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Plankton of the Strait of Juan de Fuca 1976-1977

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PLANKTON OF THE STRAIT OF JUAN DE FUCA, 1976 - 1977

by

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by

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ABSTRACT

The exploitation of Alaskan oil deposits and anticipation of increased oil transport through the Strait of Juan de Fuca to Washington State refineries have generated concerns about the effects of petroleum spillage on local marine communities. Although aspects of plankton research have been actively pursued in Puget Sound and off the Pacific coast, virtually no previous quantitative investigations have been conducted in the Strait of Juan de Fuca.

The composition and distribution of phytoplankton, zooplankton, and ichthyoplankton communities was studied during 13 cruises conducted in the Strait of Juan de Fuca from February 1976 to October 1977. Phytoplankton was numerically dominated by microflagellate species during late autumn and winter months. During June 1976, a diatom bloom composed primarily of *Skeletonema costatum* was in progress, and chlorophyll concentrations as great as 25 mg m^{-3} were measured. Diatoms were also dominant in the spring and summer of 1977, but no bloom similar to that of 1976 was encountered. Ciliates numerically dominated the microzooplankton community, with oligotrichs and tintinnids the most abundant. The settled volumes of net zooplankton increased steadily through the late winter and spring. The highest levels coincided with the June 1976 phytoplankton bloom. The most numerous zooplankters were copepods, especially near-surface and surface-living calanoids and cyclopoids. The sporadic occurrence of a group of oceanic surface-living plankton species was associated with documented oceanic intrusions and current reversals. The ichthyoplankton, composed principally of fish larvae, were most abundant during the winter and early spring months.

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1. INTRODUCTION

An important aspect of NOAA's Marine Ecosystem Analysis (MESA) Puget Sound Energy-Related Project was to characterize the communities of the inshore marine waters of Washington State. With respect to the plankton, the least known major marine area is the Strait of Juan de Fuca, which separates Puget Sound from the Pacific Ocean. The present study was conducted in the Strait during 1976 and 1977 to describe the seasonal distribution and composition of phytoplankton, zooplankton, and ichthyoplankton populations. This information will add to MESA's overall biological baseline, and could aid in monitoring and understanding the effects of possible petroleum discharges associated with increased tanker transport through the Strait of Juan de Fuca. Data and interpretations are presented concerning species composition, phytoplankton biomass as indexed by chlorophyll concentration, zooplankton densities in the water column and at the surface, and distribution of ichthyoplankton.

The Strait of Juan de Fuca is a deep estuary connecting the inland marine waters of Washington State with the Pacific Ocean (Fig. 1). It is characterized hydrographically as a two-layered system with an annual net westward flow of relatively fresh water in the upper 30 m and more saline oceanic water below. The Strait receives a large influx of fresh water from drainages into Puget Sound and the Fraser River, which empties into the Strait of Georgia to the north. There are two periods of high runoff. The major one occurs in late spring when snowmelt is at a maximum in the Cascade and Olympic mountain ranges. A smaller runoff period occurs during late fall and winter when precipitation is high.

Physical oceanographic characteristics of the Strait of Juan de Fuca have been treated elsewhere (e.g. Herlinveaux and Tully, 1961; Cannon, 1978). In general, salinity dominates the density structure throughout the year. During the summer a thermocline coincides with the halocline to reinforce the stability of the upper layer. In the winter, waters are either isothermal or the upper layers tend to be slightly colder than deeper layers. Tides and tidal currents are considered to be important oceanographic components of the Strait of Juan de Fuca system. During flood tide, dense ocean water enters the outer Strait and flows beneath the upper zone. The inner Strait is a region of exchange where brackish water contributed by the Strait of Georgia is mixed to homogeneity and enriched with ocean water. Part of this water returns to the deep zone of Georgia Strait, and part escapes seaward in the upper zone of the Strait of Juan de Fuca during ebb tide. In addition to exchange with Georgia Strait, Juan de Fuca water mixes vigorously with Puget Sound and Hood Canal waters in the region of Admiralty Inlet during tidal flow. Because the Strait of Juan de Fuca is a positive estuary where strong tides mix coastal and inner basin waters, it is of interest to determine if the plankton communities found there are mixtures of coastal and embayment populations, or are distinct from those in the source waters. The information obtained also provides a basis for comparing future plankton observations and for designing future research efforts.

2. CONCLUSIONS

Thirteen research cruises were conducted at about 6 to 8 week intervals during 1976 and 1977 to provide information on the seasonal distribution and abundance of planktonic organisms in the Strait of Juan de Fuca. Major groups examined included phytoplankton, micro- and macrozooplankton, and ichthyoplankton.

Phytoplankton, the major primary producers of organic matter in pelagic ecosystems, were studied by biomass estimation (indexed by chlorophyll *a* content) and by direct species count. Pigment concentrations were highest during June 1976 at the time of a large spring phytoplankton bloom. No large bloom was encountered in the Strait during 1977, but it is possible that a bloom occurred between sampling periods. Major forms of phytoplankton included diatoms, dinoflagellates, coccolithophorids, and miscellaneous microflagellates. In general, microflagellates were the dominant component of the phytoplankton community during late autumn and winter months. Diatoms contributed the major biomass portion during mid-spring to early summer; high concentrations were also found during a fall bloom off Neah Bay in 1976. Dinoflagellates reached their maximum numbers during late summer and early autumn, especially at stations east of Neah Bay. Coccolithophorids were rare except when intrusions of ocean water flooded into the Strait. An analysis of species similarity showed the structure of diatom communities to be non-uniform from one end of the Strait to the other during any one cruise. Often the variability in percent species similarity during a single cruise was as great as variations between cruises.

Microzooplankton is thought to be an important, and often overlooked, trophic link between the smallest phytoplankton cells and the larger zooplankton. In the Strait of Juan de Fuca, particle grazing ciliates such as oligotrichs and tintinnids were most numerous. *Mesodinium rubrum*, a ciliate that may derive a major portion of its nutrition from photosynthetic endosymbionts, was also present in significant numbers. Besides protozoans, metazoans such as juvenile crustaceans, trochophore larvae, and rotifers occurred. Maximum microzooplankton concentrations coincided with periods of high phytoplankton concentration during spring aod summer.

Larger zooplankters are the major grazers of phytoplankton and as such represent a critical trophic intermediary between primary producers and carnivores, particularly commercially valuable fish. In general, the biomass of zooplankton closely followed the seasonal distribution of chlorophyll concentration in the upper 50 m of the Strait of Juan de Fuca. That is, maximum zooplankton biomass levels were observed in the spring and summer. Copepods were always the most abundant net-zooplankters, and these organisms showed the same seasonal trends as total zooplankton volume. Three groups of "oceanic" copepods not usually associated with coastal regions were identified in the

Strait of Juan de Fuca. One group, composed of deep-living oceanic species, is excluded from Puget Sound by the shallow entrance sill; a second group of deep oceanic copepods found occasionally near the surface is present in Puget Sound; and a third group of oceanic surface-living copepods was found in the Strait during periods of ocean-water intrusions and current reversals.

In contrast to the zooplankton, the highest concentrations of fish eggs and larvae were recorded in late winter and early spring, prior to the period of greatest phytoplankton productivity. The number of fish larvae usually exceeded the number of eggs present, probably because the most common larval forms in the Strait of Juan de Fuca are demersal spawners. Most larval species showed no particular preference for the surface waters, but one group, *Hexagrammos* spp., was pleustonic.

Of particular note is the unexpected presence of oceanic surface-living phyto- and zooplankton species in the Strait. These species occurrences were well correlated with times of independently documented oceanic intrusions. These intrusions can at times influence even the eastern portion of the Strait, and their presence suggests a reevaluation of ideas regarding pollution dispersement that are based on net water transport assumptions.

The Strait of Juan de Fuca is a dynamic estuarine system joining the Pacific Ocean and the inland marine waters of Washington State and British Columbia. The structure of the plankton community at any one time is influenced by the complex physical exchanges between these bodies of water as well as the biological characteristics of individual species and groups of species. Seasonal cycles outlined in this report can only be considered approximations of natural events. Short-term fluctuations could not be examined because of the long periods between sampling. Future investigations might profitably concentrate on the winter-spring transition period, stressing the increase in primary production and the coupling of zooplankton species productivity to phytoplankton biomass.

3. SAMPLING AND LABORATORY METHODS

Thirteen sampling cruises to the Strait of Juan de Fuca were conducted at intervals of approximately six weeks during 1976 and 1977. Sampling activities are summarized in Table 1. In general, during each cruise three transects of three stations apiece were made across the Strait at Port Angeles, Pillar Point, and Neah Bay near Cape Flattery (Fig. 1). Only the Port Angeles line was occupied during cruise SF7603 due to mechanical failure of the vessel.

At every station occupied, an obliquely towed plankton net and a pleuston sampler were used to sample the zooplankton. A double bongo net was used for the initial three cruises for oblique tows, but because of handling difficulties, this was replaced by a single net of similar configuration (333 μm mesh, 60 cm mouth diameter) suspended in a newly designed frame. Like the bongo net, the new single net had no bridle or other obstruction in front, and the mouth was free to swivel to maintain the net in a plane perpendicular to the towing direction. The oblique net was towed from 50 m to the surface while being slowly retrieved. For cruise SF7607 and all subsequent cruises, a digital flowmeter (General Oceanics, Model 2030) was fitted to the net frame to more accurately measure the volume of water filtered. The pleuston net, equipped with a 333 μm net, was towed at the surface, away from the ship's wake, for 10 minutes. The zooplankton samples were preserved with sodium acetate buffered 4% formaldehyde and returned to Seattle for analysis.

At each midchannel station (2, 5, and 8) only, a bottle cast and a series of vertical closing-net hauls were made in addition to the oblique and pleuston tows. Niskin bottles (1.5 l) were used to obtain water samples at 0, 10, 20, 30, 40, and 50 m. Subsamples were drawn directly to determine chlorophyll and pheopigment content and the phytoplankton and microzooplankton species assemblages. Phytoplankton and microzooplankton subsamples were preserved in an acetate buffered 1.5% formaldehyde solution. These were later analyzed in the laboratory using the inverted microscope technique described by Utermöhl (1931). Pigment concentration was measured with a shipboard fluorometer (Turner, Model 111) following the discrete sample method of Lorenzen (1966). The vertical hauls were made with a 211 μm mesh, 60 cm mouth diameter closing net. Usual depth strata sampled were: near bottom to 100 m, 100 m to 50 m, 50 m to 25 m, and 25 m to the surface. Sampling intervals were adjusted for shallower stations.

To compare the catch efficiency of the bongo net with the single net design and to examine the precision of these methods, a series of ten alternating oblique tows was taken during cruise SF7705; five replicate samples were obtained with each net. The total volume of plankton caught per volume of water filtered was determined for each sample; no significant

TABLE 1. Summary of sampling activities in the Strait of Juan de Fuca, February 1976 - October 1977.

Cruise	Date	Vessel	No. of Stations	No. of Samples							
				Oblique	Pleuston	Vertical	Phytoplankton	Microzooplankton	Chlorophyll	Pheopigments	CTD Casts
SF7601	23-24 Feb	_Commando_	8	8	8	11	18	2	18	18	0
SF7602	5-6 Apr	_Commando_	9	9	9	11	18	5	18	18	3
SF7603	17-18 May	_Hydah_	7	7	7	11	18	4	18	18	0
SF7604	28-30 June	_Snow Goose_	9	9	9	11	18	3	18	18	3
SF7605	3-5 Aug	_Snow Goose_	9	9	9	11	18	4	18	18	3
SF7606	14-16 Sept	_Snow Goose_	9	9	9	11	18	3	23	23	3
SF7607	12-15 Nov	_Snow Goose_	9	9	9	11	18	3	18	18	3
SF7701	11-13 Jan	_Snow Goose_	9	9	9	11	18	3	18	18	1
SF7702	22-25 Feb	_Snow Goose_	9	9	9	11	18	3	18	18	3
SF7703	5-6 Apr	_Snow Goose_	9	9	9	11	18	3	18	18	3
SF7704	1-3 June	_Snow Goose_	9	9	9	11	18	3	18	18	3
SF7705	25-28 July	_Snow Goose_	9	18	9	19	22	3	30	30	3
SF7706	3-5 Oct	_Snow Goose_	9	9	9	11	18	3	18	18	3
		Totals:	114	123	114	147	238	42	251	251	31

difference (0.05 level) was found between the means of the two groups.

Settled volumes of all zooplankton samples were determined. Large or otherwise conspicuous organisms were removed, counted, and identified at least to major taxonomic group. Fish eggs and larvae were delivered to the Northwest and Alaska Fisheries Center of the National Marine Fisheries Service for further identification. Subsamples were obtained with a Folsom plankton splitter (McEwen et al., 1954) and sorted entirely to major taxonomic groups. Principal species and copepods were identified and counted.

During cruises SF7602 and SF7604-SF7702, a hand-lowered CSTD (Interocean, Model 513A) was employed at the midchannel stations to collect salinity and temperature information in the upper 100 m. During subsequent cruises, a Plessey Environmental Systems CTD Model 4600 was used.

Data collected are archived on magnetic tape and are available at NOAA's National Oceanographic Data Center in Washington, D.C.

4. RESULTS AND DISCUSSION

4.1. PHYSICAL CHARACTERISTICS

CTD casts were made during 11 cruises. The vertical profiles of temperature, salinity and density are generally consistent with the pattern described by Herliveaux and Tully (1961). During April (SF7602), the deeper waters tended to be slightly warmer than overlying layers. For all cruises the surface salinity increased in a seaward direction. A well-developed pycnocline with a distinct surface layer in late June (SF7604) coincided with a peak of phytoplankton biomass and is probably an important factor influencing the development of the bloom. Profiles obtained during later cruises clearly show that salinity controls the density field. Although surface waters were warmed, the lack of a well-defined halocline prevented the formation of a shallow stable layer.

4.2. OCEANIC INTRUSIONS AND INDICATOR SPECIES

The sporadic occurrence in the Strait of Juan de Fuca of a group of oceanic surface-living plankton species (Table 2) was unexpected, in view of the quasi-constant surface outflow. In November 1976, a large bloom of phytoplankton occurred off Neah Bay (Station 8) and was accompanied by typically offshore phytoplankton and zooplankton species. Physical parameters had been independently monitored at that time and revealed an intrusion of relatively warm ocean water in the Strait (Cannon, 1978). During two cruises in 1977, there were no independent physical data available to supplement the occurrence of some of these characteristically oceanic species. At other times these oceanic species were present only at or near times of documented oceanic intrusions and current reversals (Table 2). Thus, these species appear uniquely associated with oceanic intrusions and could act as "indicators" of surface oceanic water masses, which at times influence even the easternmost limits of the Strait. In light of the existence of these surface reversal events, thoughts about contaminants rapidly flushing out to sea in the surface outflow should be revised.

4.3. PHYTOPLANKTON DISTRIBUTION

There is little published information dealing directly with the seasonal distribution of phytoplankton in the Strait of Juan de Fuca. The available data are largely limited to the San Juan Archipelago (e.g. Gran and Thompson, 1930; Phifer, 1933; Phifer, 1934a; Thompson and Phifer, 1936) and Puget Sound proper (e.g. Hirota, 1967; Booth, 1969; Munson, 1969; Winter et al., 1975; Campbell et al., 1977). Phifer (1933) found two major diatom maxima in the waters of the San Juan Islands. These occurred from late May to early June and from mid-July to mid-August. Phifer (1934b) also studied the vertical

TABLE 2. Current reversals (intrusions) and presence of oceanic surface-living plankton species, Strait of Juan de Fuca, February 1976 - October 1977.

		ZOOPLANKTON									PHYTOPLANKTON				
Reversals	**Cruises**	*Calanus tenuicornis*	*Clausocalanus lividus*	*Clausocalanus parapergens*	*Calocalanus styliremis*	*Acartia danae*	*Phronima sedentaria*	*Dictyocysta reticulata*	*Parafavella gigantea*	Radiolarians	Coccolithophorids	*Bacteriastrum delicatulum*	*Asteromphalus heptactis*	*Rhizosolenia alata*	*Chaetoceros convolutus*
Feb 16 - Feb 22 (1976) Feb 28 - Mar 2	SF7601 (Feb 23-24)	X	X	X	X	X					X				
Mar 20 - Mar 30	SF7602 (Apr 5-6)		X	X							X				
	SF7603 (May 17-18)														
	SF7604 (Jun 28-30)														
	SF7605 (Aug 3-5)														
	SF7606 (Sep 14-16)														
Nov 14 - Nov 19 Dec 8 - Dec 9 Dec 14 - Dec 18 Dec 26 - Dec 28	SF7607 (Nov 12-15)	X	X	X				X	X	X	X	X	X	X	X
Jan 1 - Jan 5 (1977) Jan 14 - Jan 19	SF7701 (Jan 12-13)	X	X	X		X				X	X	X			X
Feb 2 - Feb 3 Feb 5 - Feb 14	SF7702 (Feb 23-24)	X	X	X	X	X	X			X	X				X
	SF7703 (Apr 7-8)		X	X											
no data	SF7704 (Jun 2-3)														
	SF7705 (Jul 26-27)										X				
Aug 31 - Sep 2 Sep 6 - Sep 8 Sep 21 - Sep 25	SF7706 (Oct 3-5)		X								X	X			

distribution of diatoms in the Strait of Juan de Fuca for a single cruise during July and reported that most diatoms were found in the upper 25 m. Shim (1976) observed diatom populations in the Strait of Georgia, B.C. and the eastern part of the Strait of Juan de Fuca and also reported two major diatom maxima. He generally found a rapid increase in standing crop in April, followed by a sharp decline in May. A second peak occurred during the early summer months. Winter et al. (1975) noted that the annual pattern of phytoplankton growth in Puget Sound was dominated by several intense blooms between early May and September and commented that the onset of blooms in the main basin of Puget Sound is late for the latitude of 48°N. They stated that algal concentrations changed drastically within time periods shorter than two weeks. Munson (1969) found incident light, freshwater runoff, and tidal range to be the three factors most useful in predicting the onset and disappearance of blooms in Puget Sound. Campbell et al. (1977) identified wind stress as a fourth important variable. These factors may also act to control phytoplankton growth in the Strait of Juan de Fuca where tidal currents, thermohaline properties, and wind stress affect water column stability. The formation of a stable upper layer is usually prerequisite to the occurrence of a phytoplankton bloom because the average light intensity in a vigorously mixed water column is insufficient for sustained growth.

4.3.1. Phytoplanktonic biomass

Chlorophyll *a* values integrated over the upper 50 m show that a large spring bloom was in progress at all stations during late June 1976 (Fig. 2). Point values as high as 25 mg Chl *a* m^{-3} were observed at that time (see Appendix A for vertical profiles of chlorophyll and pheopigments at all stations). By August, pigment concentrations had declined to prebloom levels. Progressively lower levels were encountered at the two innermost stations (2 and 5) through January 1977. At these stations, moderately increasing chlorophyll values were noted during the following spring and summer. The outermost station (8) was the site of a distinct autumn phytoplankton bloom during November 1976, coinciding with a strong oceanic intrusion. Winter chlorophyll concentrations were significantly greater at station 8 than at stations 2 and 5 during both 1976 and 1977. No large phytoplankton bloom was observed in the Strait during 1977. Surface concentrations in the range of only 1-2 mg m^{-3} were commonly measured. It is possible that a bloom did occur between sampling periods and was therefore not detected.

Measuring the chlorophyll *a* content is the only rapid method for estimating the biomass of living phytoplankton cells in seawater. Statistical reliability of the chlorophyll technique is very much dependent on the total amount of pigment being analyzed, but precision (P) is better than 8% of any value exceeding 0.5 mg m^{-3}. The 95% confidence interval about a mean of n samples is equal to $\pm P n^{-\frac{1}{2}}$ (Strickland and Parsons, 1972).

Statistical variability was briefly examined during one cruise. Six bottle casts were made in quick succession to sample surface seawater at one location. A 95% confidence level of ± 0.07 about a mean of 0.81 mg m^{-3} was calculated. This measure of variability includes errors in analysis as well as patchiness in the imediate vicinity.

TABLE 3. Diatom species in upper 1 m, Strait of Juan de Fuca.

	FEB 1976	APR	MAY	JUN	AUG	SEP	NOV	JAN 1977	FEB	APR	JUN	JUL	OCT
Actinoptychus splendens							X						
Actinoptychus undulatus							X	X	X	X	X	X	
Amphiprora gigantea v. sulcata	X						X						
Asterionella japonica				X	X		X				X	X	X
Asteromphalus heptactis							X						
Bacteriastrum delicatulum					X		X	X					X
Bellerochea malleus								X		X			
Biddulphia aurita				X									X
Biddulphia longicruris					X								X
Biddulphia longicruris v. hyalina							X						
Ceratulina bergonii							X				X	X	X
Chaetoceros affinis				X								X	X
Chaetoceros approximatus												X	
Chaetoceros brevis				X						X			
Chaetoceros compressus				X			X				X	X	
Chaetoceros concavicornis	X			X			X				X	X	X
Chaetoceros constrictus				X			X	X				X	
Chaetoceros convolutus							X	X	X				
Chaetoceros danicus													X
Chaetoceros debilis				X		X	X	X		X	X	X	X
Chaetoceros decipiens				X			X		X	X	X	X	X
Chaetoceros didymus				X			X	X	X		X	X	
Chaetoceros gracilis	X	X	X		X	X	X	X		X	X	X	
Chaetoceros laciniosus												X	X
Chaetoceros lorenzianus													
Chaetoceros radicans			X	X	X		X				X		
Chaetoceros secundus									X	X		X	X
Chaetoceros similis				X	X	X					X	X	
Chaetoceros socialis							X						
Chaetoceros subsecundus												X	
Chaetoceros teres													X
Chaetoceros tortissimus				X									
Chaetoceros vistulae												X	
Cocconeis				X					X	X	X	X	

TABLE 3. (Cont.)

