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INSTRUCTIONS FOR AUTHORS

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An Atlas of Seasonal Mean Abundances of the Common Zooplankton of the United States Northeast Continental Shelf Ecosystem

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Abstract. Standardized zooplankton monitoring of the northeast continental shelf of the United States began in 1977 under the Marine Resources Monitoring, Assessment, and Prediction (MARMAP) Program. This document contains portrayals of mean abundances for 10 of the most ubiquitous zooplankton taxa (plus total zooplankton) for six seasons based on 6192 samples collected from 1977 through 1997. These collections, captured with 333 micron nets, were dominated by three copepod species: *Calanus finmarchicus*, *Centropages typicus*, and *Pseudocalanus minutus*. These three species, on average, accounted for 46% of the total number of organisms present in the samples. Of the three species, *C. typicus* was the most abundant in the zooplankton community. This warm water omnivore dominated ecosystem waters from late summer through early winter. The herbivores *C. finmarchicus* and *Pseudocalanus minutus* utilized the spring phytoplankton bloom to dominate early and late spring samples.

Keywords: zooplankton, northwest Atlantic, U.S. Northeast Shelf, MARMAP

INTRODUCTION

In 1970, the United States government developed a new integrated approach to resource assessment of hitherto unprecedented scope that would be responsive to the needs of a wide spectrum of users. It was developed around the concept of assessing living marine resources available to the people of the United States for commercial, recreational, and aesthetic purposes within the framework of a nationally coordinated program. The acronym MARMAP was given to the concept for Marine Resources Monitoring, Assessment, and Prediction (Sherman 1980). Although now more loosely coordinated, the original rationale of MARMAP has strongly influenced ecosystem monitoring programs off the East, Gulf, West, and Alaskan coasts of the United States, as well as numerous locations around the world.

On the northeast coast of the United States, from Cape Hatteras, North Carolina to the Canadian border, standardized monitoring for ichthyo- and zooplankton began in 1977 (Figure 1). Some two hundred locations across this continental shelf were sampled six to twelve times per year during what became known as the MARMAP decade (1977 through 1987). The original MARMAP concept called for beginning this survey designed on the best information

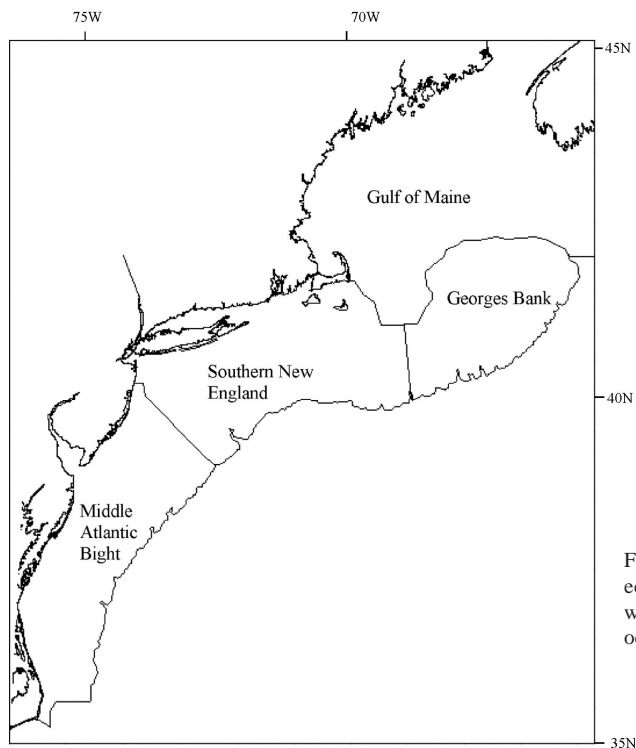


Fig. 1. The United States Northeast Shelf ecosystem showing the four regions within which zooplankton sampling occurred, 1977 through 1997.

available at the time, and after several years of sampling, evaluating the data with the aim of establishing key variables, and temporal and spatial coverages that would still meet program goals while minimizing cost. That evaluation began in the late 1980's (Dow *et al.* 1989). In reviewing the sampling achieved during the MARMAP decade it became clear that some of the attempted analyses suffered from statistical bias, confounding, and sampling variance problems due to irregularities in the time and space coverage. To reduce these problems a modified design was sought to maximize constancy of coverage in both time and space (Urquhart *et al.* 1998). The result was to conduct joint surveys, as much as possible, with programs that had high priority and a long history of fixed-times, e.g., the Northeast Fisheries Science Center's resource, or bottom trawl surveys. Three key times during the year (winter, early spring, and early autumn) could be sampled via these joint surveys. By 1996, the Center had committed ship time at three additional times per year (late spring, late summer, and late autumn) which, aside from major weather or ship's mechanical problems, have become dependable.

This report presents graphic portrayals of mean abundances for ten of the most ubiquitous zooplankton taxa (*Calanus finmarchicus*, *Centropages typicus*, *Pseudocalanus minutus*, *Metridia lucens*, *Temora longicornis*, *Acartia* spp., *Centropages hamatus*, *Oithona* spp., *Paracalanus parvus*, and *Sagitta* spp.), plus total zooplankton, for each of these seasons over the United States northeast shelf ecosystem. It represents the first time that seasonal conditions for these taxa have been described over the full extent of the ecosystem. It is meant to serve as a visual guide to the seasonal variations of the most ubiquitous zooplankton of this ecosystem, hopefully leading to a variety of ecological and fishery-relevant analyses. The method of generating these graphics is also provided.

MATERIALS AND METHODS

Sample Collection and Processing

All data used in the generations of these graphics were collected with 61 cm Bongo Nets (Posgay and Marak 1980) fitted with monofilament 333-micron mesh nets. A typical tow was at a speed of 1.5 to 2.0 knots from the surface to within 5 m of the bottom, or a maximum depth of 200 m. A digital flowmeter was suspended in the center of the bongo frame to measure the amount of water filtered. Complete details of standard sampling techniques used during the analysis period are available in Jossi and Marak (1983); Sibunka and Silverman (1984); and Jossi and Griswold (In Review). Laboratory examination involved the reduction of each sample to approximately 500 specimens, identification to specific taxonomic levels, and staging of dominant taxa. The abundances of taxa are expressed here as numbers per 100 cubic meters of water filtered. Full details of sample analysis and data processing are available in Polanski *et al.* (1998); and Goulet (In Review).

Choices of Taxa

Eleven taxa were selected for the generation of seasonal portrayals for the United States northeast shelf ecosystem. The choice of the first ten was based on ubiquity during the MARMAP decade (1977 through 1987), i.e., the taxa's percent occurrence in all samples. Life stages of a taxon generally were not considered. Rather, all life stages were lumped prior to the selection. The eleventh taxon was total organisms, chosen to represent zooplankton biomass in terms of numerical abundance. Table 1 lists the taxa for which portrayals were generated.

Definition of Seasons and Selection of Data

Distributional plots were developed for each of the six fixed survey periods which have been the standard since 1996 (Table 2). Survey completion times for the different seasons varied from three to eight weeks, and the time necessary for completing the regions within a survey

Table 1. Zooplankton taxa for which mean seasonal abundances are portrayed for the United States northeast shelf ecosystem.

Order of Ubiquity	Taxonomic Name	Life Stage	Authority
1.	<i>Calanus finmarchicus</i>	All stages	Gunner, 1765
2.	<i>Centropages typicus</i>	Copepodites 4-6	Kroyer, 1872
3.	<i>Pseudocalanus minutus</i>	All stages	Boeck, 1872
4.	<i>Metridia lucens</i>	All stages	Boeck, 1864
5.	<i>Acartia</i> spp.	All stages	Dana, 1846
6.	<i>Centropages hamatus</i>	Copepodites 4-6	Lilljeborg, 1853
7.	<i>Oithona</i> spp.	All stages	W. Baird, 1843
8.	<i>Temora longicornis</i>	All stages	Muller, 1785
9.	<i>Paracalanus parvus</i>	All stages	Claus, 1863
10.	<i>Sagitta</i> spp.	All stages	Gunter, 1907
	Total Zooplankton	All states	

Table 2. Time windows for sampling the four regions of the Northeast Shelf ecosystem during six "seasons." Names of the Northeast Fisheries Science Center survey types are listed in parenthesis.

