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LONG-TERM TRENDS IN ZOOPLANKTON DISTRIBUTION AND ABUNDANCE IN THE SACRAMENTO-SAN JOAQUIN ESTUARY

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ABSTRACT

Zooplankton abundance trends at 34 stations in the Sacramento-San Joaquin estuary between 1972 and 1988 were determined from monitoring data obtained by the California Department of Fish and Game. Zooplankton concentrations were transformed by removing the effects of salinity and seasonality on changes in abundance. The residual zooplankton concentrations, or anomalies, were tested for trends by regression analysis. Of 20 zooplankton taxa, 12 were found to have declined significantly during the period of record. Declines were distributed over all seasons and all regions of the estuary but were more prevalent in the Sacramento and San Joaquin rivers than in Suisun Bay.

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INTRODUCTION

This report presents an analysis of zooplankton data collected by the California Department of Fish and Game in its monitoring study of the Sacramento-San Joaquin estuary from 1972 to 1987. The analysis reported here is an updated and more thorough examination of the data in regard to number of species, time periods, and geographical regions used than was presented in DFG Exhibit 28 to the State Water Resources Control Board at the 1987 Water Quality/Water Rights Proceedings.

There are two reasons for this additional analysis. First, since 1987 significant changes have taken place in the estuary: new species, both planktonic and benthic, have been accidentally introduced, and the longest drought since monitoring began has reduced freshwater inflow to the estuary. Second, we have used analytical techniques that greatly improve the resolution of the analyses, our ability to detect trends, and our confidence that trends we observe are real. These techniques have allowed us to use all of the data, rather than subsets or aggregates of the data, and to eliminate the effects of salinity and season, which otherwise confound the results.

The objective of the analysis is to describe the long-term changes or trends in abundance of each zooplankton group since inception of the monitoring. A subsequent report will attempt to identify probable causes of the observed trends.

INTRODUCTION TO ZOOPLANKTON

Zooplankton is a general name for small aquatic animals that constitute an essential food source for fish, especially young fish and all life stages of many forage fishes. These sometimes microscopic animals feed extensively on phytoplankton and organic detritus and thus transfer the energy of primary production to higher levels of the food chain.

The zooplankton sampled by the California Department of Fish and Game in the Sacramento-San Joaquin estuary can be divided into four groups:

- The opossum shrimp, *Neomysis mercedis*,
- Small crustaceans called "copepods", which go through nauplius and copepodid life stages,
- Other crustaceans known as "cladocerans",
- A separate phylum of tiny animals called "rotifers".

Members of all these zooplankton groups have been found in stomachs of young-of-the-year striped bass, but rotifers are only minor food items. Adult copepods, especially *Eurytemora affinis*, and cladocerans are the first prey taken by larval striped bass after they hatch. As young bass grow, they switch to a diet dominated by *Neomysis*.

Neomysis is the least numerous but the largest of the zooplankton, ranging from 2 to 17 mm. Adult copepods and cladocerans are about the same length, 0.25 to 2.0 mm for cladocerans and 0.5 to 1.4 mm for adult copepods (depending on species). Copepods and cladocerans reach about equal densities if all life stages are considered.

The most numerous but smallest of the zooplankton are the rotifers, which range from 0.08 to 0.3 mm in length (DFG unpublished).

Most zooplankton in the estuary are primarily herbivorous, although they can consume detritus. The copepods, *Eurytemora affinis* and *Sinocalanus doerrii,* feed on a variety of diatoms, green and blue-green algae, and flagellated protozoans. Centric diatoms of the genera *Thalassiosira* and *Skeletonema* are the most important cells in their diets (Orsi 1988). The relatively large filamentous diatom, *Melosira granulata,* which is responsible for many of the phytoplankton blooms in the Delta in recent years, is also consumed. During such blooms, *Eurytemora* and *Sinocalanus* guts are often empty, although at lower phytoplankton concentrations *Melosira* cells are found in the copepods, sometimes in considerable numbers. Cyclops and probably *Limnoithona sinensis* are carnivorous copepods. *Sinocalanus doerii* may be omnivorous, since a related species, *S. tenellus,* supplements its phytoplankton diet with rotifers and nauplii (Hada and Uye 1991). Two cladoceran species studied from the Delta, *Daphnia parvula* and *Bosmina longirostris,* feed heavily on the green alga *Chlamydomonas,* but *Melosira* can also be an important food item. The cladocerans also consume a wide variety of centric diatoms and green and blue-green algae (Orsi 1988).

Neomysis is omnivorous and may obtain more of its food requirements from smaller zooplankton than from phytoplankton (Siegfried and Kopache 1980). It is large enough to consume *Melosira* chains and, by breaking them, may provide food of manageable size for the smaller zooplankton.

Rotifer food habits have not been studied in this estuary. In other areas they feed on small phytoplankton (Gliwicz 1969) or protozoa and small cladocerans, in the case of larger, predatory rotifers (Monakov 1972).

Salinity and hydrology regulate the distribution of all zooplankton species. There are groups of freshwater, estuarine, and marine coastal zooplankton in the estuary. All of the cladocerans are freshwater species, although they range or are carried downstream in low numbers into brackish water. Freshwater copepods include *Diaptomus* spp., *Cyclops* spp. and the introduced Asian copepods, *Sinocalanus doerrii* and *Limnoithona sinensis,* which also range into brackish water (Orsi *et al* 1983; Ferrari and Orsi 1984). The harpacticoid copepods found here are primarily brackish water species. Most rotifers are freshwater species, but they extend seaward into brackish water.

Eurytemora affinis is an estuarine copepod that achieves its greatest abundance in the entrapment zone but also extends into fresh water in low abundance (Ambler *et al* 1985; Orsi and Mecum 1986). *Neomysis* has a similar distribution but is more abundant in fresh water than is *Eurytemora*. A common estuarine rotifer, *Synchaeta bicornis,* also extends into fresh water.

Seaward of the entrapment zone, euryhaline marine species become numerically dominant. These include *Acartia californensis, A. clausi* s.l. (Ambler *et al* 1985), and *Oithona davisae,* an introduced Asian copepod that reaches its highest abundance in South San Francisco Bay (Ferrari and Orsi 1984; Ambler *et al* 1985).

The monitoring study started collecting *Neomysis* in June 1968 and zooplankton in January 1971. Zooplankton data from 1971 were ignored in this report because of initial difficulties in species identifications. *Neomysis* data from 1968 to 1971 cannot be retrieved from the EPA STORET system in a usable form, owing to incorrect mixing of data sets among stations. Hence, the analysis is restricted to 1972 to 1988.

Sampling surveys were initially conducted once monthly in March and November and twice monthly from April to October. The analysis is restricted to the March-to-November surveys. Although 81 stations have been sampled over the years, the analysis is restricted to the 34 stations in Suisun Bay and the Delta that were sampled every year (Figure 1).

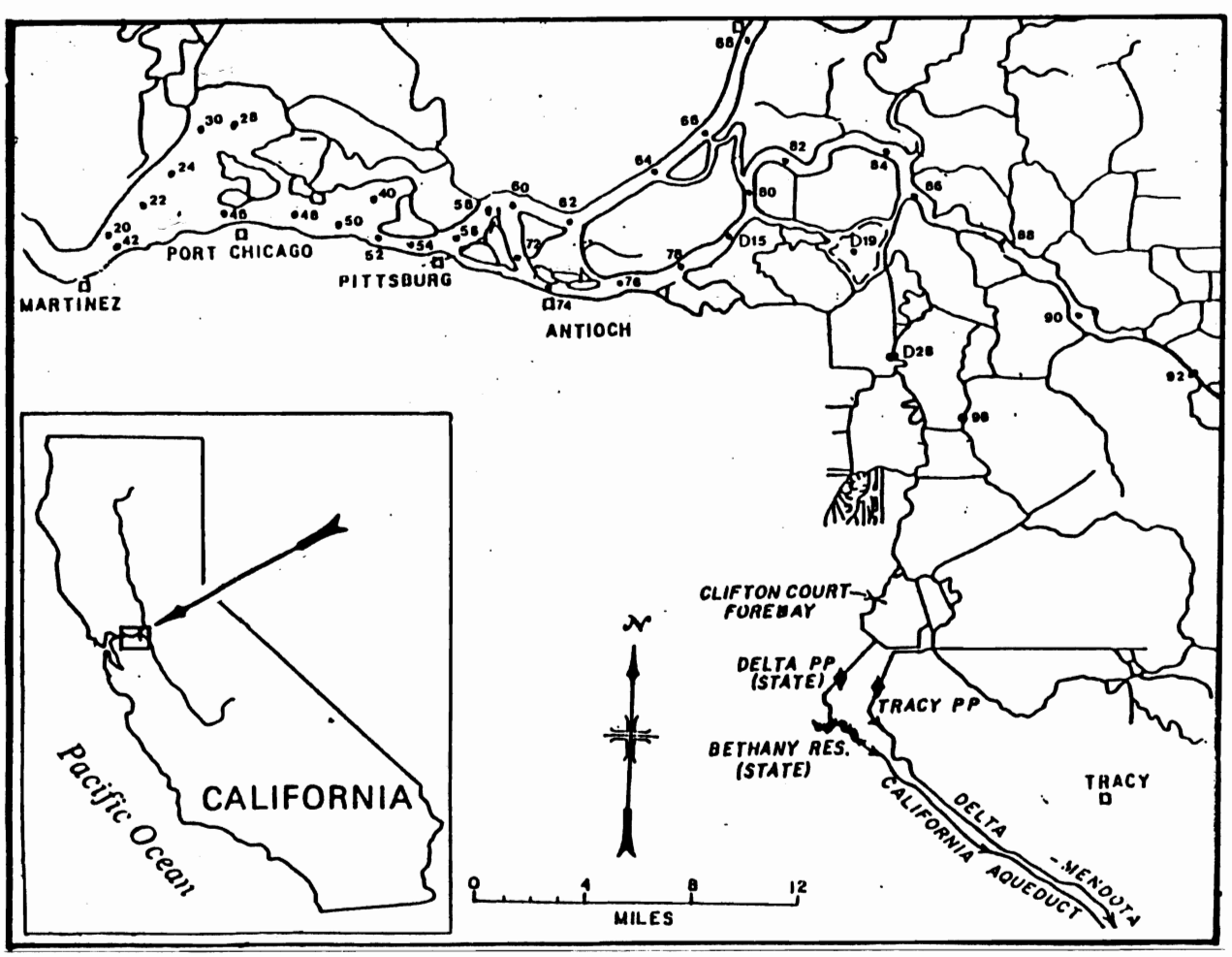
Field Methods

Samples were collected from a 19-foot boat equipped with an A-frame and winch. A tubular steel frame containing the collecting nets was towed from bottom to surface in a stepwise oblique 10-minute tow. Surface temperature, Secchi disc reading, and surface specific conductance were collected at the start of each tow. Specific conductance can be converted to salinity by the equation:

$$S_{o/oo} = -100 \ln(1 - C_{25} / 178.5)$$

where C_{25} is specific conductance in millisiemens/cm at 25°C and *ln* is the natural logarithm. Surface specific conductance samples were originally measured in the laboratory. Starting in

Figure 1
SACRAMENTO-SAN JOAQUIN DELTA AND SUISUN BAY SAMPLING STATIONS USED IN THE ANALYSIS



January 1981, a field conductivity meter was used for all specific conductance measurements. All specific conductance measurements were standardized to 25°C. Since 1982, surface and bottom pre- and post-tow specific conductance measurements have been taken at stations where the pre-tow surface specific conductance was equal to or greater than 1000 µS/cm.

Chlorophyll *a* measurement was added to the monitoring study in March 1976. For this parameter a 3.8-liter bottle was filled about half full with water pumped from a depth of 1 meter, and two 100-mL subsamples were drawn from it and aspirated separately through 47-mm-diameter glass fiber filters, pore size 0.45 µm. The filters were then frozen on dry ice. Chlorophyll *a* concentrations were measured at the Sacramento laboratory of the U.S. Bureau of Reclamation using the acidification method (Strickland and Parsons 1972).

The net used to capture *Neomysis* was initially made of 1-mm silk bolting cloth, was 1 meter long, and had a mouth area of 0.1 m^2. From 1971 through 1973, it was made of 0.93-mm mesh nylon cloth, had a mouth area of 0.07 m^2, and was 0.7-m long. In 1974, mesh size was reduced to 0.505 mm, mouth area was reduced to 0.064 m^2, and length was increased to 1.48 m. Use of the latter net was prompted by Miller's (1977) discovery that 0.505-mm mesh sampled 2- and 3-mm mysids more efficiently. In all years, the net tapered to 7.6 cm at the cod end, where a polyethylene jar screened with 0.505-mm mesh wire cloth captured the mysids. Until 1973, Pygmy flowmeters were used to estimate water volumes filtered by the *Neomysis* net. Since then, General Oceanics Model 2030 flowmeters have been used.

A Clarke-Bumpus net made of 154-um mesh nylon cloth (No. 10 mesh) mounted directly above the *Neomysis* net sampled zooplankton. This net had a mouth area of 0.013 m^2, was 73 cm long, and tapered to 4.5 cm diameter at the cod end. A stainless steel bottle with a screened opening collected the captured organisms. Microzooplankton (primarily copepod nauplii and rotifers) were collected at the end of the tow using a pump emptying into a 19-liter carboy. The pump hose was raised from bottom to surface to obtain a vertically integrated sample. The carboy was then shaken and a 1.5- to 1.9-liter subsample drawn. All *Neomysis* and zooplankton samples were preserved in 10 percent formalin with Rose Bengal dye added to aid in separating the animals from detritus and algae.

Laboratory Methods

Neomysis samples were spread evenly in a square tray equipped with removable partitions for subsampling. Those samples that appeared to have more than 400 specimens were divided into 4, 16, or 64 subsamples. All mysids in a selected subsample were counted. Initially, a minimum count of 200 was required. This was increased to 400 in 1984. The first 100 mysids counted were measured to the nearest millimeter from the eye to the base of the telson; beginning in 1976, they were identified as being juvenile, gravid female, nongravid female, or male. If available, 20 females per sample with full brood pouches had their young counted and assigned to three developmental stages: eggs, comma-shaped embryos, and eyed embryos.

Clarke-Bumpus samples were concentrated by pouring them through a cup screened with 154-µm mesh. Water was then added to the sample and the volume recorded. The sample was stirred to distribute the animals homogeneously, and a 1-mL subsample was extracted with an automatic pipet and placed in a Sedgewick-Rafter cell. All animals were identified and counted under a compound microscope. Additional 1-mL subsamples were examined until at least 200 animals had been counted.

The pump samples were processed by measuring and recording the sample volume, then concentrating the sample by pouring it through a cup with 154-µm mesh followed by one with 43-µm mesh. The organisms retained by the 43-µm mesh were identified and counted in a Sedgewick-Rafter cell.

Identification of zooplankton taxa varied over the years. From 1972 to 1975, an effort was made to identify organisms to species. Thereafter, the genus level was used except for important species or when only one species was present in a genus.

Calculations

The total number of *Neomysis* per cubic meter of water sampled was calculated using the following equation:

$$N = T(S/V)$$

Where:

N = Number of *Neomysis* per cubic meter
T = Mean number of mysids counted in tray segment(s) subsampled
S = Number of tray segments

V = Volume of water filtered through the net (m^3)

The number per cubic meter for each zooplankton taxon taken in the Clarke-Bumpus net was calculated as follows:

$$Z = CV/S/N$$

Where:

Z = Number of zooplankton per cubic meter
C = Number of specimens counted
V = Sample volume
S = Number of Sedgwick-Rafter cells counted
N = Volume of water strained by the net (m^3)

The number of organisms per cubic meter taken in the pump samples was calculated by the equation:

$$M = C(L/V)$$

Where:

M = Number of organisms per cubic meter
C = Number of specimens counted
L = Number of milliliters in 1 cubic meter
V = Sample volume in milliliters

The numbers per cubic meter in the Clarke-Bumpus and pump samples were summed for nauplii and rotifers to obtain the total number of these organisms per cubic meter. Nauplii and rotifers had a size range that made them vulnerable to both types of sampling gear.

