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Detection and analysis of unusual events in long-term zooplankton and nekton data sets from North Inlet Estuary, South Carolina, U.S.A.

Zooplankton
Nekton
Estuary
Long-term
Disturbance

Zooplancton
Necton
Estuaire
Long terme
Perturbation

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ABSTRACT

Unusual events and disturbances are important sources of variability in ecological data sets, but methods for their detection and analysis are not readily available. We have adapted widely-used quality control methods to identify and quantify unusual events in ten-year-long data sets from the relatively pristine North Inlet Estuary, South Carolina, USA. Seasonal patterns and long-term trends were first removed from biweekly zooplankton and nekton abundance and corresponding water temperature and salinity data using nonparametric smoothing algorithms. The Shewhart Control Chart Method, a quantitative technique used for quality control in industrial manufacturing processes, was used to define four types of events according to intensity and duration. Deviations of data points from the precalculated mean were determined and, based on the Shewhart criteria, unusual events were identified. Events were uncommon for most of the 39 zooplankton and nekton variables tested. Timing and frequency of events were irregular within and among years. The coincidental occurrence of biological and physical events was rare; however, unusually high or low abundances of some taxa occurred during some extreme salinity and temperature events. In general, a high degree of independence among taxa was indicated. Results of the analyses provide new insights into the ecological significance of stochasticity in the dynamic estuarine ecosystem. The Shewhart Control Chart Method is a relatively simple and unique procedure for investigating atypical variation, and its application may be useful for understanding the role of unusual events in determining long-term change in both natural and altered ecosystems.

RÉSUMÉ

Détection et analyse d'événements exceptionnels dans les données relatives au zooplancton et au necton de l'estuaire nord de Caroline du Sud.

Les événements exceptionnels et les perturbations sont les principales causes de variabilité dans les séries de données écologiques, mais leur détection et leur analyse ne sont pas simples. Des méthodes de contrôle de qualité couramment utilisées ont été adaptées ici afin d'identifier et de quantifier des événements exceptionnels dans les séries de données acquises pendant une dizaine d'années dans l'estuaire relativement préservé du nord de la côte de Caroline du Sud (North Inlet Estuary) aux Etats-Unis d'Amérique. Des modèles saisonniers et des tendances à long terme ont d'abord été extraits des valeurs bimensuelles de l'abondance du zooplancton et du necton, ainsi que des données correspondantes de température et de salinité, en utilisant des algorithmes de lissage non paramétriques. Une technique quantitative en usage dans l'industrie pour les contrôles de qualité de fabrication, la méthode Shewhart, a été utilisée pour définir quatre types d'événements classés en intensité et en durée. Les écarts entre les données et la moyenne calculée ont été déterminés et les événements ont été identifiés à l'aide des critères de Shewhart. Pour la plupart des 39 variables de zooplancton et de necton analysées, les événements sont singuliers ; leurs dates et fréquences se répartissent irrégulièrement dans l'année et d'une année à l'autre. La coïncidence des événements biologiques et physiques est rare ; cependant, l'abondance exceptionnellement faible ou élevée de quelques taxa s'est produite dans des conditions extrêmes de salinité et de température. En général, un degré élevé d'indépendance entre les groupes est observé. Les résultats apportent de nouveaux éclairages sur la signification écologique de la stochasticité de l'écosystème dynamique estuarien. La méthode de Shewhart, relativement simple et unique pour analyser la variabilité atypique, peut être utile pour comprendre le rôle des événements exceptionnels dans l'évolution à long terme des écosytèmes naturels et perturbés.

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INTRODUCTION

Ecologists have long recognized that it is essential to measure physical, chemical and biological characteristics of ecosystems continuously for periods of decades or centuries before relationships among variables and sources of variability can be evaluated. Traditional analyses of long-term data sets usually involve multivariate statistical approaches which identify trends or periodicity based on typical variations in the data. These methods tend to de-emphasize atypical variation such as unusual events in time series (Weatherhead, 1986).

An unusual event in a data set can be identified as a time at which recorded measurements deviate significantly from the seasonal or annual pattern established for that variable. Events can have both spatial and temporal dimensions. In the analysis of time series data from a single location, two characteristics, intensity and duration, appear to be most important in describing an event. Any observation or sequence of observations falling outside of the typical pattern for a variable can be described according to how much and how long it falls outside. Natural events such as lightning strikes are high intensity – short duration events whereas droughts are low intensity – long duration events.

The role of unusual events or "disturbance" in the maintenance or change of ecological systems is a contentious subject in the literature. Although acceptance of the concept of "disturbance" is widespread, there appear to be nearly as many definitions of the term as there are investigators of such phenomena (Pickett and White, 1985; Rykiel, 1985; Karr, 1994). Some authors avoid the semantic difficulty altogether by using supposedly less ambiguous terms such as "stress" (Underwood, 1989). We do not believe that the use of subjectively defined terms or jargon has a place in the ecological literature and, thus, we have not attempted to define our term "unusual event" as anything more than improbably extreme values or series of values in long-term data sets. Jassby and Powell (1990) suggest that unusual events are among the most difficult, but most crucial, phenomena that ecologists must handle effectively. In biological systems, disturbances or unusual events are largely responsible for heterogeneity, and they may play a primary role in the evolution of species and community interactions (Karr, 1994). The timing, frequency, duration and intensity of events may be important in determining the direction and magnitude of long-term changes in ecosystem structure and function. In fact, all manner of ecological processes are influenced by extremes in natural events (Vernberg, 1993).