1. Winter (Joint survey with Winter Trawl, but dedicated Ecosystem Survey in Gulf of Maine)	
A. Middle Atlantic Bight	25 JAN -- 08 FEB
B. Southern New England	31 JAN -- 19 FEB
C. Georges Bank	09 FEB -- 27 FEB
D. Gulf of Maine	18 JAN -- 02 FEB
2. Early Spring (Joint survey with Spring Trawl)	
A. Middle Atlantic Bight	01 MAR -- 22 MAR
B. Southern New England	15 MAR -- 06 APR
C. Georges Bank	29 MAR -- 21 APR
D. Gulf of Maine	12 APR -- 06 MAY
3. Late Spring (Dedicated Ecosystem Survey)	
A. Middle Atlantic Bight	22 MAY -- 02 JUN
B. Southern New England	25 MAY -- 07 JUN
C. Georges Bank	28 MAY -- 12 JUN
D. Gulf of Maine	31 MAY -- 15 JUN
4. Late Summer (Dedicated Ecosystem Survey)	
A. Middle Atlantic Bight	9 AUG -- 20 AUG
B. Southern New England	12 AUG -- 25 AUG
C. Georges Bank	15 AUG -- 30 AUG
D. Gulf of Maine	18 AUG -- 02 SEP
5. Early Autumn (Joint survey with Autumn Trawl)	
A. Middle Atlantic Bight	02 SEP -- 22 SEP
B. Southern New England	15 SEP -- 07 OCT
C. Georges Bank	29 SEP -- 22 OCT
D. Gulf of Maine	13 OCT-- 06 NOV
6. Late Autumn (Dedicated Ecosystem Survey)	
A. Middle Atlantic Bight	29 OCT -- 09 NOV
B. Southern New England	01 NOV -- 14 NOV
C. Georges Bank	04 NOV -- 19 NOV
D. Gulf of Maine	07 NOV -- 27 NOV

differed as well. For example, the early spring survey in the Middle Atlantic Bight region (Figure 1) occurred in early March, but in the Gulf of Maine not until early May. Surveys were generally covered in geographical sequence from southwest to northeast. Thus, for each region and season, a fixed time-window was defined. Data falling outside the 24 (6 seasons x 4 regions) were excluded. In all, 6193 samples fell within the seasonal time windows (Figure 2). The resulting sampling coverage, in terms of year and season, is presented in Table 3.

The Gridding Process

The data selected for each seasonal graphic were irregularly distributed in space. Since the objective was to visualize the data and to create files usable for geostatistical and ecological analyses, the raw data were gridded. Input data consisted of three values in an x - y - z coordinate

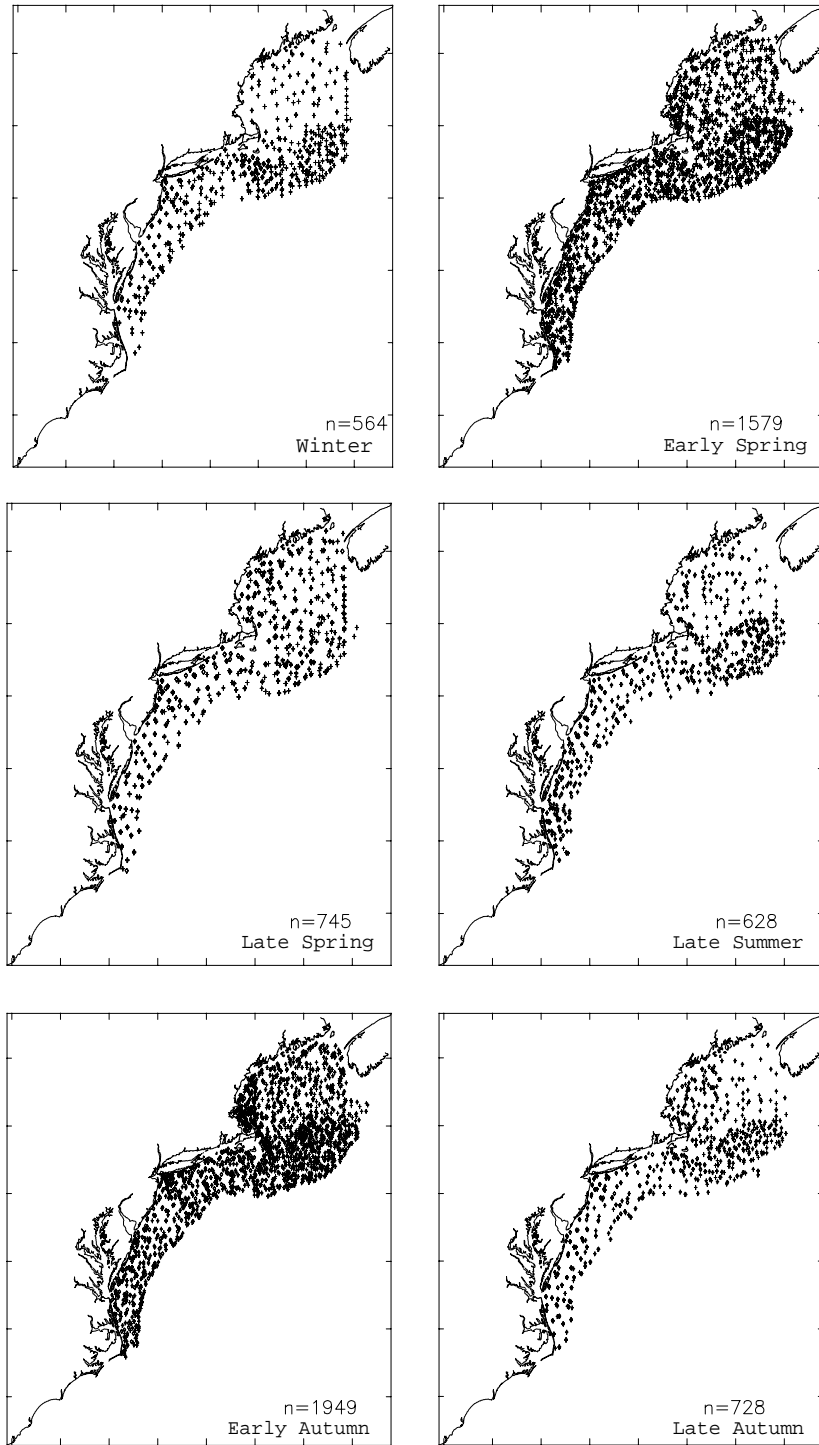


Fig. 2. Zooplankton sample coverage of the United States Northeast Shelf ecosystem during the six MARMAP ecosystem survey seasons, 1977 through 1997.

Table 3. Summary of Northeast Shelf ecosystem samples by year and survey season used in the preparation of graphic portrayals.

Year	Winter	Early Spring	Late Spring	Late Summer	Early Autumn	Late Autumn
1977	30	37	55	14	26	37
1978	22	3	0	93	146	48
1979	0	82	0	135	73	38
1980	0	99	113	0	97	0
1981	6	117	27	60	58	10
1982	0	162	61	0	71	37
1983	72	127	97	78	96	14
1984	62	132	23	26	143	73
1985	58	87	30	43	69	51
1986	4	126	75	69	142	71
1987	4	50	107	20	134	54
1988	29	106	0	0	159	60
1989	0	0	0	0	42	0
1990	7	54	0	0	93	68
1991	90	0	0	0	101	0
1992	40	69	0	21	85	0
1993	29	67	0	0	96	0
1994	23	65	40	0	108	0
1995	19	97	60	18	0	0
1996	17	0	57	36	103	86
1997	52	99	57	15	107	81
Totals	564	1,579	745	628	1,949	728

system, where x = negative longitude degrees scaled by a factor of 1.27 to approach a mercator map projection, and to result in longitude increasing westward; y = latitude degrees; and z = common logarithm transformed plankton abundance ($\log_{10}(\text{number}/100 \text{ m}^3 + 1)$); subset from the 1977 through 1997 data bases for the appropriate taxon and time windows. Log transformation of zooplankton abundance data is a common practice to produce near normal distributions, and all arithmetic operations were performed on these transformed values. The standard grid had limits of 65° W to 77° W for the x -axis, and 35° N to 45° N for the y -axis, and contained 100 grid points in either direction. The rectangular grids were blanked for the North American land mass, and offshore for delineating the extent of survey coverage. An elliptical search surrounding each grid was performed and the weighted mean value calculated based on the inverse of the square of the data's distance from the grid point. Since the spatial, x and y values had been processed to approach those for a mercator map projection the dimensions of the search ellipses vary with changing latitude (see Table 4 for summary of gridding parameters).

The Portrayals

The gridded data were contoured using identical intervals for all taxa. Five intervals, ranging from absent to greater than 100,000/100 m³ were chosen, with the non-zero abundances progressing logarithmically. Areas between the contour intervals were shaded as a visual aid.

Table 4. Summary of gridding parameters used in the preparation of graphic portrayals.

Grid Limits	X minimum = -75 (75°W) X maximum = -65 (65°W) Y minimum = 35 (35°N) Y maximum = 45 (45°N)
Grid Density	100 x 100
Grid Interval at 35° N At 45°	X = 5.4774 km Y = 11.0938 km X = 4.7309 km Y = 11.1131 km
Search Method	All data within search ellipse
Search Ellipse Radii at 35° N At 45°	X = 54.774 km Y = 66.5628 km X = 47.3094 km Y = 66.6786 km
Weighting	Inverse distance squared
Data Scaling	X data (longitude) scaled by factor of 1.27 to approach Mercator map projection proportions

RESULTS

Figures 3-13 show the mean abundances ($\log_{10}(\text{number}/100 \text{ m}^3 + 1)$) of ten zooplankton taxa and of total zooplankton for six survey seasons of the U.S. northeast shelf ecosystem, based on 1977 through 1997 data. Table 5 lists statistics resulting from the seasonal calculations, lumped for the entire ecosystem.