Emphasis in this study is on describing and analyzing changes in zooplankton abundance in the whole Suisun Bay and Delta region using the entire data set available. The analysis is based on data pooled from the stations containing an uninterrupted set of samples from 1972 to 1987 for surveys in March to November. Stations numbers were: 20, 22, 24, 28, 32, 40, 42, 46, 48, 50, 52, 54, 56, 58, 60, 62, 64, 66, 68, 72, 74, 76, 78, 80, 82, 84, 86, 88, 90, 92, 98, D15, D19, and D28. Station locations are shown in Figure 1. Species and taxonomic groups used in the analysis are summarized in Table 1. Early life stages of copepods (nauplii and copepodids) were not used in this analysis, because they represent mixtures of many species and changes in their abundance would not be interpretable. Trends are described, and simple statistical methods are used to summarize observed changes.

Table 1
ZOOPLANKTON TAXA USED IN ANALYSIS

COPEPODS	
Acartia	
Diaptomus	
Eurytemora affinis	
Cyclopoids	
Harpacticoids	
Sinocalanus doerrii	(introduced*)
Limnoithona sinensis	(introduced)
Oithona davisae	(introduced)
CLADOCERA	
Bosmina longirostris	
Daphnia	
Diaphanosoma	
ROTIFERS	
Asplanchna	
Keratella	(1973, 1976 - 1978**)
Polyarthra	(1976 - 1978)
Synchaeta bicornis	(1972)
Synchaeta spp.	(1972 - 1973)
Trichocerca	(1978)
OTHER	
Neomysis mercedis	
Barnacle Nauplii	
Crab Zoea	(1972 - 1975, 1980)

* Introduced species data run from 1979 to 1988.
** Numbers in parentheses are years for which data are missing or incomplete.

Data Transformation

The analysis for each species or taxonomic group was carried out as follows. Calculated zooplankton abundances per cubic meter were log transformed to $\log_{10}(Z+1)$ abundance values. That is, one was added to the concentration (Z) of each species and the result was transformed to its base 10 logarithm. One is added to the data because the $\log_{10}$ of 0 does not exist. All raw abundance values reported herein are $\log_{10}$ transformed, and all reported results are based on calculations using the log transformed data.

Log_{10} transformed data are used because their means are less influenced by infrequent extreme values. The reason for this can be understood by calculating the mean of a set of untransformed data used in its original arithmetic scale and comparing the result with the calculation of the geometric mean, which is the mean of the log transformed data changed back to its arithmetic equivalent. If five samples with values 10, 10, 10, 10, and 1000 are summed and then divided by five (the number of samples), their mean is 208. This mean is about 20 times higher than the four low values because the calculation is strongly influenced by the extreme value of 1000. To obtain the geometric mean, one is added to each of the five values, and their $\log_{10}$ equivalents are obtained. The five $\log_{10}$ transformed values are then summed and divided by five (the number of samples). The result is then converted from its logarithmic value to its arithmetic value and 1 is subtracted to obtain the geometric mean, which is 26.11. The geometric mean is now only about 2.6 times higher than the four lower values, showing that the extreme value of 1000 is less influential in determining the mean when the log transformation is used.

Removing Salinity and Seasonal Effects

Salinity (specific conductance) and season (corresponding to temperature) are the major influences on variation in estuarine zooplankton. These effects are the dominant factors driving between-year and within-year fluctuations in abundance of estuarine zooplankton, and they must be removed to determine if changes in abundance have occurred that may be attributable to other factors. For example, low abun-

dances previously reported for estuarine zooplankton in 1983 occurred because of high flows, which resulted in most samples being taken in fresh water. Accounting for the differences in salinity between 1983 and other years allows us to determine if abundances were low independent of salinity.

To summarize the influence of specific conductance and season on the abundance of zooplankton, the data were combined for all stations and divided into 20 specific conductance classes (EC classes) of nearly equal sample size. Average specific conductance and corresponding salinity values for each EC class are shown in Table 2.

Table 2
AVERAGE SPECIFIC CONDUCTANCE AND SALINITY IN EC CLASSES 1 TO 20

Average Specific EC Class	Conductance (µS/cm*)	Salinity (PPT**)
1	126	.071
2	150	.084
3	167	.094
4	187	.105
5	210	.118
6	240	.135
7	284	.159
8	355	.199
9	473	.265
10	674	.378
11	979	.550
12	1554	.874
13	2511	1.417
14	3934	2.229
15	5817	3.313
16	8032	4.604
17	10583	6.112
18	13665	7.964
19	17444	10.284
20	24302	14.635

* uS/cm = microSiemens/centimeter
** PPT = parts per thousand

To examine the relationships between zooplankton abundance and specific conductance, mean zooplankton abundances were calculated for each species for each combination of EC class and month. Plots of mean zooplankton abundances in the EC classes (Figure 2) show how abundance varies with specific conductance.

To remove the effects of specific conductance and season, the following procedure was adopted for each species and taxonomic group. Each abundance value at each date and station was adjusted by subtracting the mean zooplankton abundance for the EC class and month in which the abundance value occurred. For example, if on June 6, 1978, abundance of *Eurytemora* at Station 48 was 3.5 and the EC class was 13, and the mean *Eurytemora* abundance for EC class 13 for June (in the combined 1972-1987 data) was 3.0, then the adjusted abundance value for *Eurytemora* became 3.5 - 3.0 = 0.5. That is, the adjusted *Eurytemora* abundance was somewhat higher than the average value expected from the long-term mean for June and EC class 13.

Differences between actual observations and means for each EC class and month are called "anomalies". Anomalies represent zooplankton abundances after the average effects of specific conductance and season (month) are removed. Temporal trends in these anomaly values are of primary interest in determining if changes in zooplankton abundance have occurred, and all subsequent references to changes in abundance pertain to changes in anomalies. If specific conductance and season were the overwhelmingly predominant factors determining zooplankton populations, then anomaly values would all be quite small. Large deviations of anomalies from zero indicate that other factors may be influencing zooplankton abundance positively or negatively. Furthermore, using anomalies eliminates the possibility that long-term changes were due merely to trends in salinity intrusion.

Figure 2
DISTRIBUTION OF $LOG_{10}(Z+1)$ ABUNDANCE OF ZOOPLANKTON IN RELATION TO EC CLASS

Average specific conductance and salinity values for the EC classes are summarized in Table 1.
Circles are means, vertical bars are 95 percent confidence intervals.

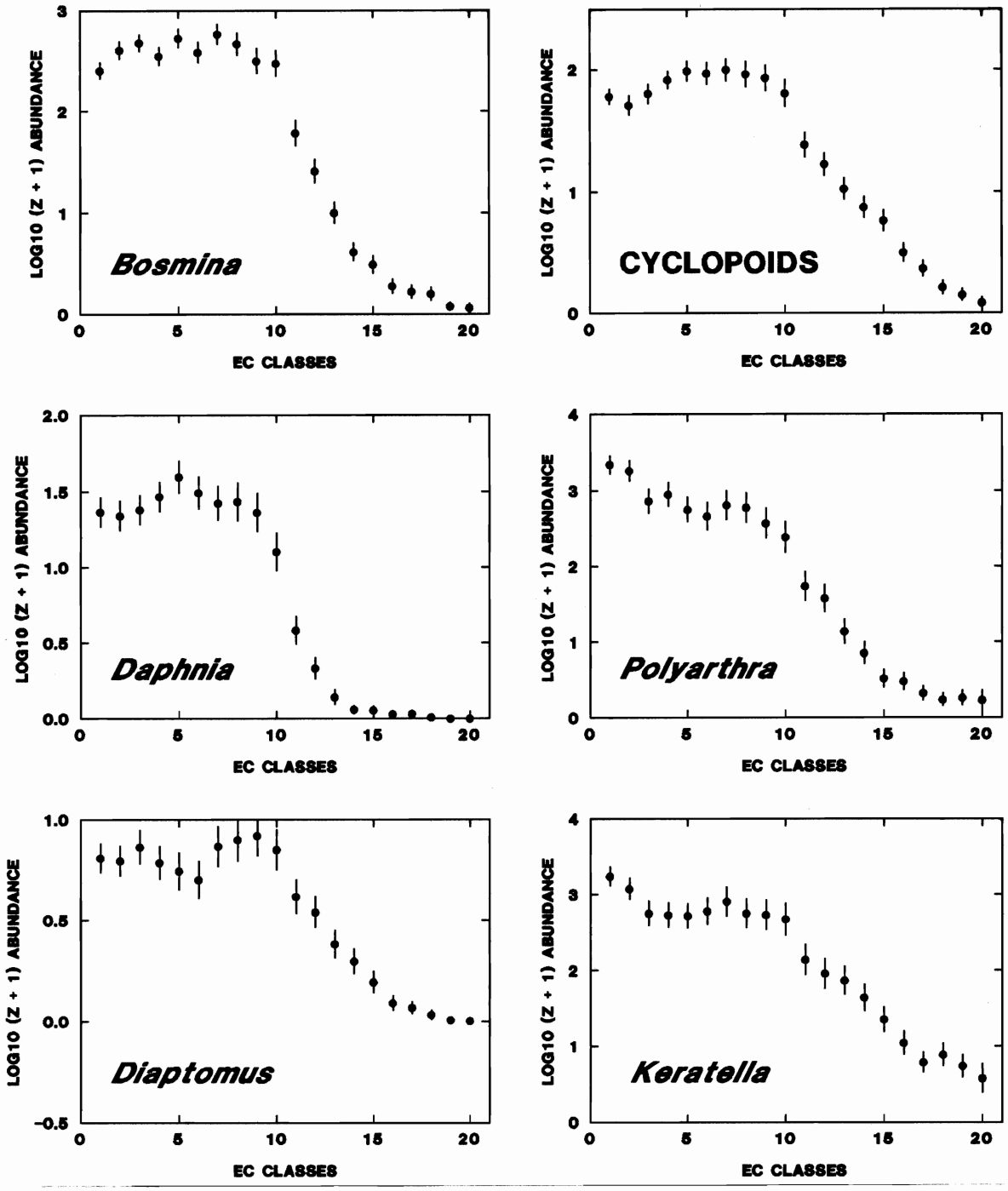
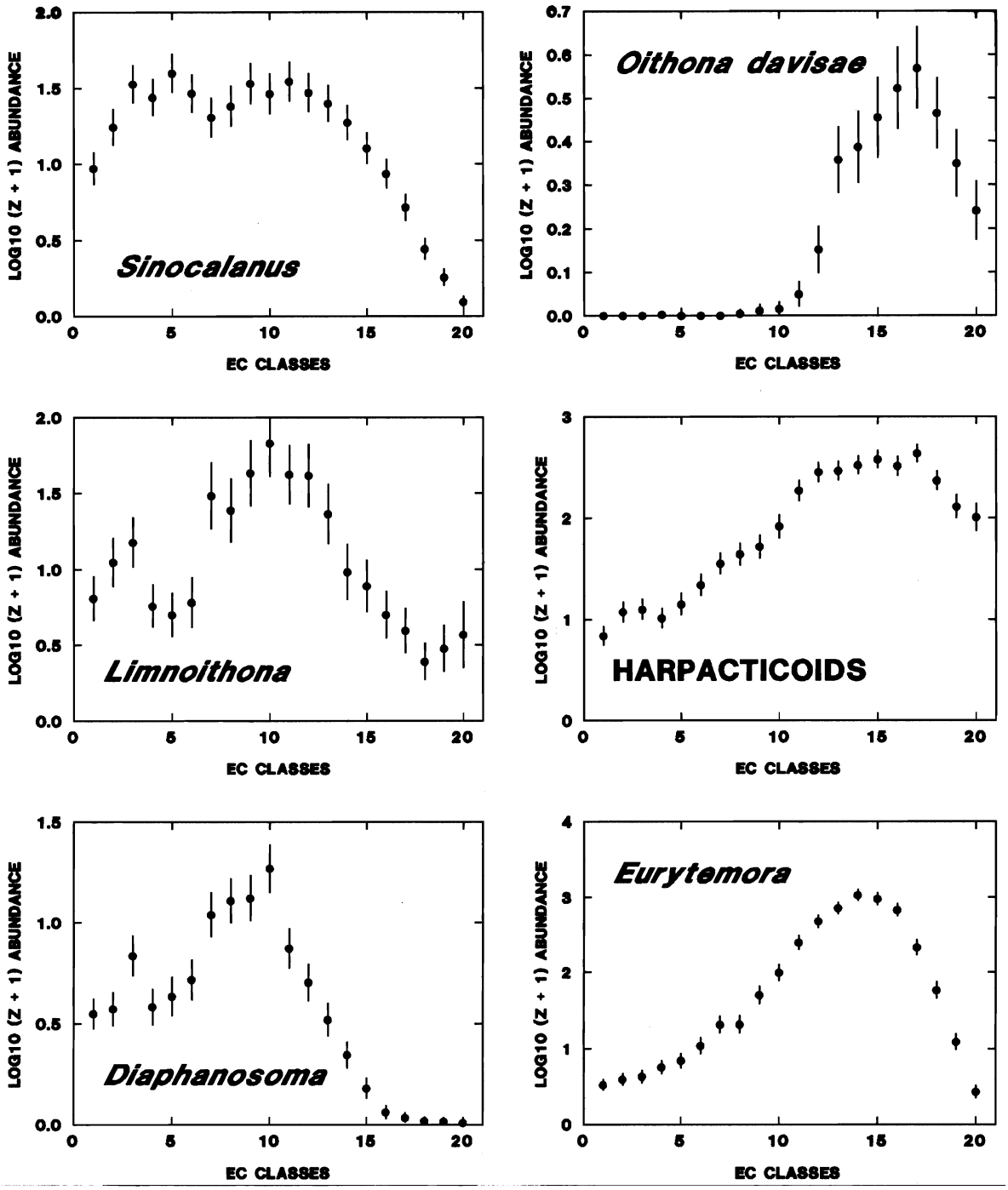


Figure 2 (continued)
DISTRIBUTION OF $LOG_{10}(Z+1)$ ABUNDANCE OF ZOOPLANKTON IN RELATION TO EC CLASS

Average specific conductance and salinity values for the EC classes are summarized in Table 1.
Circles are means, vertical bars are 95 percent confidence intervals.