	FEB 1976	APR	MAY	JUN	AUG	SEP	NOV	JAN 1977	FEB	APR	JUN	JUL	OCT
Corethron hystrix				X			X	X		X	X		X
Coscinodiscus angstii							X						X
Coscinodiscus asteromphalus							X	X	X		X		
Coscinodiscus centralis												X	X
Coscinodiscus centralis v. pacifica					X			X					
Coscinodiscus concinnus								X	X		X		
Coscinodiscus curvatulus							X		X		X		
Coscinodiscus granii											X		X
Coscinodiscus lineatus	X		X	X	X		X	X	X	X			X
Coscinodiscus marginatus			X	X			X	X	X				
Coscinodiscus nitides										X	X		
Coscinodiscus oculus-iridis													X
Coscinodiscus radiatus						X	X	X	X			X	X
Coscinodiscus stellaris	X									X			
Coscinodiscus wailesii							X						
Cylindrotheca closterium												X	X
Ditylum brightwellii			X	X		X	X	X	X		X	X	X
Eucampia zoodiacus					X	X	X	X					X
Fragilariopsis spp.	X	X			X			X	X	X			
Grammatophora marina										X			
Lauderia borealis					X								
Leptocylindrus danicus			X		X		X				X	X	
Leptocylindrus minimus										X	X		
Licmophora abbreviata	X						X	X	X	X	X	X	
Melosira sulcata	X	X	X	X	X	X	X	X	X	X	X	X	X
Navicula directa									X	X	X		
Navicula distans									X	X			
Nitzschia delicatissima			X	X	X	X	X	X	X	X	X		
Nitzschia longissima	X	X	X	X	X	X	X	X	X	X	X	X	
Nitzschia pungens				X									
Nitzschia seriata			X					X				X	X
Pleurosigma spp.									X				

TABLE 3. (Cont.)

	FEB 1976	APR	MAY	JUN	AUG	SEP	NOV	JAN 1977	FEB	APR	JUN	JUL	OCT
Rhizosolenia alata							X						
Rhizosolenia alata f. gracillima								X					
Rhizosolenia delicatula							X	X	X		X		X
Rhizosolenia fragilissima							X		X	X	X		
Rhizosolenia hebetata f. semispina											X		X
Rhizosolenia setigera	X		X	X		X	X	X	X	X	X		
Rhizosolenia simplex													X
Rhizosolenia stolterfothii						X	X	X			X	X	X
Rhoicosphenia curvata	X										X		
Skeletonema costatum	X	X	X	X	X	X	X	X	X	X	X	X	
Stephanopyxis nipponica				X			X			X	X		
Thalassionema nitzschiodes	X	X	X	X	X	X	X	X	X	X	X	X	X
Thalassiosira aestivalis			X	X	X	X	X		X	X	X	X	X
Thalassiosira bioculata							X			X	X		
Thalassiosira condensata				X							X		
Thalassiosira decipiens			X	X		X	X	X		X	X	X	X
Thalassiosira excentrica	X		X	X		X	X	X	X	X	X	X	X
Thalassiosira gravida													
Thalassiosira lineata											X	X	X
Thalassiosira nordenskioldii	X		X	X	X		X		X	X	X		
Thalassiosira pacifica			X	X	X	X	X	X	X	X	X	X	X
Thalassiosira polychorda			X	X		X	X	X	X	X		X	X
Thalassiosira rotula				X		X	X	X	X	X	X	X	X
Thalassiosira subtilis							X	X					
Thalassiothrix frauenfeldii												X	X
Thalassiothrix longissima													X
Tropidoneis antarctica polychorda							X	X					X

4.3.2. Phytoplankton species composition

Phytoplankton cells in the surface and 50 m water samples from the mid-channel stations were enumerated to provide information on the spatial and temporal distributions of algal populations in the Strait of Juan de Fuca. Tabulated data from all stations are included in Appendix B. Chester et al. (1977) commented on the statistical reliability of these data. Phytoplankton groups found included diatoms, dinoflagellates, coccolithophorids, and miscellaneous microflagellates. Unidentifiable microflagellates often dominated a community in terms of absolute numbers, but their relative biomass was not nearly as great since the size of individual cells was small (5-10 μm). Microflagellates could not be identified to lower taxonomic categories because of preservation distortions and the limitations of light microscopy.

Diatoms contributed much of the phytoplankton biomass, especially in the spring, because the average cell size was large. Over the 2-year study, 93 species in 32 genera of diatoms were identified (Table 3). In general, diatoms were most plentiful from mid-spring to early summer, but high concentrations were also observed during the fall bloom off Neah Bay (Sta. 8) in 1976 (Fig. 3). During mid-winter, *Melosira sulcata* and *Thalassionema nitzschiodes* were the most numerous diatoms encountered. *M. sulcata* is a littoral species that lives almost exclusively in association with nearshore substrates. Parts of chains often break away and occur in plankton collections. Both *M. sulcata* and *T. nitzschiodes* were present in the Strait throughout the year. By late winter, species of *Thalassiosira* joined the plankton assemblage. The bloom organism, *Skeletonema costatum*, first made a modest appearance during early spring. A large bloom of *S. costatum* accompanied by high concentrations of *Chaetoceros* spp. and *Thalassiosira* spp. was present in the early summer of 1976. No massive bloom was encountered in 1977, but sizable quantities of *S. costatum* were observed in late spring. By late summer, *M. sulcata* and *T. nitzschiodes* were again important species.

Dinoflagellates are also important components of the phytoplankton community in the Strait of Juan de Fuca. During the investigation, 23 species representing 11 genera were identified. Dinoflagellates were usually not as abundant as diatoms (Fig. 4). The seasonal cycle of abundance at stations 2 and 5 shows increased dinoflagellate populations during the late summer and early autumn. This is consistent with the pattern commonly seen in Puget Sound. Off Neah Bay (Sta. 8), however, no such pattern was discerned.

Coccolithophorids were infrequent members of the phytoplankton community, but their very presence may be significant. These phytoplankters are abundant in waters off the Washington coast, but they have not been observed in Puget Sound. Therefore, the occurrence of coccolithophorids is probably indicative of oceanic intrusions in the Strait of Juan de Fuca, and they are one of the groups referred to earlier (Section 4.2.).

Phytoplankton count data are in part analyzed as comparisons of the species composition of the samples. The Percentage Similarity (PS) index (Whittaker, 1960) has proved to be the most useful approach to determine how alike samples are with respect to species composition. The PS of two samples, X and Y, is calculated as follows:

$$PS = 100 - 50 \left(\sum_{i=1}^{n} |x_i - y_i| \right) = \sum_{i=1}^{n} \min (x_i, y_i) ,$$

where x_i and y_i are the percents of total individuals that belong to the i^{th} taxonomic category in samples X and Y, and n is the total number of categories. Miller (1970) used Monte Carlo computer techniques to show that PS is a downward-biased estimator. This bias decreases with increasing sample size and decreases with decreasing diversity of the population. That is, samples from a population strongly dominated by one or a few categories will tend toward a higher PS. PS is primarily sensitive to shifts in the more abundant groups. Miller (1970) found that with sample sizes of 2000 and 1000 individuals, a PS as low as 80% and 75%, respectively, could be obtained when comparing two samples taken from the same populations. Because many of our samples contained fewer than 1000 individuals and because not all phytoplankton classifications were of equal taxonomic weight, the acceptance level required to consider two samples identical should be lowered somewhat. The following criteria were adopted:

> if $PS \geq 70$, the samples showed excellent agreement and were considered to have the same population distribution;
>
> if $60 \leq PS < 70$, agreement was fair and it was likely that populations were the same;
>
> if $PS < 60$, agreement was poor and samples probably contained a different phytoplankton community.

The complete PS matrix (Table 4) allows station-by-station intercomparisons for all surface samples counted. Values comparing stations 2, 5, and 8 from the same cruise can be useful indicators of the uniformity of phytoplankton composition from along the east-west axis of the Strait (Table 5). According to PS values, the algal composition was homogeneous during about half the cruises. Large numbers of microflagellates, however, were often present, and their influence far outweighed that of less abundant species on the PS statistic. The result is an upwardly biased PS estimate. The microflagellate category was necessarily a composite of many species because preservation techniques and ordinary light microscopy made positive identification impossible. It was therefore decided to calculate a PS matrix restricted to diatom species. The results (Table 6) show that the structure of the diatom communities is not uniform throughout the Strait during any one cruise. Rather, distinct spatial variations exist with respect to the dominant species composition. Station 5, located approximately midway along the longitudinal axis of the Strait, was somewhat pivotal in that its diatom community sometimes resembled that at station 2 and at other times resembled that at station 8. The lack of homogeneous phytoplankton distributions makes inter-cruise comparisons tenuous, and in some cases one may say that the variation in PS during any one cruise is as great as the variation between cruises. The observed variability is probably linked to the circulation patterns and recent biological history of various source waters (e.g. Pacific Ocean, Puget Sound, Strait of Georgia) contributing to the Strait of Juan de Fuca.

TABLE 4. Percentage Similarity values for phytoplankton in upper 1 m, Strait of Juan de Fuca.

Cruise		SF7601			SF7602			SF7603	SF7604			SF7605			SF7606			SF7607		
	Station	2	5	8	2	5	8	2	2	5	8	2	5	8	2	5	8	2	5	8
SF7601	2		95	67	95	97	88	57	3	23	21	95	95	95	42	83	88	81	49	27
SF7601	5			71	96	97	90	53	3	24	21	94	94	94	39	83	88	77	46	27
SF7601	8				68	69	78	54	3	25	21	67	67	67	40	68	67	67	51	28
SF7602	2					98	89	53	3	23	21	96	97	98	39	83	89	76	45	27
SF7602	5						90	55	3	24	21	96	96	96	41	83	89	78	47	27
SF7602	8							56	3	26	22	87	88	88	42	86	89	79	48	28
SF7603	2								20	41	39	55	54	54	54	60	61	67	66	30
SF7604	2									44	55	3	3	3	13	5	4	3	3	7
SF7604	5										79	23	23	23	44	27	25	26	26	37
SF7604	8											22	21	21	30	23	23	24	24	30
SF7605	2												98	97	41	83	90	78	47	28
SF7605	5													98	40	83	90	78	47	28
SF7605	8														40	83	89	77	46	28
SF7606	2															50	47	48	48	35
SF7606	5																91	83	52	31
SF7606	8																	82	51	30
SF7607	2																		60	32
SF7607	5																			31
SF7607	8																			
SF7701	2																			
SF7701	5																			
SF7701	8																			
SF7702	2																			
SF7702	5																			
SF7702	8																			
SF7703	2																			
SF7703	5																			
SF7703	8																			
SF7704	2																			
SF7704	5																			
SF7704	8																			
SF7705	2																			
SF7705	5																			
SF7705	8																			
SF7706	2																			
SF7706	5																			
SF7706	8																			

TABLE 4. (cont.)

Cruise	Station	SF7701			SF7702			SF7703			SF7704			SF7705			SF7706		
		2	5	8	2	5	8	2	5	8	2	5	8	2	5	8	2	5	8
SF7601	2	65	38	59	34	20	60	45	43	94	39	92	23	56	87	79	86	62	94
SF7601	5	62	34	59	32	17	61	44	41	94	35	92	23	55	87	79	86	62	93
SF7601	8	62	39	69	36	18	72	54	44	67	36	66	23	56	67	67	67	63	66
SF7602	2	61	34	59	30	16	60	42	39	97	35	92	23	55	87	79	86	62	97
SF7602	5	62	36	59	32	18	60	44	41	95	37	92	23	57	87	79	86	62	95
SF7602	8	64	37	61	34	19	61	53	45	87	38	86	23	57	87	81	87	62	86
SF7603	2	70	53	57	50	35	54	67	62	54	62	52	24	57	54	55	56	53	52
SF7604	2	4	3	5	3	3	3	12	13	3	20	2	4	9	4	3	5	5	2
SF7604	5	26	25	27	25	18	24	35	36	23	47	21	25	37	24	24	26	25	21
SF7604	8	23	22	26	23	18	22	32	31	22	39	20	24	33	23	23	23	23	20
SF7605	2	63	34	59	32	18	60	43	40	97	36	92	24	57	87	79	86	62	96
SF7605	5	62	34	60	31	17	60	42	40	97	35	92	23	57	87	80	87	62	97
SF7605	8	61	34	60	31	17	60	42	39	97	35	92	23	56	87	79	86	62	98
SF7606	2	46	45	44	43	24	40	54	56	39	57	37	24	47	41	42	44	40	38
SF7606	5	64	40	62	37	20	61	46	46	83	42	81	23	59	83	81	84	64	81
SF7606	8	63	39	62	36	20	60	45	45	89	41	88	23	58	87	81	88	64	88
SF7607	2	72	48	62	44	28	60	51	51	78	47	76	24	59	77	78	80	63	76
SF7607	5	71	63	49	59	43	49	62	55	46	47	45	23	51	46	47	49	46	45
SF7607	8	30	33	35	29	18	28	32	31	29	35	27	30	37	28	28	31	33	27
SF7701	2		66	62	63	48	62	61	49	61	44	59	24	60	63	63	64	61	60
SF7701	5			41	85	63	38	55	48	34	48	32	24	36	34	35	36	35	32
SF7701	8				38	22	77	49	44	59	40	58	25	63	62	63	64	62	58
SF7702	2					69	37	52	47	31	45	29	24	34	37	38	34	30	29
SF7702	5						18	38	32	17	28	15	16	19	18	19	20	17	16
SF7702	8							42	40	60	35	59	23	57	60	61	60	60	59
SF7703	2								73	43	57	40	24	46	44	44	45	42	40
SF7703	5									40	59	38	24	44	40	41	42	39	37
SF7703	8										36	92	24	56	87	79	86	62	96
SF7704	2											33	24	41	36	37	39	35	33
SF7704	5												22	55	86	78	85	62	91
SF7704	8													25	23	23	23	25	23
SF7705	2														61	63	66	60	56
SF7705	5															90	90	64	87
SF7705	8																85	65	79
SF7706	2																	65	85
SF7706	5																		62
SF7706	8																		

TABLE 5. Percentage Similarity values for station to station comparisons of all phytoplankton populations during Strait of Juan de Fuca cruises, 1976-1977. PS values ≥ 60 are underlined.

CRUISE	STATION COMPARISONS		
	2 X 5	5 X 8	2 X 8
SF7601	95	67	71
SF7602	98	90	89
SF7603	--	--	--
SF7604	44	79	55
SF7605	98	97	98
SF7606	50	91	47
SF7607	60	31	32
SF7701	66	41	62
SF7702	69	18	37
SF7703	73	40	43
SF7704	33	22	24
SF7705	61	90	63
SF7706	65	62	85

TABLE 6. Percentage Similarity values for station to station comparisons of diatom populations during Strait of Juan de Fuca cruises, 1976-1977. PS values $\geq$ 60 are underlined.

CRUISE	STATION COMPARISONS		
	2 X 5	5 X 8	2 X 8
SF7601	28	77	24
SF7602	65	62	86
SF7603	--	--	--
SF7604	52	75	69
SF7605	59	58	47
SF7606	37	74	29
SF7607	53	7	14
SF7701	80	19	16
SF7702	79	11	29
SF7703	61	46	41
SF7704	4	1	4
SF7705	26	69	21
SF7706	30	17	28

4.4. MICROZOOPLANKTON DISTRIBUTION

The term microzooplankton embraces a large variety of protozoan and metazoan organisms which are too small to be adequately sampled by conventional plankton nets. Although they are small (generally < 200 μm), their specific metabolic rates (reproduction, ingestion, nutrient recycling, etc.) far exceed those of the larger zooplankton. Their ecological role may therefore be significantly greater than biomass alone indicates, and they may be an important trophic link between the smaller phytoplankton and larger zooplankton.

In the Strait of Juan de Fuca, ciliates numerically dominate the microzooplankton community. Oligotrichs and tintinnids, active phytoplankton grazers, are usually the most abundant ciliate taxa. A total of 26 tintinnid species and 12 oligotrich species were identified from the surface waters during the 2-year study. The population peaks of most of these species (e.g. tintinnids -- *Helicostomella subulata, Eutintinnus* spp.; oligotrichs -- *Strombidium conicum, S. strobilus*) usually coincided with periods of highest biological activity during the spring and summer (Fig. 5). However, certain species, such as the tintinnid *Stenosemella ventricosa*, were most abundant during the winter months. The distribution of *S. ventricosa* may be related to some combination of temperature preference, lorica building requirements, and nutritional needs. Besides the particle-grazing ciliates, large concentrations of *Mesodinium rubrum* were often present, especially at the innermost sites. *M. rubrum* derives its nutrition from photosynthetic endosymbionts and as such occupies a distinctly different position in the pelagic food web of neritic waters than do other ciliates. Protozoans other than ciliates include the heterotrophic dinoflagellate *Noctiluca miliaris* and various foraminiferan and radiolarian species. These were seen infrequently during the study. Metazoan organisms were also recorded. Juvenile crustaceans, trochophore larvae, mitraria larvae, and juvenile larvaceans were recognized. Adult rotifers were also fairly frequently encountered. In general, metazoans followed a pattern similar to the protozoans. That is, they were usually most abundant during the periods of high phytoplankton production.

The data gathered verify the volatile "boom or bust" nature of many of these species and reinforce the view that microzooplankton may react quickly to increased phytoplankton concentrations in such a way as to limit and control blooms of at least the smaller photosynthetic organisms. Although the general trends are clear, the rapid variation in community composition and size limits the possible interpretations . A better picture of the distribution of specific organisms as well as an understanding of interspecies relationships requires a more comprehensive sampling schedule in terms of both time and space. A more detailed report on the distribution of the microzooplankton in the Strait of Juan de Fuca has been published (Chester, 1978).

4.5. ZOOPLANKTON DISTRIBUTION

Zooplankton are important components of the environment in terms of their biomass, their roles in the ecosystem, and their probable sensitivity to the kinds of petroleum industry development and transport activity anticipated in the Puget Sound region. Zooplankton are the major grazers of phytoplankton and as such are a critical trophic link between primary producers and carnivores, particularly commercially valuable fish. Zooplankton include a variety of commercially important fish and shellfish as larval forms, and the remaining fractions are directly or indirectly food sources or predators. Many marine organisms are planktonic for their entire life cycle, but even organisms not usually thought of as plankton pass through early planktonic life stages. Most benthic and nektonic organisms have planktonic eggs and/or larval stages and are, therefore, especially vulnerable to contaminants throughout the water column (Moore et al., 1973). Zooplankton provide important mechanisms, other than ocean currents, for redistributing pollutants, especially by daily and seasonal vertical migrations and through significant repackaging of suspended materials into rapidly sinking fecal pellets.

In general, the distribution (particularly the vertical distribution) of zooplankton is not narrowly fixed, but varies with season, location, illumination, time, hydrographic conditions, and endogenous factors. Because of previous irregular space/time investigations, there is not much information on the dynamics of plankton populations within the Strait of Juan de Fuca, including seasonal cycles of species, species successions, recruitment, and vertical distributions and migrations of zooplankton. Much is known about the kinds of plankton organisms in the Strait of Juan de Fuca, and, except for larval stages and a few large and important groups like cyclopoid copepods, the general taxonomic problems are manageable.

Compared to warm-water plankton communities, the fauna of the Strait of Juan de Fuca region is not particularly diverse. Nevertheless, the net-zooplankton community here undoubtedly comprises several hundred species. The zooplankton of the Strait has been regarded as a simple mixture of species, oceanic forms becoming less important eastward, being replaced by coastal species doing well under estuarine conditions. This species mixture is governed by complex factors, giving the Strait a unique quasi-permanent zooplankton community which differs from that of the nearby Strait of Georgia as well as from Puget Sound. Relatively few species can be considered principal components on the basis of numbers and mass, or their critical roles in the transfer and conversion of matter and energy within the ecosystem.

It is of value to determine the natural zooplankton populations and levels, and ultimately to be able to detect changes in these as they occur, and then to predict serious modifications in the ecosystem. However, this is always an extremely difficult task and especially so in such a complex area as the Strait of Juan de Fuca. This is primarily because the Strait has water-mass components mixing rapidly between Puget Sound, the Strait of Georgia, and the open ocean. Pelagic populations cannot be followed and resampled, especially between time frames of several weeks. Even within stable water bodies such as lakes, it is difficult to track single planktonic populations. Along the Strait, at any one time, an investigator may encounter the same basic plankton populations, but at each locality these may be at a different stage of community and individual development. Superimposed on this time variability is variability in depth. Species have broad depth preferences that often change with age, season, or even time of day. Mixing water layers and lenses obscure these depth relations, but also add complexity to the space-time relationships that are the basis of the present study.

A 2-year study at 6-8 week intervals is not adequate to describe the limits of abundance of the zooplankton species in the Strait. We have, however, outlined the basic yearly cycle, although highs and lows of short duration may have been missed. We can also describe a typical zooplankton population, and suggest envelopes of abundance with depth and season for many species. Unless catastrophic, changes in abundance would be difficult or impossible to detect using the data of this survey. The presence or absence of species may imply a fundamental change in the environment, and we have noticed such "indicators" on a small scale during winter current reversals (see Table 2); warm-water oceanic species were unexpectedly found then in the Strait. A climatic shift could give the Strait a very different zooplankton population, but this would be accompanied by changes in physical characteristics.

4.5.1. Zooplanktonic biomass

Zooplankton samples collected during the 13 cruises in the Strait of Juan de Fuca have been processed and analyzed in the laboratory. Sampling times varied; these are given in Appendix D. Settled plankton volumes were used as an index of zooplankton biomass (Tables 7 and 8). These volumes (Fig. 6-8) followed fairly closely the seasonal cycle of chlorophyll concentration in the upper 50 m, as might be expected, since the bulk of this zooplankton volume is composed of herbivores directly dependent upon phytoplankton. Zooplankton volumes in the oblique tows (Fig. 8) tended toward a fall-winter minimum (7 months, September through March) with values below 1 ml m^{-3}, and usually less than 0.5 ml m^{-3}. Maximum zooplankton volumes were found in spring and summer (5 months, April through August) with values above 1 ml m^{-3} and as high as 2 ml m^{-3}. In the finer-mesh vertically hauled net (Fig. 6 and 7) the volumes were somewhat higher, although the trends were the same.

Zooplankton volume data are useful to show fundamental cycles, but they do not provide much insight into ecosystems. Populations under stress are often replaced by other populations, and a measure of volume would not detect this change; different species of equal volume may have very different roles and impacts.

The seasonal cycle and magnitude of zooplankton volumes appear similar to those from other years observed by somewhat different methods off the Washington coast and in the main basin of Puget Sound. These comparisons are based on the very few observations in each region (Hebard, 1956; Frolander, 1962).

TABLE 7. Zooplankton settled volumes (ml m^{-3}) from vertical tows (211 μm mesh size) taken in the Strait of Juan de Fuca, 1976-1977.