The ten taxa reported on here contributed, on average, 63.3 % to the total zooplankton organisms taken during the six seasons for the 1977 through the 1997 period. The seasonal abundance cycle for the ten taxa and total zooplankton can be seen in Table 5. All ten taxa were present at some sampled sites during all six seasons with mean seasonal log abundances ranging from 0.65 to 4.3/100 m³. Maximum log abundances for each taxa reached 5.0/100 m³ or greater at some location during the 21 year period. The highest recorded station log abundance (6.1/100 m³) was recorded in early autumn for the copepod *Centropages typicus*. Early autumn also was the time of highest log abundance for total zooplankton (7.1/100 m³).

The table and figures readily show that the plankton samples were numerically dominated by three copepod species: *Calanus finmarchicus*, *Centropages typicus*, and *Pseudocalanus minutus* (Figures 3-5). These three species, on average, accounted for 46% of the total number of organisms present in the samples.

Of the three species, *C. typicus* (Figure 4) was the most abundant one of the zooplankton community. This warm water omnivore dominates ecosystem waters from late summer through early winter. Its density was high year-round in the southern half of the region and became elevated in the more temperate northern half of the ecosystem during late summer. Ecosystem abundance peaked in late autumn when the copepods abundance was above 4.0/100m³ throughout most of the region.

The herbivores *Calanus finmarchicus* (Figure 3) and *Pseudocalanus minutus* (Figure 5) utilize the spring phytoplankton bloom to dominate early and late spring samples. Both species had similar annual abundance cycles but differed in their spatial distribution. *Pseudocalanus*

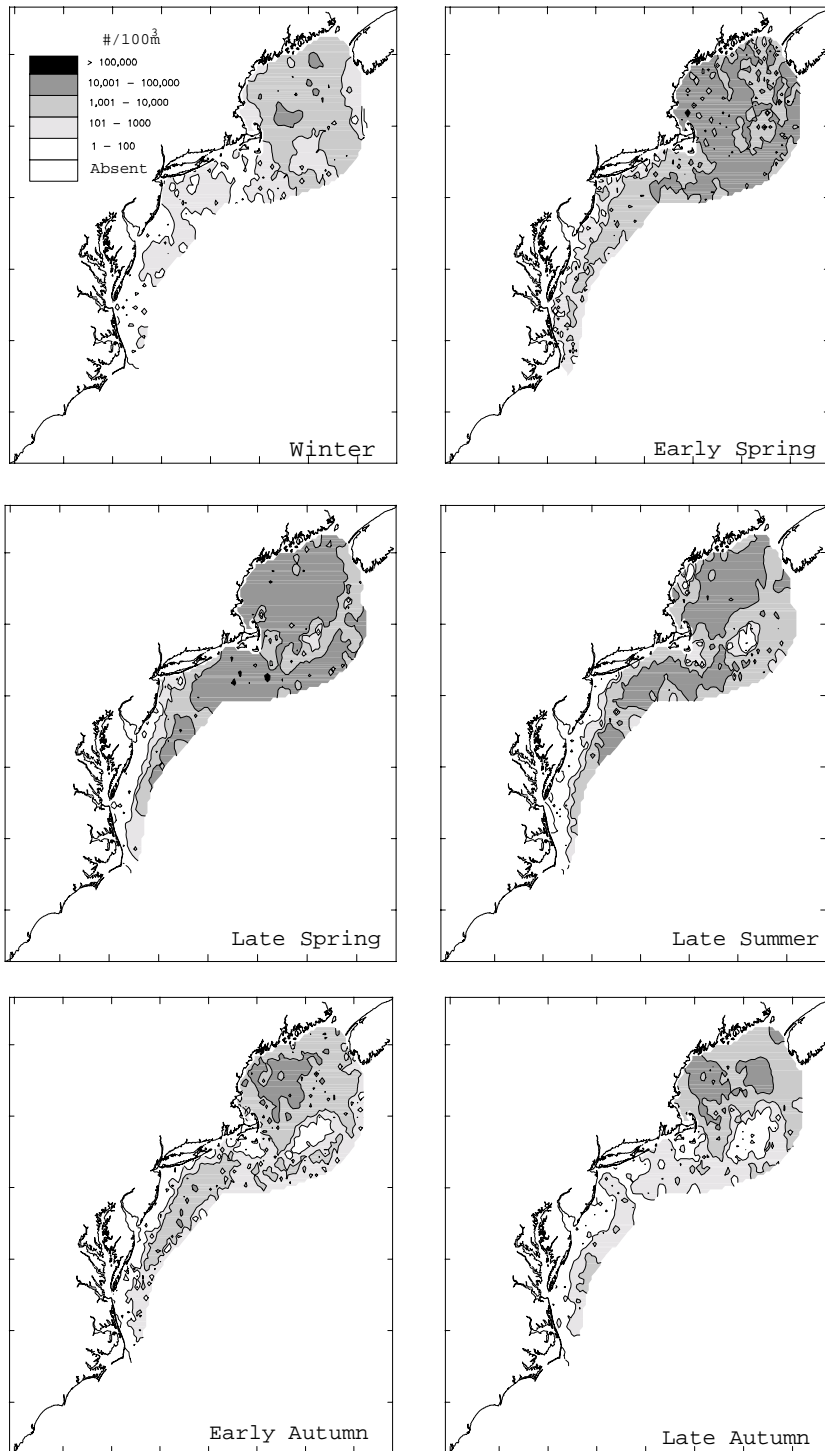


Fig. 3. Seasonal mean abundance of *Calanus finmarchicus*, all stages, based on 1977 through 1997 MARMAP ecosystem surveys data.

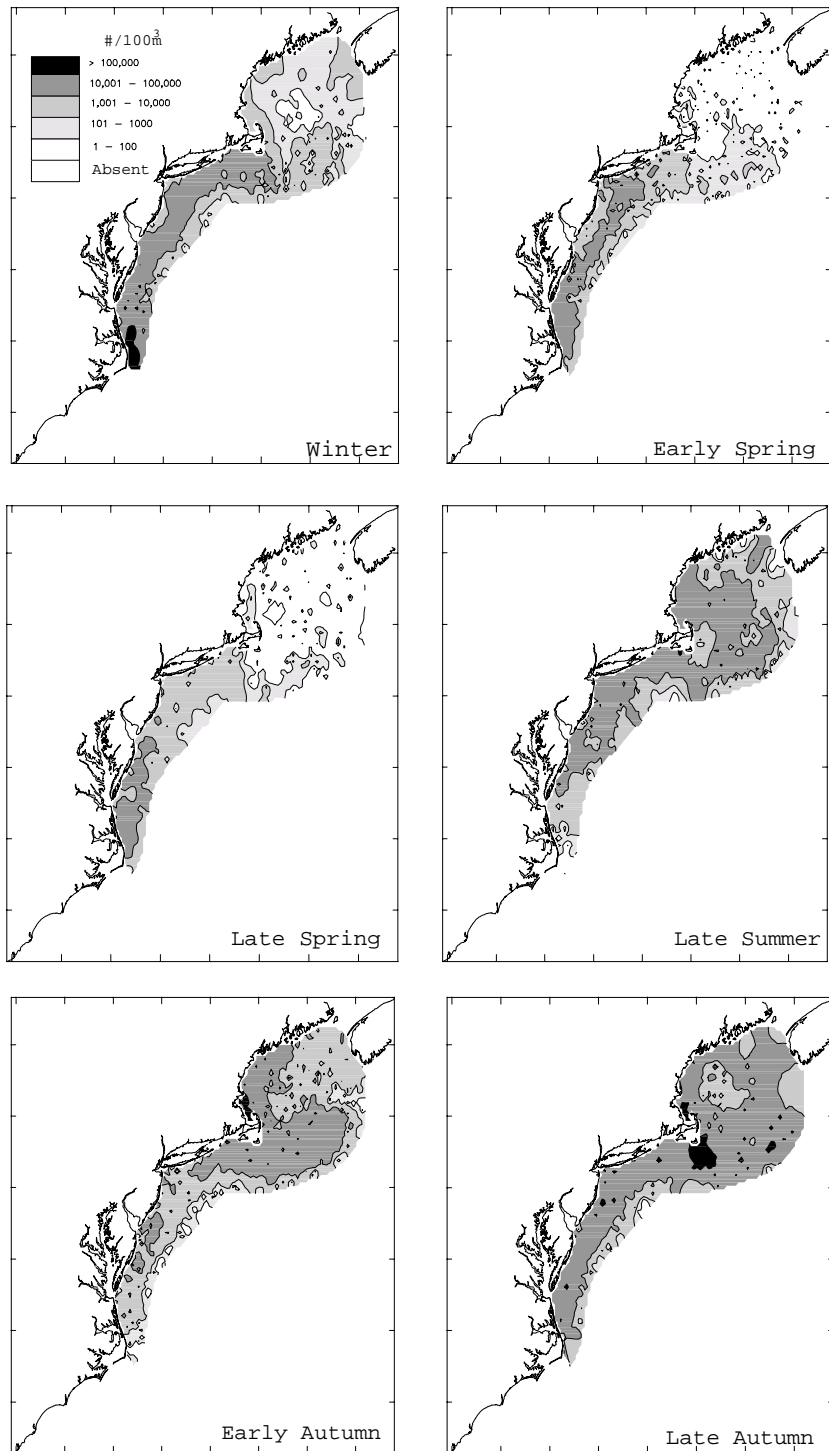


Fig. 4. Seasonal mean abundance of *Centropages typicus*, copepodites 4-6, based on 1977 through 1997 MARMAP ecosystem surveys data.