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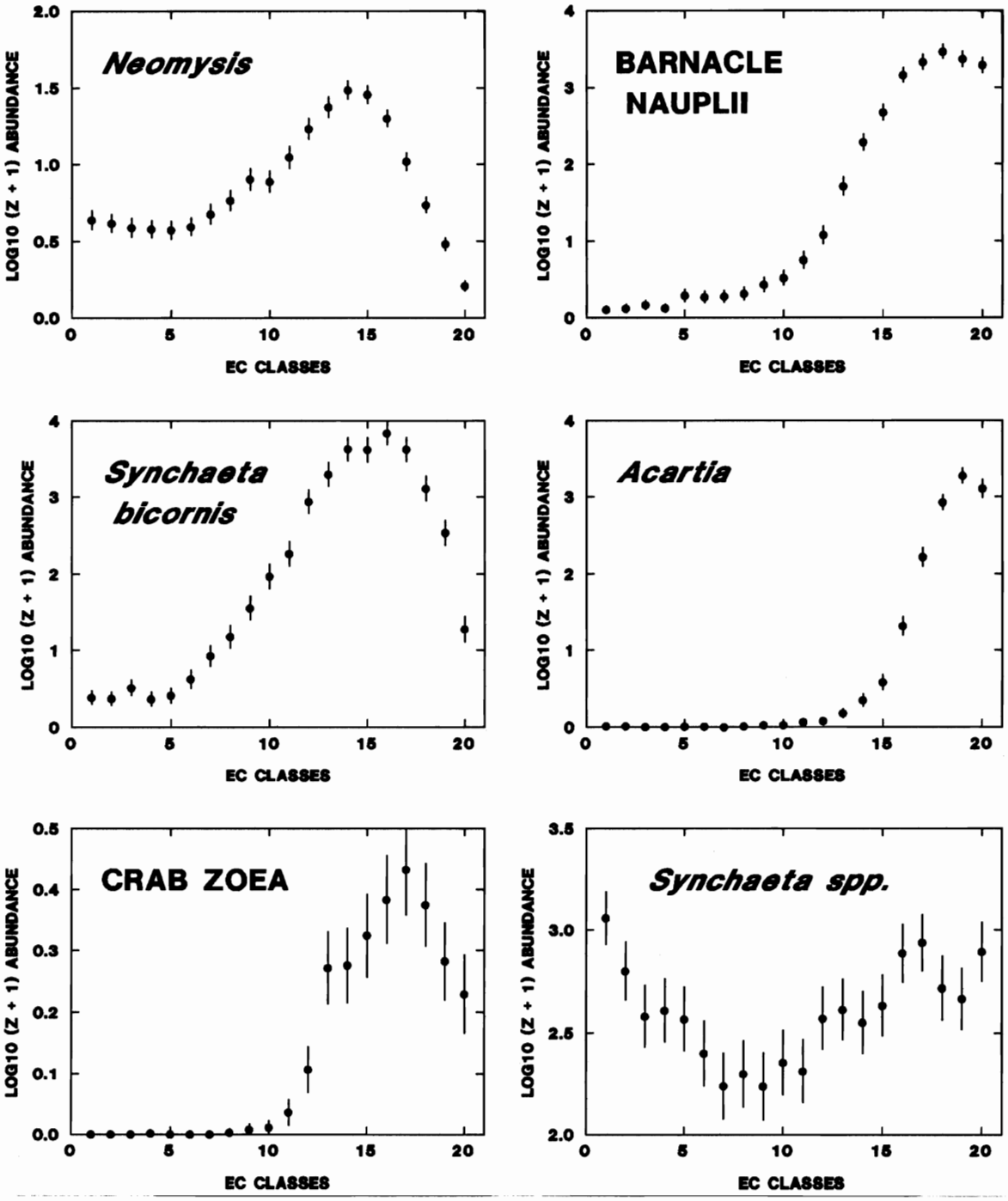

Figure 2 (continued)
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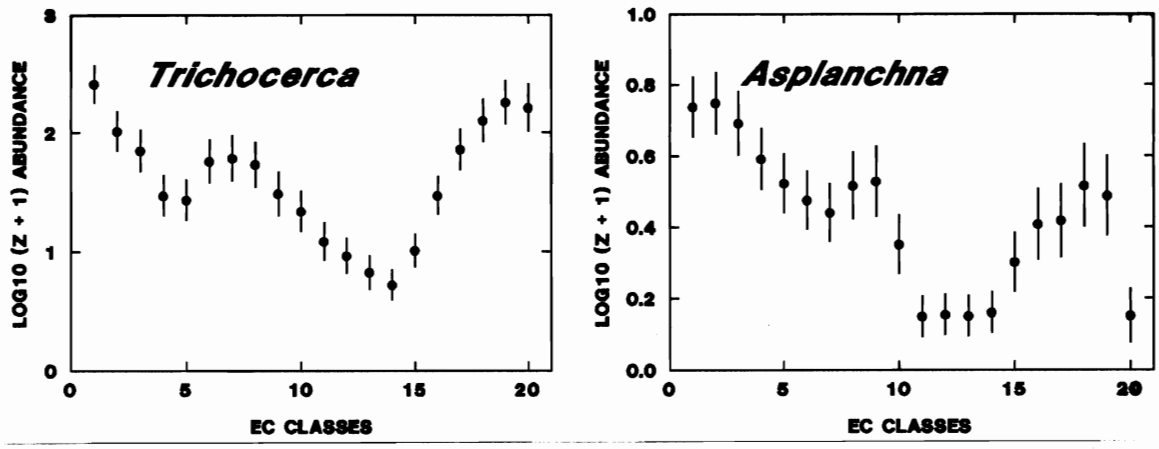

SUMMARY OF CHANGES IN ZOOPLANKTON ANOMALIES

To summarize anomaly data, mean anomaly values for each month of each year were calculated pooling the data for all stations. Pooling over all the stations means anomaly data summarized herein represent changes in the entire Delta/Suisun Bay region. Mean anomaly values and 95 percent confidence intervals for each year, pooled over all the stations and months, were also calculated. This is not the same as calculating the means of the monthly anomalies described above, which would provide only 9 monthly mean anomaly values for each year from which a grand mean for the year would be obtained. The procedure used is based on the raw anomaly values for the entire year, producing more accurate estimates of annual means with much lower confidence intervals owing to the much larger sample size used in calculating the mean.

Trends in anomaly values for all the zooplankton species and groups are summarized in Appendix A. Each figure in the appendix shows two columns of panels. The left column shows trends in $\log_{10}(Z+1)$ abundance for all the data and data pooled for three seasonal groups (SPRING = March+April+May; SUMMER = June+July+August; FALL = September+October+November). The right column summarizes mean annual anomalies and their 95 percent confidence intervals for the same seasonal groups of data.

STATISTICAL ANALYSIS OF TEMPORAL TRENDS IN ANOMALIES

In the statistical analysis for trends, the null hypothesis is that there are no trends in the zooplankton anomalies. This is different from the null hypothesis that there are no changes in the zooplankton anomalies. Owing to the large aggregate data set and the large sample size, we will always be able to show that there are differences among years by analysis of variance. The hypothesis that there are no trends in abundance requires the more specific testing of the time series by whatever means it is aggregated (over groups of years, over all years, groups of months, *etc*) by regression analysis. However, use of the monthly time series in regression analysis is complicated by serial autocorrelations, which preclude tests for trend by simple regression analysis (*ie,* abundance in a given month depends partly on abundance the preceding month).

The simplest alternative method is to use the annual mean anomalies and test for trends by regression analysis. The null hypothesis stands unrejected as long as no significant temporal trend can be found by fitting a suitable regression to the data. However, it may always be possible to detect a statistically significant trend by using successively higher level polynomial regressions, such as cubic, quadratic, or higher level polynomials. Therefore, a conservative procedure to test for trend was adopted. Only linear or quadratic (parabolic) regressions are fit to the annual mean anomalies. Linear regressions can be either not significant or describe significant linear decreases or increases. Quadratic regressions can describe a larger set of alternative temporal trends in anomalies, such as increases or decreases, increases followed by decreases, or decreases followed by increases.

The accidental introduction of the Asian clam *Potamocorbula amurensis* (Carlton *et al,* 1990) further complicates the analysis for trend. This clam became very abundant in Suisun Bay in 1988 and is believed to have affected both phytoplankton and zooplankton abundance. To avoid complicating the regression analysis, the 1988 data were not included, although the monthly and annual anomalies are retained in the plots of zooplankton abundance and anomaly changes (Appendix A).

Salinity Preferences of Zooplankton

Abundance of zooplankton in relation to specific conductance is summarized in Figure 2. Species are arranged by salinity preferences, from fresh water to increasing specific conductance.

Three groups, *Synchaeta* spp., *Trichocerca*, and *Asplanchna,* appeared to have preferences for both high and low specific conductance levels. These are shown in the last three panels of Figure 2. For the freshwater species, there appears to be an abrupt decline in abundance in EC class 11 (EC = 979 µS/cm, salinity = 0.550 ppt), the beginning of perceptible oceanic salinity. In higher EC classes, *Sinocalanus* appears to be somewhat more abundant than other freshwater species. *Eurytemora, Oithona davisae, Neomysis, Synchaeta bicornis,* and harpacticoids are all euryhaline (broad salinity tolerant) species that have peak abundances in the entrapment zone. *Acartia* are euryhaline marine copepods that enter bays.

Changes in Suisun Bay/Delta Zooplankton Anomalies

Regression analyses of the annual anomaly changes depicted in the right column of Appendix A are summarized in Tables 3 and 4. Declines in abundance are notable. Of the eight copepod categories, anomalies of *Eurytemora, Diaptomus,* and Harpacticoids declined in all or most of the seasonal groups and for data pooled over entire years. Cyclopoids showed a decline for data pooled over the year and in the fall. *Acartia* did not change. *Neomysis* declined in the fall but not in other seasons. Barnacle nauplii and crab zoea, groups of marine origin, did not change. Of the three groups of cladocera, only *Bosmina* did not change, while *Daphnia* and *Diaphanosoma* declined. All rotifers except *Synchaeta* spp. declined. Among the copepods introduced since 1980, neither *Sinocalanus* nor *Limnoithona* showed any trends. However, *Oithona davisae* anomalies show linear increases.

Regional Changes in Abundance

Twelve species and taxa found to have declined were subjected to further analysis to determine if there were specific regional patterns in the declines. The stations were divided into geographic regions: Suisun Bay (Stations 20-52), Lower Sacramento River (Stations 62-68), Lower San Joaquin River (Stations 74-82), Upper San Joaquin River (Stations 84-92) and Western Delta (Stations D19, D28, 98). Stations 54, 56, 58, 60, and 72 were not used in this analysis because they could not be unambiguously assigned to a particular region. To analyze changes in the entrapment zone, data in EC classes 13-16 were combined for all stations. Changes in anomalies were determined by using the regression methods described above.

Patterns of change in the five regions (Table 5) show the rotifers *Polyarthra, Synchaeta bicornis, Keratella,* and *Trichocerca* declined throughout the estuary, although the decline was not prominent in Suisun Bay for the two latter species. *Asplanchna* declined most prominently in Suisun Bay, the Lower San Joaquin River, and the Western Delta stations. The most significant declines in *Diaphanosoma* occurred in the Sacramento and Lower San Joaquin rivers. *Daphnia* declines were confined to summer and fall in the San Joaquin River and Western Delta stations. Harpacticoid declines were most significant in the Lower San Joaquin river. Cyclopoid declines were confined mainly to the San Joaquin River. *Eurytemora* declined most significantly in the Lower San Joaquin River, but also in other regions. *Diaptomus* declines were most significant in the Sacramento and San Joaquin rivers but also in Suisun Bay in the fall.

In the entrapment zone, declines in abundance of *Diaptomus* occurred only in the fall; *Eurytemora* and *Neomysis* declined in summer and fall (Table 5). The rotifers *Asplanchna, Keratella,* and *Polyarthra* declined in the entrapment zone during all seasons; *Trichocerca* and *Synchaeta bicornis* declined in spring and summer. Harpacticoids, cyclopoids, *Daphnia*, and *Diaphanosoma* did not decline in the entrapment zone.

In general, the results show declines of species were scattered throughout the entire estuary and not distinctly confined to particular regions. However, declines were more prevalent in the Sacramento and San Joaquin rivers than in Suisun Bay (Table 5).

Table 3
SUMMARIES OF CHANGES IN SUISUN BAY/DELTA ZOOPLANKTON ANOMALIES
Results of Regression Analysis of Annual Mean Anomalies

	POOLED DATA (All Months)	SPRING (March-May)	SUMMER (June-August)	FALL (September-November)
COPEPODS				
Acartia	0	0	0	0
Diaptomus	D**	0	D**	D***
Eurytemora	D***	D**	D***	D**
Harpacticoids	D**	D**	D*	D*
Cyclopoids	D*	0	0	D*
Sinocalanus	0	0	0	0
Limnoithona	0	0	0	0
Oithona davisae	I*	0	I*	I*
CLADOCERA				
Bosmina	0	0	0	0
Daphnia	D*	0	D*	D*
Diaphanosoma	D*	U*	D*	D***
ROTIFERA				
Asplanchna	D**	D*	D**	D**
Keratella	D***	D**	D**	D***
Polyarthra	D***	D***	D***	D***
Synchaeta spp.	0	0	0	0
Synchaeta bicornis	D***	D**	D***	D***
Trichocerca	D***	D**	D**	D**
OTHER				
Neomysis	D*	0	0	D**
Barnacle Nauplii	0	0	0	0
Crab Zoea	0	0	0	0

0 = NO CHANGE D = DECLINE I = INCREASE U = U SHAPED TREND
* 0.01 <P < 0.05
** 0.001 < P < 0.01
*** P < 0.001

Table 4
CHANGES IN SUISUN BAY/DELTA ZOOPLANKTON ANOMALIES, 1972 TO 1987
Results of Regression Analysis of Annual Mean Anomalies

	POOLED DATA (All Months)	SPRING (March-May)	SUMMER (June-August)	FALL (September-November)
COPEPODS				
Acartia	NS	NS	NS	NS
Diaptomus	Q2(.48) +-	NS	Q2(.40) +-	Q3(.66) +-
Eurytemora	Q3(.65) +-	L1(.21) +-	L3(.59) +-	Q2(.60) +-
Harpacticoids	Q2(.44) +-	L1(.20) +-	Q1(.42) +-	L1(.30) +-
Cyclopoids	L1(.23) +-	NS	NS	L1(.22) +-
Sinocalanus	NS	NS	NS	NS
Limnoithona	NS	NS	NS	NS
Oithona davisae	L1(.53) -+	NS	L1(.45) -+	L1(.44) -+
CLADOCERA				
Bosmina	NS	NS	NS	NS
Daphnia	L1(.27) +-	NS	Q1(.34) +-	L1(.40) +-
Diaphanosoma	Q2(.59) +-	Q1(.44) +-+	Q1(.44) +-	L3(.63) +-
ROTIFERA				
Asplanchna	Q2(.53) +-	Q1(.34) +-	Q2(.62) +-	Q2(.59) +-
Keratella	Q3(.85) +-	Q2(.59) +-	Q2(.72) +-	Q3(.90) +-
Polyarthra	Q3(.93) +-	L3(.76) +-	L3(.88) +-	Q3(.87) +-
Synchaeta spp.	NS	NS	NS	NS
Synchaeta bicornis	L3(.79) +-	Q2(.51) +-	Q3(.77) +-	L3(.60) +-
Trichocerca	Q3(.76) +-	Q2(.64) +-	Q2(.64) +-	Q2(.53) +-
OTHER				
Neomysis	Q1(.31) +-	NS	NS	Q2(.52) +-
Barnacle Nauplii	NS	NS	NS	NS
Crab Zoea	NS	NS	NS	NS

NS = NOT SIGNIFICANT L = LINEAR MODEL Q = QUADRATIC MODEL
1 $0.01 < P < 0.05$
2 $0.001 < P < 0.01$
3 $P < 0.001$
.## Adjusted R squared
+- Decline
-+ Increase
+-+ Decline followed by increase
+-o Decline followed by increase to values near 0 anomaly
-+o Increase to asymptotic value

Table 5

SUMMARY OF REGIONAL CHANGES IN ABUNDANCE OF ZOOPLANKTON TAXA THAT DECLINED BETWEEN 1972 AND 1987

Numbers are adjusted R^2 for either a linear or quadratic model, whichever yielded the highest R^2.
AL = data pooled for all months, SP = spring, SU = summer, FA = fall

	SUISUN BAY				SACRAMENTO RIVER				LOWER SAN JOAQUIN RIVER				UPPER SAN JOAQUIN RIVER				WESTERN DELTA				ENTRAPMENT ZONE			
	AL	SP	SU	FA	AL	SP	SU	FA	AL	SP	SU	FA	AL	SP	SU	FA	AL	SP	SU	FA	AL	SP	SU	FA
Diaptomus	.33 *	NS	NS	.55 **	.29 *	NS	.24 *	.36 *	.23 *	NS	NS	.41 *	.62 **	.25 *	.57 ***	.60 **	.52 **	NS	.31 *	.67 ***	.26 *	NS	NS	.57 **
Eurytemora	.26 *	NS	.20 *	.22 *	.57 **	.50 **	.42 *	NS	.67 ***	.50 ***	.44 **	.61 **	.40 *	.36 *	.42 *	NS	.68 ***	NS	.52 **	.63 **	.39 **	NS	.61 ***	.21 **
Harpacticoids	NS	NS	NS	NS	.20 *	NS	.29 *	NS	.73 ***	.58 ***	.58 **	.61 **	NS	NS	.23 *	NS	.57 **	NS	NS	.59 **	NS	NS	NS	NS
Cyclopoids	NS	NS	NS	NS	NS	NS	NS	NS	.22 *	NS	NS	.23 *	.40 *	NS	.31 *	.34 *	.37 *	NS	NS	NS	NS	NS	NS	NS
Daphnia	NS	NS	NS	NS	NS	NS	NS	NS	.32 *	NS	.31 *	.36 *	.48 *	NS	.38 *	.41 **	.59 **	NS	.41 *	.41 **	NS	NS	NS	NS
Diaphanosoma	NS	NS	NS	NS	.72 ***	.60 **	.63 **	.41 **	.78 ***	NS	.45 *	.74 ***	.44 **	NS	.35 *	.64 *	.37 *	NS	NS	.60 **	NS	NS	NS	NS
Neomysis	.45 **	NS	.45 *	.70 ***	.62 **	.46 **	NS	.62 **	.39 *	NS	NS	.57 **	.65 ***	.62 **	NS	.47 **	.55 **	.58 **	NS	.57 **	.36 **	NS	.23 *	.61 **
Trichocerca	.61 **	.54 **	.59 **	.58 **	NS	NS	.29 *	NS	.30 *	.21 *	.51 **	NS	NS	NS	NS	NS	.58 **	.46 **	.52 **	NS	.59 **	.48 **	.59 **	.55 **
Polyarthra	.69 ***	.74 ***	.47 **	.64 **	.87 ***	.58 **	.86 ***	.69 ***	.93 ***	.72 ***	.91 ***	.73 **	.89 ***	.73 **	.86 ***	.88 ***	.93 ***	.78 ***	.87 ***	.80 ***	.73 **	.73 **	.64 **	.70 **
Synchaeta bicornis	.46 **	.30 *	.68 ***	.47 **	.62 ***	.51 **	.49 **	.35 *	.53 **	.34 *	.50 **	.31 *	.59 ***	NS	.49 **	.34 *	.58 **	.38 *	.54 **	.54 **	.50 **	.30 *	.45 *	NS
Asplanchna	.39 *	NS	NS	NS	.84 ***	.77 ***	.79 ***	.75 ***	.82 ***	.70 ***	.81 ***	.74 ***	.50 **	NS *	.59 **	.46 *	.76 ***	.62 **	.72 ***	.60 **	.53 **	.38 *	.23 *	NS
Keratella	NS	NS	NS	NS	.89 ***	.74 ***	.83 ***	.75 **	.90 ***	.60 **	.87 ***	.71 **	.78 ***	.57 **	.74 ***	.85 ***	.91 ***	.74 ***	.70 **	.88 ***	.77 **	.64 **	.51 *	.71 **