Cruise	Date	Interval Depth (m)	Station 2 (100 m)	Station 5 (180 m)	Station 8 (250 m)
SF7601	23-24 Feb	0-25	0.9	2.0	1.0
		25-50	1.0	2.4	1.1
		50-100	0.3	0.4	1.0
		100-bottom		0.7	3.2
SF7602	5- 6 Apr	0-25	2.9	1.3	1.3
		25-50	1.6	0.4	1.1
		50-100	0.8	0.7	0.8
		100-bottom		0.7	0.4
SF7603	17-18 May	0-25	4.1		
		25-50	2.8		
		50-100	0.8		
		100-bottom			
SF7604	28-30 Jun	0-25	16.6	3.0	36.4
		25-50	9.4	7.4	1.9
		50-100	5.9	4.5	3.0
		100-bottom		3.2	3.4
SF7605	3- 5 Aug	0-25	1.7	0.6	0.6
		25-50	1.4	0.7	0.7
		50-100	1.8	0.9	0.7
		100-bottom		0.9	1.2
SF7606	14-16 Sep	0-25	1.0	0.7	0.1
		25-50	0.9	0.7	0.1
		50-100	2.2	1.7	0.6
		100-bottom		2.5	0.5
SF7607	12-15 Nov	0-25	0.6	0.7	2.0
		25-50	0.4	1.4	0.1
		50-100	1.2	1.3	0.3
		100-bottom		2.5	0.9
SF7701	11-13 Jan	0-25	0.3	0.3	1.0
		25-50	1.0	0.5	0.5
		50-100	1.7	0.4	0.3
		100-bottom		1.1	0.03
SF7702	22-25 Feb	0-25	1.3	1.0	2.0
		25-50	0.6	0.6	0.6
		50-100	0.5	0.4	0.7
		100-bottom		0.6	0.6

TABLE 7. (Cont.)

Cruise	Date	Interval Depth (m)	Station 2 (100 m)	Station 5 (180 m)	Station 8 (250 m)
SF7703	5- 6 Apr	0-25	0.7	0.4	2.4
		25-50	0.9	0.4	0.4
		50-100	0.2	0.8	0.6
		100-bottom		0.8	0.7
SF7704	1- 3 Jun	0-25	1.0	3.1	4.3
		25-50	1.4	0.4	0.3
		50-100	2.5	1.3	1.8
		100-bottom		2.4	1.0
SF7705	25-28 Jul	0-25	3.7	1.1	1.0
		25-50	1.7	0.4	0.3
		50-100	2.1	0.7	0.6
		100-bottom		0.7	0.8
SF7706	3- 5 Oct	0-25	1.3	2.4	0.7
		25-50	1.0	0.7	0.4
		50-100	1.7	1.4	0.5
		100-bottom		6.4	0.7

TABLE 8. Zooplankton settled volumes (ml m^{-3}) from oblique tows (333 µm mesh size) taken in the upper 50 m of the Strait of Juan de Fuca, 1976-1977.

Cruise	Date	Station No.								
		1	2	3	4	5	6	7	8	9
SF7601	23-24 Feb	0.6	0.5	0.3	0.4	1.2	1.2		0.5	0.5
SF7602	5- 6 Apr	1.0	1.0	1.1	1.9	1.7	1.2	1.4	1.1	1.3
SF7603	17-18 May	0.8	1.1	0.6						
SF7604	28-30 Jun	1.2	1.7	1.9	2.8	2.4	0.8	1.7	1.3	2.4
SF7605	3- 5 Aug	1.2	0.8	1.2	1.1	0.5	0.4	1.2	0.6	0.3
SF7606	14-16 Sep	1.1	0.4	0.3	0.4	0.2	0.2	0.3	0.2	0.2
SF7607	12-15 Nov	0.2	0.2	0.4	2.1	0.1	0.1	0.1	0.4	0.2
SF7701	11-13 Jan	0.2	0.1	0.8	0.2	0.1	0.1	0.1	0.2	0.2
SF7702	22-25 Feb	0.9	0.4	0.2	0.4	0.4	0.2	0.2	0.3	0.4
SF7703	5- 6 Apr	0.4	0.2	0.3	0.4	0.1	0.2	0.3	0.3	0.4
SF7704	1- 3 Jun	1.2	0.7	0.8	1.5	1.5	1.7	1.9	1.5	1.9
SF7705	25-28 Jul	0.9	1.1	1.1	0.4	0.2	0.1	0.3	0.2	0.2
SF7706	3- 5 Oct	0.7	0.7	0.6	0.8	1.3	1.9	0.3	0.3	0.2

4.5.2. Zooplankton species composition

Zooplankton volumes are obtained relatively quickly and simply, but interpretations are complicated by the irregular occurrence of phytoplankton. Some phytoplankters form long intertwining chains and do not settle from the sample, but entangle zooplankton to give the appearance of a large plankton volume. A better characterization of the zooplankton is given by the identification and counting of specimens. There was a substantial variety of taxonomic groups represented in the samples. The most common groups were Copepoda, Chaetognatha, Polychaeta, Medusae, Siphonophora, Cladocera, Ostracoda, Amphipoda, Euphausiacea, Decapoda, Chordata, and larval fishes. See Appendix B for a list of species and major groups.

The zooplankton of the Strait of Juan de Fuca and Puget Sound are a mixture of cold-temperate species and (warm) transition-water species. From the zooplankton retained by nets, there are more than 100 species. None of these species is found only in the inland marine water system. That is, all of these zooplankton species are also found offshore in the open ocean. In addition, a great many species found offshore cannot enter or go beyond the Strait of Juan de Fuca, or cannot maintain populations there for one reason or another.

There is a group of 16 species (marked * in Appendix C) of large, deep-living "oceanic" copepods, which in most cases were persistent components of Strait zooplankton. As expected, these copepods were most abundant in the deeper samples and occurred most commonly at the westernmost stations. These species do not occur above 50 m, and they are unable to cross the shallow sill at Admiralty Inlet; therefore, they are not found to the southeast in Puget Sound, Hood Canal, or Dabob Bay. Apparently, this is a strictly mechanical phenomenon, with the vertical distribution of a number of important oceanic species limiting their horizontal distribution.

Five other species (marked ** in Appendix C) of "oceanic" copepods, with a similar preference for depth but which are occasionally found at or near the surface, can cross the Admiralty Inlet sill and are found, generally as juveniles, in Puget Sound and/or Dabob Bay (Hood Canal). It is not known if these populations are entirely dependent upon periodic immigration, or if they can breed in the inland marine areas.

A third group is of five "oceanic" surface-living copepods (Table 2); their sporadic occurrence in the Strait was unexpected in view of the quasi-constant surface outflow. Initially, these specimens were believed to be deep strays entering the Strait at depth, but they were not seen in deep samples, nor were they found in summer when they can be very abundant offshore. Recent physical evidence (Cannon, 1978) suggested winter ocean-surface intrusions and periodic current reversals. The occurrence of the surface oceanic species was associated with or close to these reversals (see Section 4.2.).

The Copepoda of the Strait of Juan de Fuca were represented by about 60 species. Copepods were always the most abundant net-zooplankton, and copepod numbers showed the same seasonal trends as zooplankton volumes (Fig. 6-9). The fall-winter period was characterized by a large number of zooplankton species, but each species was in small numbers. This period of high species diversity was in contrast to the lower diversity of spring and summer, where about the same number of species was present (not always the same species as in fall and winter), but where a few species were very abundant. Zooplankton diversity, therefore, shows an inverse relationship to zooplankton volume. During the spring-summer zooplankton volume increase, over 80% of the numbers were of a single copepod type (*Pseudocalanus* species), while during the fall, winter, and early spring volume lows, this same copepod type often amounted to less than 50% of the numbers (Fig. 9).

In addition to *Pseudocalanus* spp. (Fig. 10-15), the most abundant copepods include the calanoid *Acartia longiremis* (Fig. 16-18) and the cyclopoid *Oithona similis* (Fig. 19-21). These animals can be present in high concentrations (hundreds to thousands m^{-3}) and probably play a key role in the conversion of plant material to animal substance. Moreover, they are an important food web link because of their high metabolic rates and energy turnover potential. Of the larger, common species of copepods, *Calanus marshallae*, a key grazer (Frost, 1974), is most abundant during the spring and summer months; the adult form virtually disappears from the water column in late fall and winter in the Strait of Juan de Fuca (Fig. 22-24). The highest concentrations of this species were found at station 8, with a maximum in April 1977 of 368 m^{-3} in the upper 25 m.

Euphausids were not nearly as abundant as copepods, yet euphausids are a critical link between lower trophic levels and the large carnivores (Parsons and LeBrasseur, 1970). Five species were found: *Euphausia pacifica*, *Thysanoessa inermis*, *T. longipes*, *T. raschii*, and *T. spinifera*. For the most numerous, *Euphausia pacifica*, the data suggest a maximum or near-maximum during the late spring-early summer months: 51 m^{-3} in the upper 25 m, station 2, May 1976; and 123 m^{-3} at 100-50 m, station 2, June 1977. Nevertheless, the 6-8 week time intervals between cruises make it difficult to generalize.

Four species of chaetognath were identified: *Sagitta elegans*, the most abundant, *S. lyra*, *S. scrippsae*, and *Eukrohnia hamata*. While almost always present, *Sagitta elegans* was highly variable in abundance throughout the 2-year sampling period (Fig. 25-27). The highest concentrations for this species were found during the spring and summer months (> 100 m^{-3}) and in the surface layer.

A number of amphipods were collected including species representing the families: Calliopiidae, Lysianassidae, Hyperiidae, Lycaeidae, Oxycephalidae, Phronimidae, Paraphronimidae, and Phrosinidae (see Appendix C). No species was found to be present in great numbers, but *Parathemisto pacifica* was consistently the most abundant, reaching concentrations of 25-50 m^{-3} in the fall of 1976 and 1977.

The seasonal cycle, as outlined in this report, is only an approximation of natural and variable events. Short-term fluctuations (weekly/biweekly) were not examined at all, and between-year trends were not fairly examined. Future investigations of this type in the Strait of Juan de Fuca might look intensively at the winter-spring transition, noting particularly the increase in primary production and the coupling of zooplankton species to chlorophyll. Also, to assess the impact of zooplankton in the ecosystem, there is a need to examine more closely the detailed depth distributions of species, especially daily vertical migrations.

The most abundant zooplankton species are essentially the same in all three principal inland marine areas: the Strait of Juan de Fuca, the Strait of Georgia, and Puget Sound. However, the proportions of some of these vary with region, giving each area a characteristic zooplankton community. This is clear with the various *Calanus* species, all of which are important herbivores. In the Strait of Georgia, the most numerous of all net-zooplankton species is the large *Calanus plumchrus*, a cornerstone of the ecosystem. In contrast, *C. plumchrus* is rare in the Strait of Juan de Fuca and Puget Sound. This is probably a mechanical phenomenon, since *C. plumchrus* seems to require depths in excess of 300 m to complete its life cycle.

In Puget Sound, a smaller *Calanus* species, *C. pacificus*, is among the most abundant zooplankton. Very few *C. plumchrus* or *C. pacificus* were found in the Strait of Juan de Fuca, but a third species, *C. marshallae*, of intermediate size is one of the most numerous zooplankton species.

Because of these regional communities, it may continue to be necessary to examine separately the zooplankton of each principal area. Also, because of the physical interchanges between the Strait of Juan de Fuca, the Strait of Georgia, and Puget Sound, the responses of the zooplankton of one region will not be fully understood without an understanding of the distribution and abundance of the zooplankton in the adjacent regions.

4.6. ICHTHYOPLANKTON DISTRIBUTION

Fish eggs and larvae are particularly sensitive to oil pollution because many forms aggregate at the surface. Also, since reproductive intervals are long relative to those of other planktonic organisms, the population recovery rates may be correspondingly slower. Several species spawn only during one short period of the year. The recruitment of such species might be seriously disrupted by a single coincidental pollution episode. The results of fish eggs and larvae analyses are tabulated in Appendix E.

During the study, a total of 49 taxa, representing 21 fish families, were identified. Fifteen of these taxa have commercial value (Hart, 1973; Clemens and Wilby, 1949). They include salmon, sole, smelt, greenling, herring, cod, and ling cod (Table 9). The greatest number of taxa occurred during late winter and early spring (Fig. 28) in both the pleuston and oblique samples. The greatest population densities of fish eggs and larvae were also recorded in late winter and early spring; they mark this period as one of active spawning and recruitment (Fig. 29 and 30).

It is evident from the large number of eggs captured by the pleuston sampler that many fish eggs aggregate in the extreme upper water layer. For the 13 cruises, the average abundance of pleustonic fish eggs in the open water of the Strait of Juan de Fuca was estimated to be 100 million. The greatest density of fish eggs was observed in April 1977, when there were an estimated one-half billion pleustonic eggs in the Strait. Estimates of the total number of fish eggs in the upper 50 m of the Strait of Juan de Fuca, based on oblique

TABLE 9. Ichthyoplankton organisms caught in surface and oblique net hauls, Strait of Juan de Fuca, 1976-1977.

TAXON	COMMON NAME	COMMERCIAL VALUE (X)
LARVAE		
Agonidae	Sea-poacher	
Ammodytes hexapterus	Sand-lance	
Artedius spp.	Sculpin	
Bathylagus stilbius	Black smelt	
Bathymasteridae	Ronquil	
Citharichthys spp.	Sand dab	X
Clinidae	Kelp-fish	
Clupea harengus pallasii	Pacific Herring	X
Cottidae	Sculpin	
Cyclopteridae	Lump-sucker	
Gadidae	Cod	
Gadus spp.	Cod	X
Gasterosteus aculeatus	Three-spined stickleback	
Gibbonsia spp.	Kelp-fish	
Hemilepidotus spp.	Irish lord	
Hexagrammos spp.	Greenling	X
Hexagrammos decagrammus	Kelp greenling	
Hexagrammos lagocephalus	Rock greenling	
Hexagrammos stelleri	Whitespotted greenling	
Hexagrammos superciliosus	Fringed greenling	
Icelinus spp.	Sculpin	
Isopsetta isolepis	Butter sole	X
Lepidopsetta bilineata	Rock sole	X
Leptocottus armatus	Cabezon	
Lumpenus maculatous	Eel-blenny	
Lyopsetta exilis	Slender sole	
Microgadus proximus	Tom cod	
Ophidon elongatus	Ling cod	X
Osmeridae	Smelt	X
Parophrys vetulus	Lemon (English) sole	X
Pholis spp.	Blenny	
Pleuronectidae	Flounder	X
Platichthys stellatus	Starry flounder	
Pleuronichthys decurrens	Curl-fin sole	
protomyctophum thompsoni	Bigeye lanternfish	
Psettichthys melanostictus	Sand sole	
Psychrolutes spp.	Sculpin	
Salmonidae	Salmon	X
Scorpaenichthys marmoratus	Giant marbled sculpin	

TABLE 9. (Cont.)

TAXA	COMMON NAME	COMMERCIAL VALUE (X)
Sebastes spp.	Rock-fish	X
	Northern lampfish	
Stichaeidae	Northern blenny	
Theragra chalcogramma	Whiting	
Zaniolepis latipinnis	Long-spined greenling	
OVA		
Engraulis mordax	Anchovy	X
Hippoglossoides spp.	Sole	
Microstomus pacificus	Dover sole	X
Pleuronichthys spp.	Sole	
Pleuronichthys decurrens	Curl-fin sole	
Pleuronichthys coenosus	C-O sole	X
Trachypterus spp.	Ribbon fish	

net catches, averaged 1.3 billion. Similar calculations for total fish larvae gave average values of about 100 million pleustonic juveniles for the entire Strait of Juan de Fuca (maximum of 650 million during February 1977), and estimates from the oblique net data showed an overall average of 31 billion larvae in the upper 50 m.

There are apparently far greater numbers of larvae than eggs in the upper waters of the Strait. This conclusions seems contradictory, but knowledge of the life cycles of the dominant fish populations makes it more plausible. Most of the common larval taxa found in the Strait of Juan de Fuca are demersal spawners (e.g. smelt, greenling, sculpin, herring, cod, blennies, ling cod); others (e.g. rockfish) are live bearers. The only major group which produces pelagic eggs is the sole. Therefore, the relative paucity of eggs in the open waters of the Strait is understandable because the common larvae encountered represent species that do not release pelagic eggs.

The number of fish taxa present as eggs or larvae throughout the year and their abundances clearly show that the major spawning season in the Strait of Juan de Fuca is winter and early spring (Fig. 28-30). The osmerids (smelt) were overwhelmingly the most abundant larval type found in the upper 50 m, especially during late winter and spring. Population densities approximating 2 m^{-3} were recorded during both 1976 and 1977. The osmerids were captured primarily by the oblique net, indicating that they had no great preference for the extreme surface layer. Other common species showing no particular depth pattern included *Ammodytes hexapterus*, *Sebastes* spp., *Hemilepidotus* spp., and members of the Cottidae, Gadidae, and Cyclopteridae.

One other group merits attention. *Hexagrammos* spp. (greenlings) were the most numerous larvae taken in the pleuston sampler. They were only rarely seen in any oblique net samples, however. Hexagrammids were only observed during the months of October through April. According to Hart (1973), adults of the family Hexagrammidae are common bottom fish in shallow waters. The diet of young fish taken from British Columbian waters during spring included copepods, amphipods, oikopleurans, and smaller fish. The genus *Hexagrammos* provides an excellent example of demersal organisms whose larval stages are closely coupled to the surface and may be particularly susceptible to pollution by oily slicks and films.

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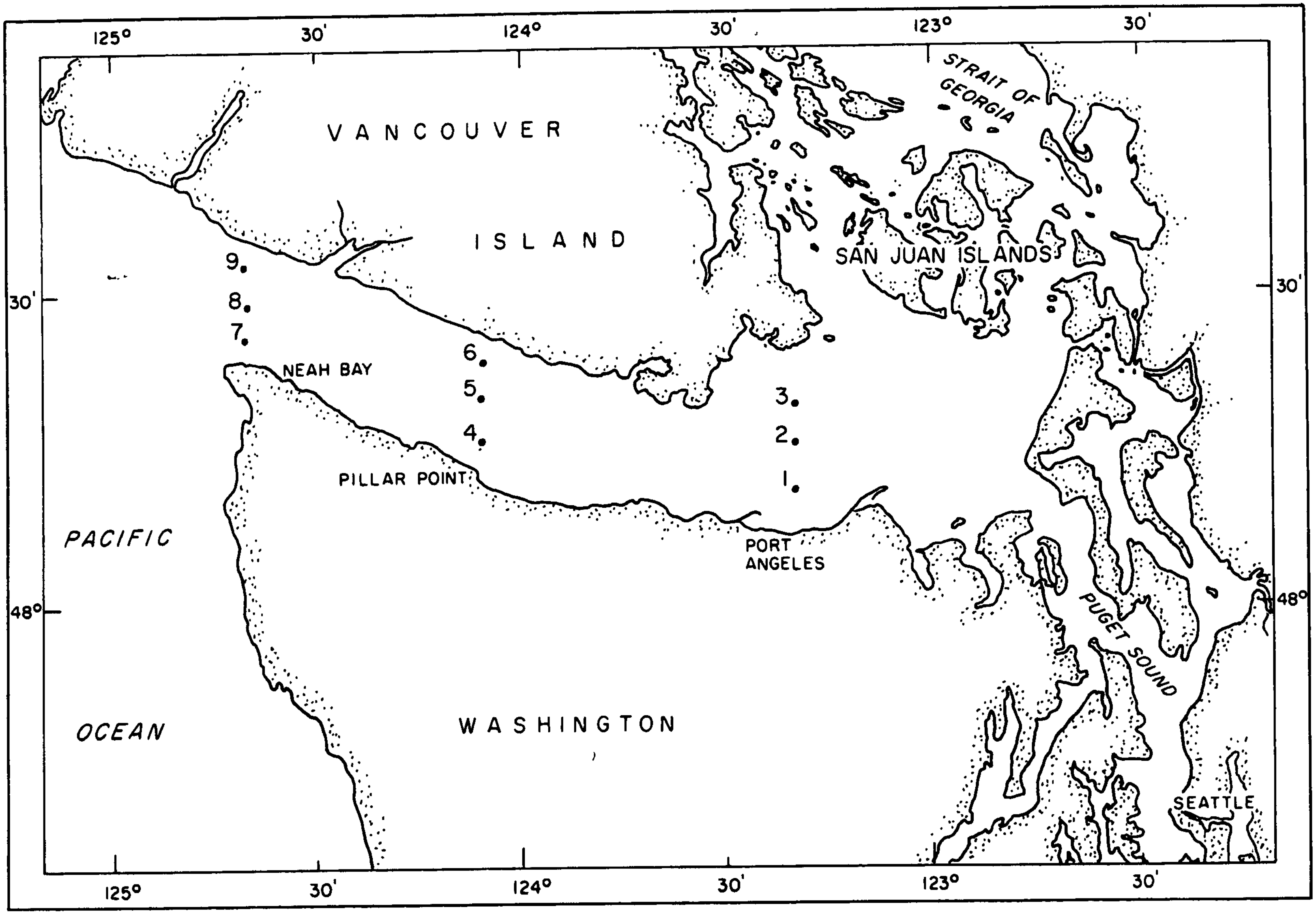

Figure 1. Area chart and station locations for Strait of Juan de Fuca cruises, February 1976 - October 1977.