Certain fields of technology have long had the need to detect unusual events in data, and some have well-developed methodology for doing so (sensu Weatherhead, 1986). In particular, the detection of unusual observations or sequences of observations is vital to the maintenance of quality in the manufacturing and service industries. Unusual data in these settings usually signal a change in the process which, if left alone, would result in the degradation of quality. Early this century, Walter Shewhart proposed control charting methods for this purpose (e.g. Grant and Leavenworth, 1980). These methods continue to evolve (Roes and Does, 1995), and they are now almost universally used in manufacturing. Control chart methods can detect unusual observations based on both intensity and duration. This paper demonstrates our adaptation of the Shewhart Method to the detection of unusual events in long-term ecological data sets collected in North Inlet Estuary, South Carolina, USA.

The data were collected in a relatively pristine coastal ecosystem which is subject to changes on many spatial and temporal scales. Superimposed on regular annual, seasonal, lunar, and tidal cycles are floods, droughts, wind storms, and other weather events which influence ecosystem structure and processes (Vernberg, 1993). Our goal was to remove the subjectivity in defining unusual events and to provide quantitative flexibility in defining the type of event that we may want to detect in the time series. The Shewhart Method proved to be an appropriate and effective means to achieve this goal. In addition to demonstrating how we used the Shewhart Method to identify events of different intensities and durations, we offer examples of how event patterns for different variables can be used to understand relationships between those variables.

STUDY SITE AND METHODS

North Inlet Estuary (33° 20′N, 79° 20′W), located in South Carolina, USA, is a 2800 ha coastal wetlands system separated from the ocean by barrier islands. Semidiurnal tides (mean range about 1.4 m) occur within the network of shallow tidal creeks (Kjerfve *et al.*, 1982). On an average ebbing tide about 55 % of the system's volume flushes to the ocean through North Inlet (Dame *et al.*, 1986). The high tidal exchange rate and small surrounding watershed contribute to the maintenance of high salinity (>30) in the major waterways. Intertidal habitats are dominated by the salt marsh cordgrass, *Spartina alterniflora*, and by non-vegetated mudflats and oyster reefs. Water and habitat quality are outstanding and, thus, results of long-term studies can be interpreted without concern for the influence of human activities. More than one hundred papers describing seasonal and interannual variations in North Inlet ecosystem variables have been published. These include studies of the hydrology (Dame *et al.*, 1986), nutrients (Dame *et al.*, 1991; Blood and Vernberg, 1992), sediments (Wolaver *et al.*, 1988; Gardner *et al.*, 1989), primary producers (Morris and Haskin, 1990; Pinckney and Zingmark, 1993), benthos (Coull, 1986; Service and Feller, 1992), zooplankton (Allen and Barker, 1990; Feller *et al.*, 1992; Allen *et al.*, 1995), nekton (Allen *et al.*, 1992; Ogburn-Matthews and Allen, 1993), and birds (Bildstein *et al.*, 1990; Shepherd *et al.*, 1991).

For this paper, we used long-term measurements of physical and biological variables made at two sites within the estuary. One site was an intertidal creek (Oyster Landing) located near the forest border about 3 km from the ocean. Fishes, shrimps, and crabs were collected every two weeks from April 1984 through December 1990. Salinities measured with refractometers were accurate to one unit, and water temperature was measured with a hand-held thermometer accurate to 0.5 °C. Nekton were collected with a 15.2 x 1.2 m bag seine with 6 mm nylon mesh. Details of the method and sampling site at Oyster Landing are found in Allen *et al.* (1992). The single seine haul was made by pulling the net across a 1 m deep pool which was isolated in the intertidal creek bed at low tide. Abundances of selected species (Table 1) were used in the Shewhart analyses to identify unusual events during the 7-year period.

The second site was a subtidal creek (Town Creek) near the ocean inlet. Zooplankton collections were made about every two weeks from January 1981 through December 1990. Salinity and water temperature were measured using an induction salinometer from an anchored boat. Measurements were made about two hours before the midday low tide when the depth was about 3 m. On these dates, 153 μm mesh zooplankton collections were made using 30 cm diameter weighted closing nets which were opened near the bottom and fished for 1 min intervals each at the bottom, middepth, and surface. A General Oceanics Model 2040 flowmeter mounted inside the mouth of each net was used to estimate the volume of water filtered. Two nets were deployed simultaneously and samples were fixed in seawater-buffered formalin. All zooplankton larger than copepod nauplii were counted to determine the total 153 μm catch. Densities of major copepod species and other invertebrate larvae groups were also used in the analyses (Table 1). Immediately after the 153 μm collections were secured, the boat was used to tow an epibenthic sled with a one-half meter 365 μm mesh net.

The sled was designed to keep the bottom edge of the net within 5 cm of the sediment. Zooplankton larger than adult copepods (>1 mm) and small motile epifauna (<20 mm) were collected and fixed on board. In the laboratory, all animals (except copepods) within the 1-20 mm size range were counted to determine the total 365 μm catch. Data for the most abundant taxa were used in the Shewhart analysis.

A Shewhart control chart is a simple but effective set of graphically-oriented monitoring tools aimed at detecting atypical (improbable) variation in an evenly-spaced series of observations. It is meant to be carried out on "prewhitened" data, which in our setting means data have been corrected for seasonality and long-term trends in both mean and variance. The resulting data are called "residuals". Basic to the Shewhart methods are the concepts of common cause variability. These include typical, day-to-day variability in the measurements which cannot be removed and special cause variability ("events") which, in an assembly line application, might require remedial action. Extreme residuals or series of residuals are flagged if they would be improbable given the magnitude of common cause variability as measured by standard deviation. For instance, an atypical single observation is defined as a single point which lies more than three standard deviations from the mean. An atypical set of three observations is defined as a set in which two out of three observations lie more than two standard deviations above, or two standard deviations below, the mean. Thus, for an event of this description, duration is longer and intensity is lower.