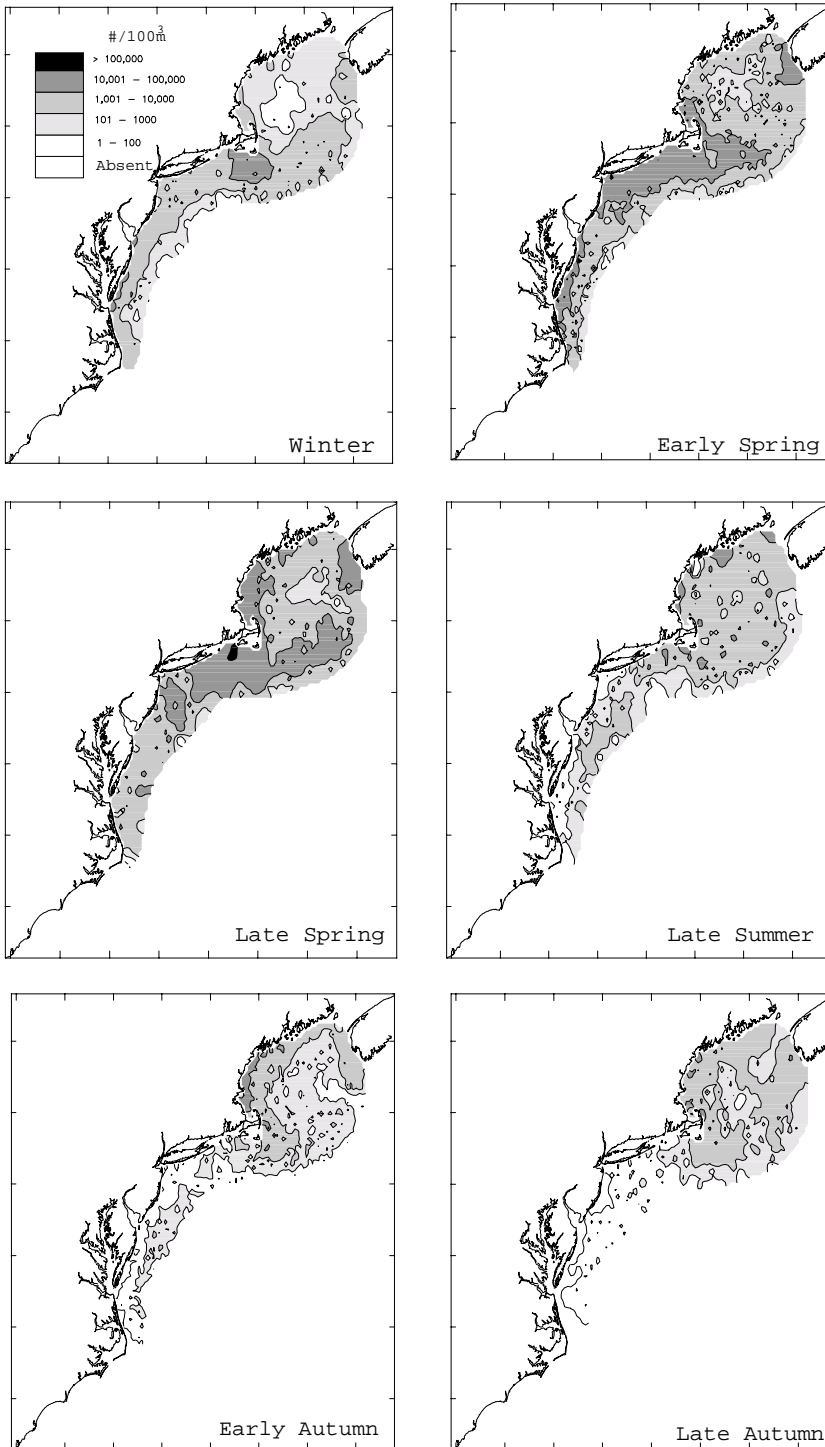


Fig. 5. Seasonal mean abundance of *Pseudocalanus minutus*, all stages, based on 1977 through 1997 MARMAP ecosystem surveys data.

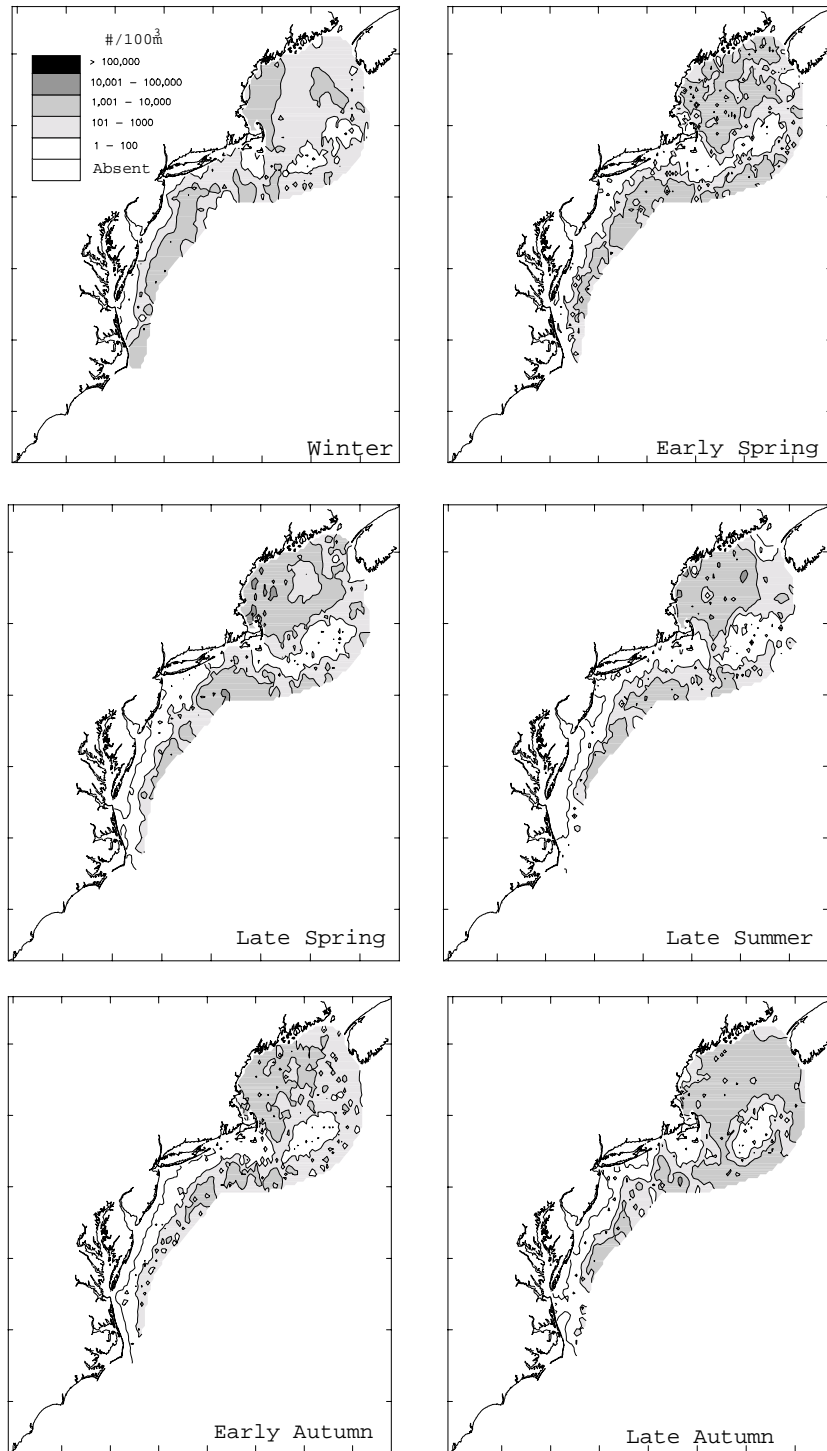


Fig. 6. Seasonal mean abundance of *Metridia lucens*, all stages, based on 1977 through 1997 MARMAP ecosystem surveys data.