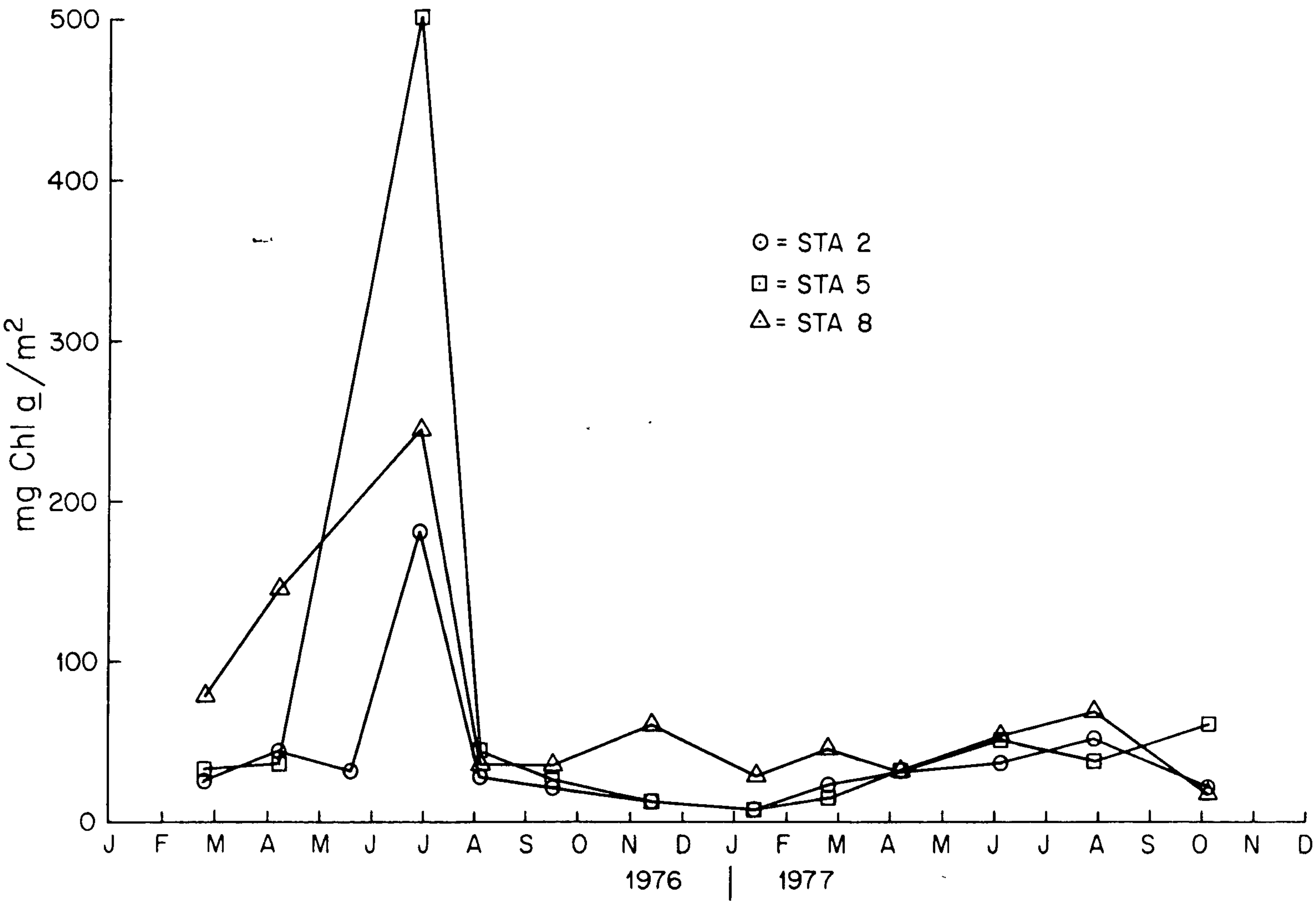

Figure 2. Chlorophyll *a* in the upper 50 m of the Strait of Juan de Fuca, 1976-1977.

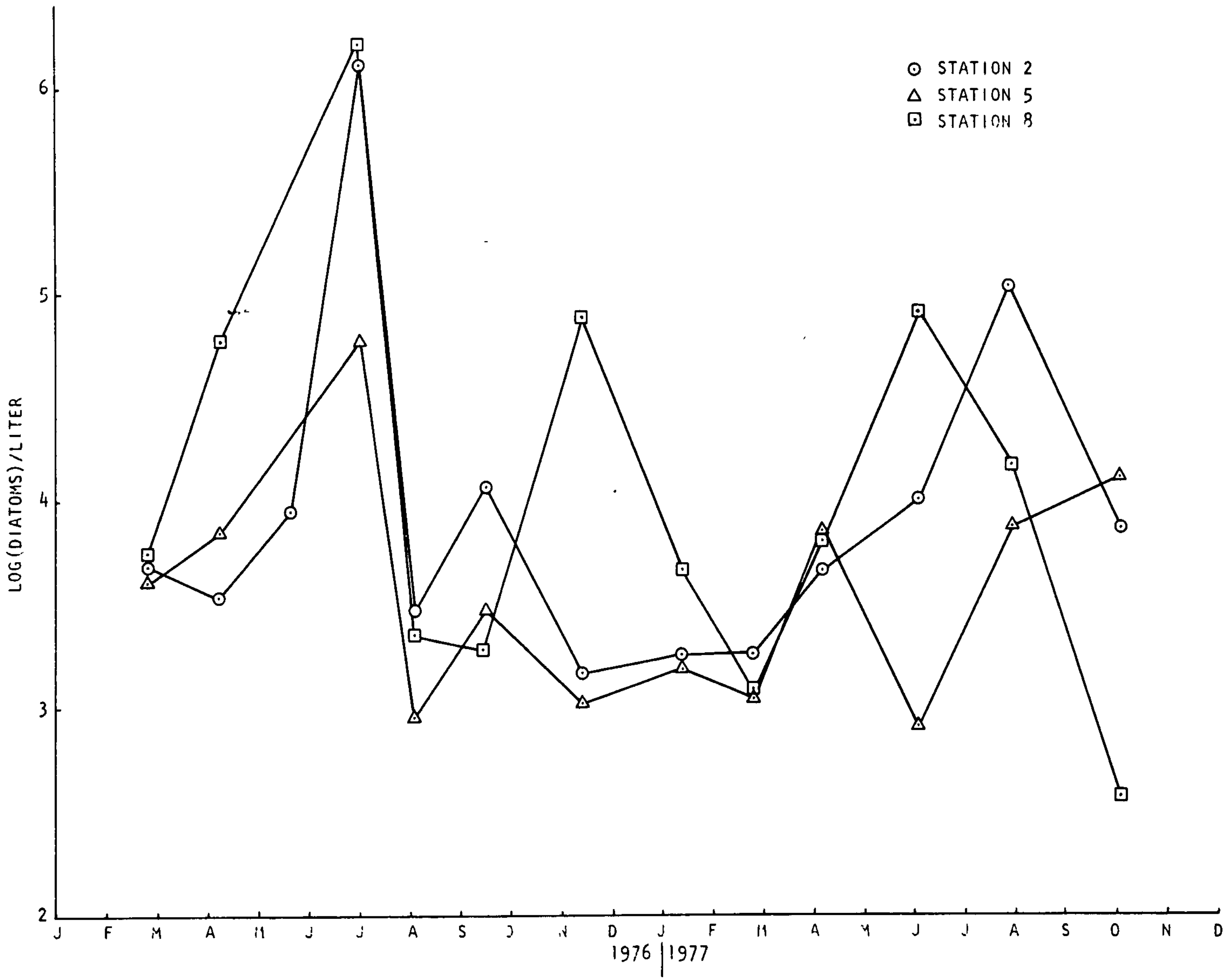

Figure 3. Diatom concentrations in the upper 1 m of the Strait of Juan de Fuca, 1976-1977.

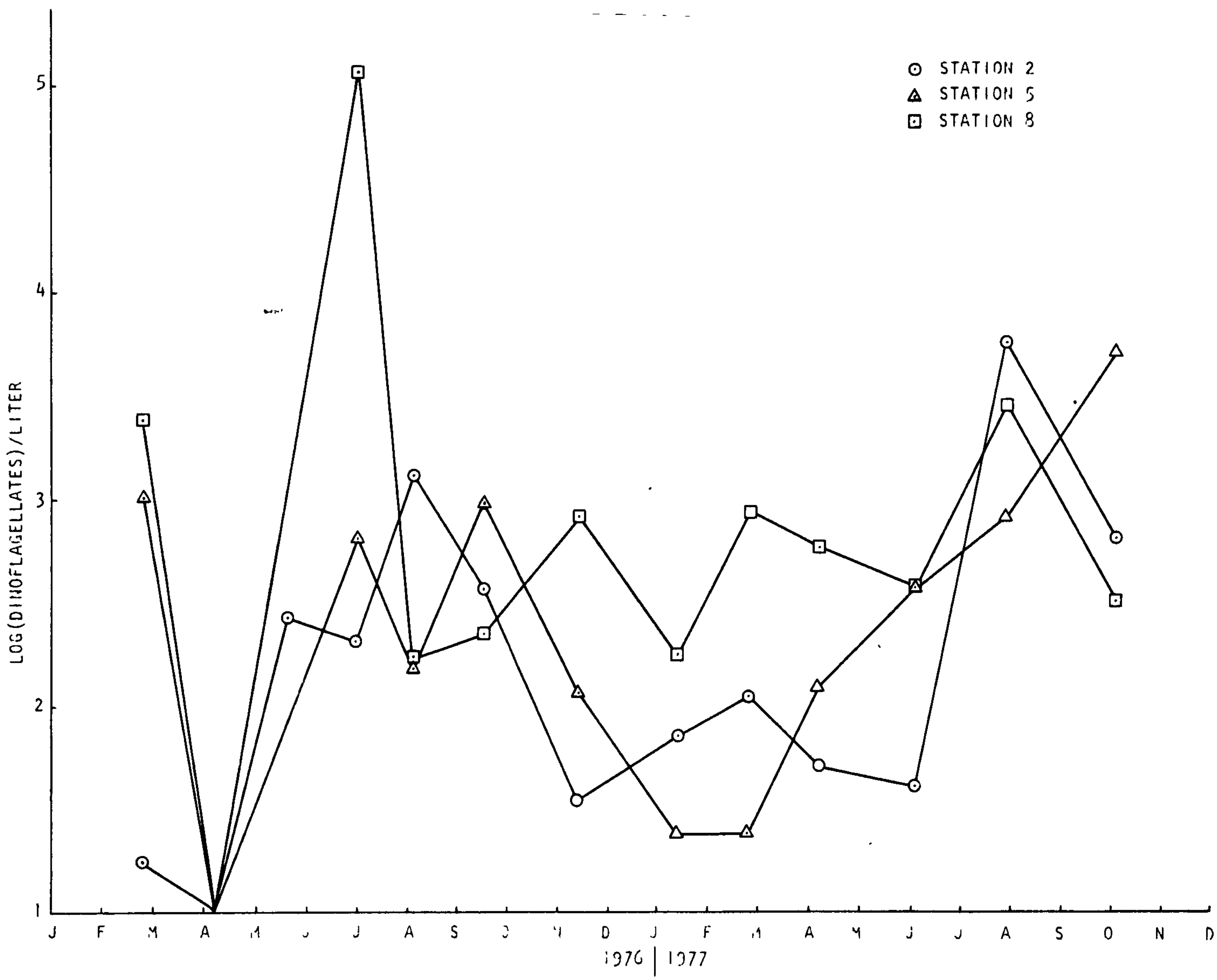

Figure 4. Dinoflagellate concentrations in the upper 1 m of the Strait of Juan de Fuca, 1976-1977.

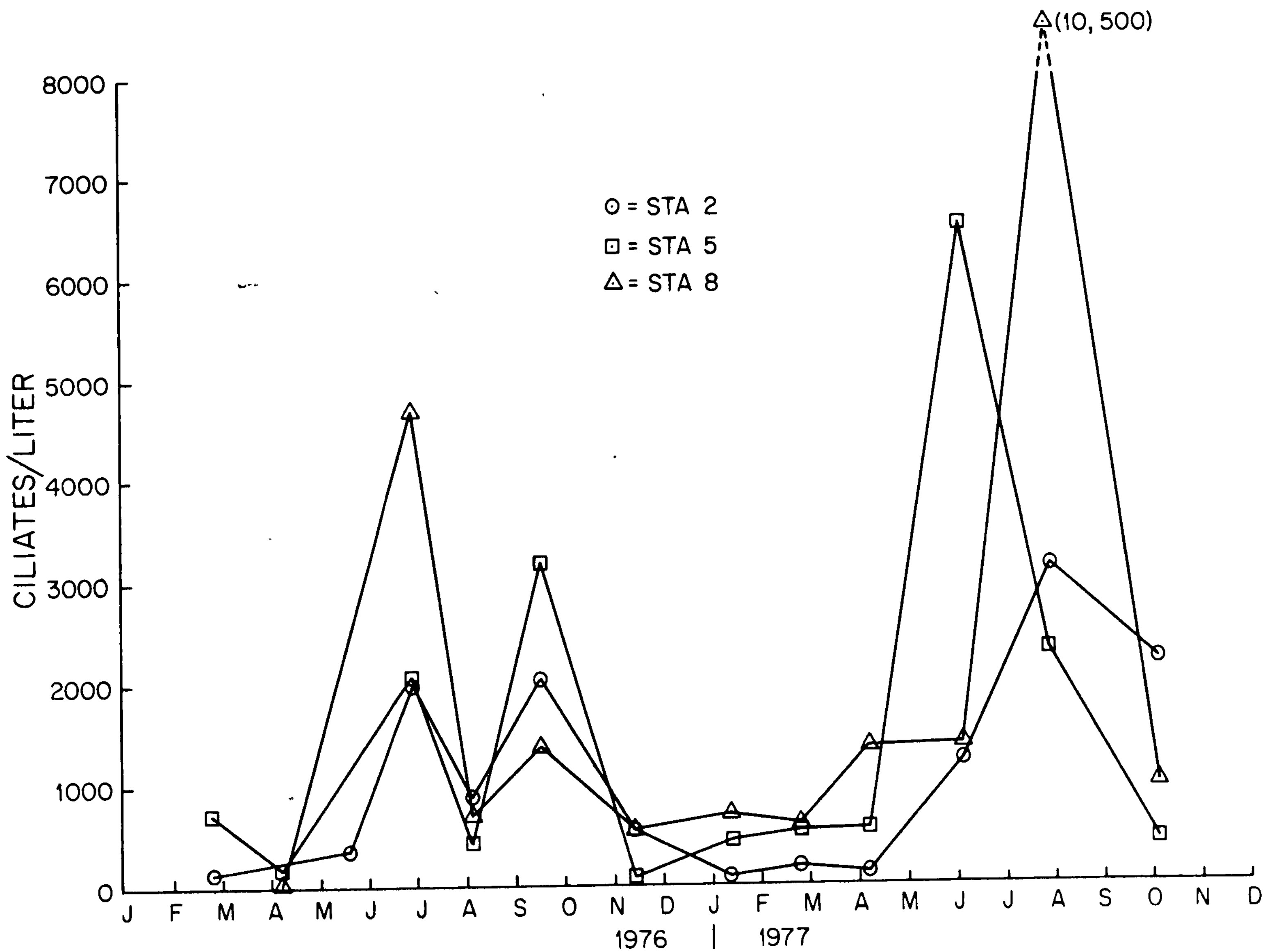

Figure 5. Concentrations of ciliates in the surface waters of the Strait of Juan de Fuca, 1976-1977.

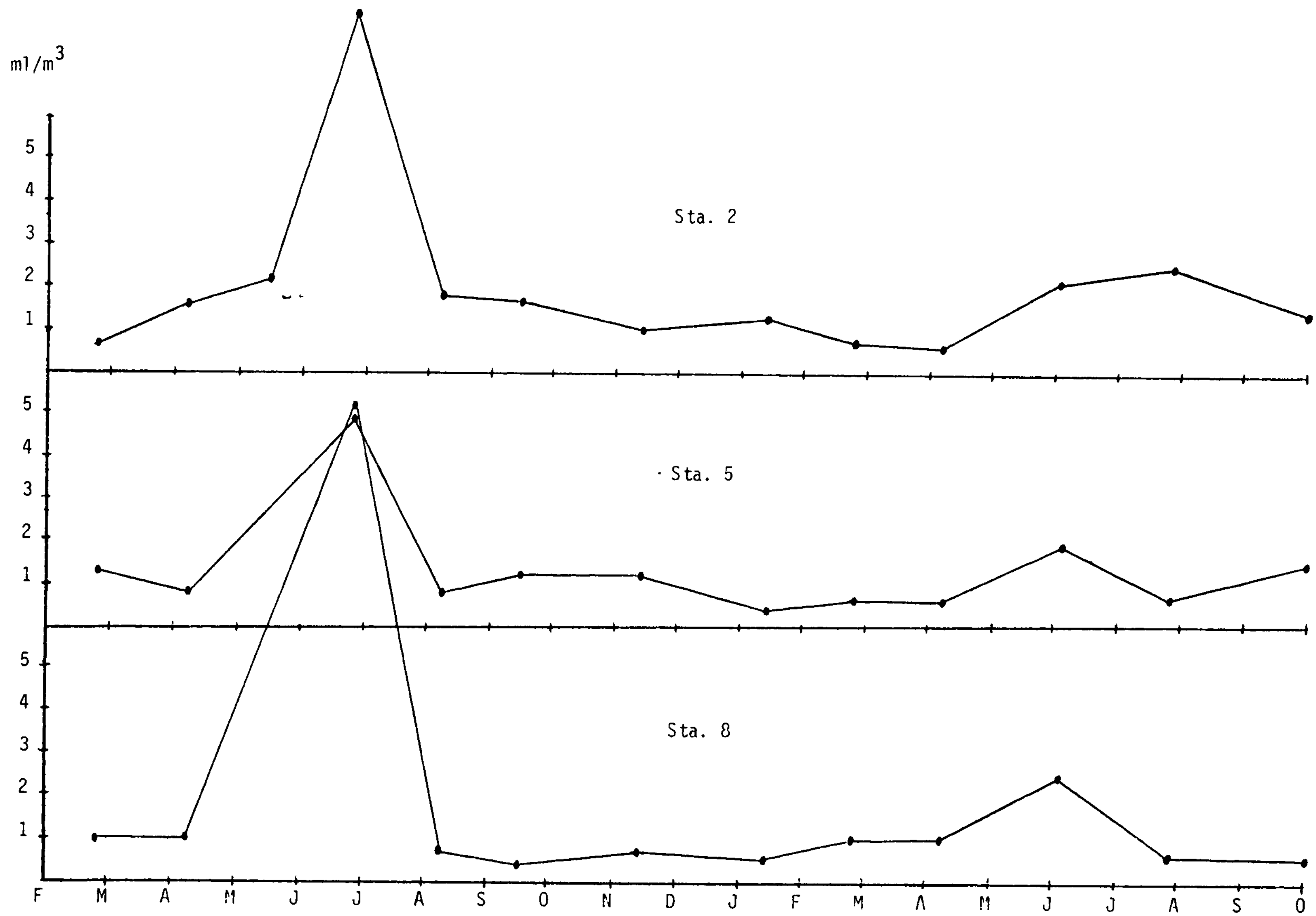

Figure 6. Zooplankton settled volumes. Vertical tows, 211 μm mesh size; total water column. Strait of Juan de Fuca, 1976-1977.

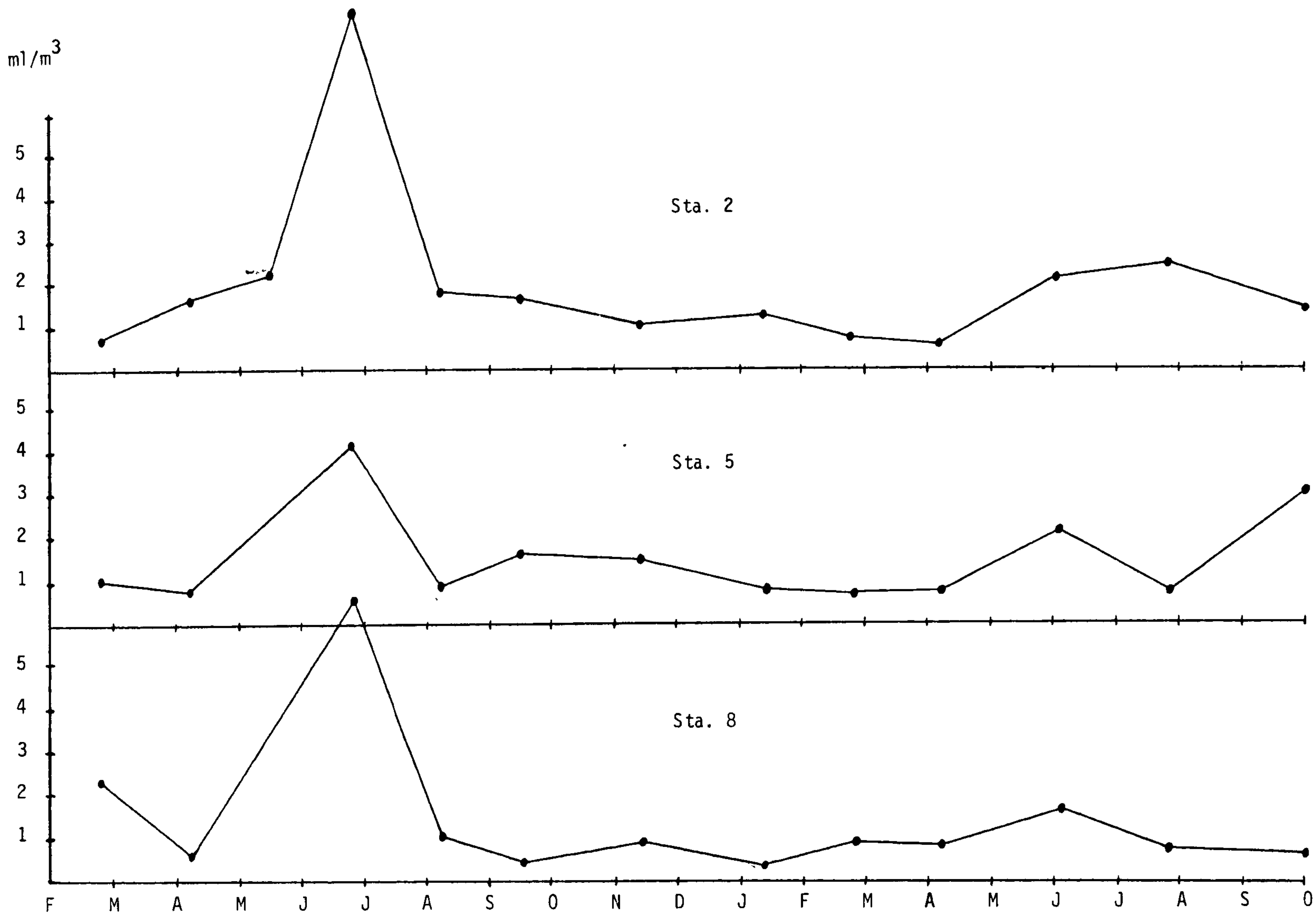

Figure 7. Zooplankton settled volume. Vertical tows, 211 μm mesh size; top 100 m. Strait of Juan de Fuca, 1976-1977.

