

A Note on Seasonal Variation in Radiolarian Abundance

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A statistical analysis of two consecutive sequences of observations on radiolarian abundances in the western North Pacific, by methods appropriate to data on the simplex (i.e., compositional data), show that although the overall graphical presentations of the frequencies appear similar, there are substantial differences in the earlier part of each of the series. The results of the multivariate analyses are used for identifying those species that contribute most to the analysis. A brief guide to the mathematical properties of compositional data is given.

KEY WORDS: Radiolaria, seasonal variation, compositions, multivariate analysis.

INTRODUCTION

Marine biologists and marine micropalaeontologists are often concerned with two aspects, productivity and composition, of plankton (palaeo)ecology in pelagic realms. Productivity is represented by “flux” (i.e., abundance per unit area per unit time) observed in terms of sediment-trap experiments; composition is assessed as percentage abundance of species. Vertical fluxes of Radiolaria from the surface to the depths have been investigated by several workers to acquire an understanding of production rate and sinking processes (e.g., Takahashi and Honjo, 1983; Takahashi, 1987; Abelmann, 1992; Boltovskoy, Alder, and Abelmann, 1993). These studies have revealed that dissolution of sinking polycystine radiolarians in the water column is not significant before settling on the seafloor and that modern radiolarian fluxes in the high-latitude and

equatorial oceans are associated with clear seasonal signals. For the other plankton groups, Kuroyanagi and others (2002), Eguchi and others (2003), and Mohiuddin and others (2005) have reported apparent seasonality in faunal composition of planktonic foraminifers based on sediment-trap experiments in the North Pacific. Considering these observations, Nakato and others (2005) and Motoyama and others (2005) considered seasonal variability in radiolarian composition as well as fluxes at the studied station in a temperate marine climatic zone where environmental seasonality is clear. They found, however, insignificant seasonal variation at the family-level composition, although there was seasonal variability in total radiolarian abundance. The Radiolaria are a very diversified planktonic group composed of some 500 living species in the world ocean which is why the analyses have been made at the family-level, instead of at the species-level, (a time-consuming procedure) for the preliminary reports by Nakato and others (2005) and Motoyama and others (2005). We now have a species-level radiolarian abundance data-set from a two-year observational period at a sediment-trap station in the Northwest Pacific which permit analysis of their seasonal variation or seasonal stability in reasonable detail.

In the present note, we apply standard methods of compositional multivariate statistical analysis to

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frequency data for radiolarians observed over two consecutive years. The compositional mode for analyzing the data is necessary inasmuch as abundances are characterized by each row of an array of observations summing to a constant. Constrained data of this kind are said to lie in simplex space, a subspace of full space. Full-space methods of multivariate statistical analysis cannot be applied to constrained data-sets without appropriate modifications. Although not immediately obvious, flux-data are also constrained in that the observations derive from observations on a fixed area.

We document here substantial seasonal variations in the radiolarian faunal composition. The statistical analysis suggests that this variation can be ascribed to a small number of species and that many of species incorporated in the analysis do not show marked seasonal variability.

MATERIAL AND METHODS

Particularly for shell-bearing microplankton, the sediment-trap method is a powerful tool for fixed-point collection of series in time over several days to years (Honjo and Doherty, 1988). Time-series sediment traps (coned-shaped traps with 21-cup collectors and a collection area of 0.5 m²) were used to collect sinking particles at Station WCT-2 (39°N, 147°E; trap depth, ~1500 m) in the Northwest Pacific (Fig. 1; Table 1). Forty samples were collected over a period of 1 year and 10 months between November 18th 1997 and August 9th, 1999 (Tables 1 and 2). Sampling intervals for each sample were 13 days for

the 20 samples set up by Cruise NH97, and 6 days for 1 sample and 18 days for 19 samples by Cruise NH98. Samples were fixed with formalin to create a 3% solution buffered with sodium borate.

The samples were wet-sieved through a 1-mm mesh and a 63- μ m mesh to remove large and small particles. Each sample <1 mm, >63 μ m was split into several aliquots (1/16–1/512) using a high precision rotary splitter. Each aliquot was treated with HCl to remove calcareous components, followed by rinsing with a 63- μ m mesh, and then filtered through Millipore filters (0.45 μ m pore size) using a vacuum pump. After filtering, the filters were air dried and then mounted on the glass slides with Canada Balsam. All specimens in a slide were counted under a transmitted light microscope. More than 500 polycystine species were encountered during the investigation. Of these species, 31 were selected for statistical analysis. These species constitute 70–85% of the total polycystine assemblage in each sample. The taxonomic information is summarized in Table 3.