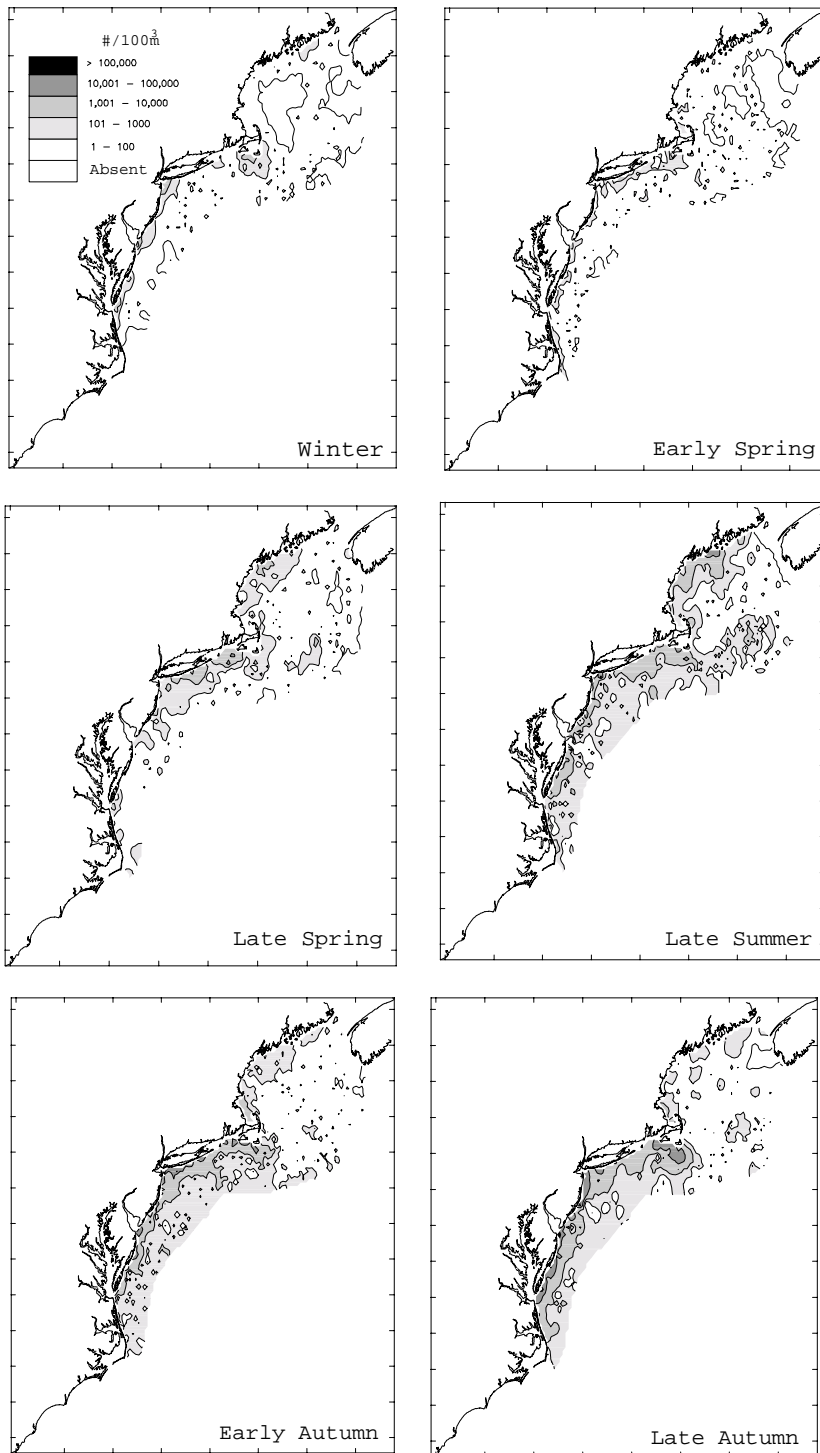


Fig. 7. Seasonal mean abundance of *Acartia* spp., all stages, based on 1977 through 1997 MARMAP ecosystem surveys data.

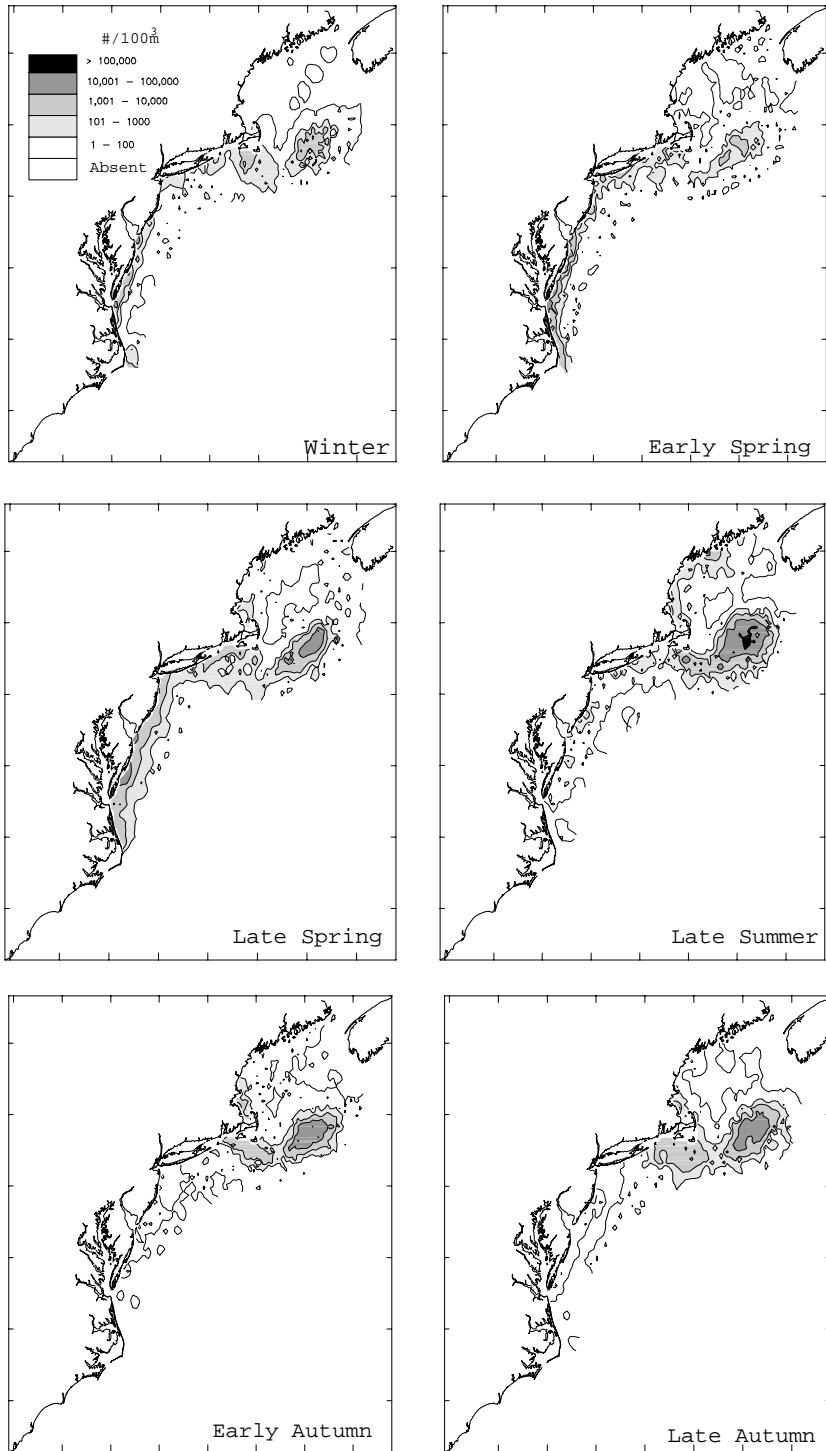


Fig. 8. Seasonal mean abundance of *Centropages hamatus*, copepodites 4-6, based on 1977 through 1997 MARMAP ecosystem surveys data.

