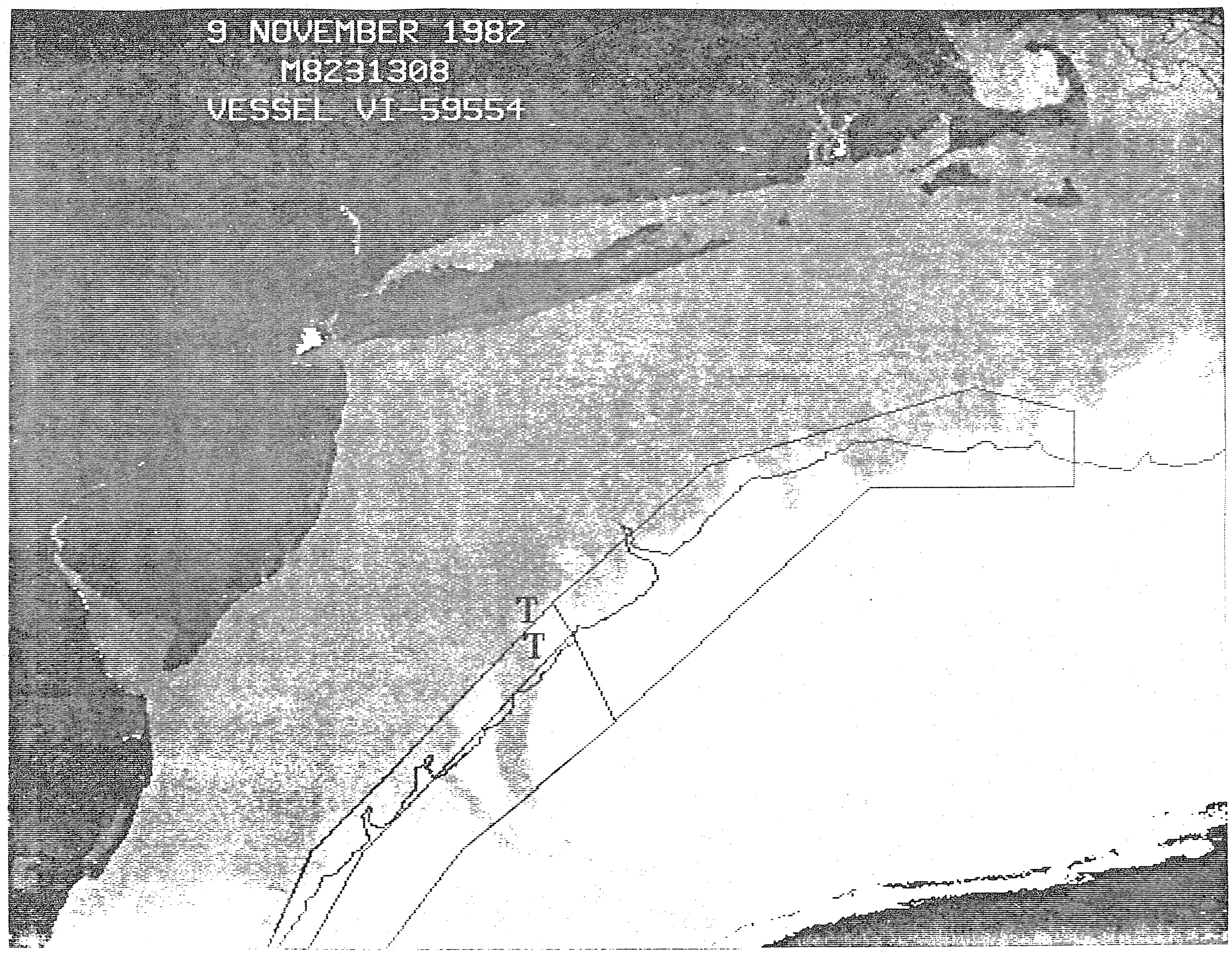
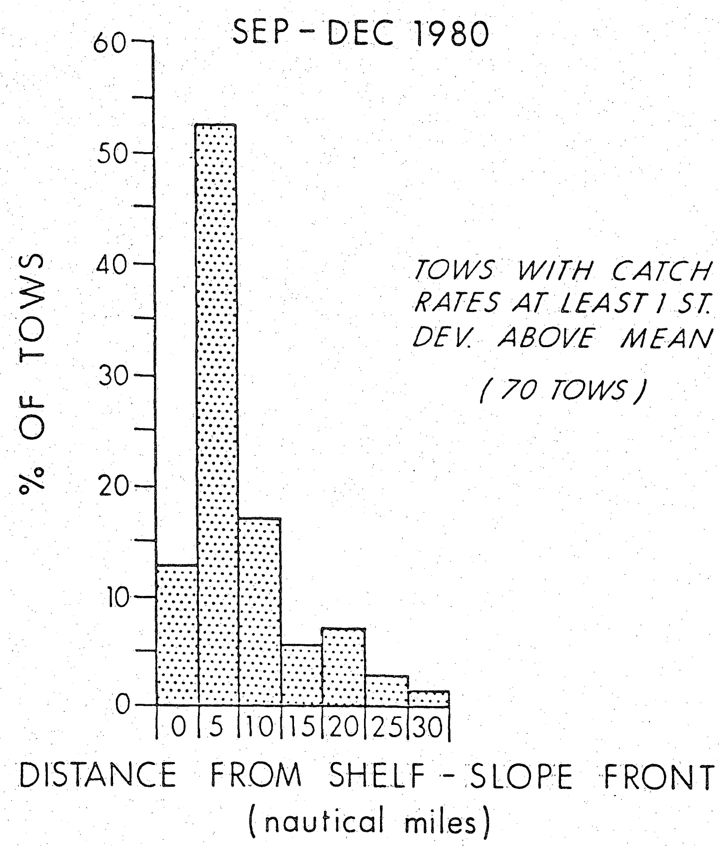