The total of 40 observational sets were divided into two equally sized samples. The first set comprises 20 observations made over 10 months from November 1997 to August 1998. The second set comprises 20 observations made over the period of 12 months ranging from August 1998 to August 1999.

OCEANOGRAPHIC SETTING

Surface-waters in the Northwest Pacific off Japan can be classified into three zones, subtropical, transitional, and subarctic zones (Fig. 1). Our observation site, Station WCT-2, was located at the transitional water-mass between the warm Kuroshio Current and the cool Oyashio current. The sea surface temperature ranges from 9.7 to 22.7°C during the period encompassed by the observations (Reynolds and Smith, 1994).

BRIEF DESCRIPTION OF THE STATISTICAL PROPERTIES OF COMPOSITIONAL DATA

Compositional data analysis is little known among marine biologists and marine geologists. For this reason, we have deemed it necessary, to include a short account of the basic principles.

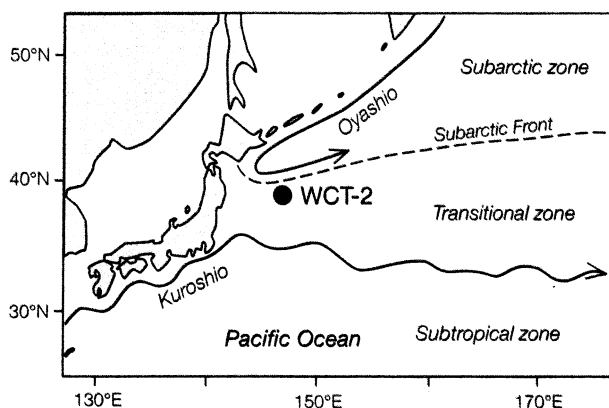


Figure 1. Index map showing location of the sediment trap site and hydrography of the upper layer of the northwestern Pacific Ocean.

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Table 1. Locations, Mooring Depths, and Duration of Sediment Traps at Station WCT-2

Location	Seafloor depth (m)	Duration	Trap depth (m)
39 00.1' N, 146 59.7' E	5356	18 November 1997–5 August 1998	1371
39 01.0' N, 147 00.1' E	5322	26 August 1998–9 August 1999	1586

Table 2. Samples from Station WCT-2

No.	WCT-2 sample	Trap cup		Duration (days)
		Opened	Closed	
<i>Cruise NH97</i>				
1	39N U01	18 Nov. 1997	1 Dec. 1997	13
2	39N U02	1 Dec. 1997	14 Dec. 1997	13
3	39N U03	14 Dec. 1997	27 Dec. 1997	13
4	39N U04	27 Dec. 1997	9 Jan. 1998	13
5	39N U05	9 Jan. 1998	22 Jan. 1998	13
6	39N U06	22 Jan. 1998	4 Feb. 1998	13
7	39N U07	4 Feb. 1998	17 Feb. 1998	13
8	39N U08	17 Feb. 1998	2 Mar. 1998	13
9	39N U09	2 Mar. 1998	15 Mar. 1998	13
10	39N U10	15 Mar. 1998	28 Mar. 1998	13
11	39N U11	28 Mar. 1998	10 Apr. 1998	13
12	39N U12	10 Apr. 1998	23 Apr. 1998	13
13	39N U13	23 Apr. 1998	6 May 1998	13
14	39N U14	6 May 1998	19 May 1998	13
15	39N U15	19 May 1998	1 Jun. 1998	13
16	39N U16	1 Jun. 1998	14 Jun. 1998	13
17	39N U17	14 Jun. 1998	27 Jun. 1998	13
18	39N U18	27 Jun. 1998	10 Jul. 1998	13
19	39N U19	10 Jul. 1998	23 Jul. 1998	13
20	39N U20	23 Jul. 1998	5 Aug. 1998	13
<i>Cruise NH98</i>				
21	39N U01	26 Aug. 1998	1 Sep. 1998	6
22	39N U02	1 Sep. 1998	19 Sep. 1998	18
23	39N U03	19 Sep. 1998	7 Oct. 1998	18
24	39N U04	7 Oct. 1998	25 Oct. 1998	18
25	39N U05	25 Oct. 1998	12 Nov. 1998	18
26	39N U06	12 Nov. 1998	30 Nov. 1998	18
27	39N U07	30 Nov. 1998	18 Dec. 1998	18
28	39N U08	18 Dec. 1998	5 Jan. 1999	18
29	39N U09	5 Jan. 1999	23 Jan. 1999	18
30	39N U10	23 Jan. 1999	10 Feb. 1999	18
31	39N U11	10 Feb. 1999	28 Feb. 1999	18
32	39N U12	28 Feb. 1999	18 Mar. 1999	18
33	39N U13	18 Mar. 1999	5 Apr. 1999	18
34	39N U14	5 Apr. 1999	23 Apr. 1999	18
35	39N U15	23 Apr. 1999	11 May 1999	18
36	39N U16	11 May 1999	29 May 1999	18
37	39N U17	29 May 1999	16 Jun. 1999	18
38	39N U18	16 Jun. 1999	4 Jul. 1999	18
39	39N U19	4 Jul. 1999	22 Jul. 1999	18
40	39N U20	22 Jul. 1999	9 Aug. 1999	18