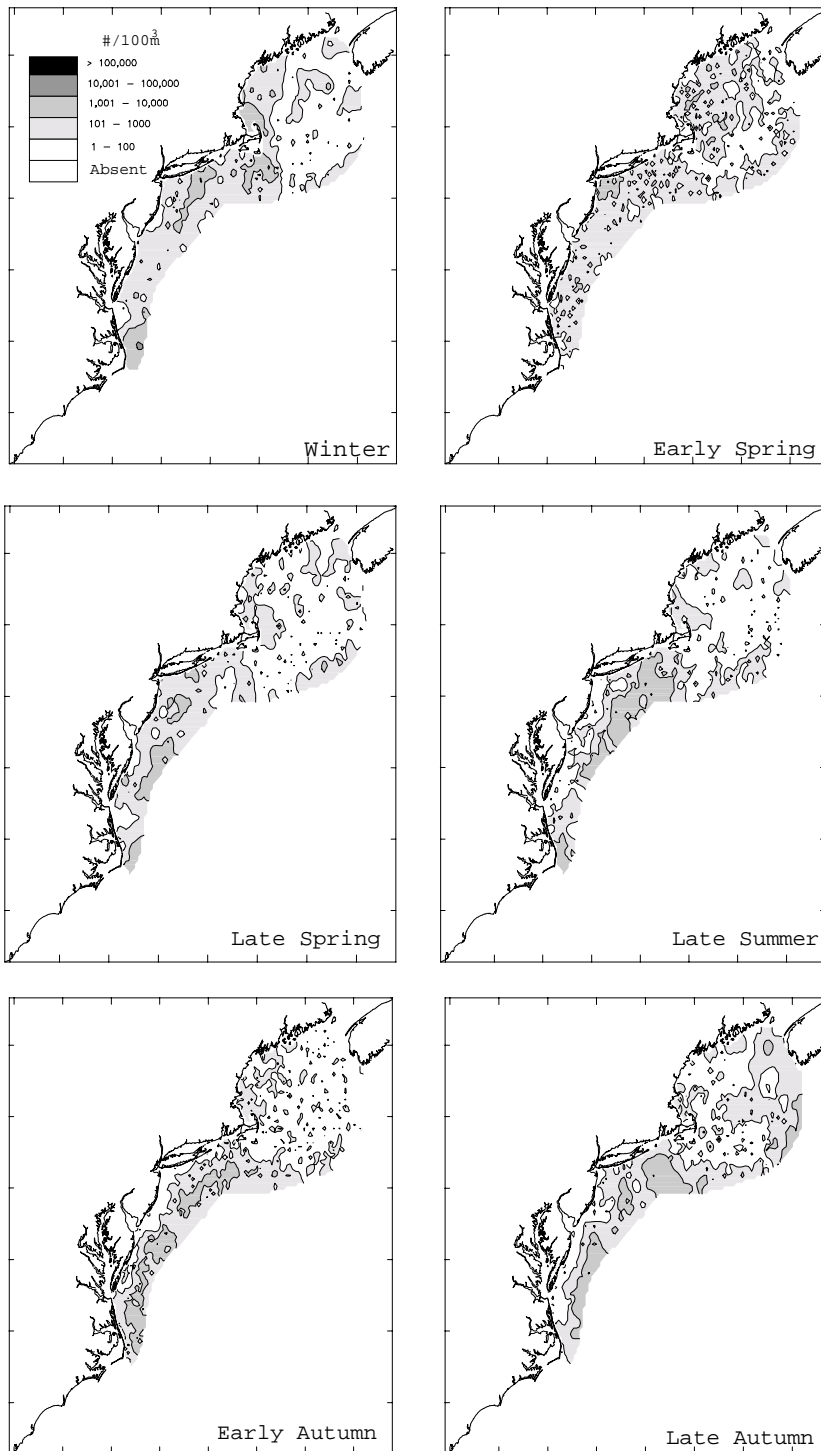


Fig. 9. Seasonal mean abundance of *Oithona* spp., all stages, based on 1977 through 1997 MARMAP ecosystem surveys data.

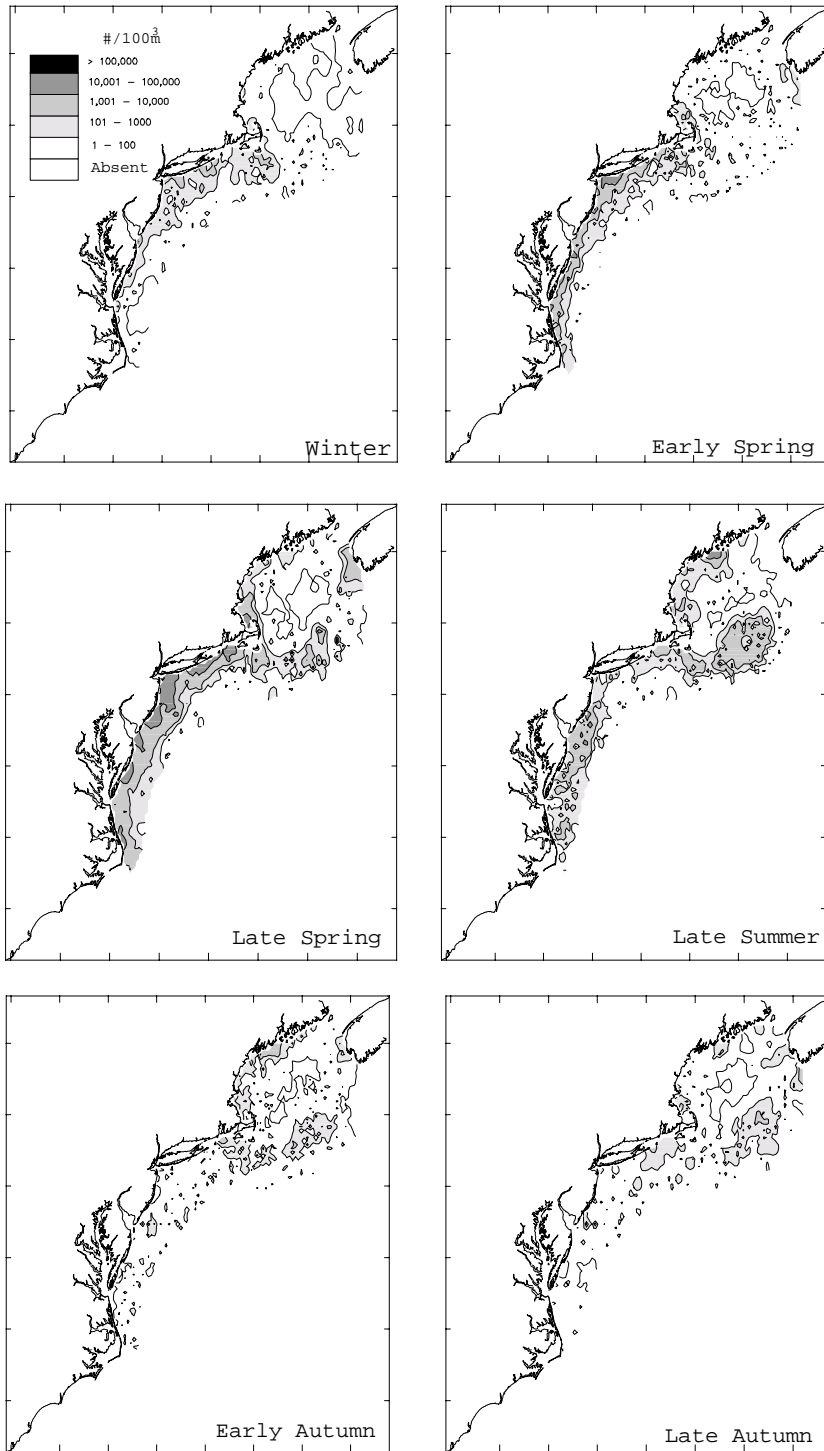


Fig. 10. Seasonal mean abundance of *Temora longicornis*, all stages, based on 1977 through 1997 MARMAP ecosystem surveys data.