NS Not Significant
* $0.01 < P < 0.05$
** $0.001 < P < 0.009$
*** $P < 0.001$

DISCUSSION

The analysis presented here differs from all previous analyses in the following ways. First, it uses log transformed data for analysis. Most parametric statistical analyses (*eg,* regression, t-test) are invalid if used with abundance data that have not been log transformed; thus, reported changes in abundance determined using these tests are unreliable. Second, it uses anomalies to eliminate the confounding effects of season and, especially, salinity on abundance patterns. This improves the sensitivity of the analysis for detecting changes in abundance due to other factors that could have been masked if salinity and seasonal effects were not removed. Third, it uses data from all stations and times of year for which sampling has been consistent, as opposed to using subsets of stations or seasons. All of these differences provide the benefit that the results are unequivocal: for example, *Eurytemora* did decline in the late 1970s. This does not mean results of this analysis differ greatly from previous analyses, because some of the trends are very prominent and therefore detectable by almost any method. What it does accomplish is to eliminate any remaining doubt about what species declined, when, and by how much.

Previous analyses of zooplankton population changes were made in California Department of Fish and Game Exhibit 28 (DFG 1987) and Orsi & Mecum (1986). Exhibit 28 reported changes to 1985 in the abundance of Neomysis, *Synchaeta bicornis, Eurytemora, Acartia, Cyclops vernalis* combined with other cyclopoids, *Diaptomus,* all cladocera combined, and all other rotifers combined. Decreases were found in all categories except *Acartia*. In general, the present results agree with past results, but the resolution is better. For example, we have been able to show that *Neomysis* declined in abundance in the mid-1970s but that the decline was significant only in the fall. Orsi & Mecum (1986) analyzed results just for 1972 to 1978 in the Delta. The taxa were all copepods, all cladocera, and all rotifers. Declines were also observed in all these groups. Owing to the regional analysis added in the present study, it is clear that zooplankton species or taxa have declined throughout the estuary and the declines are not localized to particular regions, although declines in Suisun Bay appeared to be less prevalent than in higher regions of the estuary.

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Appendix A
CHANGES IN ZOOPLANKTON ABUNDANCE FOR ALL DATA AND DATA POOLED BY SEASON

Figure A-1
ACARTIA

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.

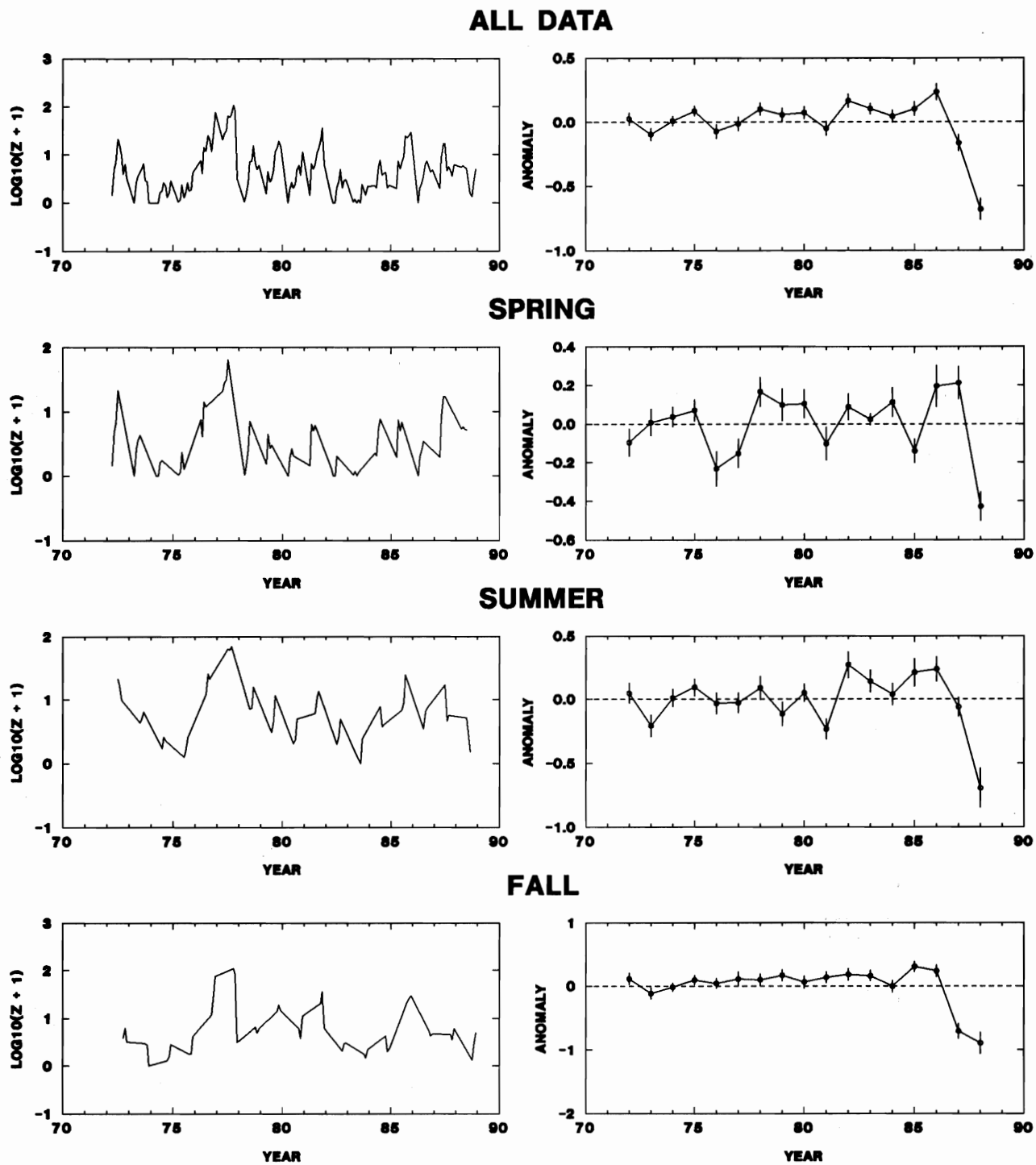


Figure A-2
DIAPTOMUS

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.

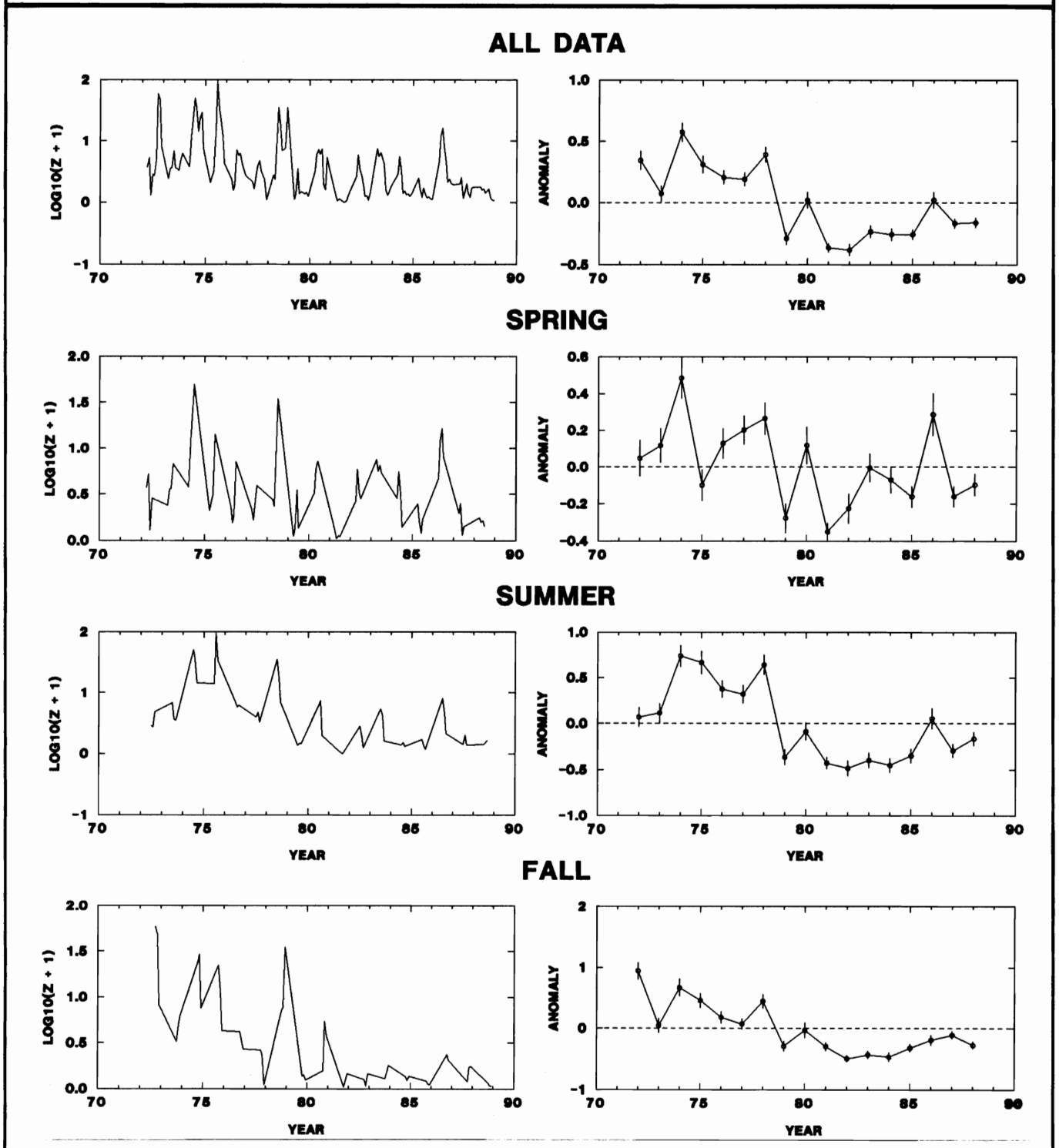


Figure A-3
EURYTEMORA

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.

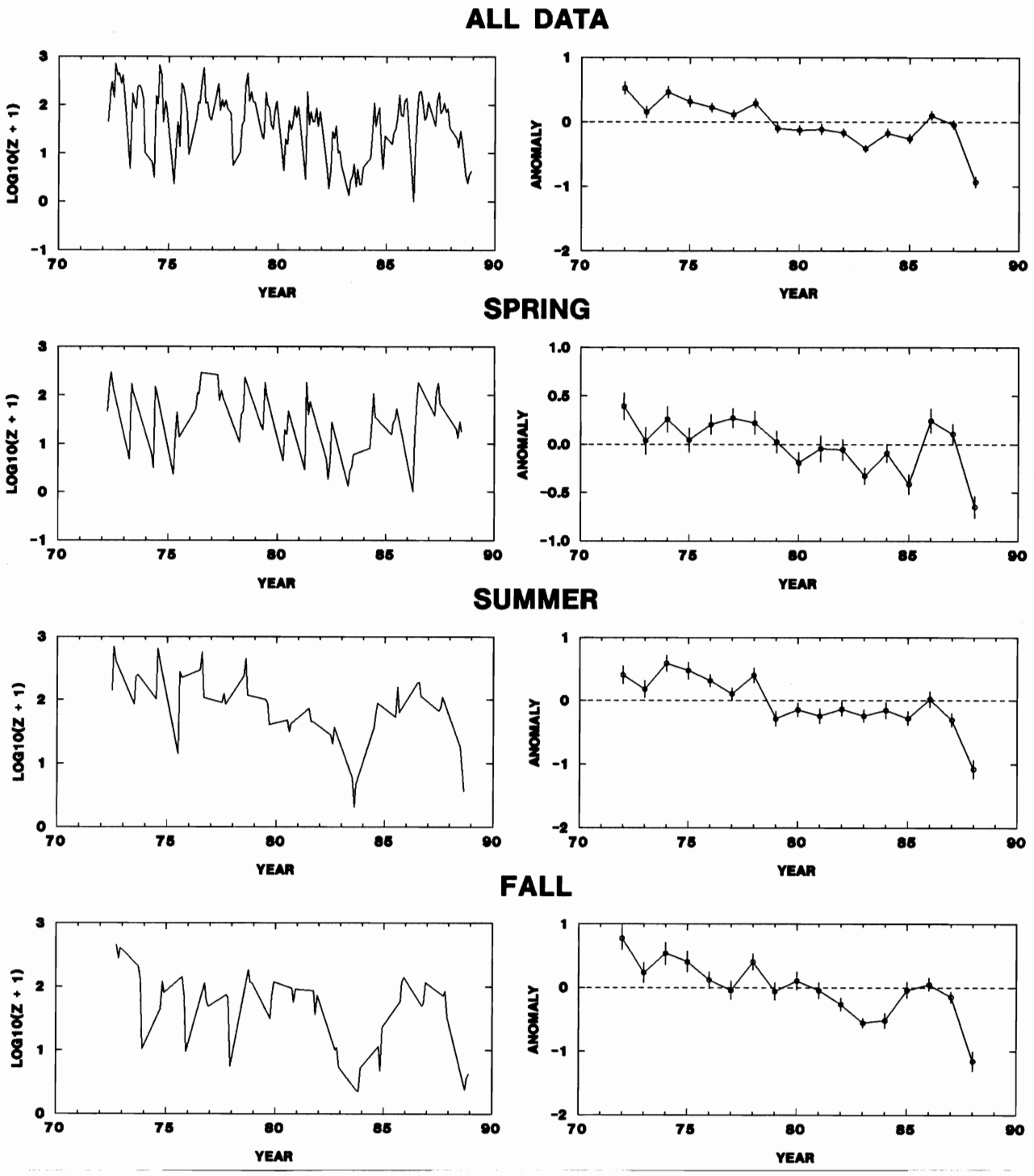
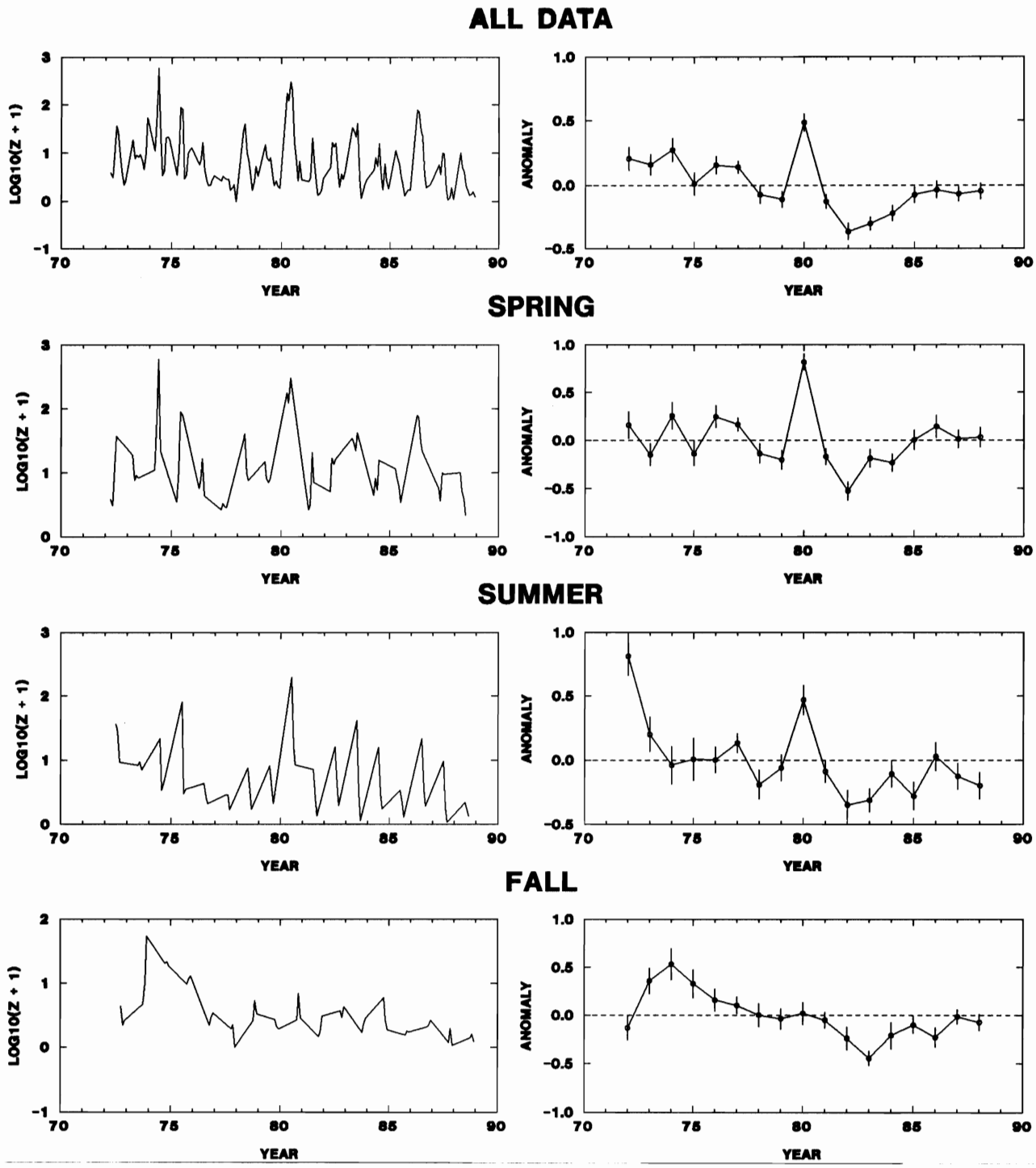