One of the most common types of observations occurring in applied geology concerns compositions, a significant aspect of which is that the data are in

the form of frequencies, proportions or percentages, and all of which have the common property that the rows of the data-matrix sum to a constant. This may

Table 3. Taxonomic List at Station WCT-2

Sample no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1 <i>Actinomma medianum</i> Nigrini	1.6	1.9	2.3	3.1	1.4	4.2	3.0	3.1	2.0	3.4	2.6	1.8	1.6	0.3	1.2	0.9	0.8	0.6	1.5
2 <i>Cladococcus cervicornis</i> Haeckel	2.4	0.7	1.5	4.6	3.3	0.5	0.5	0.9	0.8	0.4	0.3	0.4	1.4	0.7	0.7	0.7	0.9	4.8	4.6
3 <i>Rhizoplegma boreale</i> (Cleve)	1.2	1.7	1.3	1.8	1.9	1.5	2.4	3.5	2.6	2.6	1.2	0.8	0.7	0.7	1.0	0.4	0.6	1.9	0.6
4 <i>Stylochlamydidium venustum</i> (Bailey)	0.6	0.2	0.1	0.5	0.5	0.5	0.5	0.4	0.7	1.4	0.8	1.6	1.6	1.6	0.7	0.8	2.3	0.4	1.9
5 <i>Stylodiotya validispina</i> Joergensen	1.0	0.3	0.3	0.2	0.9	0.2	0.6	0.5	0.2	0.4	0.7	1.1	0.9	0.2	0.0	0.4	0.2	0.4	0.3
6 <i>Spongotrochus glacialis</i> Popofsky	1.0	1.9	1.1	2.2	1.9	2.0	1.7	2.4	1.5	1.2	1.2	1.0	1.4	1.2	0.5	0.9	0.9	1.0	1.9
7 <i>Tetrapyle octacantha</i> Mueller	6.0	2.6	1.1	2.6	1.4	1.8	1.2	1.4	1.1	1.0	0.8	0.7	0.0	0.3	0.0	0.5	0.2	0.4	0.2
8 <i>Larcopele buetschlii</i> Dreyer	2.2	1.8	2.0	2.6	1.4	2.4	3.1	2.4	2.0	3.0	3.1	2.9	2.3	2.0	1.2	1.0	0.7	0.6	1.5
9 <i>Tholospira cervicornis</i> Haeckel	4.2	2.0	1.6	2.2	0.9	0.6	1.1	1.4	0.3	1.4	1.0	0.7	1.1	1.0	0.7	0.5	0.7	0.4	1.3
10 <i>Cladoscenum ancoratum</i> Haeckel	1.6	1.8	2.0	2.0	2.3	2.0	1.8	1.9	2.2	2.0	1.0	1.2	3.0	1.7	1.7	0.7	1.0	2.3	2.3
11 <i>Gonosphaera primordialis</i> Joergensen	1.4	0.9	0.1	0.7	0.0	0.2	0.9	0.5	0.3	0.6	0.6	0.3	0.2	0.5	0.7	0.4	0.8	1.2	1.1
12 <i>Plagiacantha arachnoids</i> Claparede	0.0	0.9	1.6	3.5	5.6	1.5	3.3	4.0	3.5	2.0	1.9	1.4	1.4	1.0	0.9	1.1	1.3	2.3	1.7
13 <i>Plagiacantha panarium</i> Dumitrica	0.8	0.4	0.1	0.5	0.5	1.3	1.4	1.6	4.1	2.2	5.0	4.6	14.2	19.1	34.2	41.3	37.3	20.2	7.8
14 <i>Pseudocubus obeliscus</i> Haeckel	0.8	3.9	2.1	2.0	1.9	2.6	3.0	2.5	4.2	3.6	6.4	5.5	5.7	8.4	5.2	10.3	4.8	4.8	1.2
15 <i>Semantis gracilis</i> Popofsky?	0.0	0.4	2.4	0.5	0.5	0.6	0.3	0.0	0.5	0.2	0.1	0.1	0.2	0.0	0.0	0.2	0.2	0.6	0.2
16 <i>Antarctissa</i> sp. 1	0.0	0.0	0.0	0.0	0.0	0.2	0.8	1.8	1.5	1.9	2.2	2.4	0.9	2.6	0.2	0.9	0.5	1.2	0.4