Over the years, partly by logic and partly by tradition, many detection rules have been proposed for detecting different sorts of process deviations (DeVor *et al.*, 1992). We have selected four of these and modified them slightly, labeling them as event types A, B, C, and D:

Type A: one point at least 3 standard deviations above or below the mean

Type B: two out of three consecutive points, both of which are at least 2 standard deviations above or below the mean

Type C: four out of five consecutive points, which are at least 1.5 standard deviations above or below the mean

Type D: eight consecutive points, all of which are at least 0.2 standard deviations above or below the mean

Any such event could be either positive or negative relative to the overall mean. Threshold deviation levels of 2, 1.5, and 0.2 are our only modification to the analogous control chart rules. They have been chosen to insure a probability on the order of 1 in 400 of false positives, *i.e.* declaring common cause observations to be events. Specifically, the false positive rates for Types A, B, C, and D are 1:370, 1:323, 1:435, and 1:500, respectively. With these restrictions, analysis of time series with either 174 or 247 observations (the lengths of the nekton and zooplankton data sets, respectively) would be expected to yield only one or two false positives.

In order to use the Shewhart Method on the ecological time series from the North Inlet Estuary, seasonality and long-term trend in both mean and variance of the series had to be removed. For many of the taxa, abundance varied over several orders of magnitude. Thus, prewhitening began with a log transformation of the data, using the logarithm base 10 of the count data (abundance) plus 1. This transformation was absolutely essential if unusual lows in the series were to be detected. The nonparametric smoothing algorithm known as LOWESS (locally weighted scatterplot smoother; Cleveland, 1979) was then used to remove two kinds of cyclic variation in the mean and variance of the logged data. Leaving seasonal cyclic variation would have resulted in all "events" occurring during periods of minimum or maximum abundance. Similarly, cycles or events occurring on longer time scales than ten years were not events on our predetermined time scale. The algorithm used in removing these cycles and trends consisted of four steps:

1) The logged data were plotted versus Julian date and smoothed to remove seasonality in the mean. Specifically, all data from all years were plotted on the same graph versus day-of-year. In order to avoid December 31 - January 1 discontinuities, a copy of the November-December data was affixed to the beginning of this plot, and a copy of the January-February data to the end. This extended-year data was then smoothed using a LOWESS tension coefficient of 0.2.

2) Residuals from step 1 were replotted versus time and smoothed using a tension coefficient of 0.5 to remove gross trend.

3) Since residuals from step 2 often displayed seasonality in variance, the absolute values of these residuals were smoothed versus Julian date using a tension coefficient of 0.2. These residuals were obtained by dividing rather than subtracting smooth values.

4) Residuals from step 3 were replotted in absolute value versus time and smoothed as in step 2. A tension coefficient of 0.2 was used.

All analyses were perfomed using Systat 5.1TM (Wilkinson, 1989) on a Macintosh SE/30 computer. Tension choices were settled upon (as is usually the case with LOWESS) by trial and error, using judgment to decide when smooths were too noisy or too highly constrained. It is expected that the tension values used in other data sets would be different, especially if the sampling interval and/or series length differed from ours.

After these manipulations, the 4th stage residuals of most series were of approximately zero mean and constant variance. They were also approximately independent over time, with no substantial serial correlation (spatial variation dominated the remaining common cause variability). Though several of the residual series displayed non-normality, it was felt that the false positive rate, nominally set at the very low level of about 1 in 400, was still acceptably small. Even if one or more false events were detected, their numbers would be small compared to the many others identified. Since all major events that we detected by simple inspection of the data were identified in the Shewhart analyses, we are confident that our algorithms are appropriate. This confidence is further justified by the detection of simultaneous events for multiple taxa which corresponded to dates of major physical events. The greatest value of the Shewhart Method is in the detection of longer, low level events (Types B, C, and D) which could not be identified by our visual inspection of the data or by other statistical means.

RESULTS

The total number of positive and negative Type A, B, C, and D events for the 27 zooplankton and associated salinity and water temperature variables ranged from 0 to 16 over the 10-year period (Fig. 1). Various types of events were recorded on 232 of 247 dates, but on most dates only 1 to 4 events were detected. The highest number of events (16) occurred on a single winter date in 1983. Other sample dates during which the total number of events were high were spring 1982 (9) and winter 1984 (7). During a 3-month period in 1989-1990 (December through February), 5 to 9 events occurred during each biweekly sampling. Distributions of total events were not similar among seasons or among years. Periodicity in the occurrence of total events was not evident in the ten year time series (Fig. 1).

The patterns of occurrence of the eight individual event types (positive and negative A, B, C, D) for the same subset of zooplankton and physical variables also varied considerably over the ten year period (Fig. 2). More positive Type A's than negative Type A's were observed.

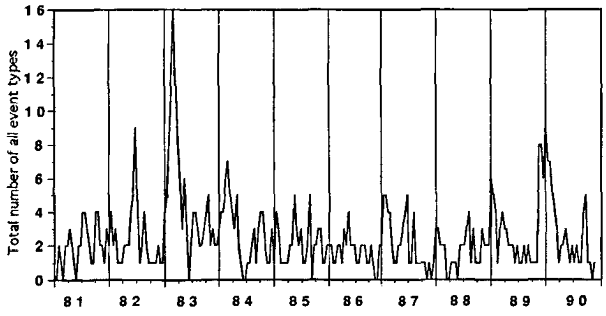

Figure 1

Total combined number of positive and negative Type A, B, C, and D events for the 27 zooplankton, salinity, and water temperature data sets collected on 247 dates from January 1981 through December 1990.

The distribution of Type B events was similar to that of Type A events. Type C events were rare among the 27 variables. Negative Type D events outnumbered positive Type D events. The distribution of each event type was generally irregular within and among years. Throughout the 247 date series, the number of variables for which events were recorded on the same date was consistently low. A maximum value of only four Type A positive events was recorded among the 27 variables measured on a single date in 1989 (Fig. 2).