Figure 5. Sample of copy made from the image display monitor showing on infrared portrayal of the sea surface, with trawl positions (base of T symbols), fishing window and 200-m isobath superimposed. The image has been enhanced to show the shelf-slope front clearly, with the shelf water as grey and the slope water white.



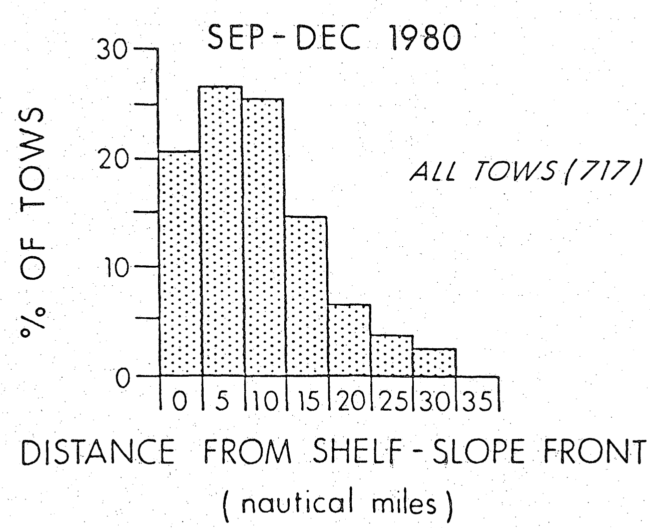
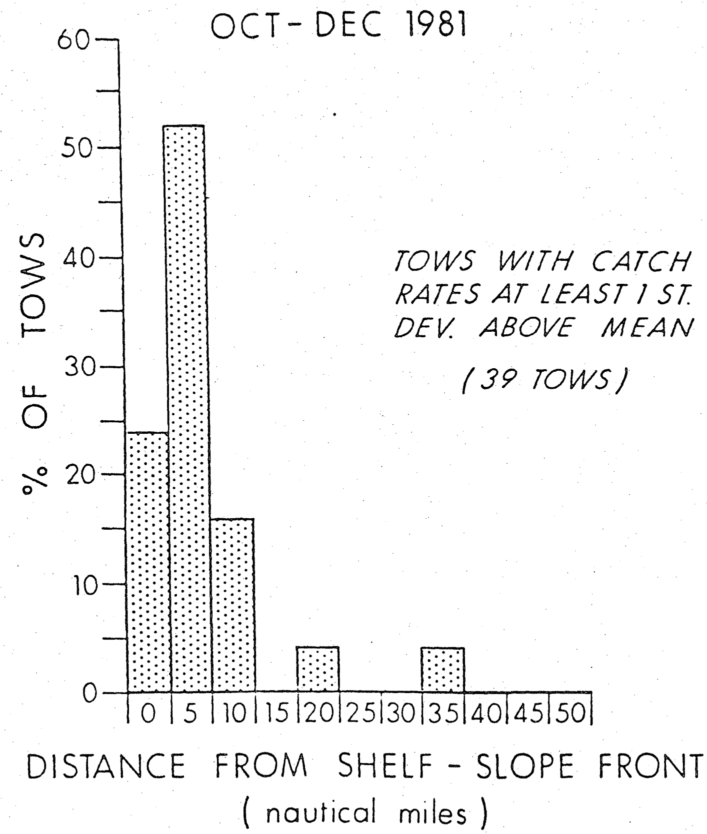


Figure 6. Distribution of fishing effort (lower graph) and high catch rates (upper graph) relative to the shelf-slope front for autumn 1980.