17 <i>Arachnocorys circumtexta</i> Haeckel	0.0	0.5	0.5	0.2	1.9	0.4	0.0	0.1	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.5	0.4	2.2	0.0
18 <i>Lithomelissa setosa</i> Joergensen	0.4	0.9	1.5	1.1	0.9	1.2	1.3	2.6	6.6	3.8	10.2	9.7	3.4	4.7	6.1	3.6	2.1	0.6	1.3
19 <i>Lithomelissa thoracites</i> Haeckel	1.8	2.0	1.9	1.5	2.3	1.7	1.6	1.6	2.0	3.0	2.1	1.8	1.1	1.1	2.1	0.8	0.7	0.4	0.9
20 <i>Lophophaena</i> cf. <i>captio</i> Ehrenberg	0.2	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.5	1.0	1.2	1.7	1.8	1.7	0.3	1.0	0.9	1.2	1.3
21 <i>Peridium longispinum</i> Joergensen	0.4	4.9	3.6	4.2	4.2	4.4	4.5	2.9	3.5	1.8	1.6	2.1	1.6	3.0	3.1	1.5	1.1	1.7	1.5
22 <i>Peridium spinipes</i> Haeckel	2.2	3.7	4.0	1.5	0.5	2.1	3.0	3.5	2.2	2.1	3.7	3.6	0.7	1.9	2.1	0.6	0.7	1.5	1.0
23 <i>Peromelissa phalacra</i> Haeckel	0.8	0.7	0.9	0.9	2.3	1.8	1.4	0.1	0.8	1.2	1.8	1.0	0.9	1.2	0.3	0.4	0.4	0.0	0.2
24 <i>Phormacantha hystrix</i> (Joergensen)	4.4	7.2	10.9	7.1	11.6	14.2	8.3	4.5	8.0	5.2	8.1	6.9	9.4	6.7	8.2	7.1	7.5	14.4	10.3
25 <i>Plectacantha oikiskos</i> Joergensen	0.4	4.1	10.9	6.8	6.0	2.7	4.0	5.5	6.5	4.2	3.3	5.1	8.0	3.7	6.1	2.3	3.5	10.0	6.9
26 <i>Plectacantha trichoides</i> Joergensen	0.8	1.2	1.5	0.7	0.9	0.7	0.8	1.3	1.1	0.9	0.5	0.3	0.7	0.3	0.2	0.5	1.7	2.1	4.8
27 <i>Pseudodictyophimus gracilipes</i> (Bailey)	3.4	3.6	1.9	3.1	5.1	3.7	3.1	4.1	3.0	2.9	2.1	2.9	2.5	2.4	0.9	1.5	1.8	1.5	3.7
28 <i>Lophophaeniinae</i> sp. A8	0.2	0.0	0.1	0.2	0.5	0.5	0.2	0.9	0.4	0.3	0.4	0.3	0.2	0.2	0.0	0.1	0.1	0.0	0.0
29 <i>Plagiacanthinae</i> sp. F	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.0	1.4	0.6	1.2	0.9	0.6	0.2	0.2	0.3	0.4	0.0
30 <i>Eucecryphalus</i> sp. A	1.0	1.1	0.4	1.1	2.8	1.8	2.1	1.8	0.7	0.6	0.7	0.2	0.0	0.1	0.2	0.1	0.2	0.0	0.0
31 <i>Pterocorys zancaeus</i> (Mueller)	2.2	0.9	0.8	0.4	0.9	0.8	0.1	0.8	0.3	0.2	0.3	0.4	1.4	0.4	0.2	0.3	0.3	0.0	0.4
32 Other polycystins	57.2	48.0	41.4	42.1	35.8	41.7	43.9	42.0	36.0	43.8	34.3	36.3	30.5	30.7	21.2	18.9	25.2	22.9	37.0

Taxonomic key to Fig. 6.

not seem to be much of an obstacle, but there is indeed a geometrical stumbling block involved that may be severe enough as to distort, or even invalidate, an analysis (Reyment and Savazzi, 1999). Geometrically, compositions lie in simplex space, a subspace of real space. The analysis of compositional data is not well known to scientists and for this reason we present a brief introduction to the subject.