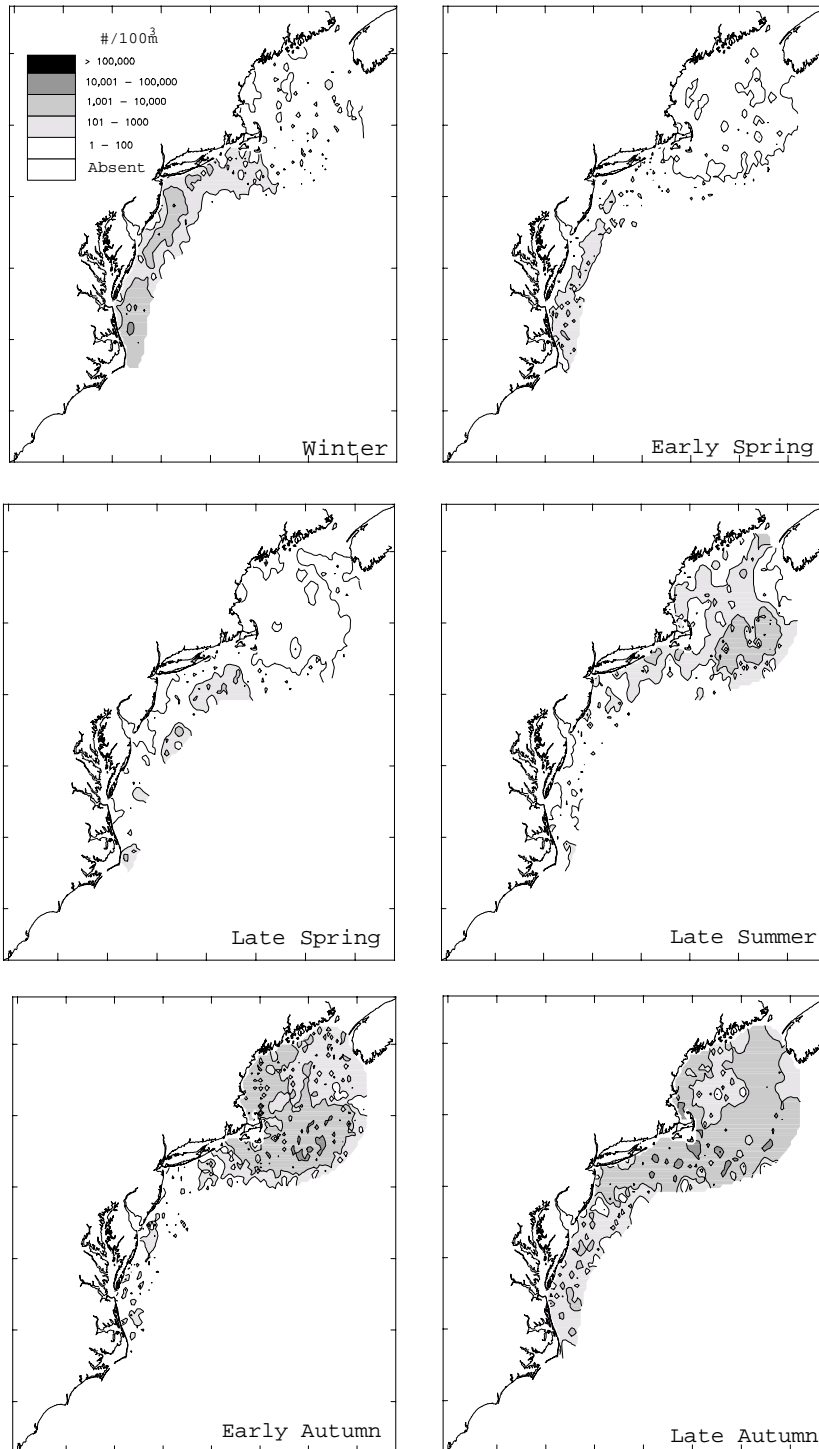


Fig. 11. Seasonal mean abundance of *Paracalanus parvus*, all stages, based on 1977 through 1997 MARMAP ecosystem surveys data.

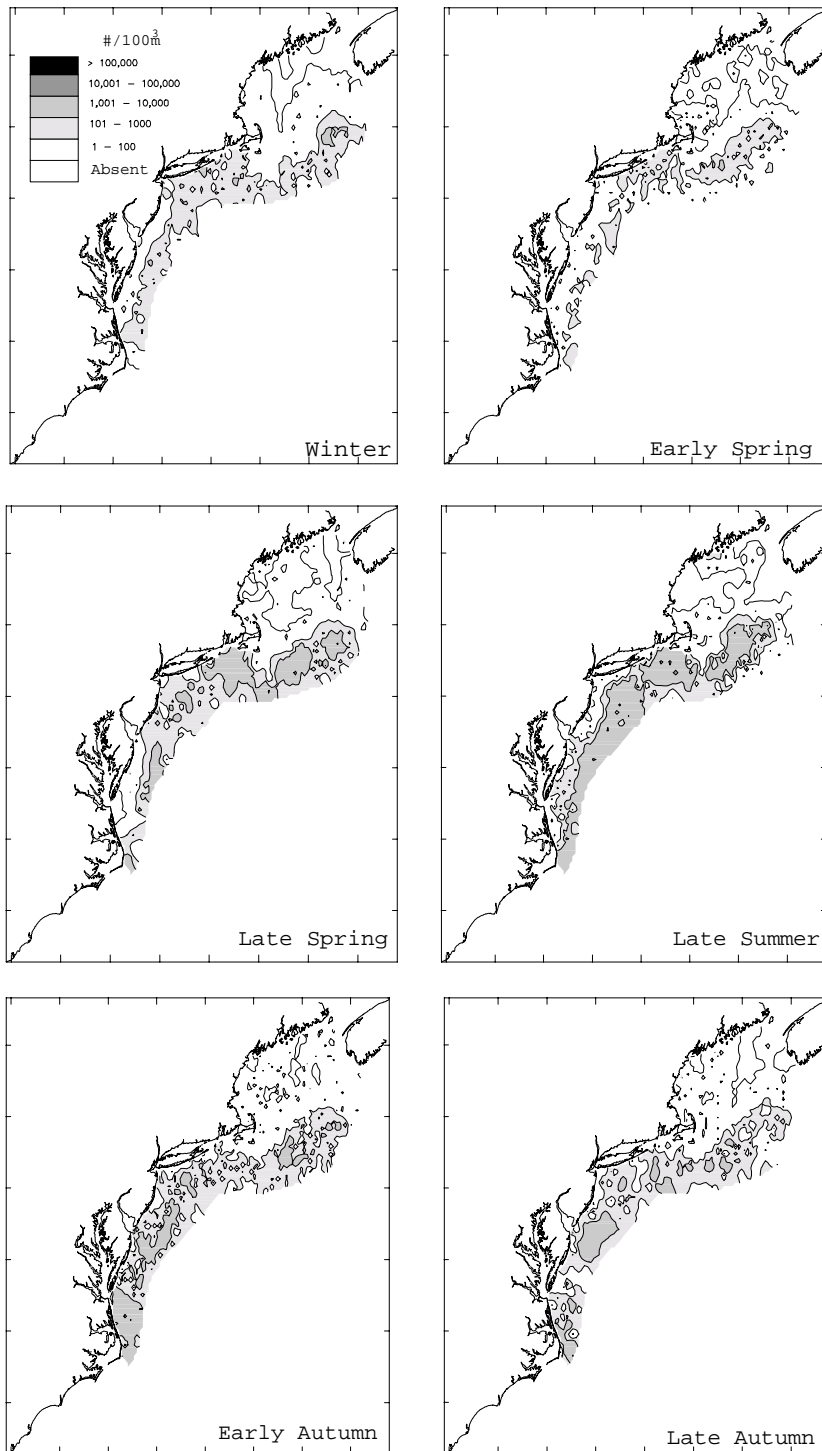


Fig. 12. Seasonal mean abundance of *Sagitta* spp., all stages, based on 1977 through 1997 MARMAP ecosystem surveys data.