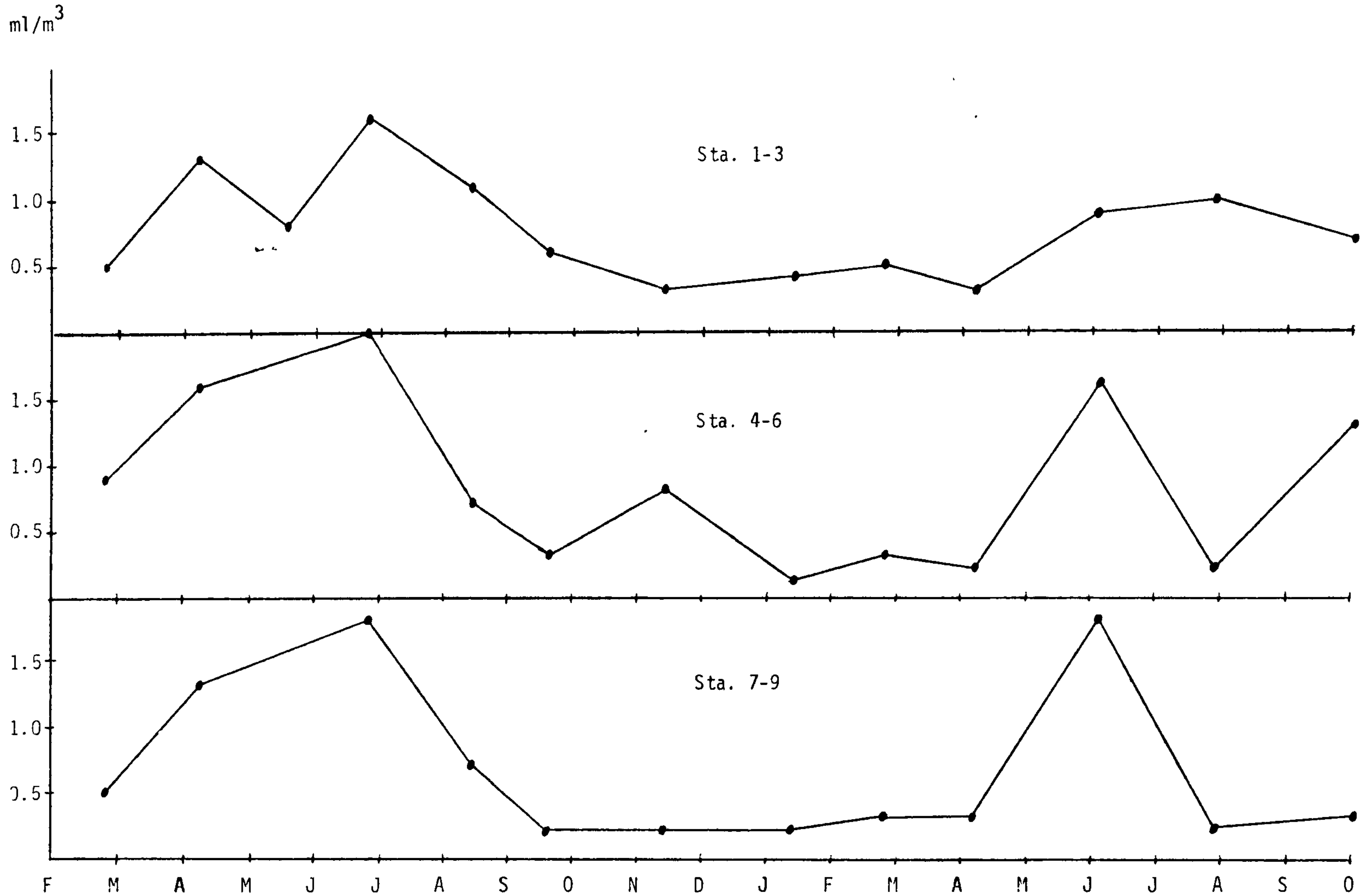

Figure 8. Zooplankton settled volumes, means of grouped stations. Oblique tows (50-0 m), 333 μm mesh size. Strait of Juan de Fuca, 1976-1977.

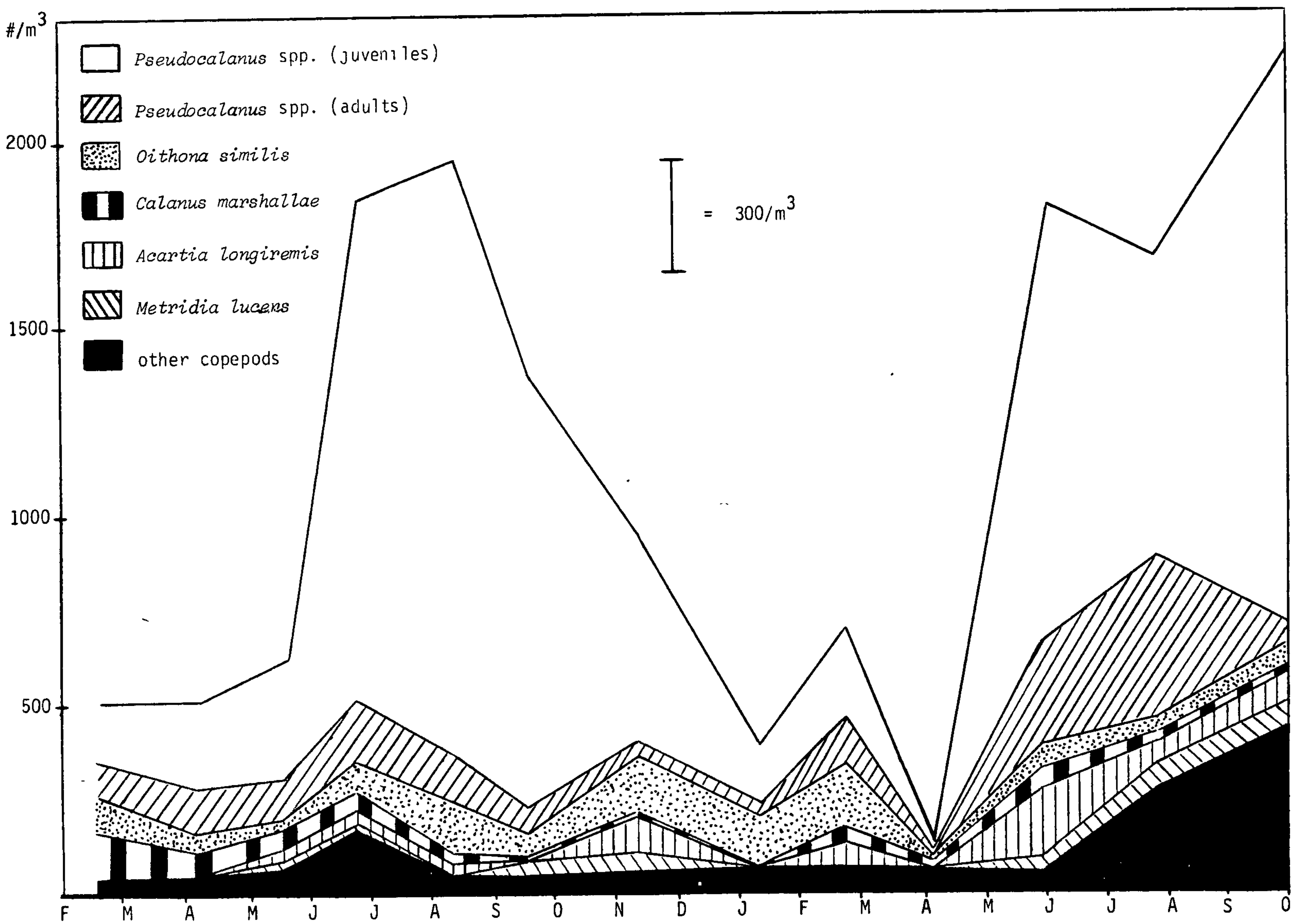

Figure 9. Copepod abundance from vertical hauls, Strait of Juan de Fuca, February 1976 - October 1977; total number collected per total water volume filtered, by cruise.

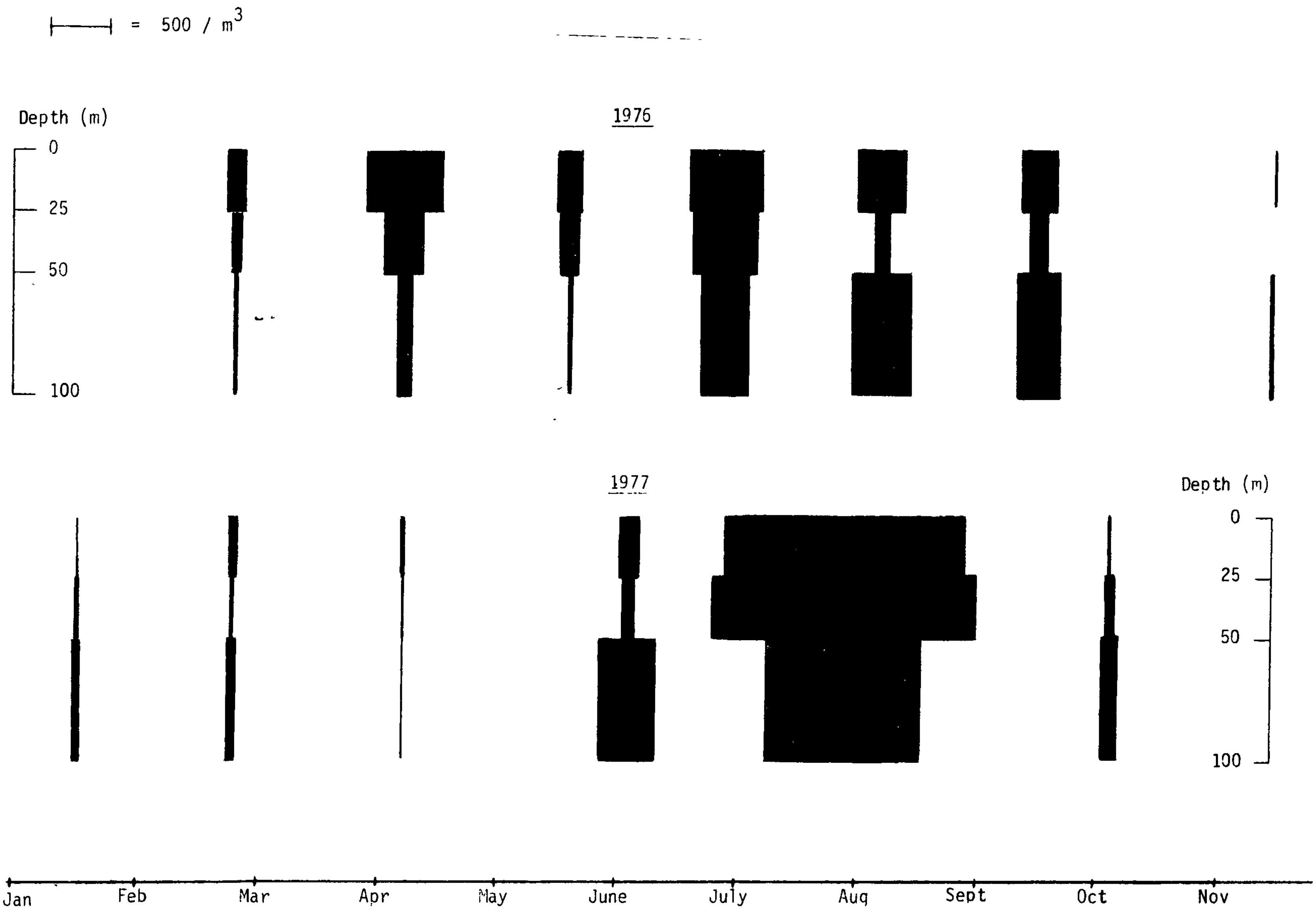

Figure 10. *Pseudocalanus* spp. (adults). Number of animals m^{-3}. Station 2, Strait of Juan de Fuca, 1976-1977.

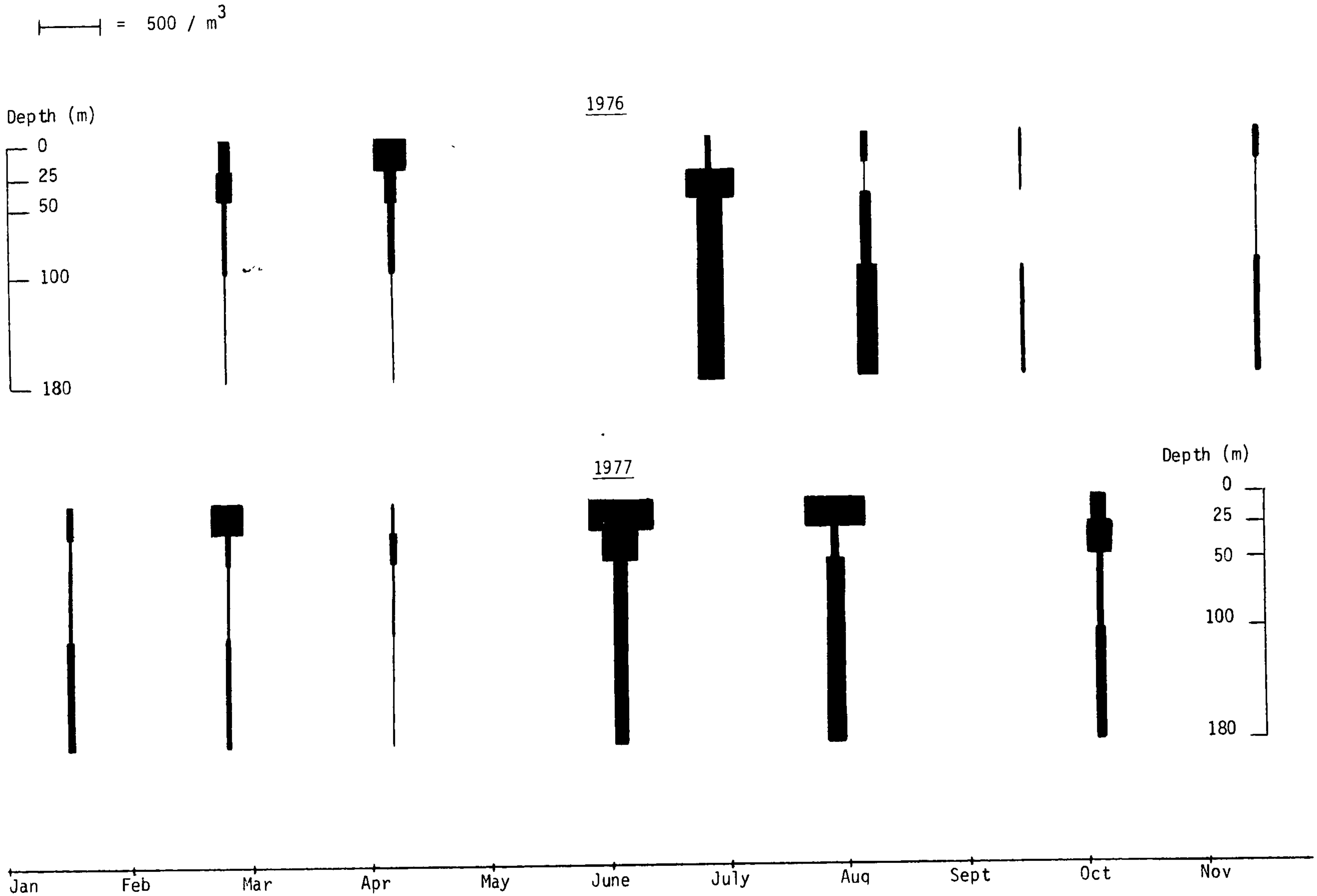

Figure 11. *Pseudocalanus* spp. (adults). Number of animals m^{-3}. Station 5, Strait of Juan de Fuca, 1976-1977.

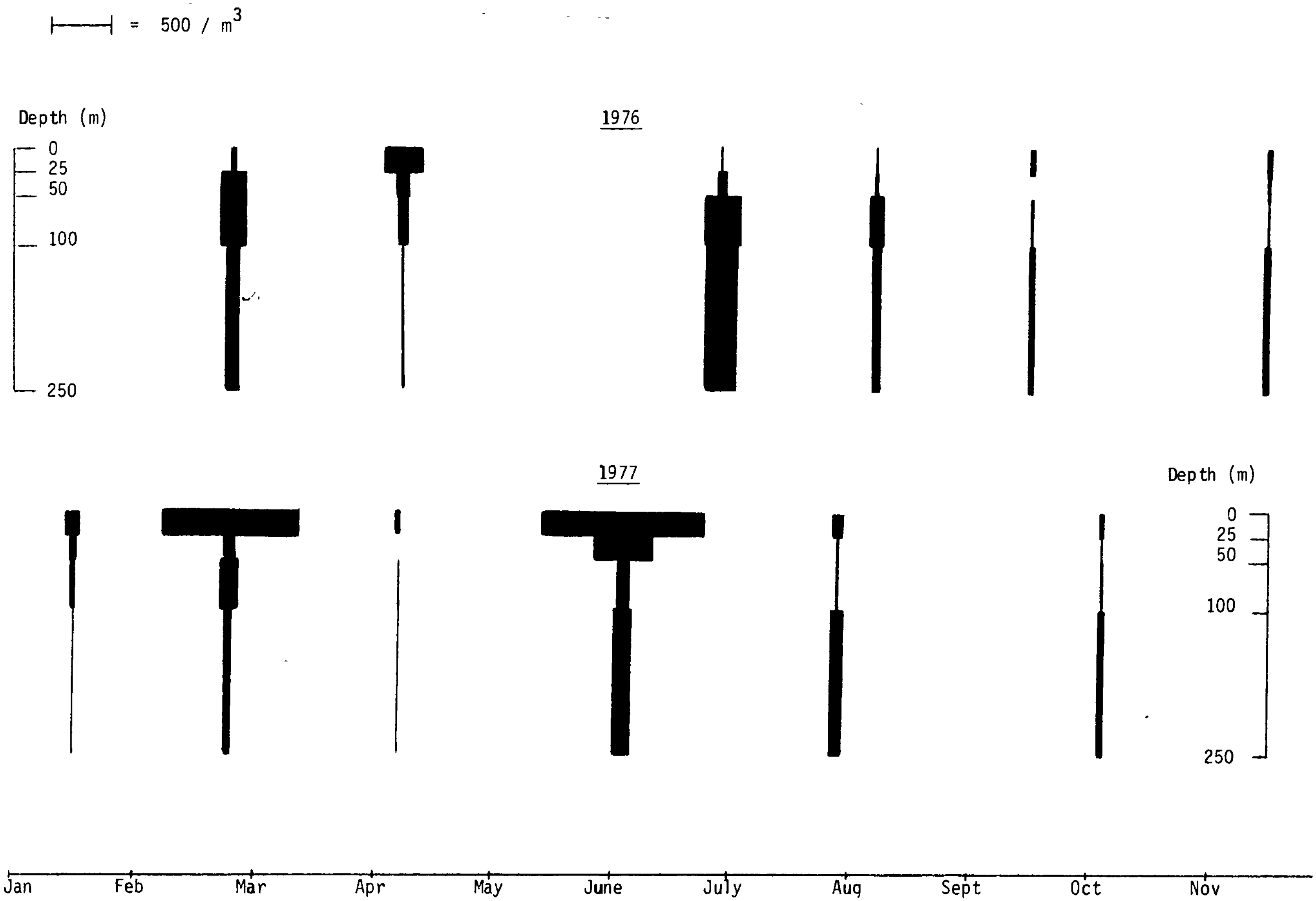

Figure 12. *Pseudocalanus* spp. (adults). Number of animals m^{-3}. Station 8, Strait of Juan de Fuca, 1976-1977.

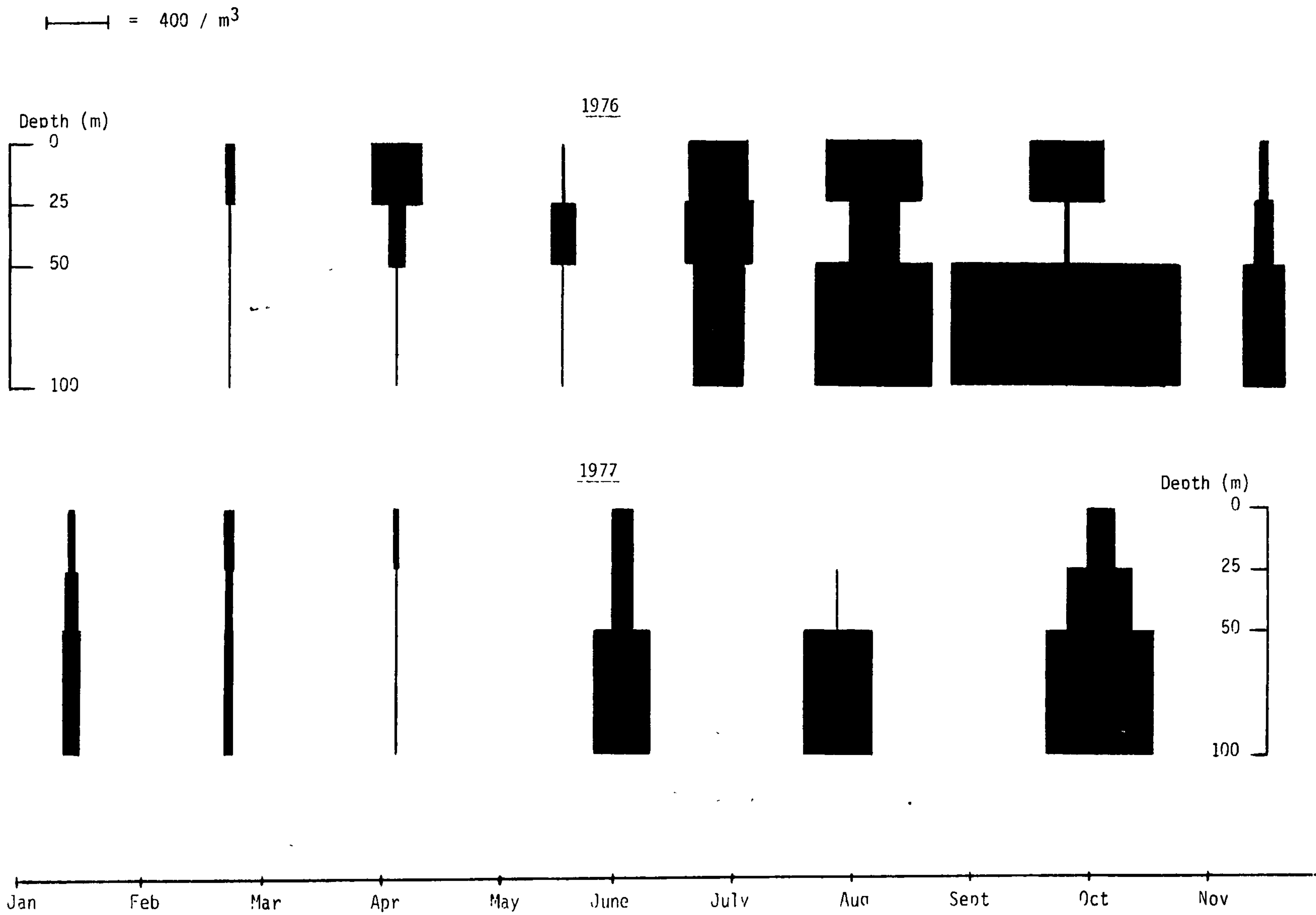

Figure 13. *Pseudocalanus* spp. (juveniles). Number of animals m^{-3}. Station 2, Strait of Juan de Fuca, 1976-1977.