The study of compositions is essentially concerned with the relative magnitudes of “ingredients” and not their absolute values such as is the case for, say, measurements on a skull. These ingredients are not variables in the accepted sense of that term in statistics, but *parts*. What justifies this distinction? Consider any compositional vector \mathbf{x} with non-negative elements

$$x_1 + x_2 + \cdots + x_D = 1 \quad (1)$$

This vector is subject to the “unit-sum constraint,” which means that the composition \mathbf{x} is composed of D parts summing to 1. The components of Eq. 1

cannot be independent because they are constrained to sum to the same value.

The characteristic features of a compositional data-set are:

- Each row of the $N \times D$ data-matrix corresponds to a single object (in the present connexion, a biological population or equivalent).
- Each column of the data-matrix represents the frequency of a single part.
- Each row of the data-matrix sums to 1 (for proportions), respectively, 100 (for percentages).
- Correlations fluctuate erratically when one or more of the parts are removed from the data matrix (or a new part is added) because of the mathematical necessity of re-establishing the constant row-sum.
- Each entry in the data-matrix is non-negative.

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Property (d) provides part of the key to understanding the complexity of compositional data. Correlations computed for “normal” data-matrices are invariant to the number of variables included. If you delete one or more variables from a set of measurements (array) on some anatomical feature, this has no effect on the correlations between the remaining variables. Deleting a part does, however, change correlations between all remaining parts. For example, removing the proportion of CaO from a chemical array of values does influence all other oxides in an unpredictable way, row by row, each of which will after the deletion have a row-sum differing generally from all other rows of the array and which must be restored to the constant-sum state. A multivariate statistical analysis performed on an “unadjusted” compositional data-set is seldom useful.

Is all of this a recent discovery? Not at all, and in fact the problem of spurious correlation is perhaps one of the oldest in biometry, but probably the one that is least observed in practice. The founding father of Biometry, Karl Pearson, wrote in 1897 in his essay on the mathematical foundations to the theory of evolution that a form of spurious correlation may arise when indices are used in the measurement of organisms. The modern theory of compositional data analysis is due to Aitchison (1983, 1986, 1997). Important expansions of the geometrical aspects of theory are given in Ezogué and Pawlowsky-Glahn (2007).

Subcompositions

The question is often put by people unfamiliar with the geometrical properties of data lying in simplex space as to why it is not acceptable just to delete uninteresting parts from a data-set. The formation of a subcomposition is not merely a matter of deleting a part from each composition. If this is done, the entire balance in the data is disturbed in an unpredictable manner. If S is any subset of the parts $1, \dots, D$ of a D -part composition \mathbf{x} , and \mathbf{x}_S is the subvector formed from the corresponding components of \mathbf{x} , then $C(\mathbf{x}_S)$ is called the subcomposition of the parts S (Aitchison, 1986, p. 196). The significance of this can be seen from the following exemplification for five parts from which parts 1, 4, and 5 are selected to form a subcomposition.

$$(s_1, s_2, s_3) = C(x_1, x_4, x_5)$$

Geometrically, this is a transformation from the original sample space \mathbf{S}^4 to a new simplex \mathbf{S}^2 . An important property of compositional data, and one that overrules the “leave-one-out” manipulation, is that the ratio of any two components must be the same as the ratio of the corresponding two components in the full, original composition. Hence,

$$s_i/s_j = x_i/x_j \quad (2)$$

which is the attribute of “preserved ratio relationships”.

The concepts of covariance and correlation in simplex space:

1. The problem of negative bias. A correlation coefficient computed between two parts is not free to range over the interval $(-1, +1)$. Thus, in the case of two parts, say alleles A and B of the ABO relationship of serology, $\text{Corr}(x_1, x_2) = -1$ and the product-moment correlation is constrained to taking a specified value.
2. There is no relationship between the product-moment correlations of a subcomposition and those of the full composition. As the dimensionality of a subcomposition is decreased, so do the crude covariances/correlations fluctuate in sign, which is an outcome of the incoherency of the product-moment correlation coefficient in simplex space (Aitchison, 1997).
3. The concept of null correlation in reference to simplex space does not have the same meaning with respect to independence as is the case for full-space data. Futile attempts have been made in the past in geochemistry and analytical chemistry to define a zero correlation in simplex space.
4. The concept of perturbations within the simplex is another fundamental property of compositional data. A perturbation with the original composition \mathbf{x} is operated upon by the perturbing vector \mathbf{u} to form a perturbed composition $\mathbf{X} = \mathbf{u} \circ \mathbf{x}$. This is familiar to mathematical geneticists as the relationships of genotypes before and after selection (Edwards, 2000, Chapter 2).