The frequency with which the four types of events occurred varied considerably among the total array of zooplankton and nekton variables (Table 1). Events were identified in the time series of each of the variables, but for several categories of zooplankton and nekton, some types of events did not occur on any of the dates. Type A (single biweekly) events were detected for most physical and biological variables. The highest frequency (9 % of the dates) of Type A events was determined for the copepod *Eurytemora affinis* and the flounder *Paralichthys lethostigma*, both of which were relatively sporadic in their occurrences in collections (Table 1). For most variables, the frequency of occurrence for Type B events was similar to that of Type A. Less intense and longer duration events identified as Type C were the least frequently observed events. The highest occurrence of Type C events was 4 % and for most variables, Type C occurred on less than 1 % of all dates. Type D, the event type with the lowest intensity and longest duration (eight consecutive biweekly observations), was the most frequently identified of the four types for most variables. Maximum values of 30 % and 22 % were determined for *E. affinis* and *P. lethostigma*, the same taxa for which maximum numbers of Type A events occurred. However, the variations in the frequency of Type D events among variables was large with some taxa showing frequencies of zero or 1 event during the time series. Overall, events were uncommon; however, with a

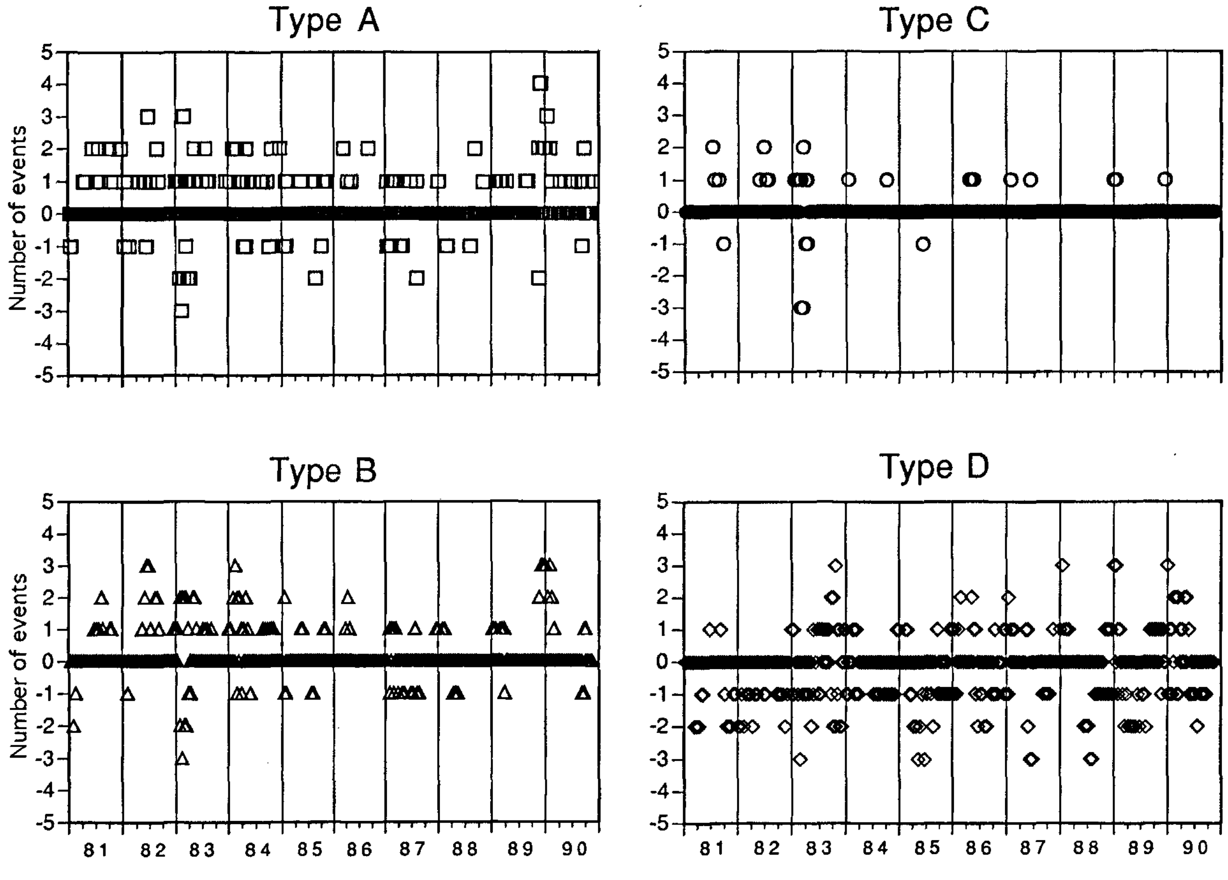

Figure 2

Distribution of positive and negative events for each of the four types (A, B, C, D). The number of events is based on the combined total for all 27 zooplankton, salinity, and water temperature variables collected on each of 247 dates.

Table 1

List of physical and biological variables used in Shewhart event analysis of long-term datasets from North Inlet Estuary, South Carolina, USA. Columns indicate the four types of events (A, B, C, D) and the values represent the percentage of all sampling dates on which such an event was identified. n and yr indicate the number of sampling dates and number of years the variable was measured.