Figure A-4
DAPHNIA

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.



FigureA-5
HARPACTICOIDS

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.

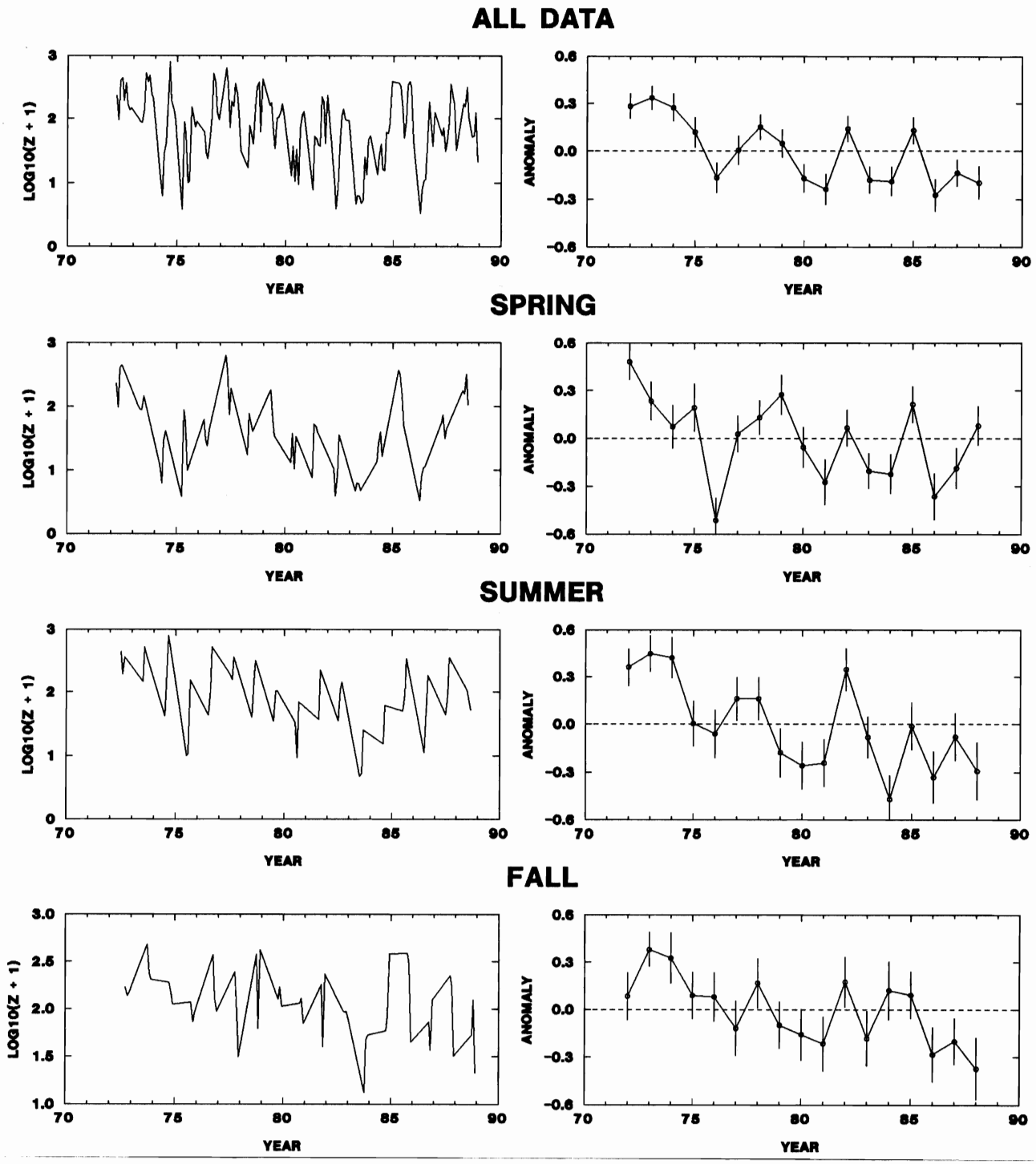


Figure A-6
SINOCALANUS

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.

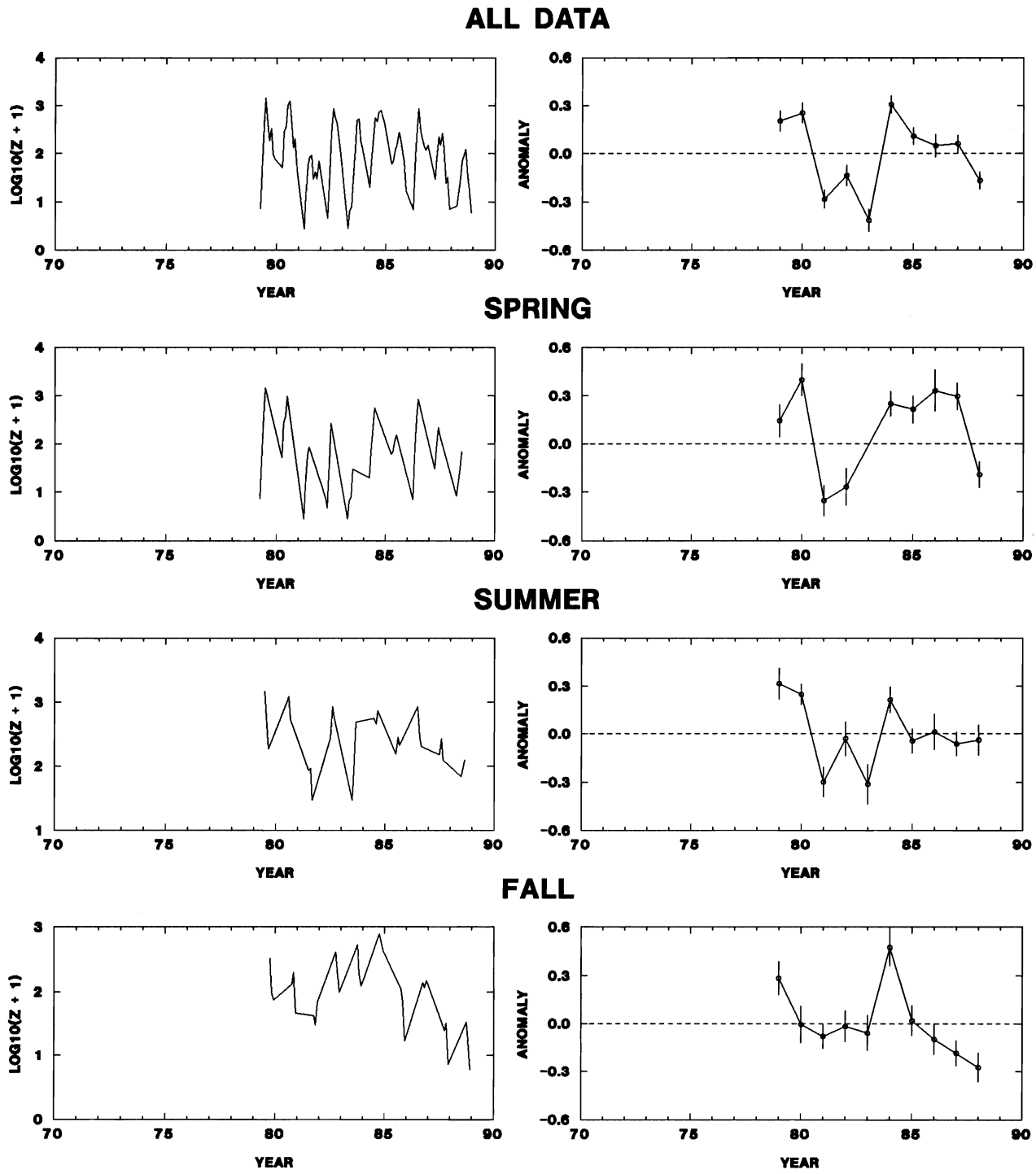


Figure A-7
LIMNOITHONA

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.

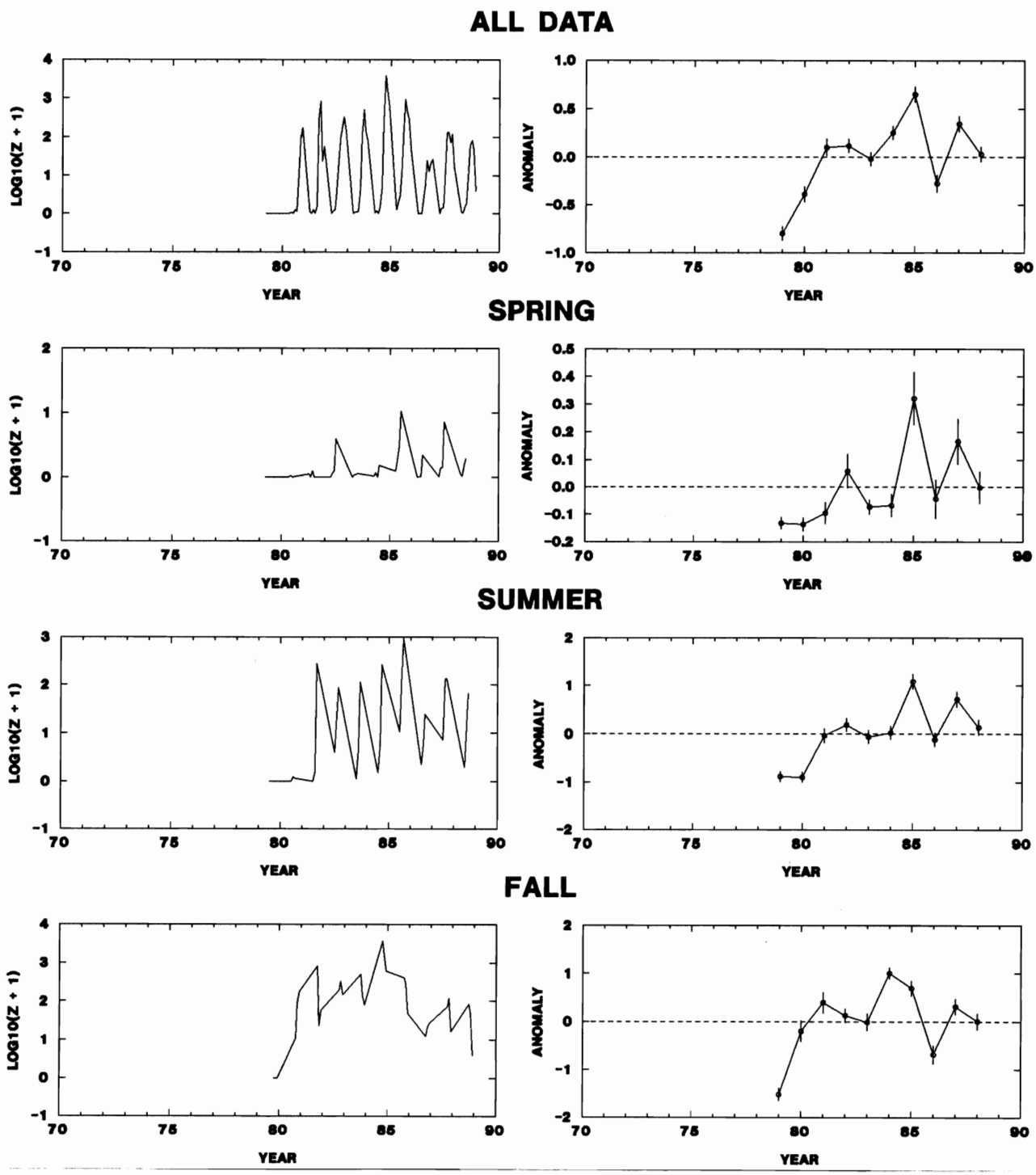


Figure A-8
OITHONA

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.