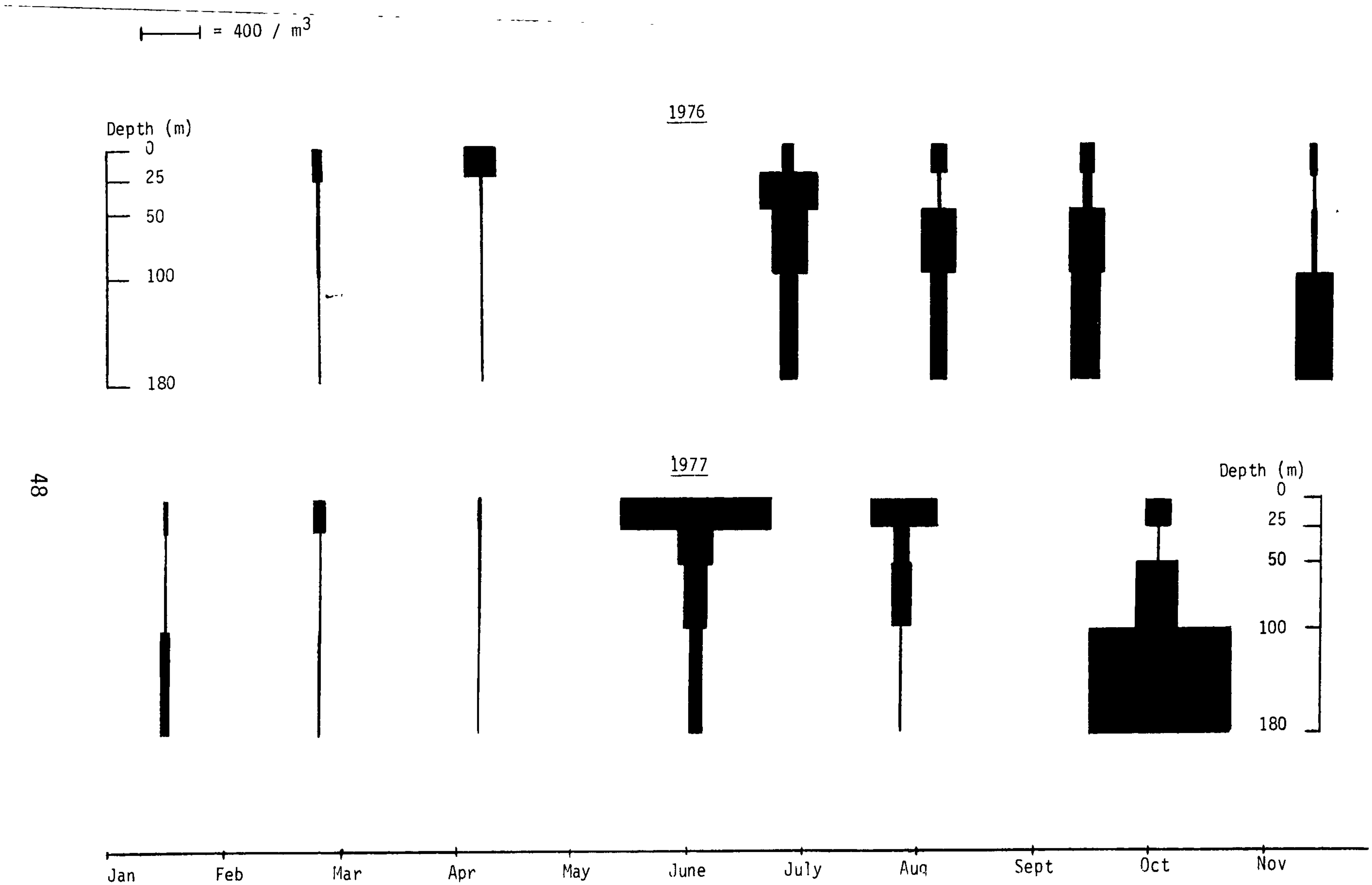

Figure 14. *Pseudocalanus* spp. (juveniles). Number of animals m^{-3}. Station 5, Strait of Juan de Fuca, 1976-1977.

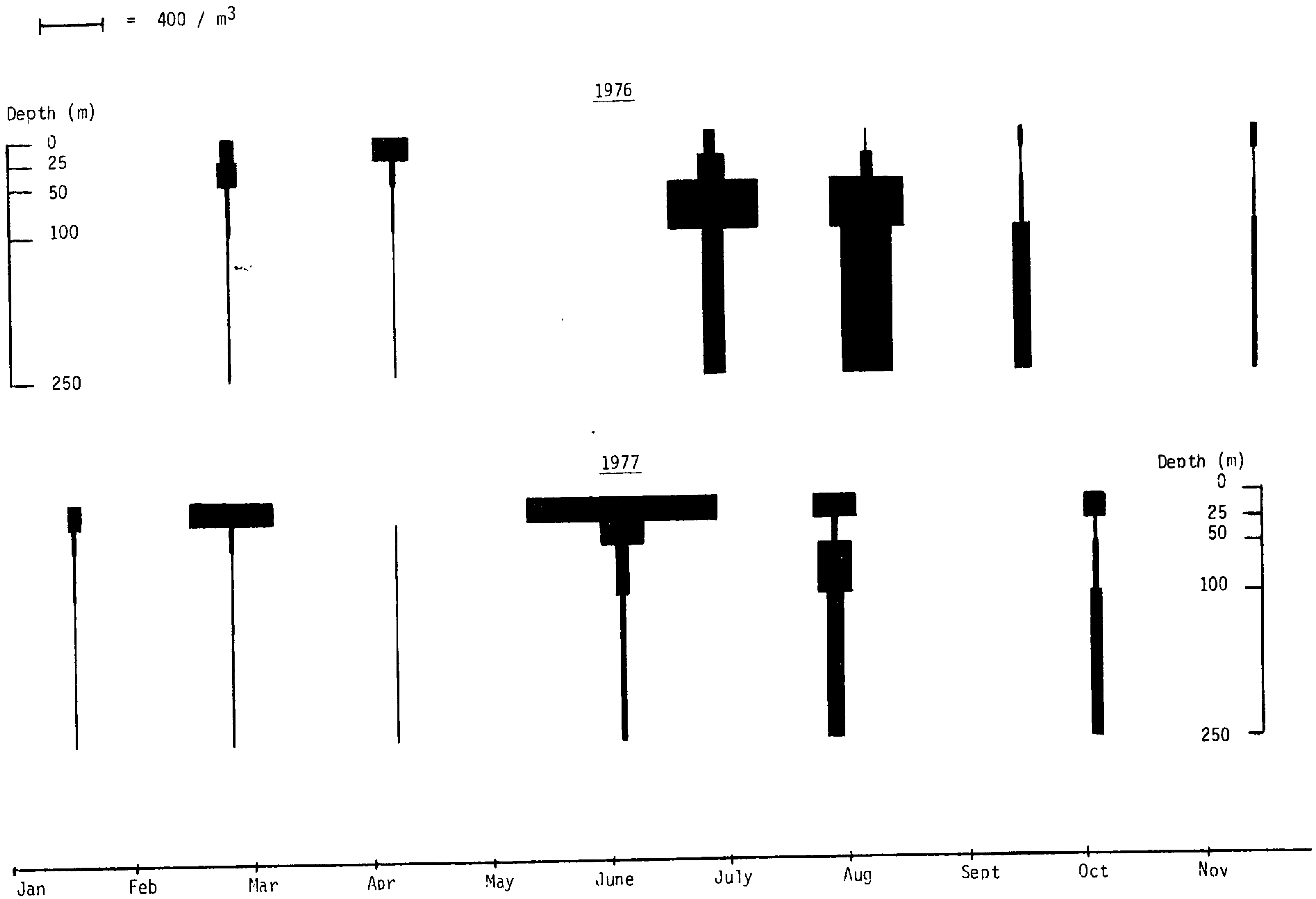

Figure 15. *Pseudocalanus* spp. (juveniles). Number of animals m^{-3}. Station 8, Strait of Juan de Fuca, 1976-1977.

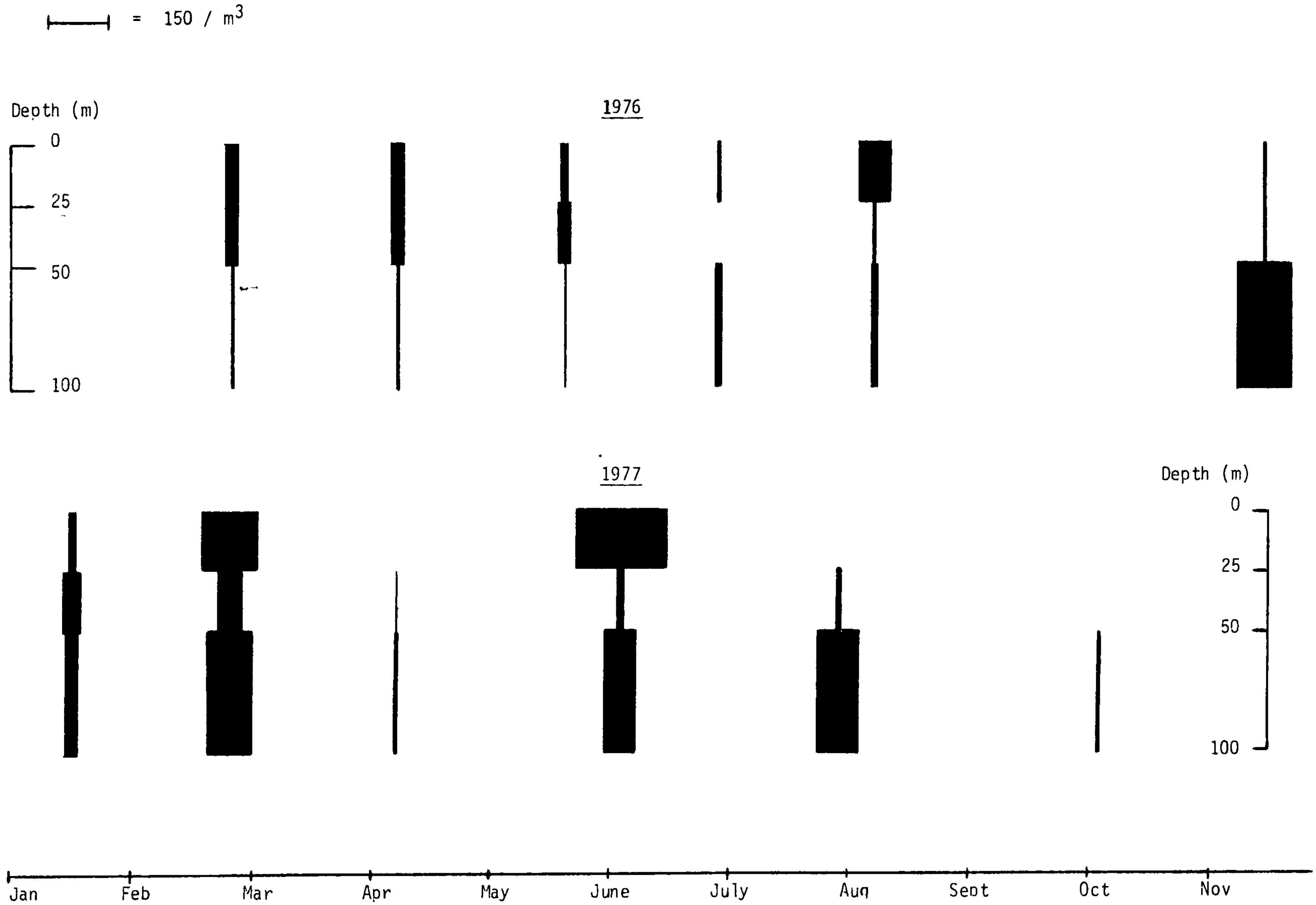

Figure 16. *Acartia longiremis* (adults). Number of animals m^{-3}. Station 2, Strait of Juan de Fuca, 1976-1977.

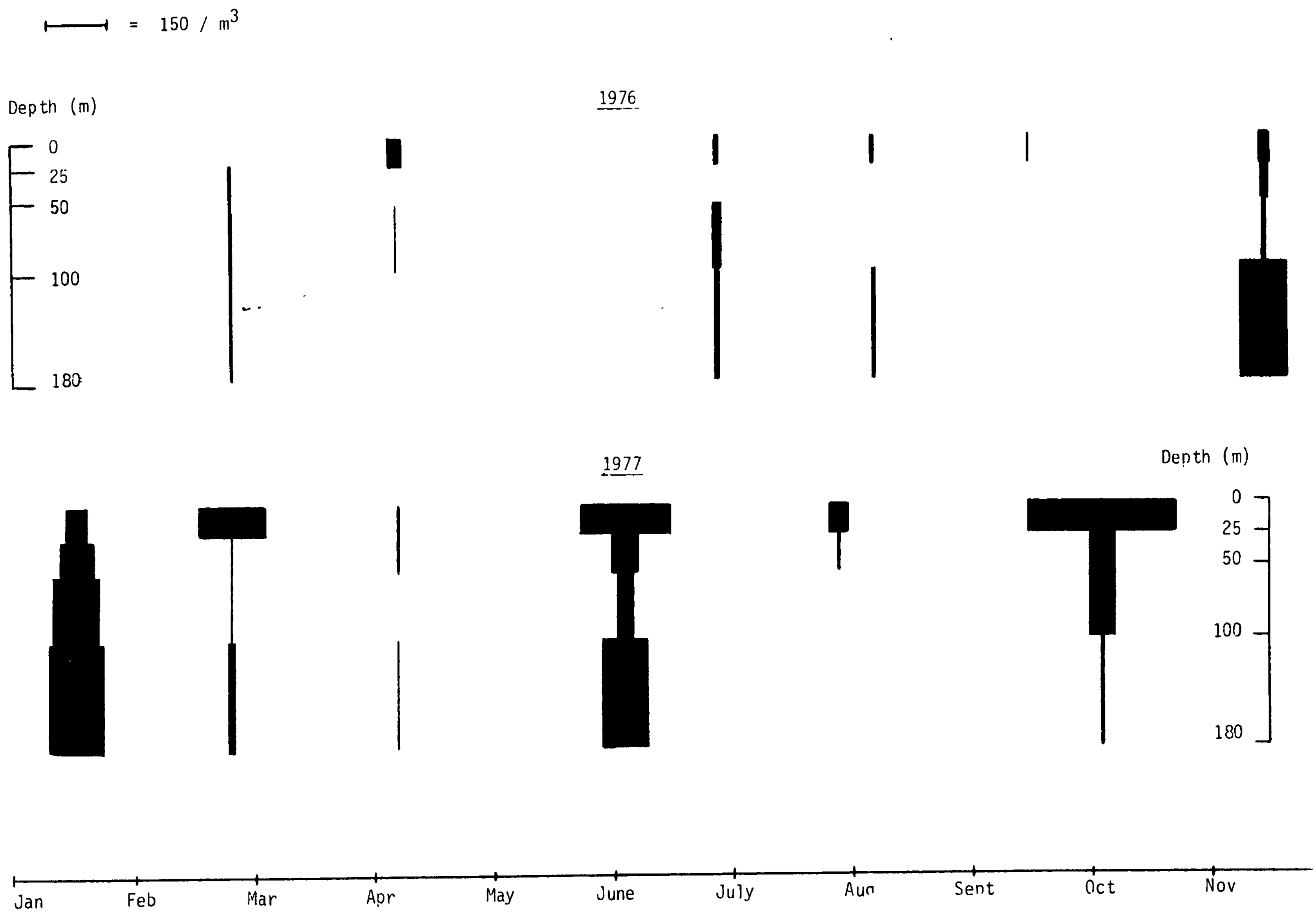

Figure 17. *Acartia longiremis* (adults). Number of animals m^{-3}. Station 5, Strait of Juan de Fuca, 1976-1977.

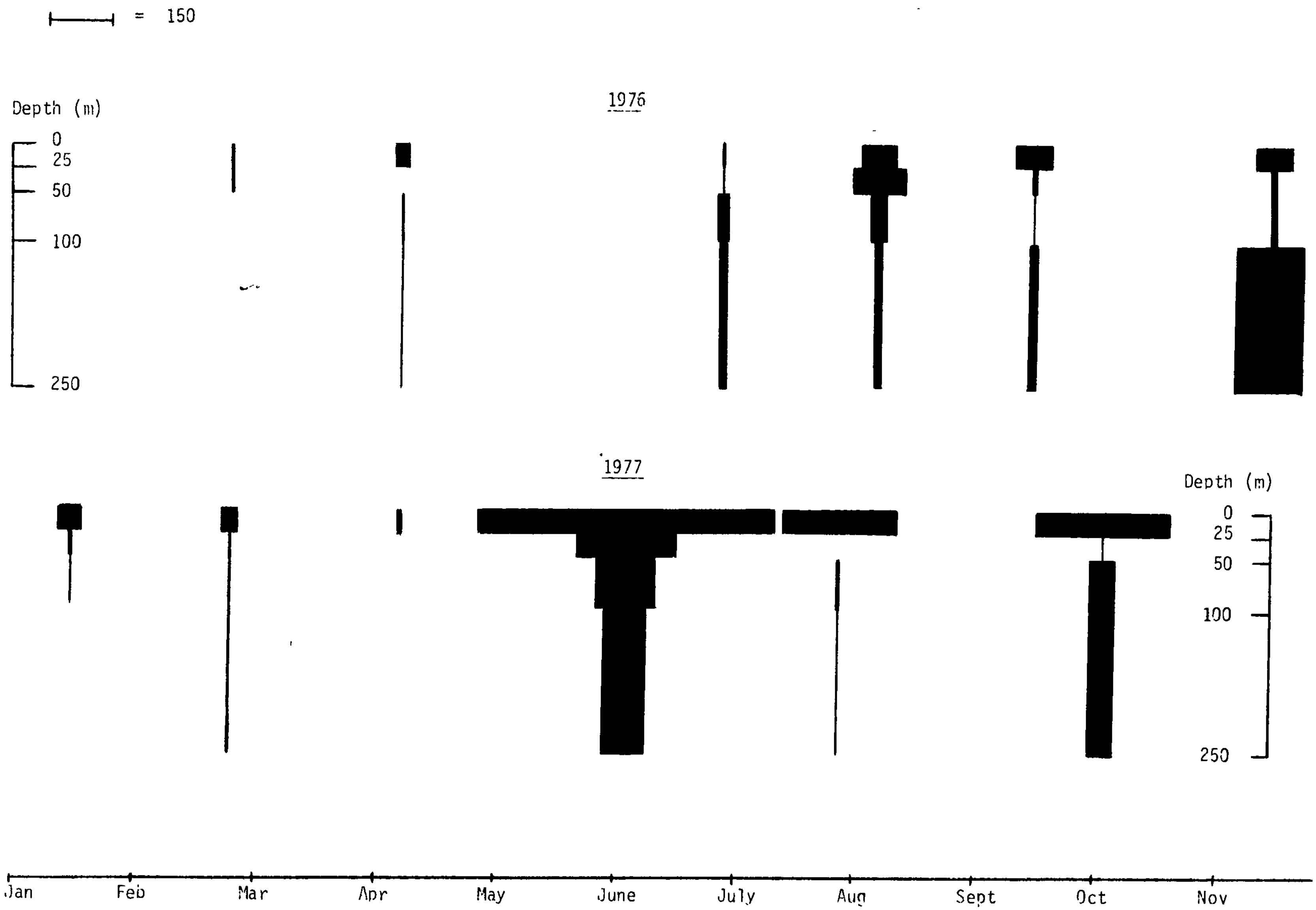

Figure 18. *Acartia longiremis* (adults). Number of animals m^{-3}. Station 8, Strait of Juan de Fuca, 1976-1977.

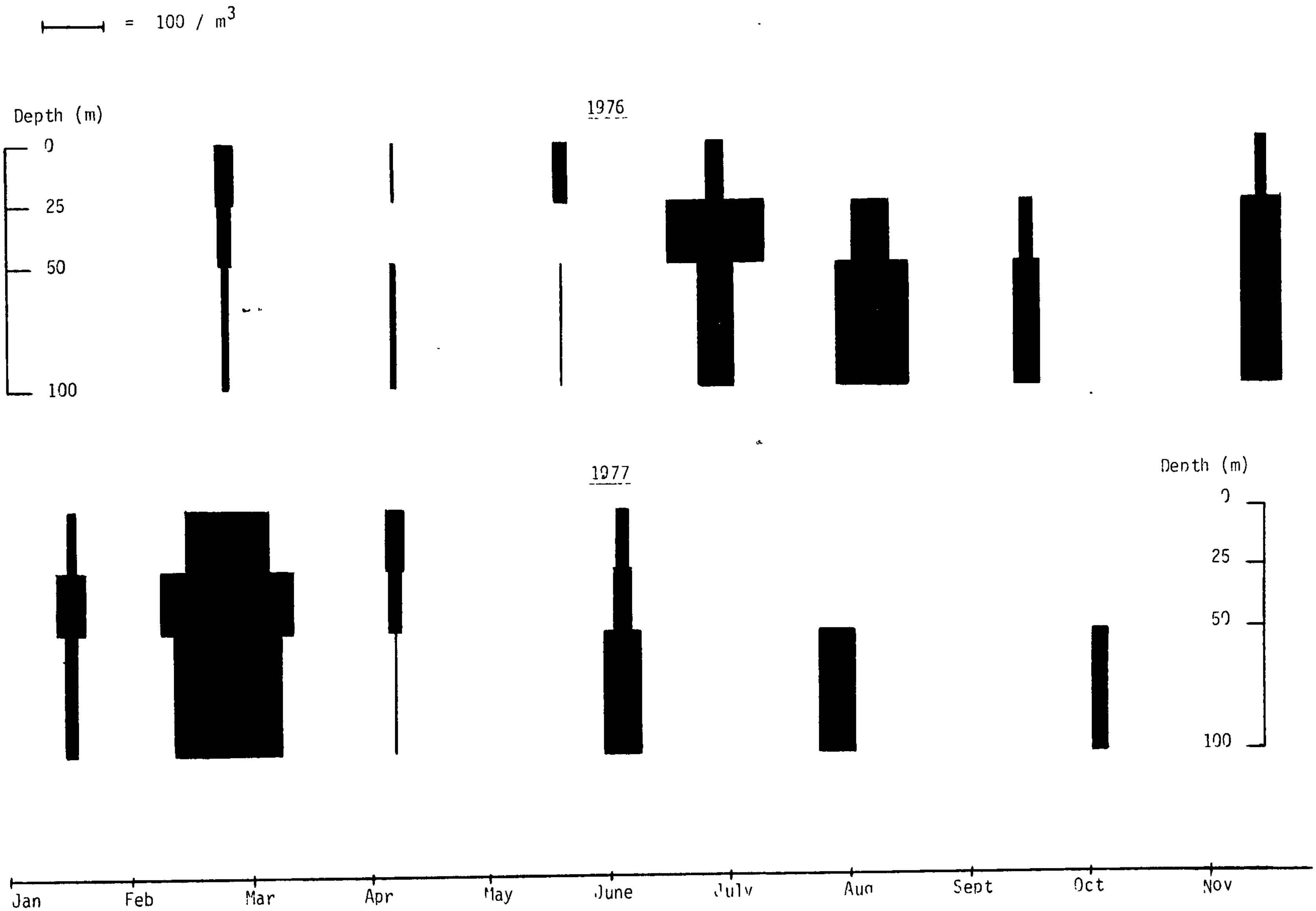

Figure 19. *Oithona similis* (adults). Number of animals m^{-3}. Station 2, Strait of Juan de Fuca, 1976-1977.