Physical	*A*	*B*	*C*	*D*	*n*	*yr*
Salinity in subtidal creek	5	6	2	5	247	10
Salinity in intertidal creek	0	0	0	5	172	7
water temperature in subtidal creek	1	0	0	1	247	10
water temperature in intertidal creek	0	< 1	0	5	172	7
153 micron zooplankton						
Acartia tonsa	0	0	0	1	247	10
Parvocalanus crassirostris	1	1	1	1	247	10
Oithona colcarva	4	2	1	5	247	10
Eurytemora affinis	9	11	1	30	247	10
Centropages typicus	3	2	1	2	247	10
Barnacle nauplii	< 1	0	< 1	10	247	10
Crab zoeae	1	1	0	3	247	10
Bivalve larvae	2	2	0	0	247	10
Polychaete larvae	1	0	0	0	247	10
Total 153 micron catch	0	0	0	1	247	10
365 micron zooplankton						
Acetes americana	4	2	< 1	13	247	10
Lucifer faxoni	4	4	1	5	247	10
Penaeus postlarvae	4	4	1	7	247	10
Uca postlarvae	2	3	3	6	247	10
Alpheus larvae	2	2	< 1	0	247	10
Palaemonetes larvae	2	2	1	2	247	10
Sagitta spp.	2	1	0	1	247	10
Gobiosoma larvae	2	3	0	7	247	10
Leiostomus larvae	4	4	2	3	247	10
Mysid shrimps	2	4	0	2	247	10
Amphipods	< 1	2	0	7	247	10
Hydromedusae	3	2	1	1	247	10
Total 365 micron catch	1	2	0	2	247	10
Nekton						
Leiostomus xanthurus	2	2	1	0	172	7
Menidia menidia	1	1	0	3	172	7
Menidia beryllina	2	3	0	9	172	7
Eucinostomus argenteus	2	5	3	3	172	7
Bairdiella chysoura	4	< 1	0	0	172	7
Brevoortia spp.	2	< 1	1	2	172	7
Morone americana	2	8	4	14	172	7
Lagodon rhomboides	3	4	2	13	172	7
Paralichthys lethostigma	9	6	1	22	172	7
Fundulus heteroclitus	2	0	0	1	172	7
Fundulus majalis	< 1	2	0	2	172	7
Mugil curema	2	2	0	1	172	7
Mugil cephalus	1	0	0	0	172	7
Penaeus aztecus	0	1	0	1	172	7
Penaeus setiferus	0	2	0	6	172	7
Callinectes sapidus	2	1	0	1	172	7

predetermined error rate of about 1:400 (or less than one event expected by chance in a 247 date time series), some unusual deviations from the long-term mean occurred for almost every variable.

Only Type D events were identified in the 7-year record of salinity measured at the intertidal creek site (Fig. 3). Compared to the salinity pattern at the deep subtidal creek site (which was closer to the ocean), the intertidal site's salinity was lower, more variable, and more seasonal. Fluctuations from the long-term mean were often 10-15. Type A and B events did not occur at the intertidal creek. In contrast, salinity variations of 10-15 were more unusual at the subtidal site, and Type A and B events were more common than Type D events. On many dates, Type A and B events co-occurred on the same date, indicating that at least two consecutive large deviations (including the Type A value) occurred in a series. Some Type C events also overlapped with Type A and B events. At the characteristically high salinity subtidal site, all Type A, B, and C events were negative values which could be described as incidences of significant salinity depressions. The timing of Type D events differed at the two sites

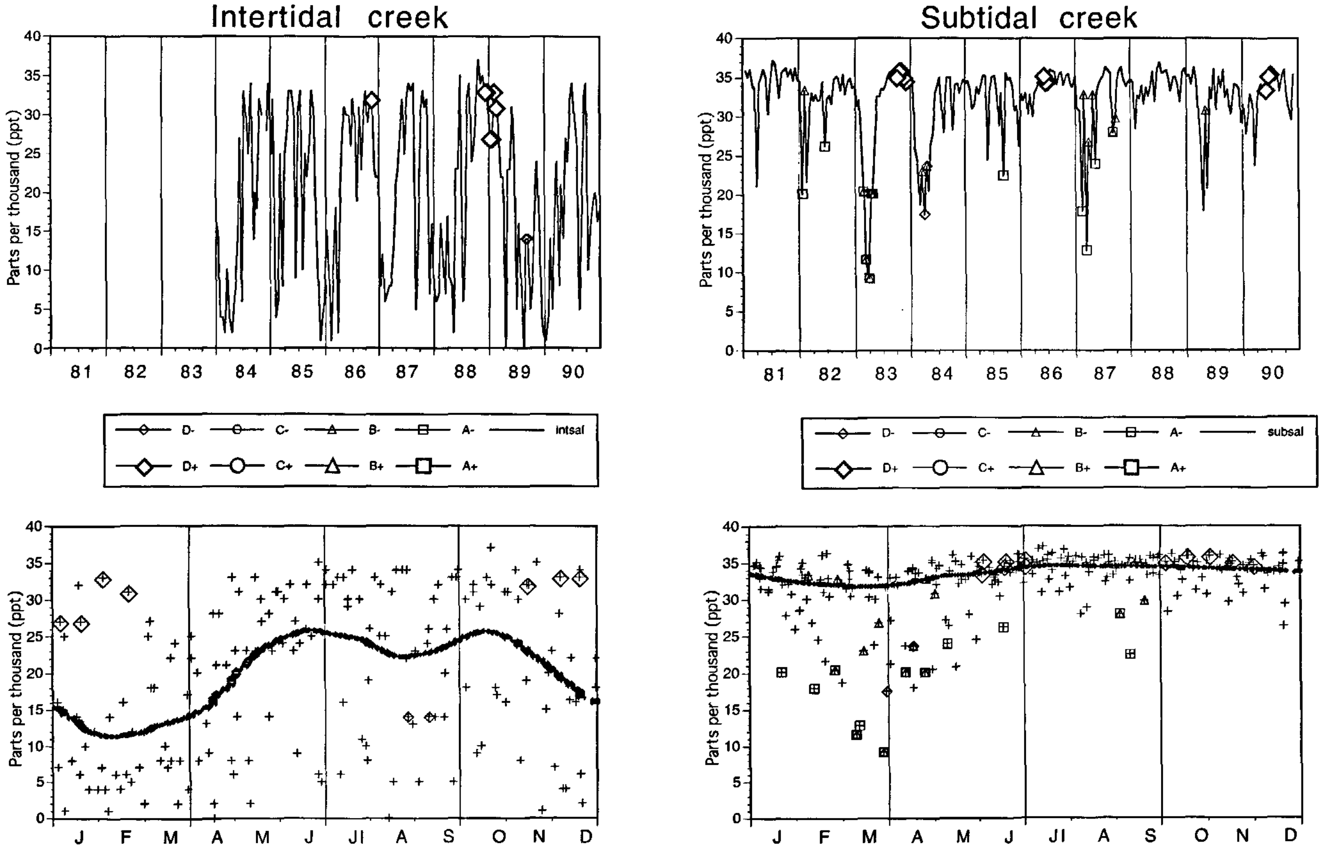

Figure 3

Occurrence of unusual salinity events at the intertidal and subtidal creek sampling sites. On the upper graphs, events (symbols) are shown on plots of the raw data (solid line). On the lower graphs, all biweekly data (crosses) and events (symbols) are plotted according to Julian day. A mean determined by a LOWESS smooth of all data indicates the seasonal pattern for the variable.