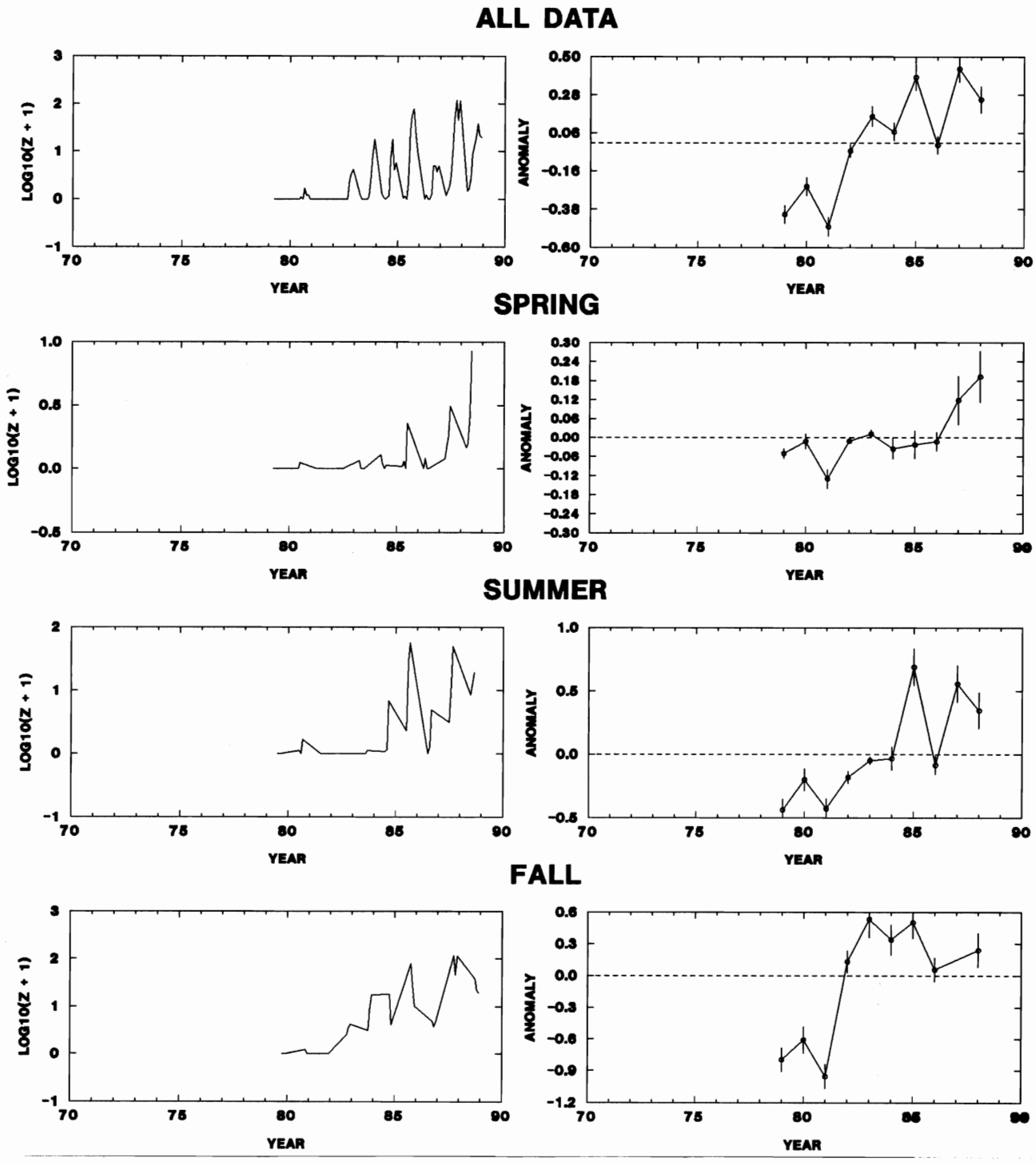
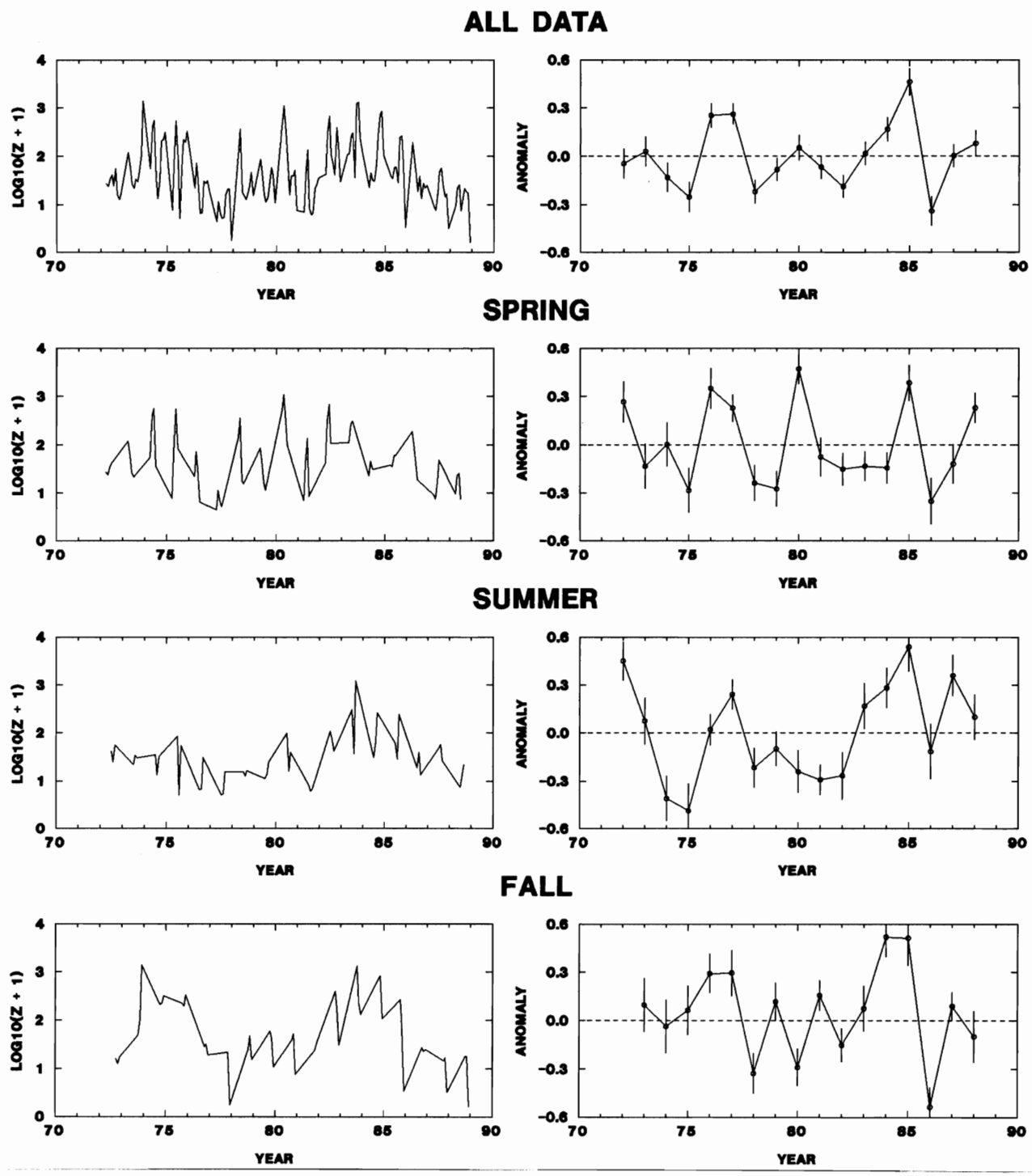


Figure A-9
BOSMINA

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.



FigureA-10
CYCLOPOIDS

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.

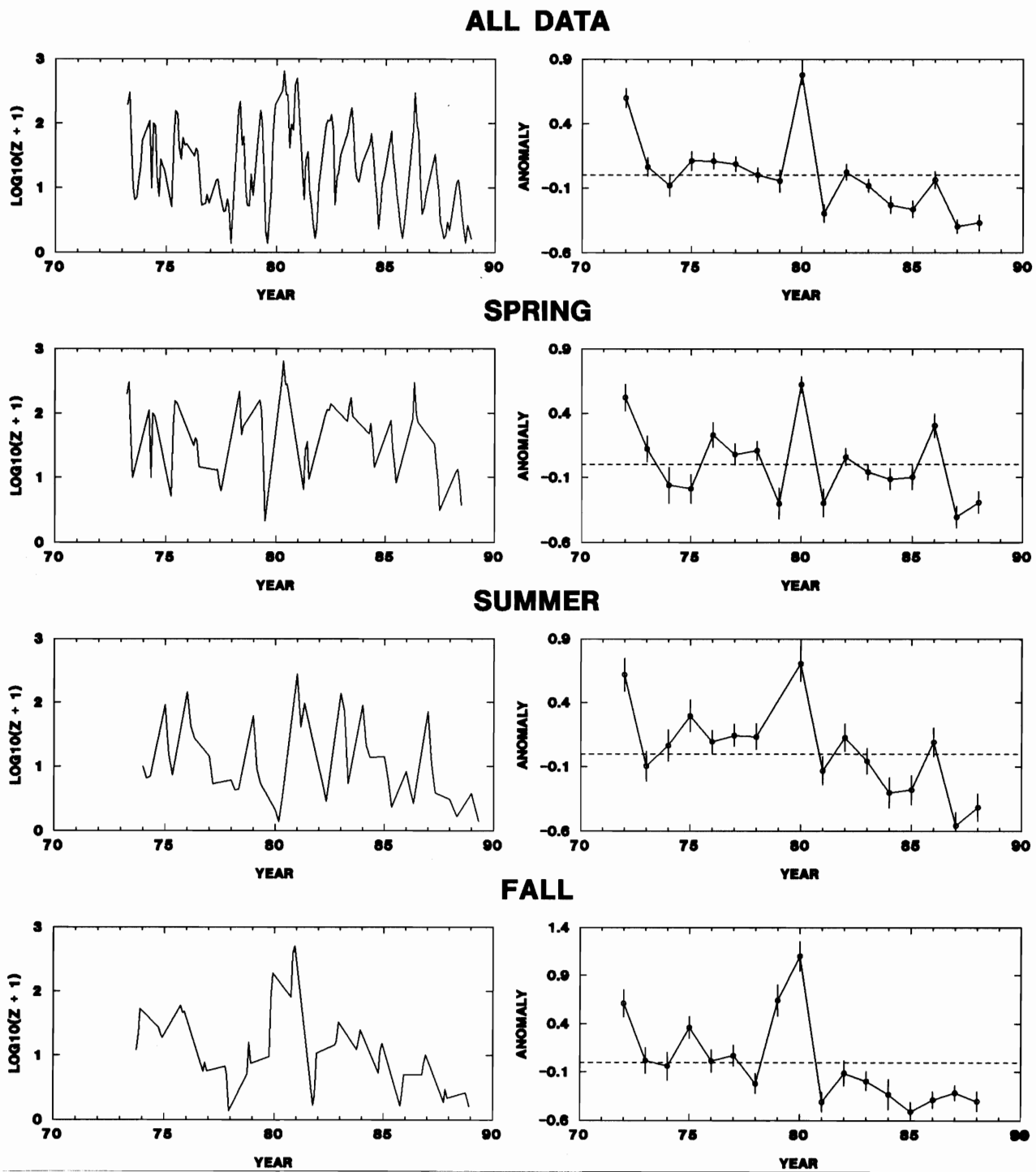


Figure A-11
DIAPHANOSOMA

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.

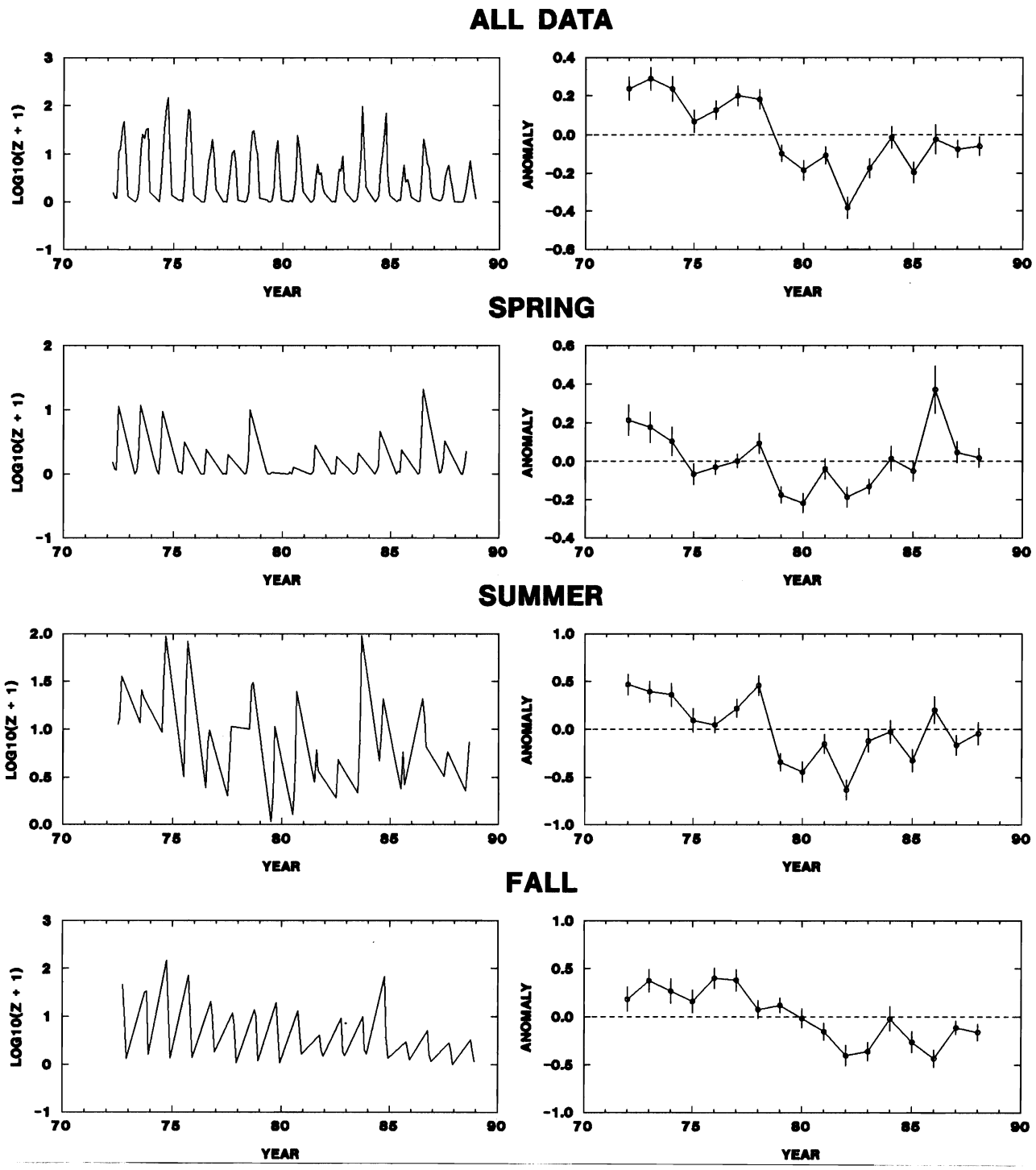


Figure A-12
ASPLANCHNA

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.

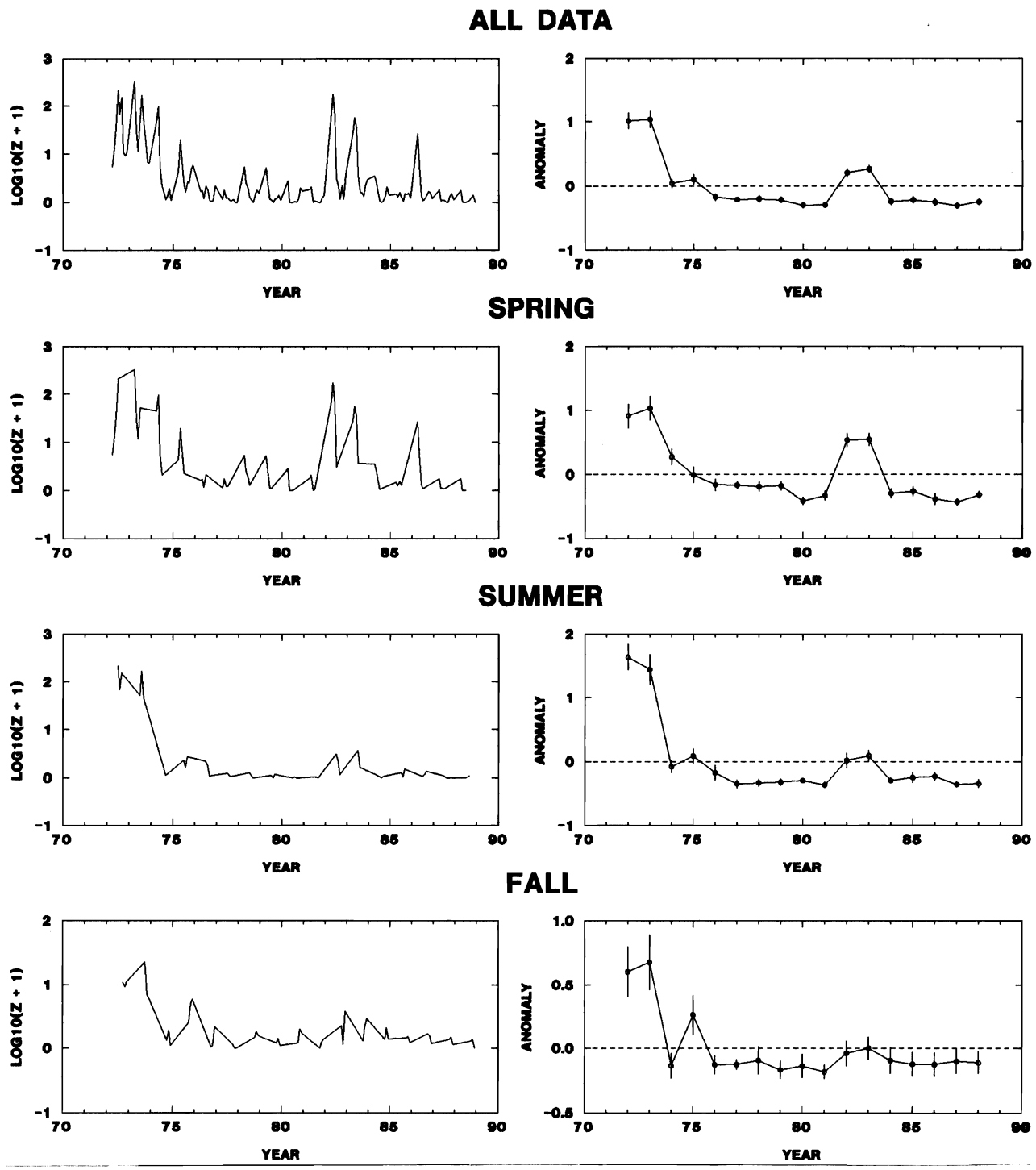


Figure A-13
KERATELLA

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.