The logical necessities of scale-invariance, subcompositional coherence, and perturbation as

fundamental operations in the simplex led Aitchison (1986, 1997) to adopt certain log-ratio forms of defining patterns of compositional variability. These are compatible with the *additive logistic normal class* of distributions on the simplex. One example is the set of final divisor log-ratios

$$y_i = \log(x_i/x_D) \quad (i = 1, \dots, D - 1) \quad (3)$$

Log-Ratio Covariance-Matrices

Three log-ratio covariance matrices are available for constrained multivariate analysis, the variation matrix, the log-ratio covariance matrix, and the centered log-ratio covariance matrix (Aitchison, 1986; Reyment and Savazzi, 1999). It is the latter variant that is employed in the present analysis. The centered log-ratio covariance matrix is defined as the symmetric treatment of all D parts of a vector of compositions achieved by the manipulation using the geometric mean of all D components as a divisor. For a D -part composition, the centered log-ratio covariance matrix of the D -dimensional random vector

$$\mathbf{Z} = \log \{ \mathbf{x}/g(\mathbf{x}) \}$$

where $g(\mathbf{x}) = (x_1, \dots, x_D)^{1/D}$ is the geometric mean of the parts, is

$$\Gamma = \text{cov}[\log(x_i/g(\mathbf{x})), \log(x_j/g(\mathbf{x}))] \quad (4)$$

This matrix is the one that is interpretationally most useful for many multivariate analogs of full-space statistics. It is easy to explain in that it is symmetric with respect to all parts. The drawback is that this matrix is singular and hence does not possess a “normal” inverse and, where relevant, requires a generalized matrix inverse.

Log-Contrast Principal Component Analysis and Principal Coordinate Analysis

For the purposes of the present exposition, the multivariate method chosen is the widely used one of principal component analysis (Aitchison, 1983; Aitchison, 1986, p. 190) well known from many spheres of quantitative biology. The covariance matrix used as input is that of Eq. 4, the centered log-contrast covariance matrix. A log-contrast of a D -part composition \mathbf{x} is defined as any log-linear combination $\mathbf{a}'\log \mathbf{x}$ with

$$a_1 + \dots + a_D = 0$$

The principal component analysis follows from the reduction of a centered log-ratio covariance matrix in the usual manner by finding the latent roots and vectors satisfying,

$$(\Gamma - \lambda_i \mathbf{I})\mathbf{a}_i = \mathbf{0} \quad (5)$$

Log-contrast principal coordinate analysis is interpretable as the Q-mode dual of log-contrast principal component analysis as expressed by Eq. 5. The computations were made using the program *prcrd.exe* given in Reyment and Savazzi (1999, p. 140).

THE STATISTICAL ANALYSIS

The first step in the analysis is a constrained principal coordinate analysis of the full data-set consisting of 40 observational time-points on which frequencies of 31 species were recorded. The plot of the first two constrained axes for the first set of 20 observational vectors shows that the points do not form a homogeneous cluster (Fig. 2). There are three distinct groupings.

1. Observations 1–8 form a group.
2. Observations 9–17 form a second group.
3. Observations 18–20 form a third group.

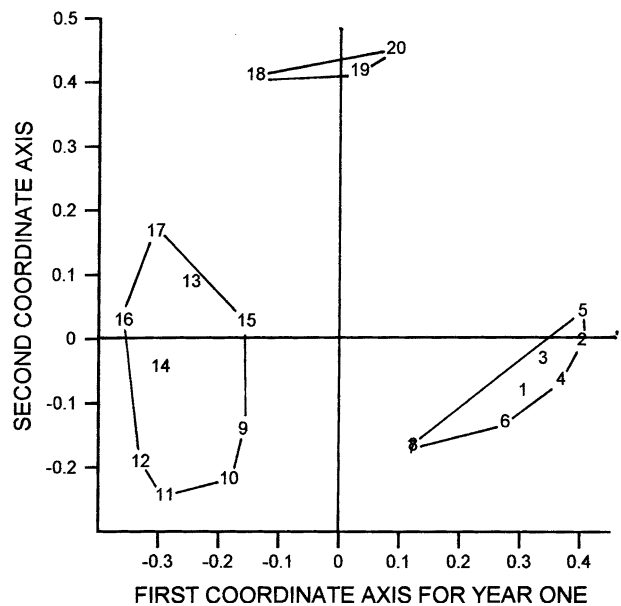


Figure 2. Plot of first and second constrained principal coordinate axes for Set 1.