with long periods of higher salinity occurring during different times of the year. A comparison of the salinity event distributions shows no evidence of co-occurrence or coincidence of events at the two sites even though they were separated by only about 3 km.

Total 153 μm zooplankton abundance remained at high levels throughout the 10-year period, but a seasonal pattern was apparent with lower densities occurring during December through March (Fig. 4). The only events determined for the 153 μm zooplankton were two negative Type D events. The 365 μm zooplankton assemblage, was less abundant, but the seasonal pattern was similar to that of the smaller assemblage. Positive Type A and Type B events were observed during the winter period when abundances were typically low and in spring when densities approached the annual high. Positive Type D events were also detected during both periods with a period of unusually high densities occurring in June 1986 and February 1988 and 1990; unusually low densities of 365 μm zooplankton occurred in April 1989. Most events for the two size fractions of zooplankton did not correspond to events in the salinity or temperature records, but some could be explained by unusual physical events. For instance, the negative long duration (Type D) events identified for the 153 μm zooplankton during March-April 1983 (Fig. 4) corresponded to the longest period of depressed salinity in the subtidal creek during the 10- year period (Fig. 3). Although events for the 365 μm zooplankton were not observed during March-April (Fig. 4), several unusually high densities of animals occurred in May-June as salinities returned to typical levels (Fig. 4). A similar period of low salinity in March-April 1984 may be related to the positive Type A event observed during May of that year.

Considerable differences were observed in the frequencies and patterns of events for species of fishes which utilize the intertidal creek as nursery areas. Ladyfish, *Elops saurus*, occur each summer and, although numbers varied within and among years, no events occurred during the periods of maximum abundance (Fig. 5). However, on each of four falls during the period when young ladyfish leave the intertidal creeks, Type A and B events were detected. All events were positive indicating that, on some years, unusually high numbers remained in the estuary later than usual. Gag grouper, *Mycteroperca microlepis*, also occurred on most summers. During years of maximum abundance (1985 and 1986), multiple positive Type A and B events were recorded as unusually large catches were made. However, during some years (1988, 1989, 1990) no gag grouper occurred and consecutive Type D events were indicated. No events occurred outside of the period of maximum abundance. Neither abundance nor event records for the two species of fishes coincided even though both originated from ocean spawning areas and occupied the same intertidal habitat during the same period.

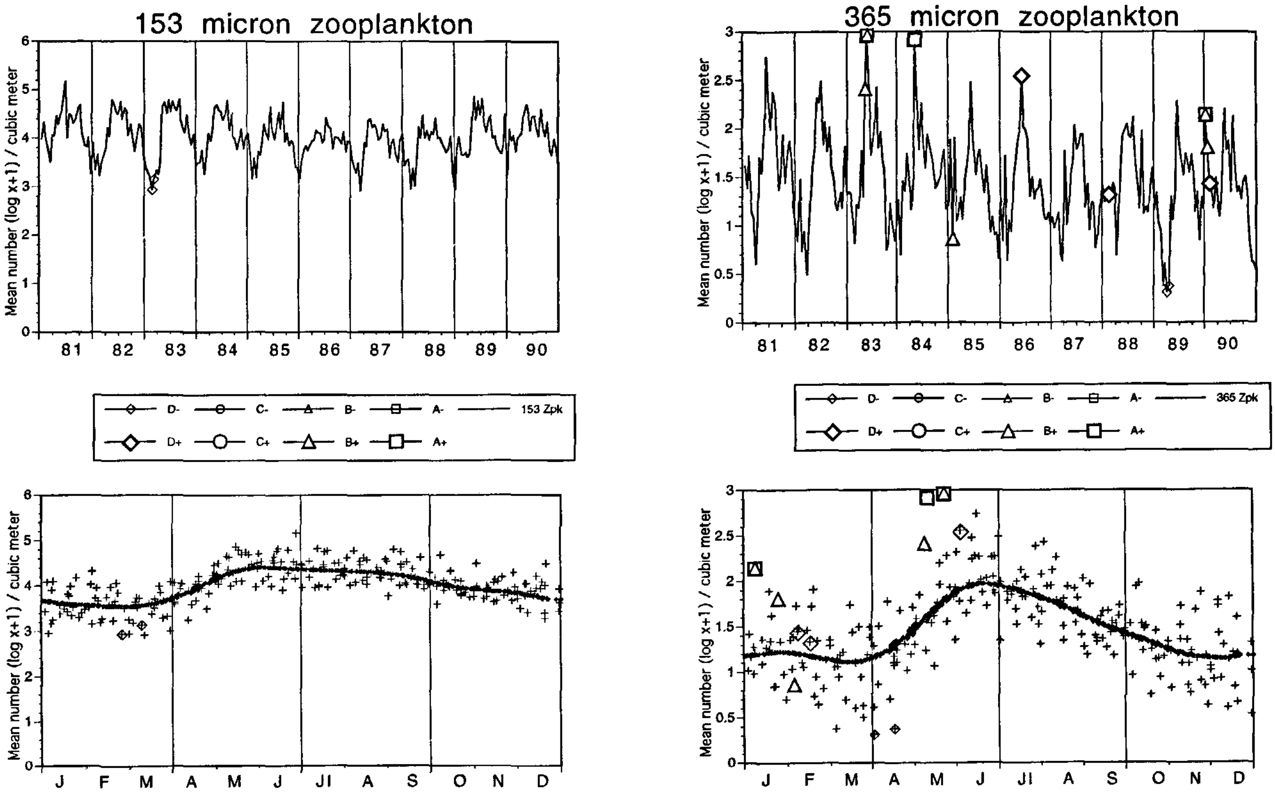

Figure 4

Occurrence of unusual events in the 153 µm and 365 µm zooplankton total catch data sets. Symbols and lines are the same as in Fig. 3.