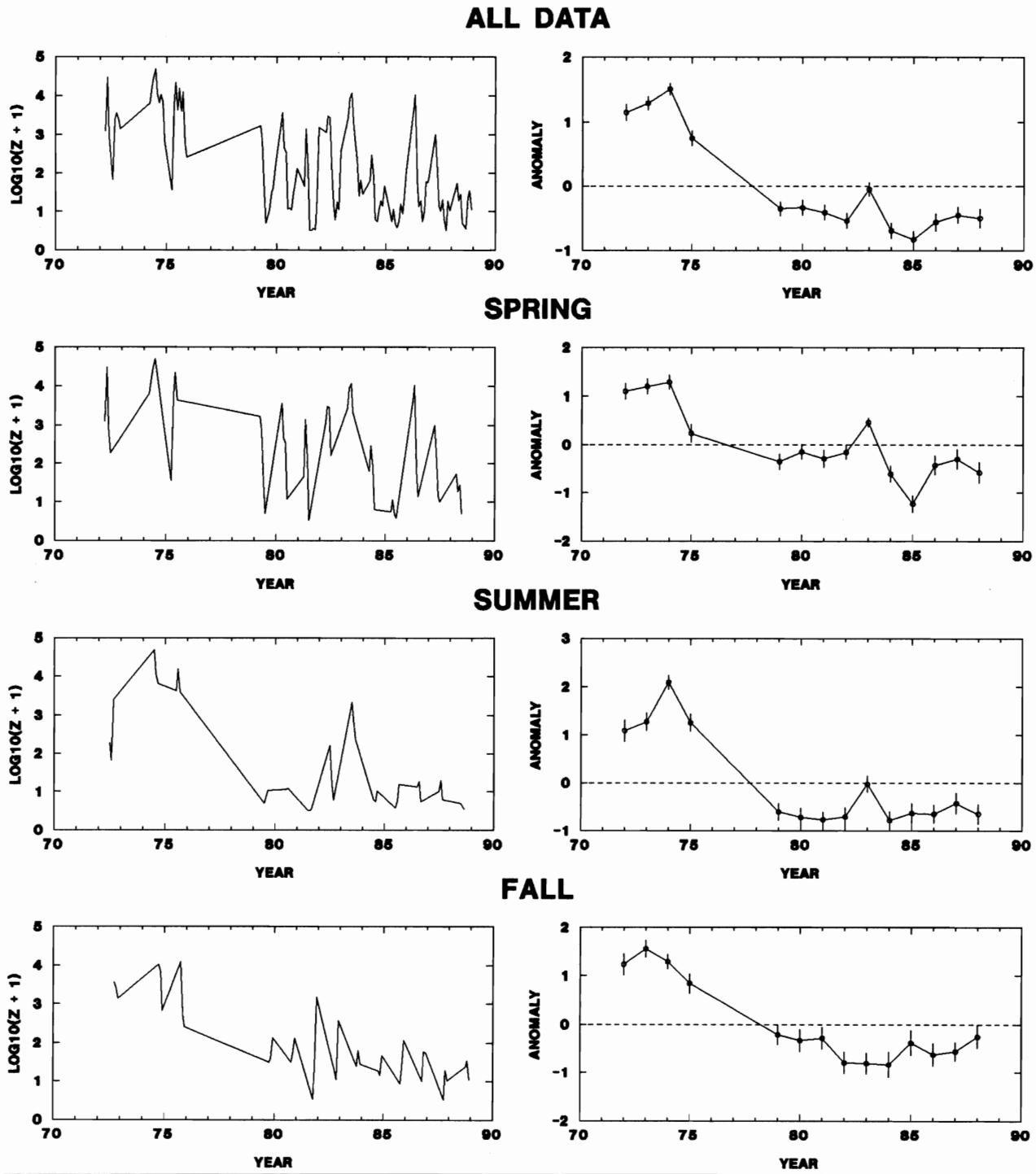


Figure A-14
POLYARTHRA

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.

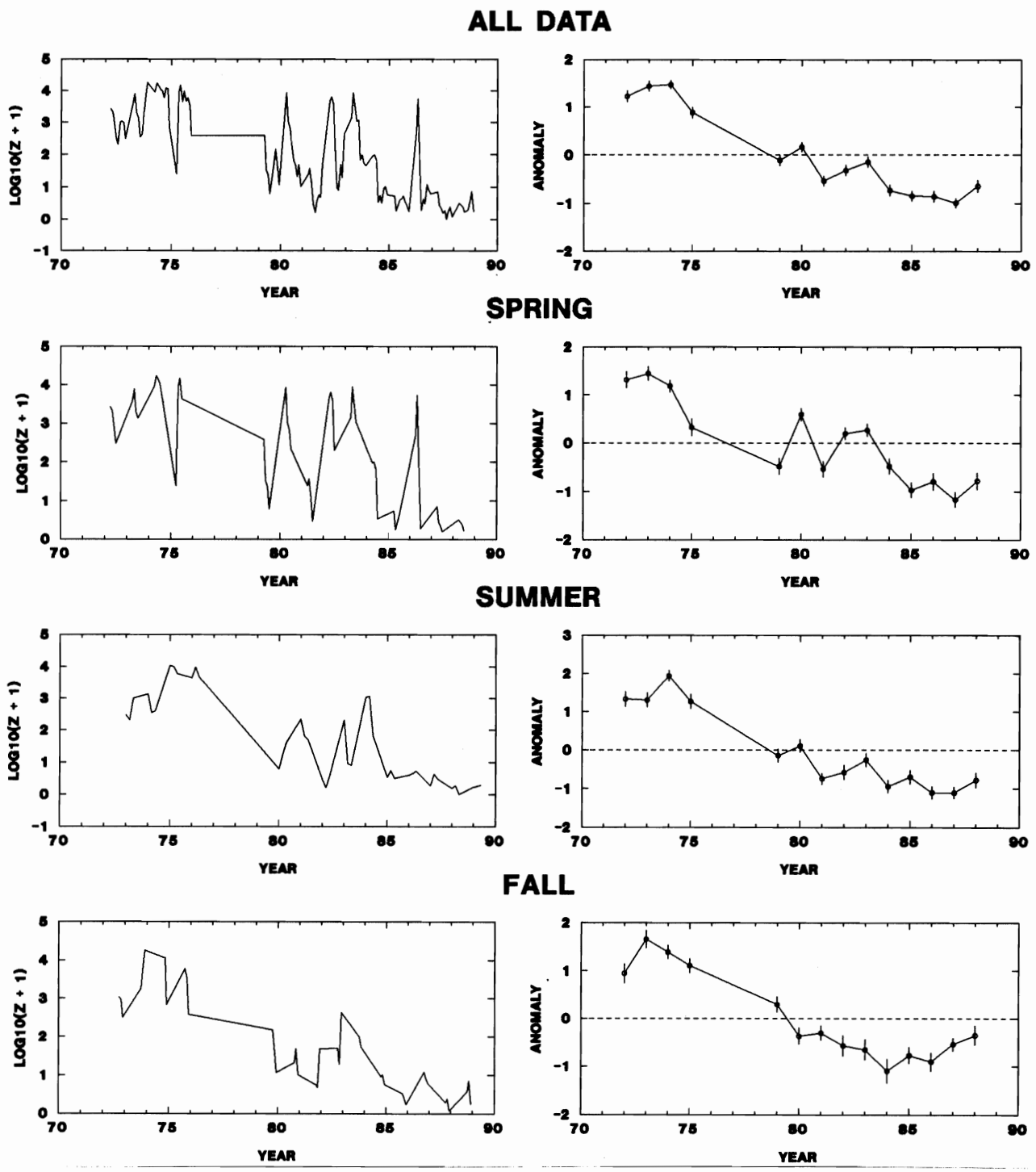


Figure A-15
SYNCHAETA BICORNIS

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.

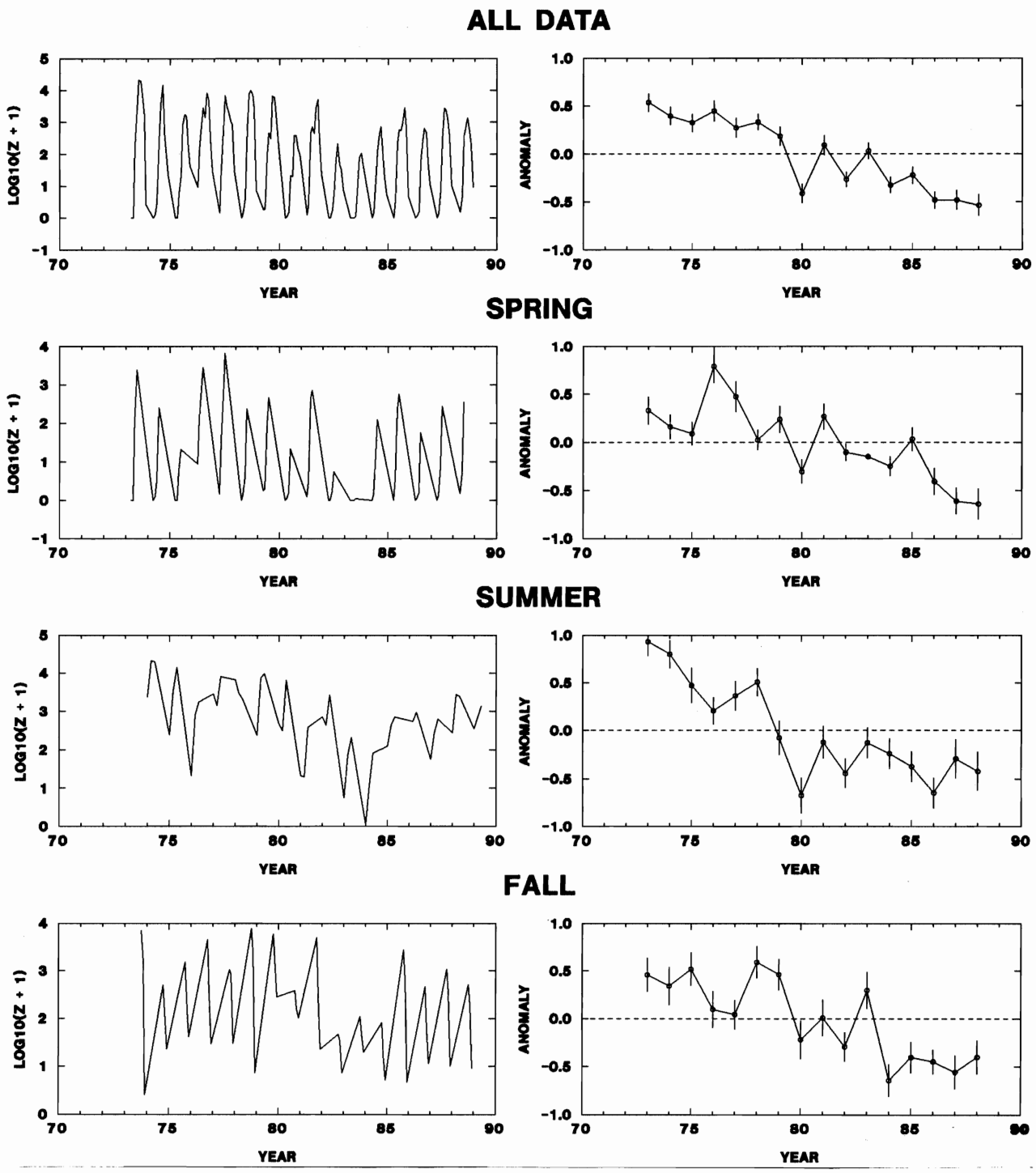
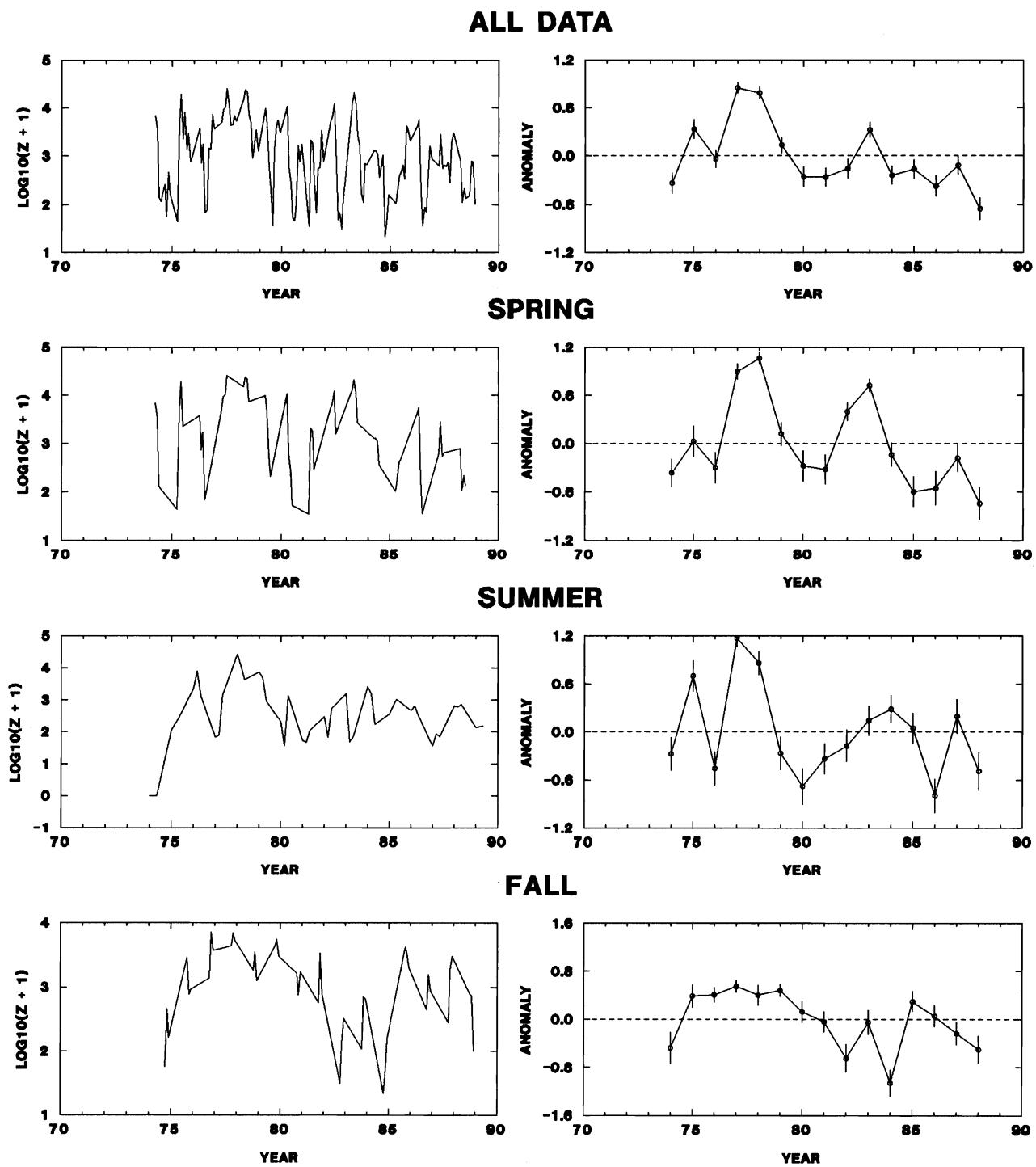


Figure A-16
SYNCHAETA SPP.