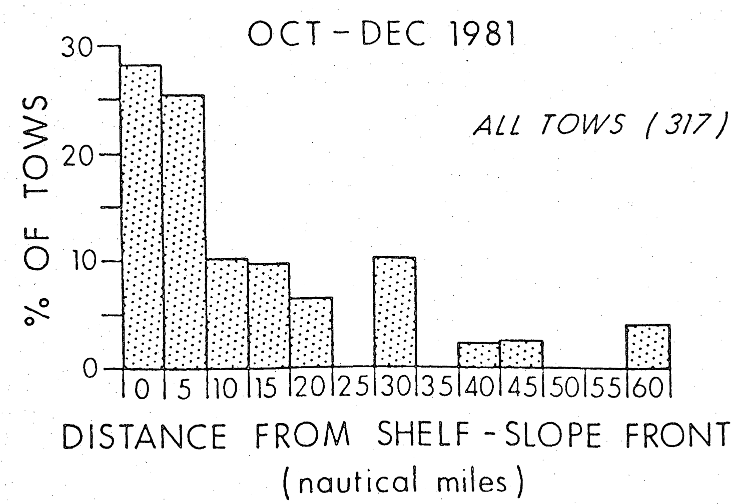
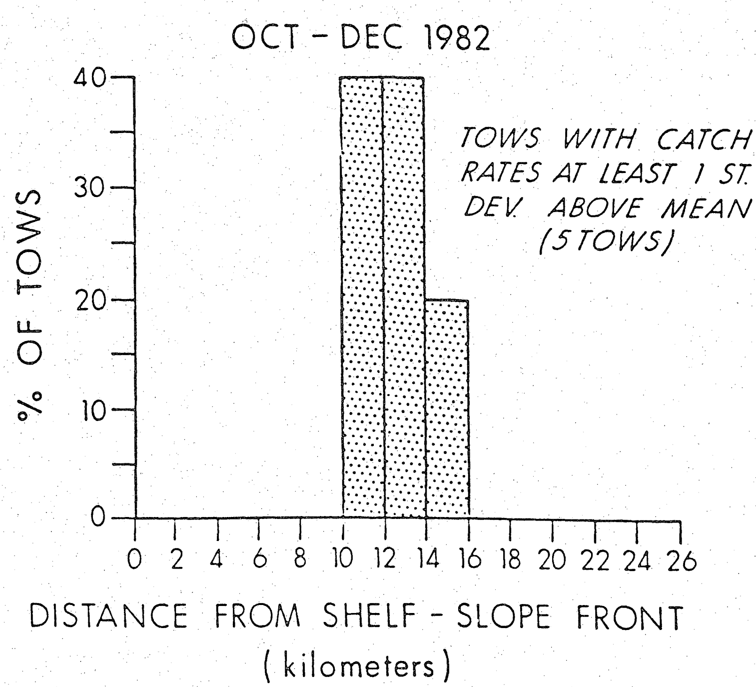


Figure 7. Distribution of fishing effort (lower graph) and high catch rate (upper graph) relative to the shelf-slope front for autumn 1981.



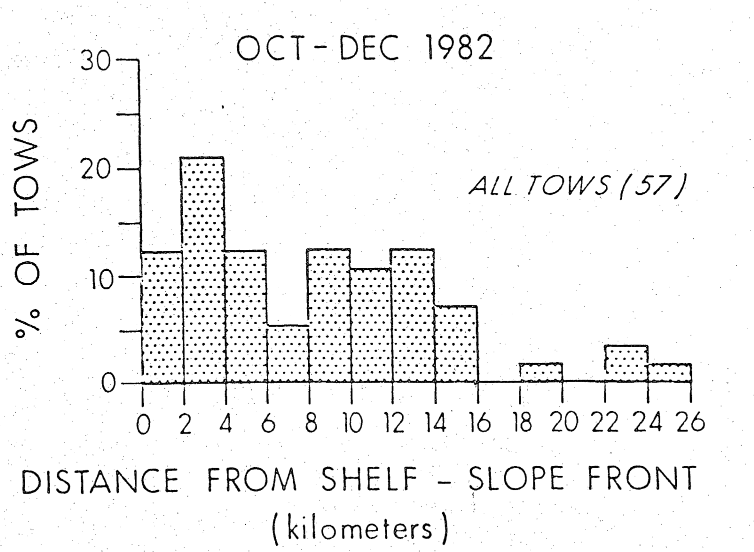


Figure 8. Distribution of fishing effort (lower graph) and high catch rates (upper graph) relative to the shelf-slope front for autumn 1982.