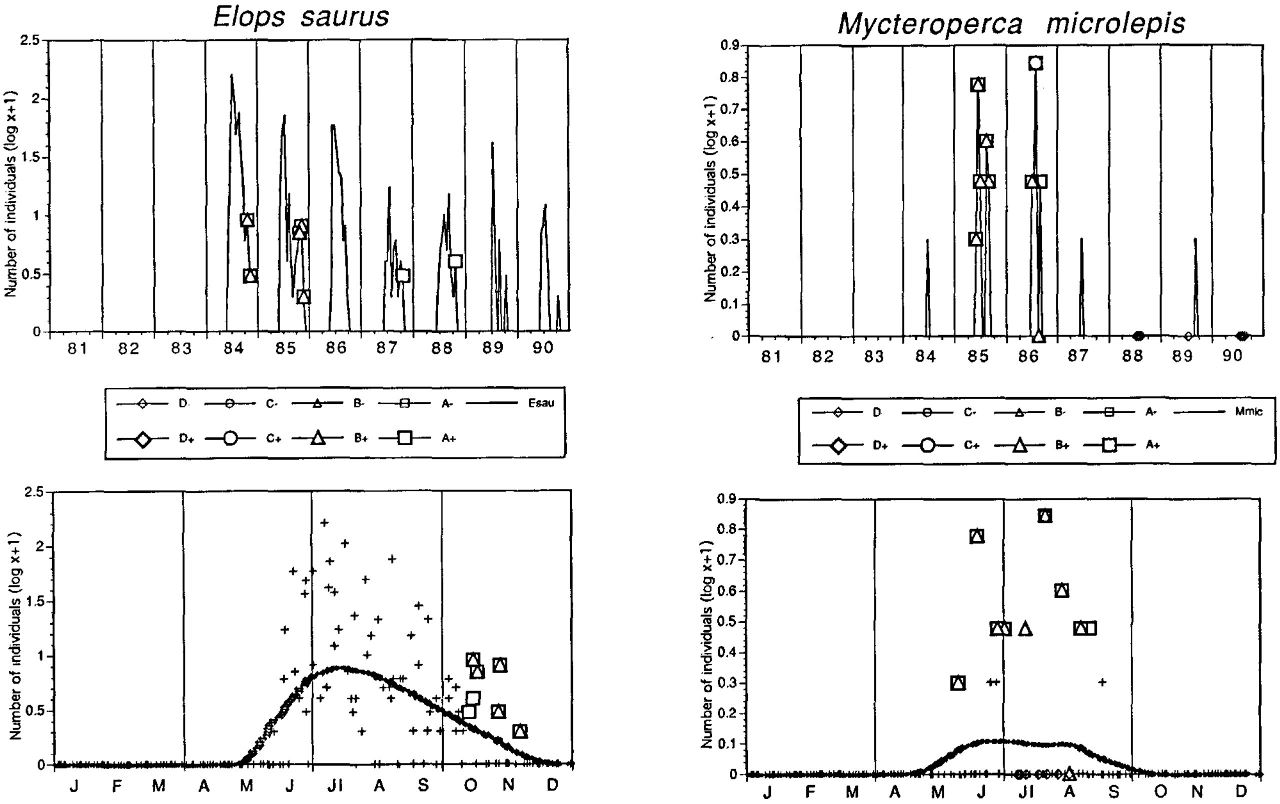

Figure 5

Occurrence of unusual events in the Elops saurus *(ladyfish) and* Mycteroperca microlepis *(gag grouper) data sets. Symbols and lines are the same as in Fig. 3. The occurrence of a positive B event on the x axis of the* M. microlepis *plot results from the selection of the second of the three consecutive data points when the event is plotted; in this case, a low value was flanked by two unusually high values.*

Relationships between this abundance and either salinity or temperature in the intertidal creek were not apparent.

DISCUSSION

The Shewhart Control Chart Method is a useful, objective, and quantitative tool for identifying unusual events in ecological data sets. With it, we were able to identify significant deviations from regular seasonal and annual patterns for a variety of physical and biological variables collected in a warm temperate estuary. Of particular importance was our ability to distinguish different types of events based on their intensity and duration. We are not aware of any other published accounts wherein the Shewhart Method has been adapted and used for this purpose.

The selection of criteria defining event types must take into consideration the temporal characteristics of the variables being measured. Shewhart used three standard deviations as the criterion for identifying a high intensity - short duration event. Plus or minus three sigma is a widely accepted definition of an outlier, a single data point which deviates from an overall mean by so much that natural variation is an improbable cause. We adapted it as a definition of a Type A event. An example of a Type A event in nature would be the peak release of invertebrate larvae during a lunar or weather event and their subsequent disappearance before the next sample is collected. Type A events can often be identified by simple visual inspection of data sets; however, events of lower intensity and longer duration are usually not easily recognized. The definitions of Type B and Type C events are somewhat more arbitrary, but they represent intermediate event types in terms of intensity and duration. A Type D event, defined as a series of eight consecutive points which deviate by at least 0.2 sigma, represents the extreme end of the low intensity - long duration scale. For a biweekly data set, eight consecutive points represent a four month period during which the values consistently vary by a small amount from the long-term mean. Since four months approximates the length of a relatively stable period of summer or winter conditions, the choice of eight consecutive points has ecological significance. For a species using the estuary as a nursery area for one or more seasons each year, one or a series of Type D events may indicate an unusually good or poor year class. Although extremely low or high densities of a taxon occurring over an extended period may be apparent to an investigator scanning a long time series plot, less extreme deviations would escape detection. Most Type D events were not recognized by visual inspection. We believe that the use of the Shewhart Method to detect events is a novel and logical approach to investigating the role of unusal events in ecological systems.