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.



FigureA-17
TRICHOCERCA

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.

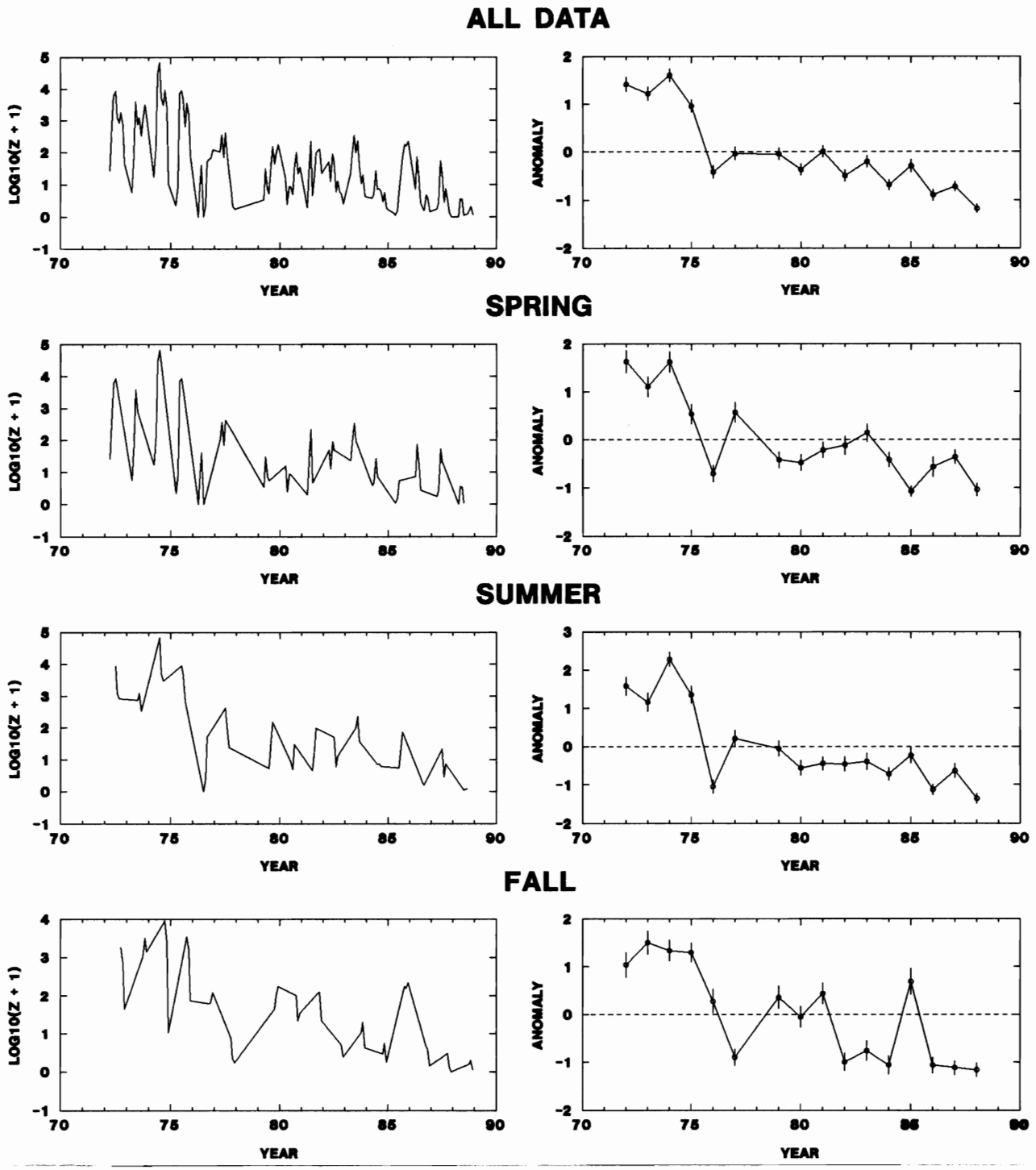
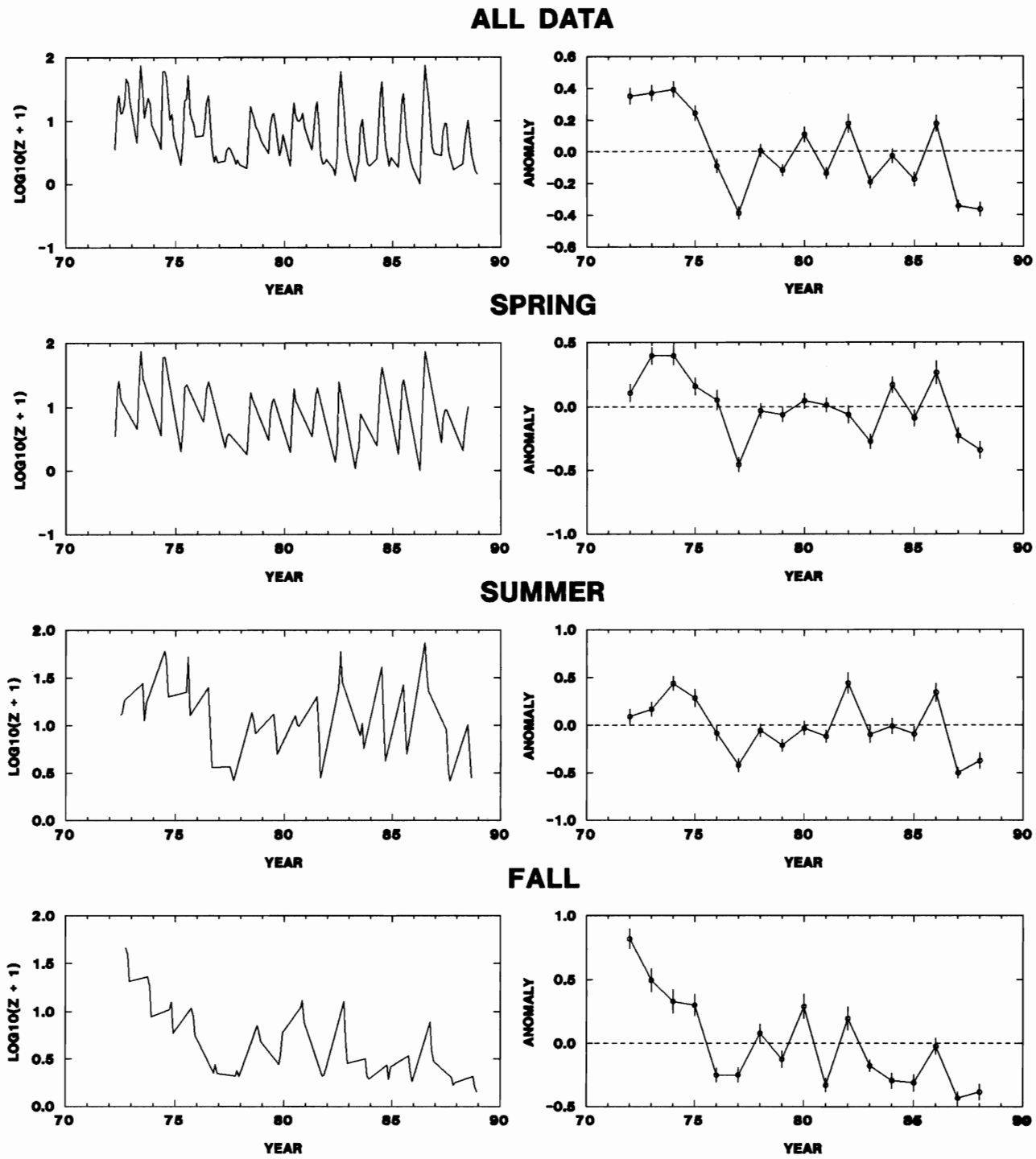


Figure A-18
NEOMYSIS

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.



FigureA-19
BARNACLE NAUPLII

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.

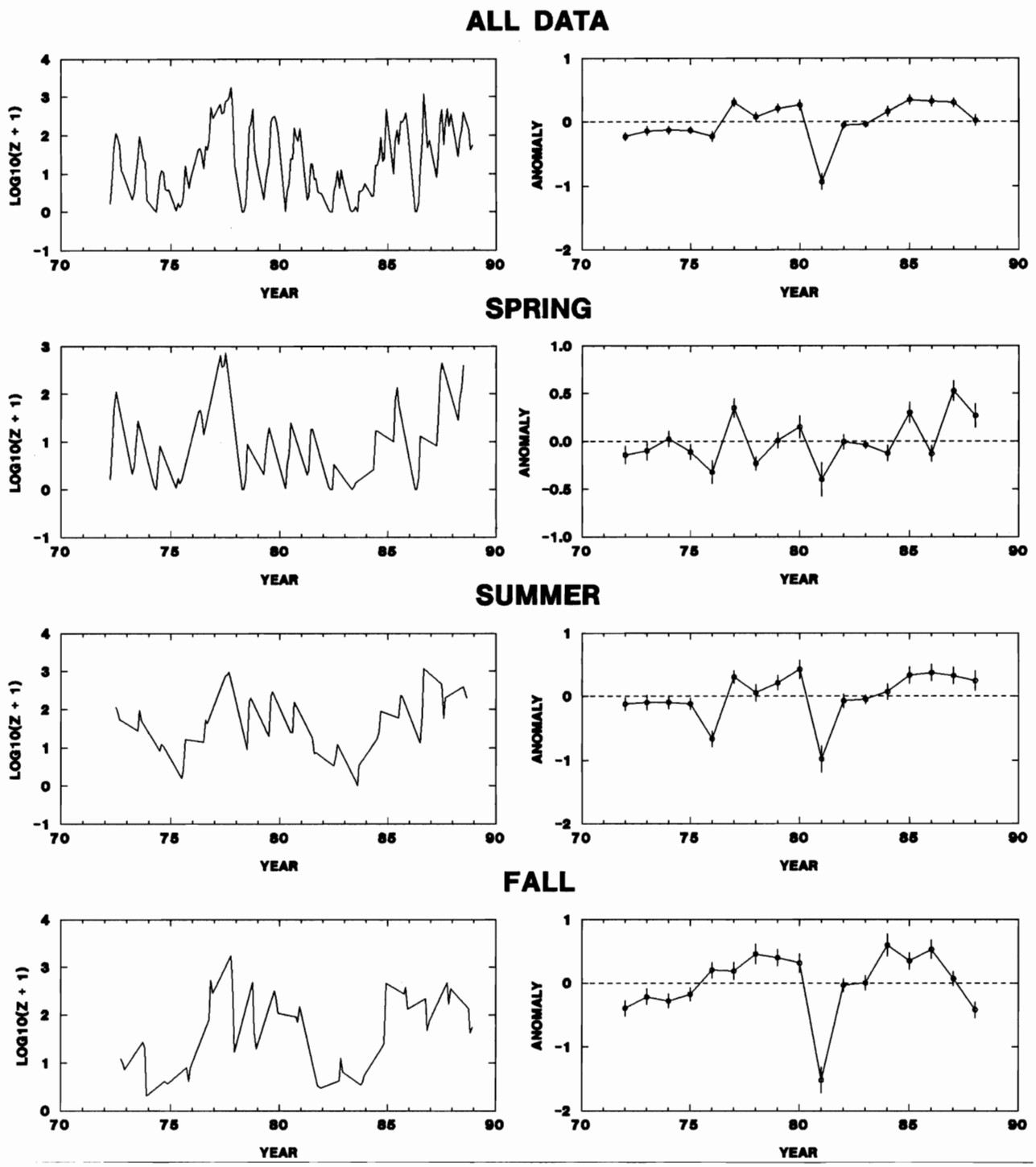
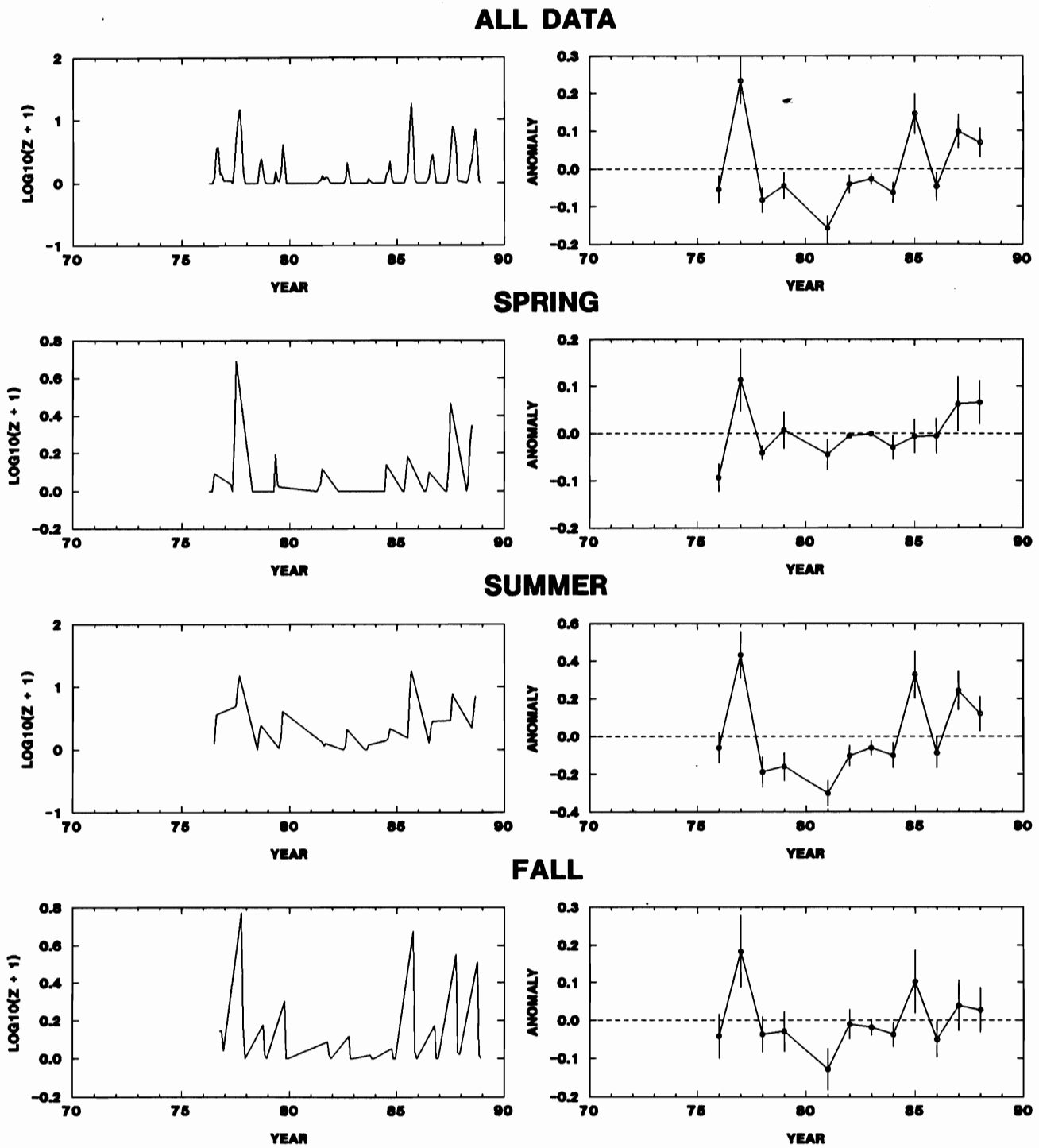


Figure A-20
CRAB ZOEA

Spring = March, April, May Summer = June, July, August Fall = September, October, November
Left column = $\log_{10}(Z+1)$ abundance; Right column = Mean annual anomalies with 95 percent confidence intervals.
Taxa are shown in the same order as in Table 2.