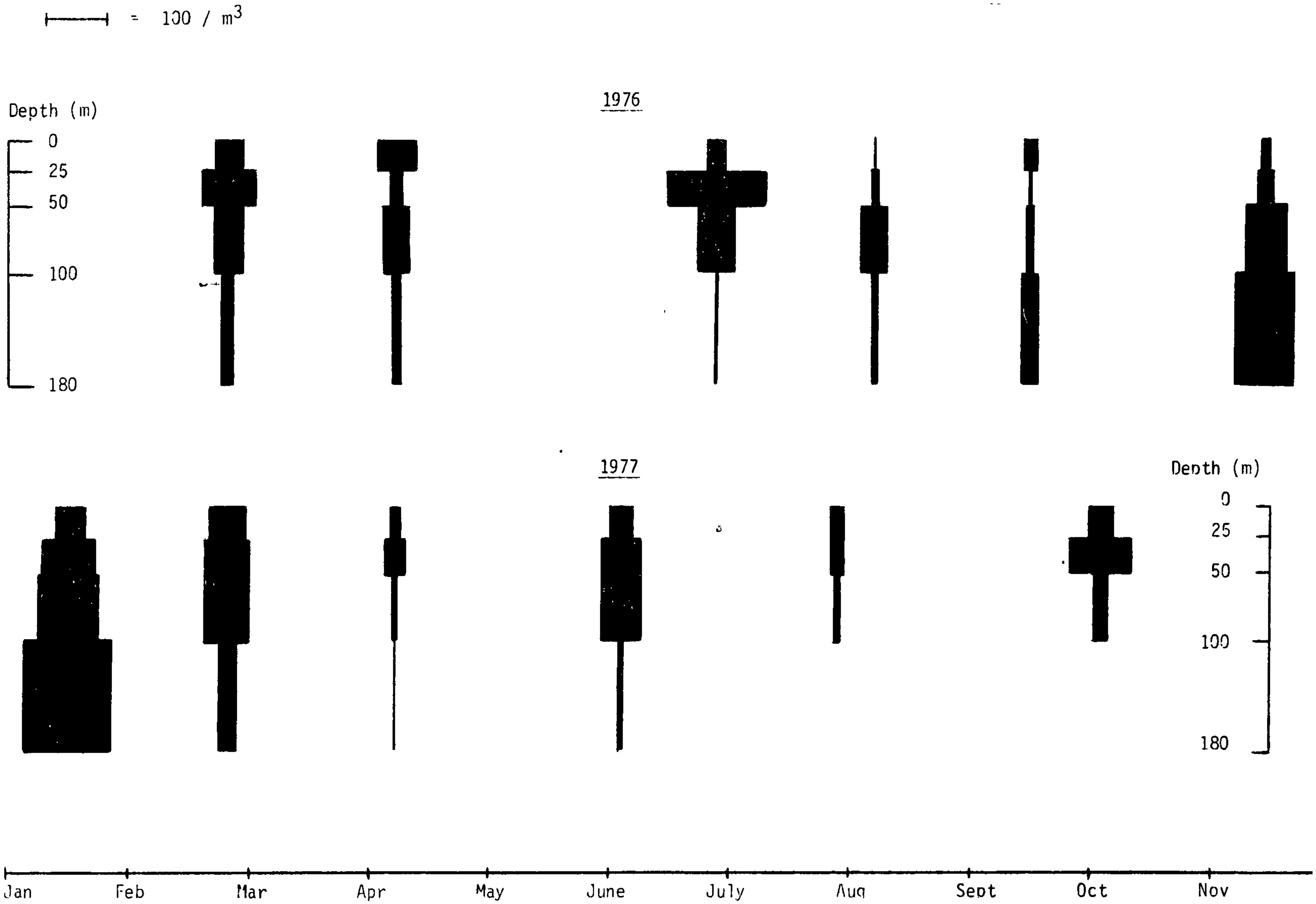

Figure 20. *Oithona similis* (adults). Number of animals m^{-3}. Station 5, Strait of Juan de Fuca, 1976-1977.

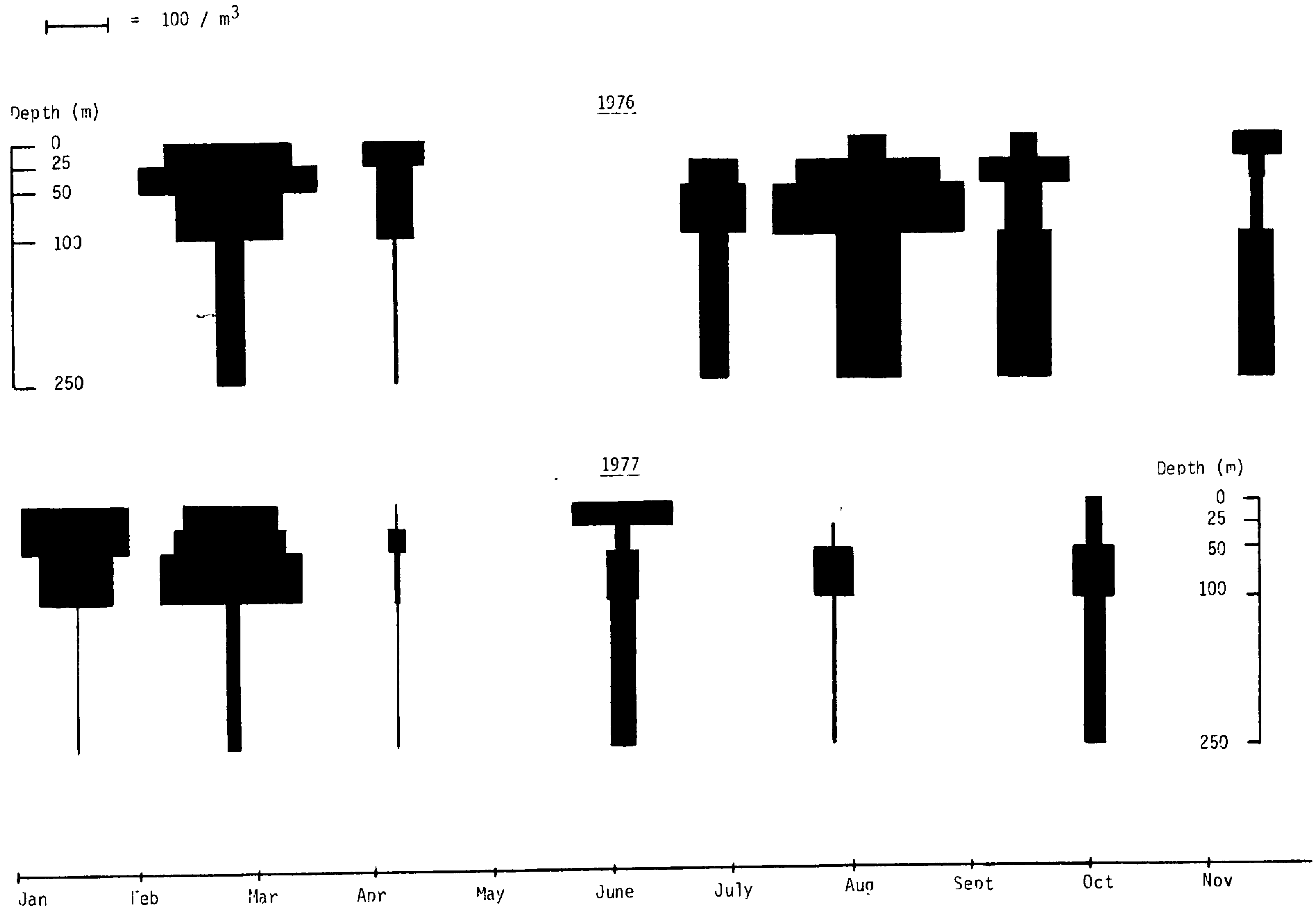

Figure 21. *Oithona similis* (adults). Number of animals m^{-3}. Station 8, Strait of Juan de Fuca, 1976-1977.

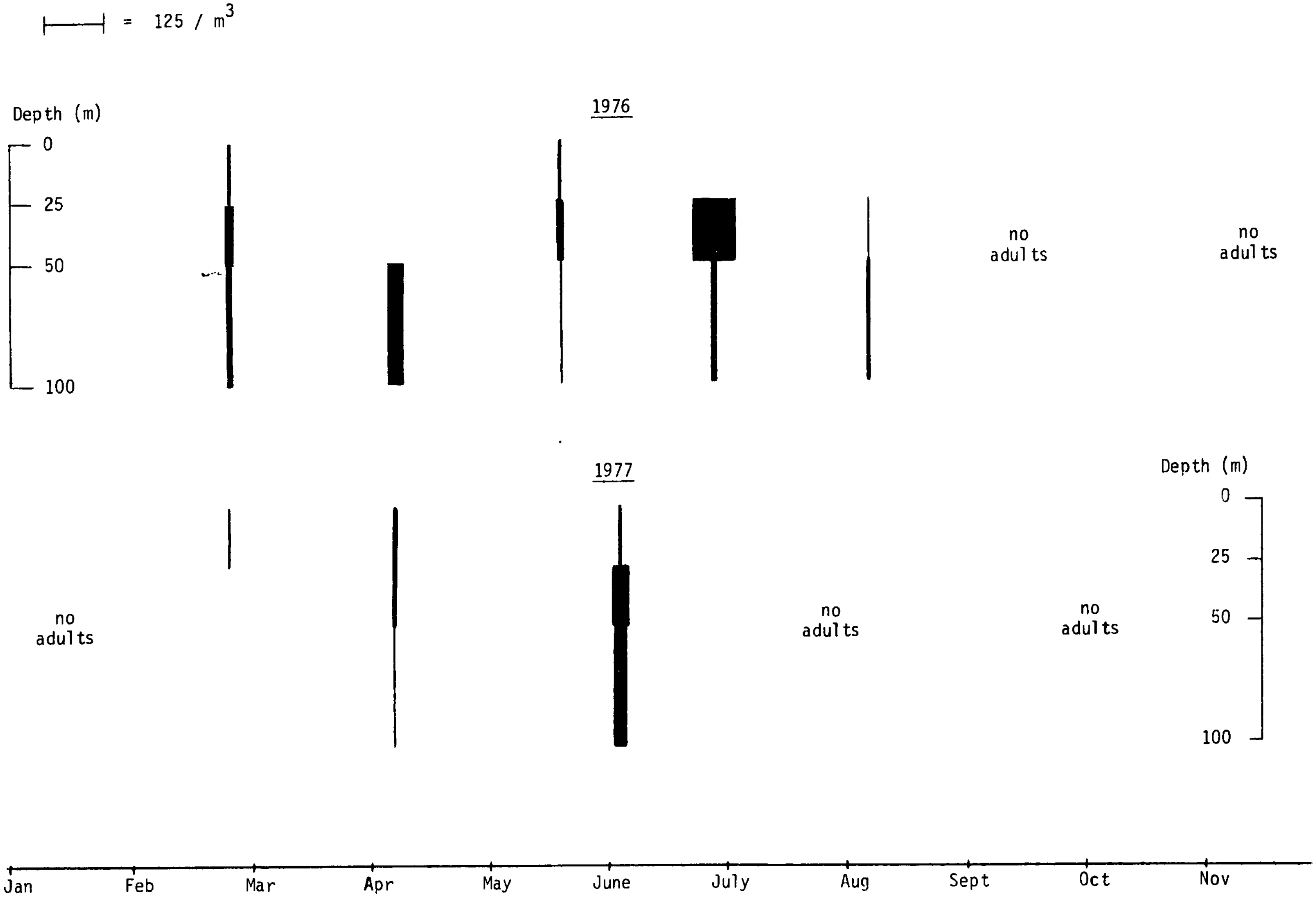

Figure 22. *Calanus marshallae* (adults). Number of animals m^{-3}. Station 2, Strait of Juan de Fuca, 1976-1977.

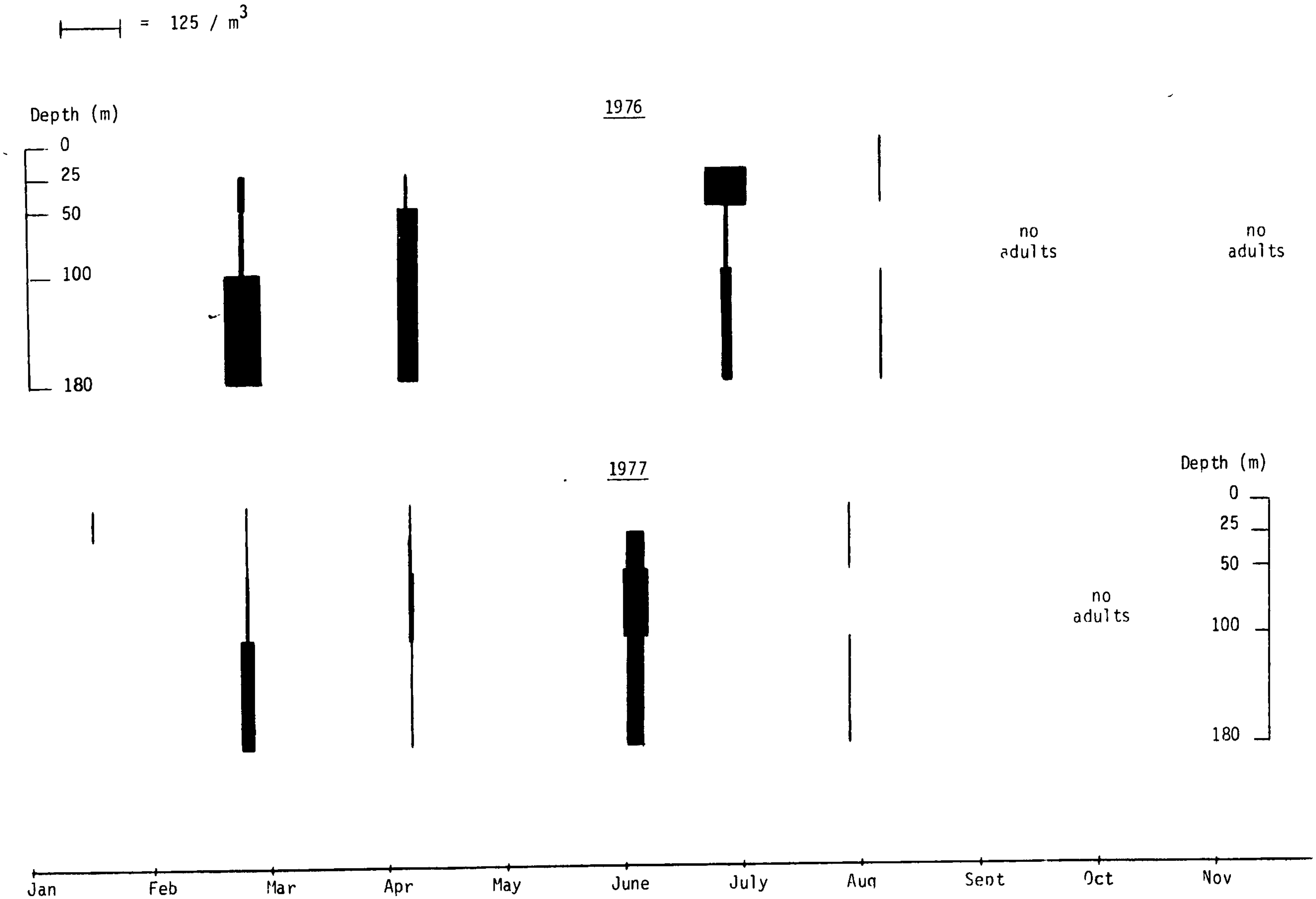

Figure 23. *Calanus marshallae* (adults). Numbers of animals m^{-3}. Station 5, Strait of Juan de Fuca, 1976-1977.

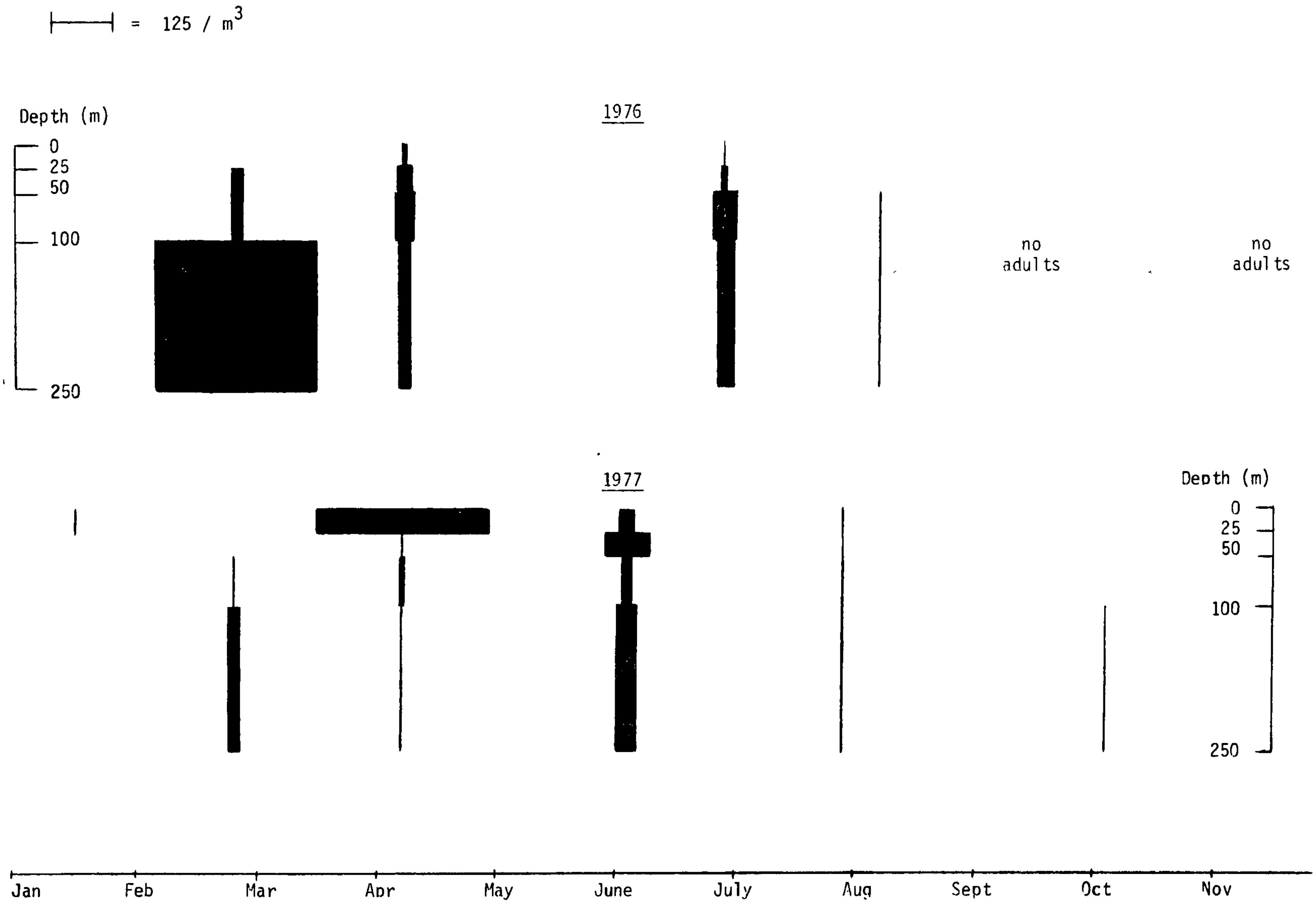

Figure 24. *Calanus marshallae* (adults). Number of animals m^{-3}. Station 8, Strait of Juan de Fuca, 1976-1977.