Interpretation of the ecological significance or physical meaning of an event within a time series requires a basic understanding of the natural variability associated with the variable. For instance, in comparing the salinity records for the intertidal and subtidal creeks, we could attribute differences in the number and types of events to differences in the dynamics of the salinity regimes in the two habitats. The influence of freshwater runoff in the intertidal creek was greater than in the deep channel near the source of ocean water. The existence of large variations in salinity between biweekly measurements at the intertidal creek throughout the year made the detection of unusual short-term events unlikely. Since large deviations from the usually high salinity conditions in the subtidal creek were much less frequent, events were more easily detected. The timing and frequency of events of low intensity and long duration also differed between sites. General differences in salinity patterns at the two sites could be recognized from simple plots of the raw data; however, results of the Shewhart analysis provided us with more specific information about how intense those differences were and how long they persisted. A comparison of salinity event patterns at the two locations during the same multi-year period indicated that the events did not occur at both locations at the same time. Information generated by the Shewhart analysis suggested that factors controlling short-term variations in salinity at the two sites were operating independently. Simple visual comparisons of the raw data plots could not provide the quantitative information necessary to support this conclusion.

Although the occurrence of an event in a time series signifies a statistically determined deviation from typical conditions, it does not necessarily indicate that an event has ecological significance. Artificially high or low values in long-term data sets can result from problems in sample collection or laboratory analysis. However, with confidence that such problems (by sampling or algorithm design) are rare, an investigator may search for an explanation for each event identified by the Shewhart Method. Establishing relationships among variables provides insights into mechanisms of long-term change. Quantitative methods can be developed to explore relationships between the event analysis output from multiple variables, but, at this stage, we are only able to conduct qualitative comparisons based on the coincidence of events on a common time line. For instance, we identified events in both the 153 μm and 365 μm zooplankton total catch data sets which corresponded with the major low salinity period during winter-spring 1983. Events were determined for most common taxa during what appeared to be the single greatest deviation from the typical salinity regime during the 10-year period. Similar correspondences were observed between an unusual winter freeze and the abundance of many taxa at the intertidal and subtidal creek sites. Qualitative assessments of the coincidental occurrence of other physical and biological events suggested potential cause and effect relationships. However, the majority of events for organisms, regardless of type, could not be explained by a corresponding change in any of the physical variables measured at the same time. This result was not surprising given that simultaneous biweekly measurements of variables provide only a snapshot in a dynamic and continuously interacting set of those and many other variables. Comparisons in which one of the variables is lagged by one or more dates may be appropriate for some pairs of variables, but the chance that consistent relationships exist among most variables seems unlikely. The general lack of coincidence in the timing of events may suggest that the Shewhart Method identifies many false positives, but it seems more likely that the occurrence of so many unexplained events reconfirms the complexity of ecosystem structure and function. Of course, some of the events that we detected may have no ecological significance.

We were surprised by the lack of repeatable patterns or periodicity in the occurrence of unusual events in the biological data sets. The temporal distribution of events for most variables was irregular and clustered. Irregularity during the time series may indicate that the prewhitening process was successful in removing the seasonal components characteristic of most variables. Patchiness partially resulted from the inherent overlap of criteria in the hierarchy of event types. Often a Type A event was identified for a point which was one of two or more points with large deviations within a short period. In these instances, combinations of Type A, B, and even C events sometimes occurred at about the same time. Type D events rarely occurred at the same time as shorter intense events, but multiple Type D events often occurred sequentially. Consecutive Type D events occurred when, rather than eight points in a row, nine or more points in a row deviated from the overall mean by 0.2 sigma. Regardless of these demonstrated relationships among events, regular or recurrent patterns of distribution during the 7- or 10-year time series were not observed for any variable.

The Shewhart Control Chart Method has allowed us to quantify what has been, up to now, only an intuitive determination of the timing and coincidence of events within this dynamic and complex estuarine ecosystem. Although we have long considered stochasticity to be a primary characterisitic of the ecosystem variables that we have measured, the Shewhart Method has enabled us to characterize it quantitatively. For instance, by quantifying deviations in the long-term record, we demonstrated that events did not occur every year, nor did they occur at the same time of year. These observations suggest that the same factor or combination of factors are probably not responsible for generating most events during a time series. These observations also suggest that events may not occur every time the same set of conditions that caused an event previously occurred again.

At the current stage of its development, the Shewhart Control Chart Method only provides information on the occurrence of unusual events along a time line. The analysis generates quantitative data, but we have not yet developed quantitative techniques for merging output for multiple variables. Although qualitative assessments of distributions of events have revealed a new understanding of the temporal dynamics of individual variables and relationships among some physical and biological variables, we have not exhausted the usefulness of the Shewhart results in understanding how well-defined unusual events contribute to long-term changes. One of the challenges will be relating events of long duration in one variable to multiple intense events in other variables. Adaptation of the Shewhart Method may also be useful for detecting changes in the spatial domain. As ecologists move from investigating ecological phenomena at small and short-term temporal scales to ever larger landscapes (Rykiel *et al.*, 1988), the ability to unambiguously detect change will be invaluable. The Shewhart Method effectively eliminates the ambiguity generally associated with the definition of an unusual event.

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