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A significant detail arising from this graph is that the clusters are homogeneous in that constituents of each group are located sequentially in time. The three clusters are well separated from each other.

The plot of the first two constrained principal coordinate axes for the second set of 20 observational vectors (Fig. 3) differs from the first group (Fig. 2) in being less markedly differentiated. The three subdivisions obtained for the graph of the constrained principal coordinate axes for the first group occur again, with one time-point displaced (the ninth). The conclusion suggested here is that notwithstanding the difference in spread of the points in each of the three groupings for both years, there is evidence of an ecological factor (temperature?) that seems to be controlling the abundance of species.

Turning now to the constrained principal coordinates graph for the pooled samples ($N = 40$), the location of the points is fairly compatible (Fig. 4), such that the first eight, respectively, nine, samples fall in the right-hand quadrants (without overlap) and the second set of samples in the left-hand quadrants, with some overlap. The last three samples for both sets are located close to each other.

The second step in the analysis is to examine the time-sequence expressed by all samples as represented by the first coordinate axis where the

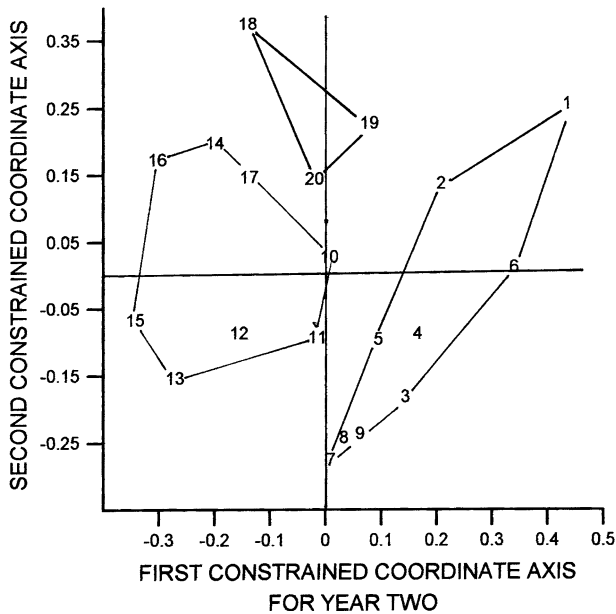


Figure 3. First and second constrained principal coordinate axes for Set 2.

elements of the first vector of coordinates are plotted against time. The graph (Fig. 5) for 2 years has an oscillatory shape without obvious outlying points, thus suggesting that there is a systematic pattern of fluctuations in frequencies such that it could seem logical to assume that the order was practically identical for both series.

Closer inspection shows, however, that the two sequences are not identical, notwithstanding that they do resemble each other. The following differences occur. The sinusoidal appearance of the curve for the first year (denoted "1") is more pronounced than for the curve for the second year (denoted "2"). For the first year, the initial gradient is a descent, whereas that for the second year is an ascent. After this initial divergence, the agreement in the curves begins to increase until, over the last third of the sequences, when the shapes agree more closely.

Contrasting Samples

An appropriate procedure for comparing and contrasting the two samples is that of constrained discriminant function analysis. The plot of the discriminant scores (Fig. 6) discloses that there is

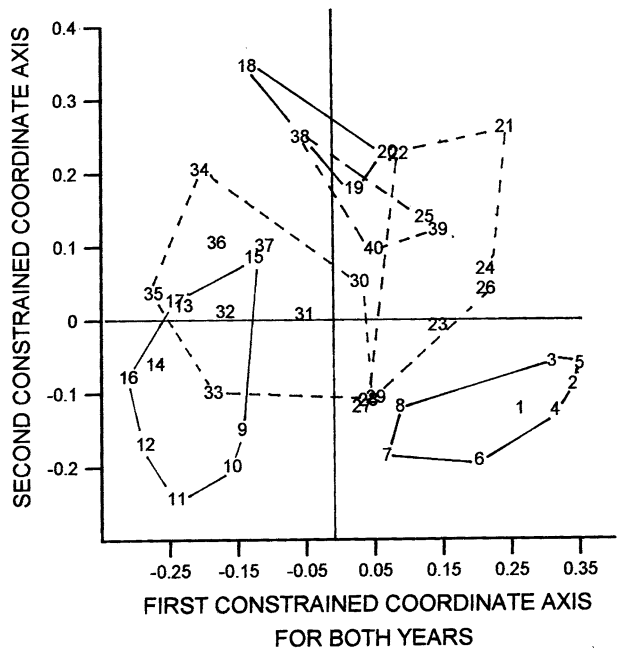


Figure 4. The first constrained principal coordinate plotted against time-points over two consecutive years. The convex hulls for the first set are shown by *complete lines*, those for the second set by *dashed lines*.