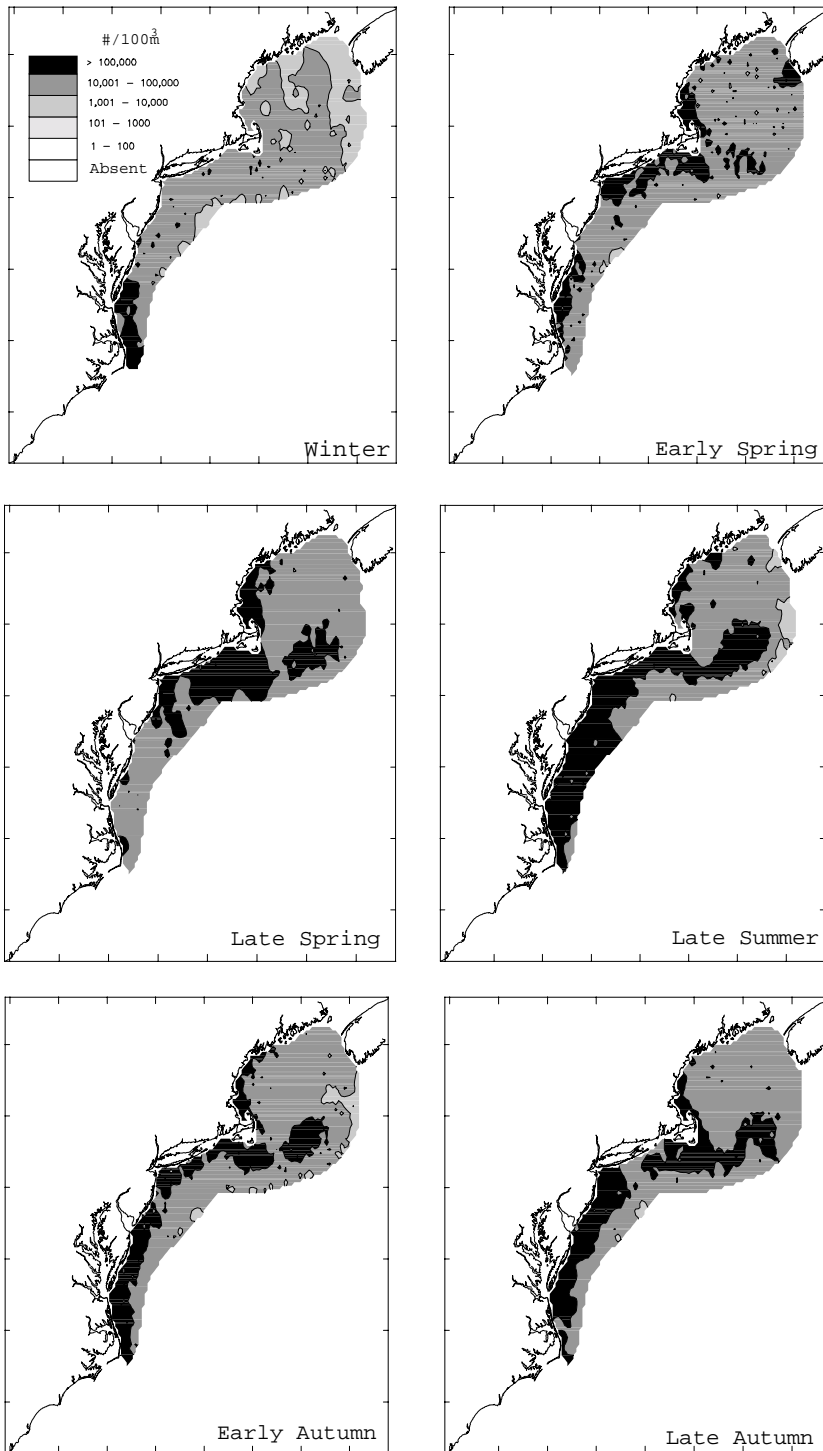


Fig. 13. Seasonal mean abundance of total zooplankton, all stages, based on 1977 through 1997 MARMAP ecosystem surveys data.

Table 5. Statistics resulting from the seasonal zooplankton abundance calculations.
 Except for the number of observations, all units are $\log_{10}(\text{number of organisms}/100 \text{ m}^3 + 1)$.

	Statistic	Late Winter	Early Spring	Late Spring	Late Summer	Early Autumn	Late Autumn
Taxon	n - >	564	1,579	745	628	1,949	728
<i>Calanus finmarchicus</i> , all stages	Min	0	0	0	0	0	0
	Max	4.55	5.81	5.88	5.47	5.05	5.28
	Mean	2.47	3.55	3.74	3.04	2.80	2.52
	Std	1.22	1.30	1.45	1.66	1.46	1.51
<i>Centropages typicus</i> , c. 4-6	Min	0	0	0	0	0	0
	Max	5.54	5.63	5.31	5.57	6.11	5.86
	Mean	3.53	2.59	2.11	3.95	3.94	4.31
	Std	1.14	1.57	1.72	1.03	1.15	0.88
<i>Pseudocalanus minutus</i> , all stages	Min	0	0	0	0	0	0
	Max	5.39	6.20	5.60	5.40	5.77	5.16
	Mean	3.19	3.65	3.75	2.96	2.37	2.12
	Std	1.11	1.03	1.02	1.36	1.48	1.56
<i>Metridia lucens</i> , all stages	Min	0	0	0	0	0	0
	Max	4.38	4.86	5.06	5.20	4.94	4.67
	Mean	2.35	2.30	2.35	1.79	2.16	2.08
	Std	1.25	1.50	1.61	1.65	1.50	1.61
<i>Acartia</i> spp., all stages	Min	0	0	0	0	0	0
	Max	5.05	4.53	5.32	5.59	6.06	5.95
	Mean	1.00	1.02	1.45	2.27	2.01	2.22
	Std	1.29	1.30	1.47	1.51	1.44	1.55
<i>Centropages hamatus</i> , c. 4-6	Min	0	0	0	0	0	0
	Max	5.40	5.73	5.53	5.84	5.50	5.00
	Mean	1.42	1.30	1.68	1.72	1.26	1.33
	Std	1.55	1.54	1.70	1.87	1.65	1.70
<i>Oithona</i> spp., all stages	Min	0	0	0	0	0	0
	Max	4.25	5.06	4.29	4.51	4.71	4.24
	Mean	2.08	2.18	1.98	1.91	1.89	1.95
	Std	1.18	1.31	1.35	1.46	1.46	1.42
<i>Temora longicornis</i> , all stages	Min	0	0	0	0	0	0
	Max	4.49	5.27	5.64	5.37	4.86	5.73
	Mean	1.22	1.47	1.94	2.19	1.15	1.16
	Std	1.42	1.61	1.84	1.78	1.48	1.43
<i>Paracalanus parvus</i> , all stages	Min	0	0	0	0	0	0
	Max	4.71	4.54	4.57	4.87	4.97	4.90
	Mean	1.78	0.72	0.65	1.93	2.63	2.99
	Std	1.40	1.20	1.21	1.54	1.47	1.29
<i>Sagitta</i> spp., all stages	Min	0	0	0	0	0	0
	Max	4.66	4.73	5.18	4.87	4.79	4.66
	Mean	1.81	1.34	1.65	2.03	1.82	1.99
	Std	1.33	1.37	1.65	1.70	1.57	1.61
Total Zooplankton, all stages	Min	2.34	2.55	2.57	2.79	1.67	3.35
	Max	5.75	6.29	6.47	6.59	7.10	6.59
	Mean	4.40	4.73	4.84	5.03	4.78	4.91
	Std	0.56	0.56	0.53	0.55	0.58	0.43

minutus abundance rose sharply in early spring when it concentrated in coastal areas of the Middle Atlantic Bight (MAB), throughout Southern New England (SNE), and the western and eastern margins of the Gulf of Maine (GOM). Peak seasonal abundances occurred in late spring with high values found throughout SNE, in the more shallow waters of Georges Bank (GBK), and along coastal GOM. *C. finmarchicus* abundance was high year-round in the GOM and on GBK from early spring through late summer. Dense concentrations of the copepod were also found in the offshore waters of SNE and the MAB in late spring and late summer. Abundance was low year-round in the coastal waters of these latter two regions.

The annual abundance cycle and spatial distribution of *Metridia lucens* (Figure 6) was very similar to *Calanus finmarchicus*, though overall abundance levels were much lower. Density was highest during late spring and the largest concentrations were usually found in the western GOM and along the outer shelf of the MAB and SNE subareas. Abundance was low year-round in southern coastal waters and within the central shoals of GBK.

Mean abundance of *Acartia* spp. (Figure 7) peaked during late summer when it concentrated in shallow coastal waters throughout the ecosystem. Numbers remained high inshore through late autumn in the southern half of the ecosystem. It became very rare in the GOM during winter and early spring.

The copepod *Centropages hamatus* (Figure 8) reached peak abundance during the late summer season when dense concentrations formed in the central shoals region of GBK that persisted there through late autumn. High levels were also found in MAB and SNE coastal waters during early and late spring. The copepod was sparsely distributed year-round in the GOM and also during the latter half of the year in the MAB and SNE subareas.

Oithona spp. (Figure 9) was captured year-round in nearly all samples from the ecosystem. However, there was no strong seasonal cycle and only relatively large concentrations were found scattered throughout the MAB and SNE regions. It should be noted that the abundance levels of this comparatively small copepod species are underestimated because it is not quantitatively caught with the nets used in our surveys.

Temora longicornis (Figure 10) mean abundance peaked during late summer when high concentrations of the copepod were found scattered in shallow waters throughout the ecosystem. It was very scarce in the GOM during the colder months.

Paracalanus parvus (Figure 11) abundance was maximum during late autumn when high concentrations were found across SNE and GBK, and during winter throughout the MAB. It was present year-round in the SNE and MAB subareas and became very rare in GOM and GBK waters during the spring seasons.

The chaetognath *Sagitta* spp. (Figure 12) reached its maximum abundance during late summer when high numbers became established from mid- to outer-shelf regions of the MAB and SNE and within the shallow waters of GBK. It was only sparsely distributed year round in the GOM.

Total counts of zooplankton (Figure 13) within the ecosystem exceeded 5.0/100 m³ during late summer when dense concentrations pervaded throughout the MAB and within the shallow waters of the SNE and GBK regions. These high aggregations persisted through late autumn, nearly dissolved during winter, and began to reappear during early spring. Overall abundance was lowest in the GOM region, but there was a band of high abundance along the southwestern coastal zone that was present in all seasons except winter.

DISCUSSION

This report marks the first time that the seasonal means and spatial distributions of these taxa have been reported for the United States northeast continental shelf ecosystem. They are presented here as an introduction to the most ubiquitous zooplankton conditions of this ecosystem, and a basis for further studies of their role in ecosystem health and productivity.

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