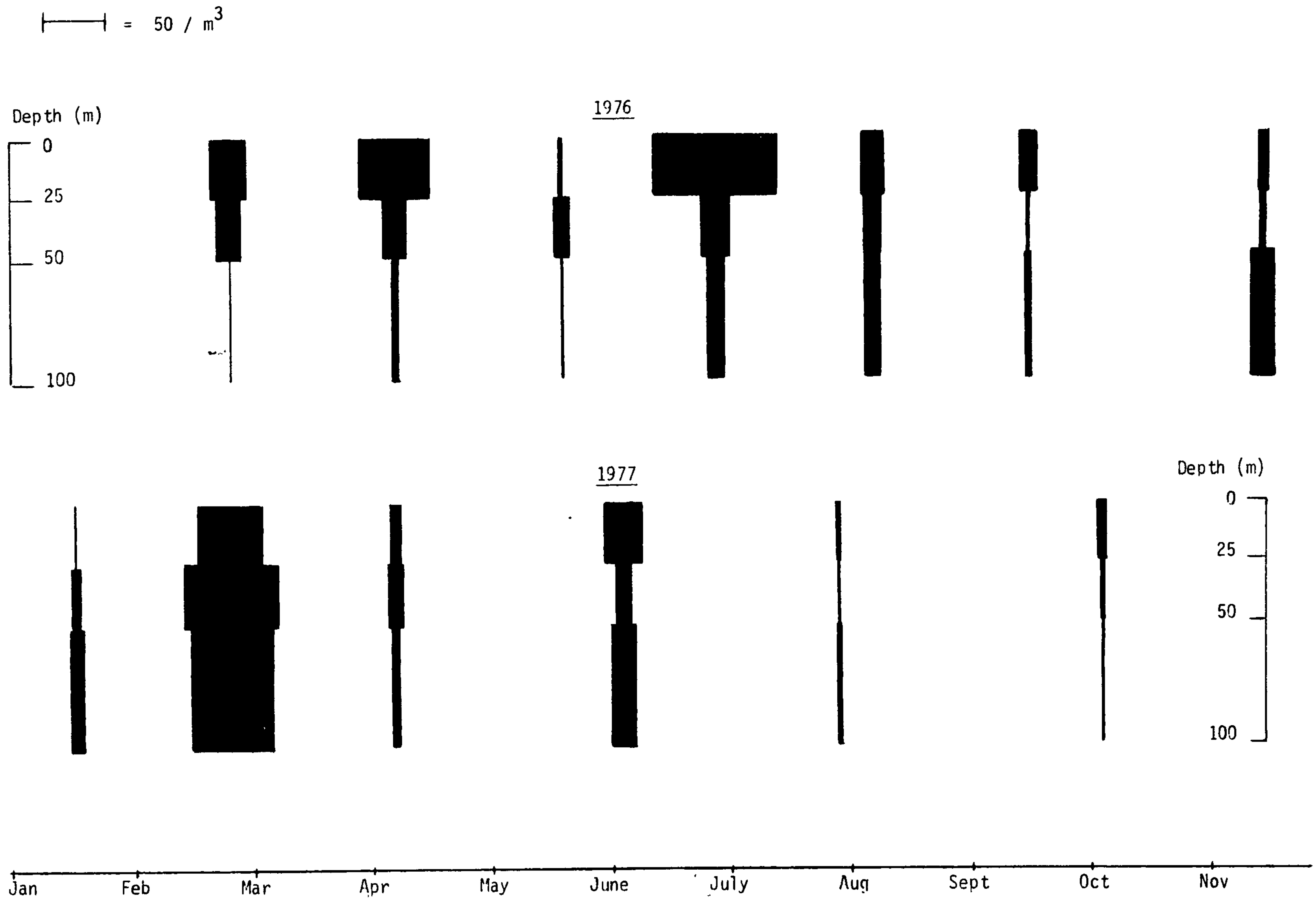

Figure 25. *Sagitta elegans*. Number of animals m^{-3}. Station 2, Strait of Juan de Fuca, 1976-1977.

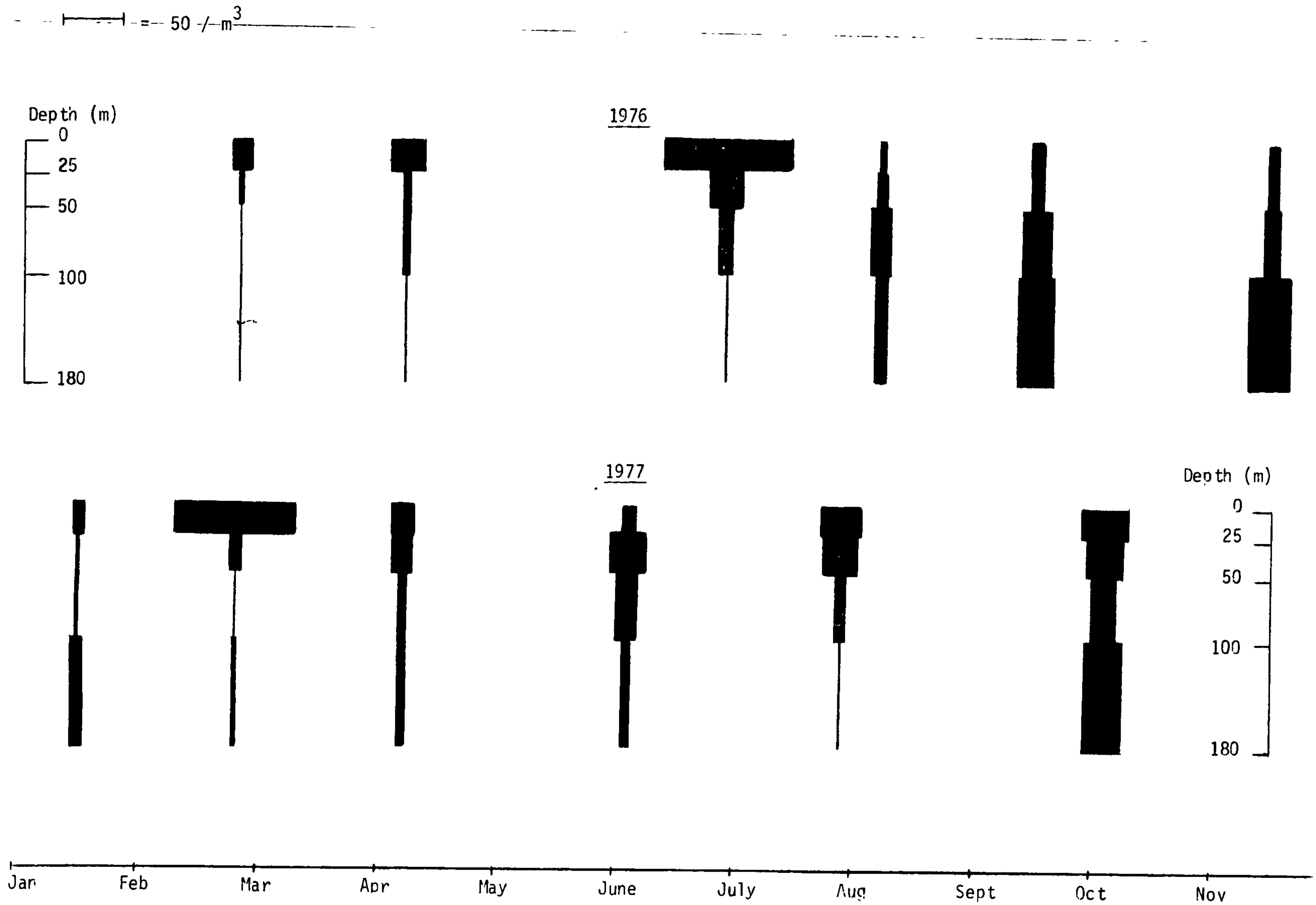

Figure 26. *Sagitta elegans*. Number of animals m^{-3}. Station 5, Strait of Juan de Fuca, 1976-1977.

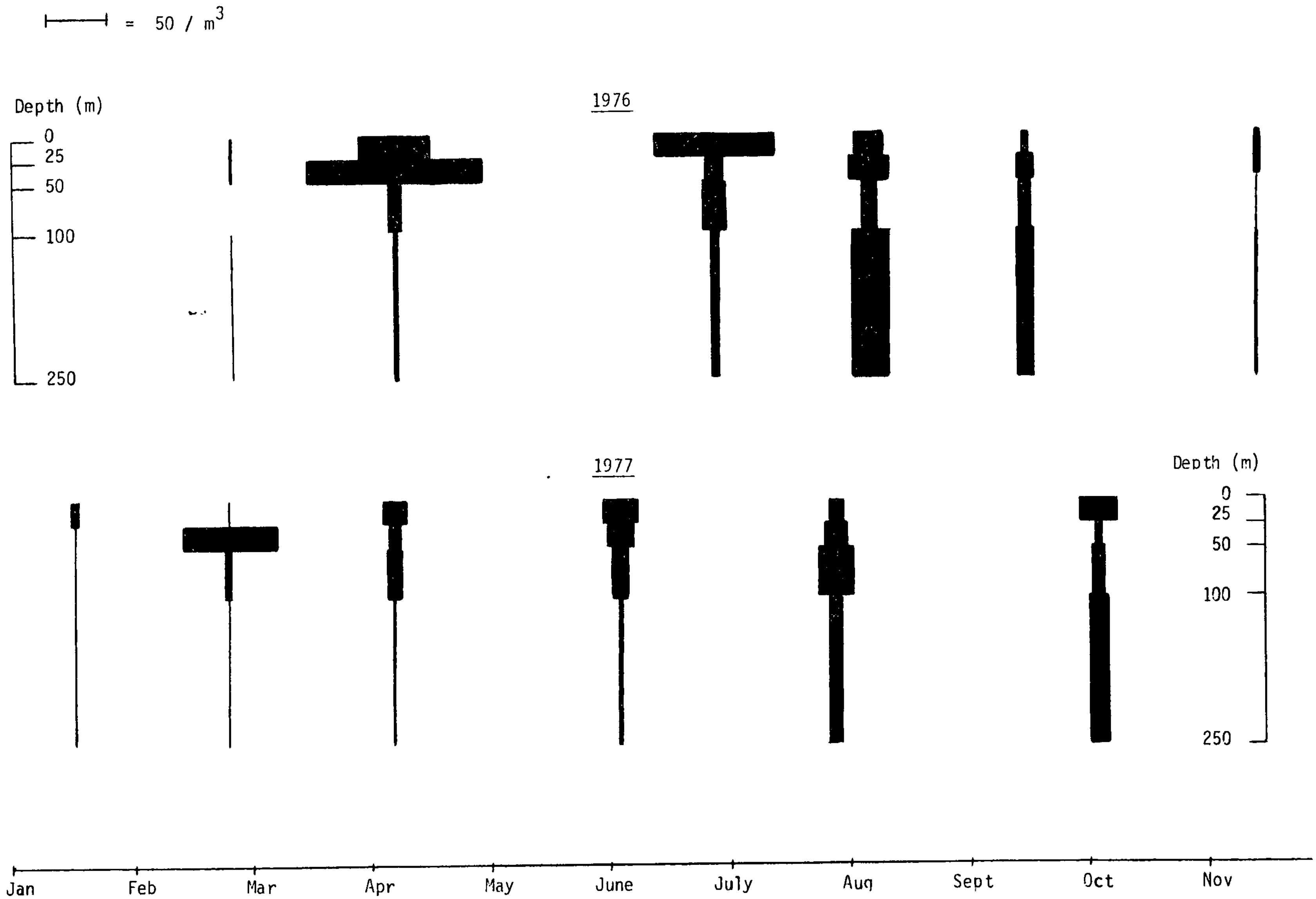

Figure 27. *Sagitta elegans*. Number of animals m^{-3}. Station 8, Strait of Juan de Fuca, 1976-1977.

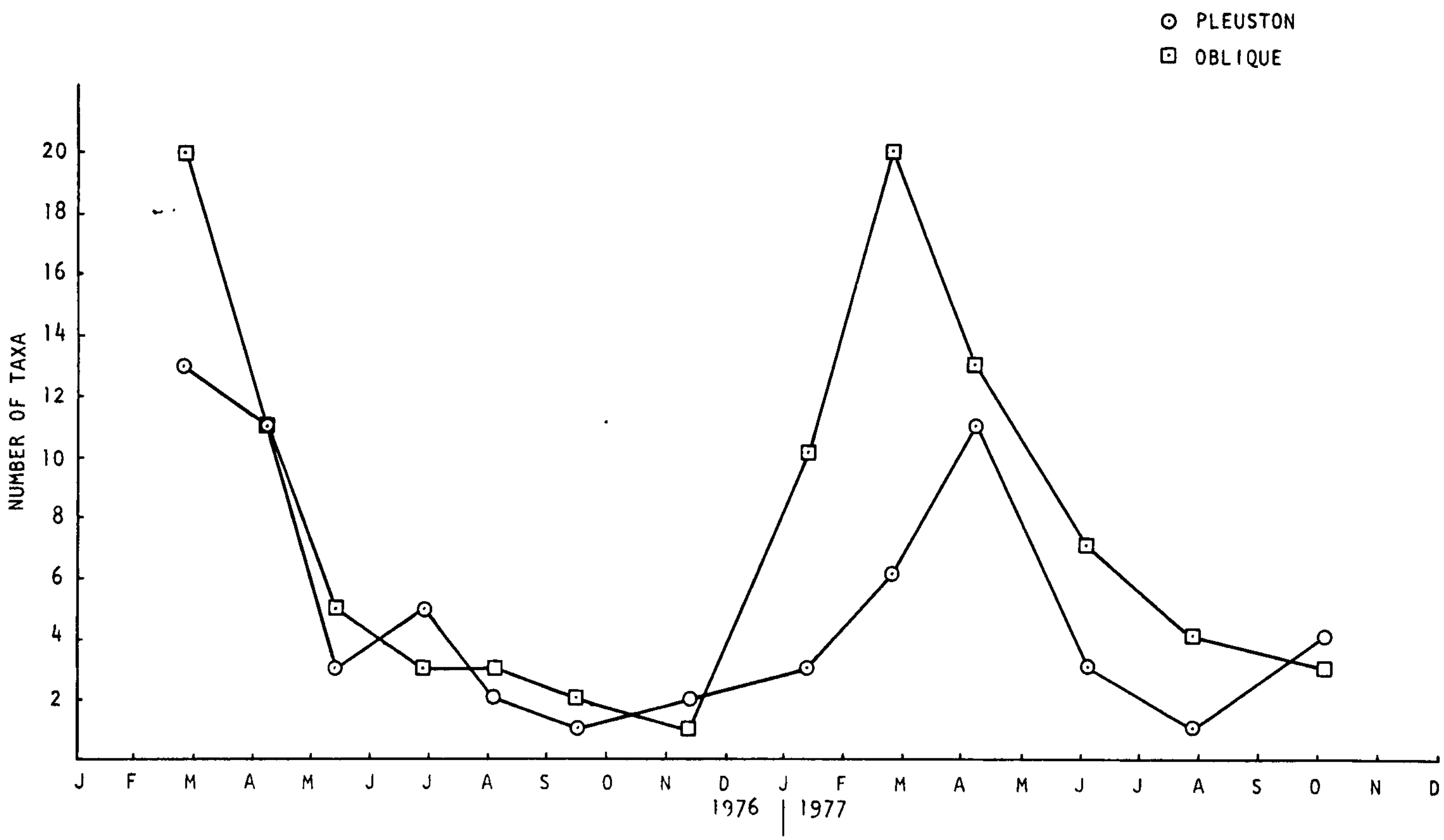

Figure 28. Number of ichthyoplankton taxa caught in surface and oblique net hauls, Strait of Juan de Fuca, 1976-1977.

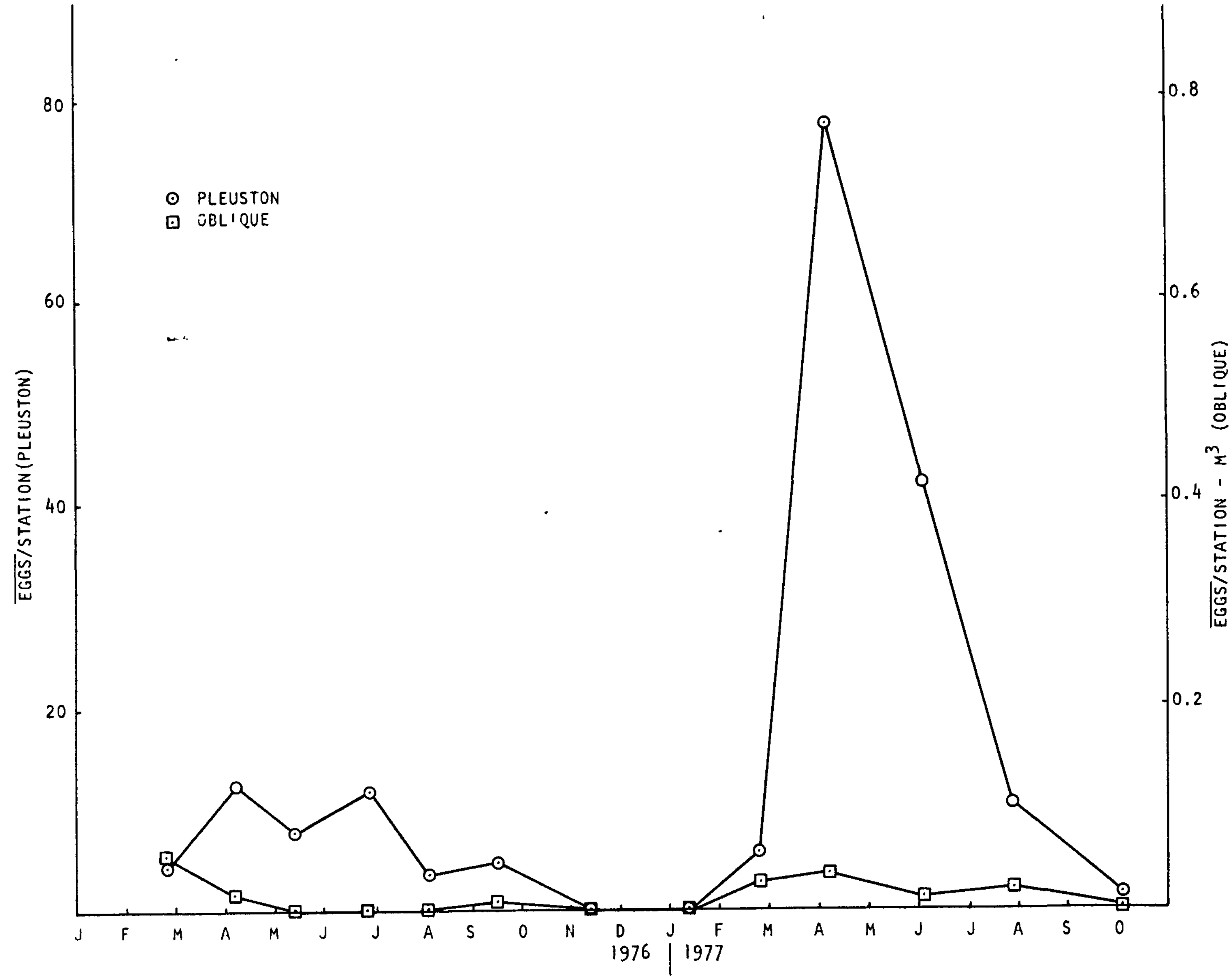

Figure 29. Concentration of fish eggs caught in surface and oblique net hauls, Strait of Juan de Fuca, 1976-1977.

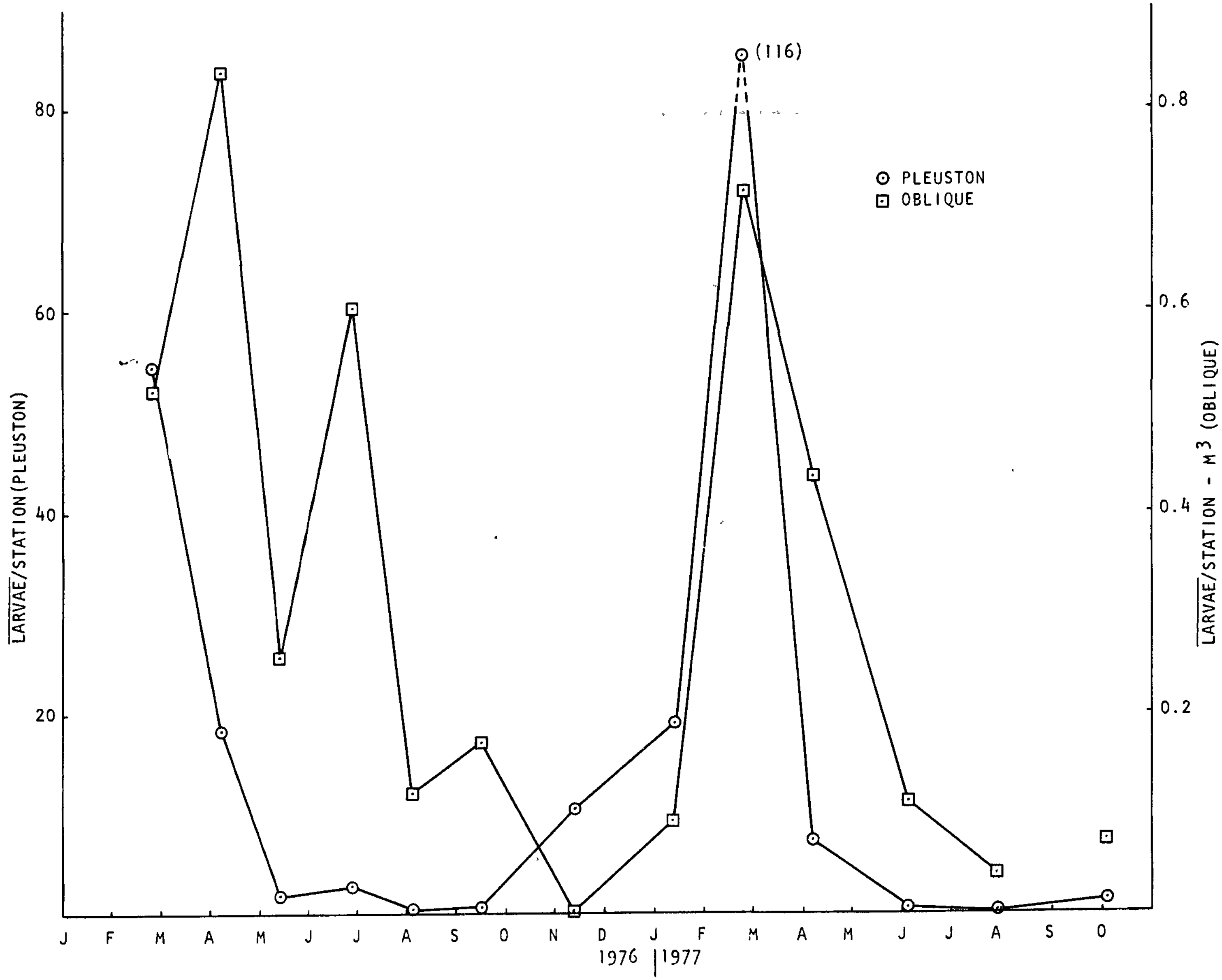

Figure 30. Concentration of fish larvae caught in surface and oblique net hauls, Strait of Juan de Fuca, 1976-1977.