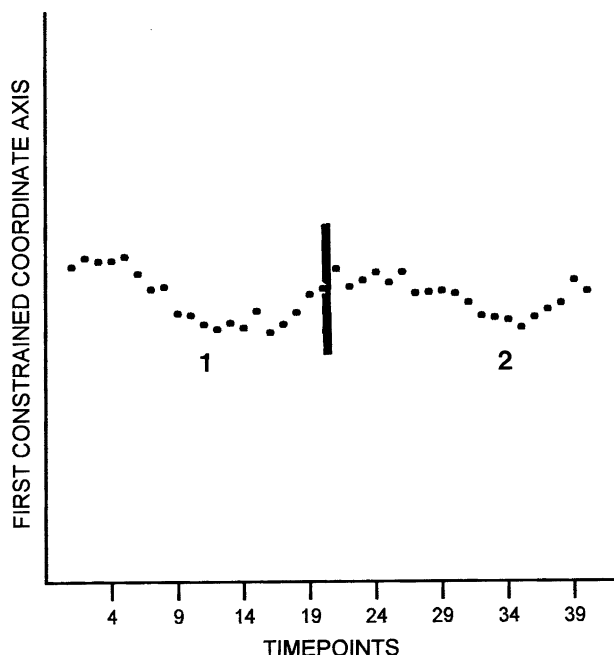


Figure 5. The first constrained principal coordinate score plotted against time-point for the first (denoted “1”) and second year (denoted “2”) ($N = 40$). The vertical bar marks the end the series for the first set and the beginning of the series for the second set.

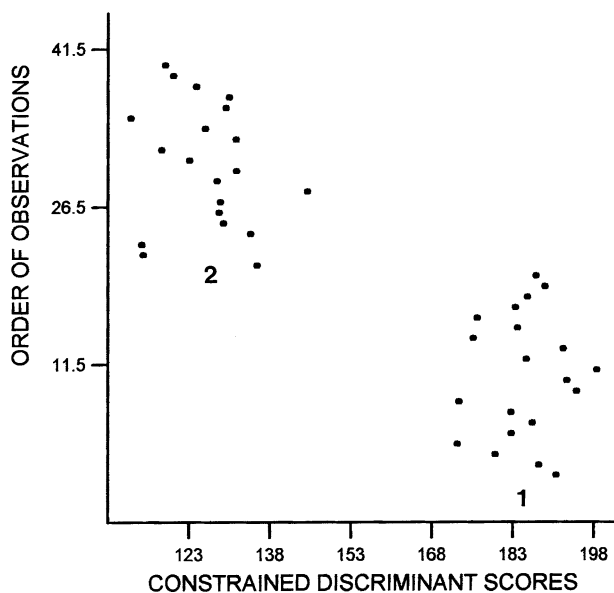


Figure 6. The constrained discriminant function scores for the two sets of observations (first year in right half (denoted “1”), second year in left half of the graph (denoted “2”).

complete separation between the two groups of observations. A check for misidentifications of observations showed that none of them classifies wrongly. The method of discriminant functions can

also be used to ascertain, approximately, which components are responsible for most of the separation by inspecting the standardized discriminant coefficients. Examination of the coefficients suggests that most of the separation between sets is due to species 2, 4, 10, 12, 13, 16, and 21, with less important support from species 1, 5, 8, 9, 23, 26, 27, and 28 (the key to these species is given in Table 3). A further implication of this result is that the species bringing about most of the separation are variably represented due, possibly, to environmental parameters, whereas those that do not vary markedly in frequency are not affected by such influences.

This result, if valid under repeated sampling, could be a significant feature in the study of the temporal distribution of radiolarians. Radiolarians are, as Foraminifera, marine protozoans. Considering the great importance of foraminifers in the petroleum industry, it would be worth expanding the range of our radiolarian study to the palaeoecology of that group.

CONCLUSIONS

The present brief study suggests that some species of radiolarians react differently from season to season, whereas others may be less affected by environmental conditions, as disclosed by the constrained discriminant function analysis of the data. Moreover, over the course of a particular season, constellations of species are formed which are expressed by heterogeneity in frequency patterns. An interesting outcome is that these patterns are consistent, as far as can be understood from the limited dataset available. There is evidence that an ecological factor such as temperature could be influencing the abundance of some of the species. The results presented here are to be regarded as preliminary.

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