DEMONSTRATION OF THE SEASONAL KENDALL TEST FOR WATER QUALITY TREND ANALYSIS ALONG THE MAIN STEM OF THE CHESAPEAKE BAY

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September 1988

ICPRB Report 88-6

Interstate Commission on the Potomac River Basin
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INTERSTATE COMMISSION ON THE POTOMAC RIVER BASIN

This publication has been prepared by the Interstate Commission on the Potomac River Basin. Funds for this publication are provided by the United States Government, the U.S. Environmental Protection Agency, and the signatory bodies to the Interstate Commission on the Potomac River Basin: Maryland, Pennsylvania, Virginia, West Virginia, and the District of Columbia. The opinions expressed are those of the authors and should not be construed as representing the opinions or policies of the United States or any of its agencies, the several states, or the Commissioners of the Interstate Commission on the Potomac River Basin.

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INTRODUCTION

Many factors complicate the analysis of water quality time series data. These factors include the non-normal distribution of data, seasonality, missing records within the data set and data values reported as below the limit of detection. While linear regression is a powerful and common statistical tool for detecting trend, the problems with water quality data render the technique less effective. To overcome these difficulties a nonparametric test statistic known as the Seasonal Kendall Tau was developed (Hirsch et al. 1982). The Seasonal Kendall test is employed in place of more common tests based on linear regression and other parametric techniques. In this report, a trend analysis, using the Seasonal Kendall test, is performed on five water quality parameters along seven segments of the Chesapeake Bay. The parameters analyzed are: Dissolved Oxygen, Percent Oxygen Saturation, Salinity, Water Temperature, and Chlorophyll-a.

SEASONAL KENDALL TEST FOR TREND

The Kendall Tau is a statistic that can be readily used to test for trends in water quality time series. Values below the limit of detection (LD data), seasonality, and missing data can be handled without difficulty. The Kendall Tau statistic for each season (say all winters in the period of record) is calculated as the sum of integer scores (-1,0,1) representing the relative magnitude of each observation compared to all later observations. Since only the relative magnitude of observations is used to calculate the value of the Kendall Tau statistic, LD observations are handled easily: all LD's are equal to each other and are less than all measured observations. If multiple observations within a season exist, the median is used. The nonparametric test does not assume any underlying distribution in the data, so observations that deviate significantly from the normal distribution pose no problem. When gaps in the record exist, parametric techniques can implicitly over weight outliers or isolated observations. The Kendall Tau statistic uses only relative position in time and relative magnitude, estimating the variance using the number of observations and ties alone. For this reason the nonparametric test is insensitive to gaps in the record (a common feature in real water quality time series).

Using the Seasonal Kendall test eliminates the problem of seasonality since each season is considered separately. Similarly, differences in the number of observations per season do not present difficulties in calculating the significance of the trend. In order to assess the trend for the entire period of record (all seasons collectively) the Kendall Tau statistics for each season are combined into a Seasonal Kendall Tau. Under the null hypothesis of no trend, the Kendall Tau statistic for each month can be viewed as a zero mean normal random variable (regardless of the distribution of the raw data). The sum of the Kendall Tau statistics for each month will also be a zero mean normal random variable. The variance of this normal variable, under the assumption of independence, will equal the sum of the individual monthly variances.

The Seasonal Kendall Tau is calculated as the sum of the monthly Kendall Tau statistics divided by the square root of its variance estimator (the sum of the variance estimators for each month). Since the Kendall Tau statistic approaches the standard normal distribution for the sample sizes that were examined in this report, the value of the statistic can be compared to standard normal probability levels in order to evaluate the significance of the trend. All test statistics with absolute values greater than 1.645 have trends that are significant to at least the .05 level. This indicates a probability greater than 95% that a significant trend exists. Similarly test statistics with absolute values greater than 2.576 are significant to at least the .005 level, denoting 99.5% or greater probability of trend. Absolute values of the test statistic less than 1.645 indicate no significant trend.

As a summary statistic to describe the rate of change of the value of a parameter in a segment over time, the Seasonal Kendall slope was proposed (Hirsch et al. 1982). The estimated slope is simply the median of the slopes (gradients) between observations. By using the median instead of the mean, the results are again buffered from the effects of outliers and extreme points.

Monte Carlo simulations, comparing the Seasonal Kendall test to linear regression (Hirsch et al. 1982), show that the Seasonal Kendall test is robust against seasonal behavior, departures from normality, and censoring of the data (LD). Although a linear regression-based test is more powerful than the Seasonal Kendall Tau if the data are normally distributed and nonseasonal, this is seldom the case with water quality data. The Seasonal Kendall test also more accurately reflects the significance of the trend results if a situation of missing or unevenly spaced data exists (Hirsch and Slack 1984). This is the advantage of using a nonparametric test, which does not have the underlying assumption of evenly spaced data inherent in linear regression.

DATA AND PROCEDURE

ICPRB performed a statistical analysis of Chesapeake Bay monitoring data using the Seasonal Kendall test for trend. The data set received from the Chesapeake Bay Liaison Office, U.S. EPA (CBLO), consisted of thousands of observations of five parameters measured over the period 1964-1987: Dissolved Oxygen (DO), Percent Oxygen Saturation, Salinity, Water Temperature, and Chlorophyll-a. There was no data for the period November 1980 - May 1984. The data were classified geographically by station number and segment name. There were 174 stations within a total of seven segments. The data were also characterized by the layer at which the sample was taken, either close to the surface or near the bottom. In the bulk of the Seasonal Kendall analysis the data were grouped by segment, not station. The segments analyzed are depicted in Fig. 1 (CB1-CB7). This aggregation helped alleviate problems of sparse data. Additionally, the number of segment/parameter pairs (70) is easier to work with than the number of station/parameter pairs (1740) (A pair is defined for each parameter both on the surface and bottom layer for each segment or station -- 7*5*2=70 and 174*5*2=1740). In the effort of completeness the Seasonal Kendall test was performed on the 1740 station/parameter pairs. These results were sparse and are available upon request.

The Seasonal Kendall test can be calculated for an arbitrary number of seasons within a year. Defining each season as consisting of one month was done and the results were once again sparse. Therefore four seasons, as defined by the CBLO, were used. Since there were often multiple measurements in a season for a particular layer (surface or bottom) and specific segment, the median of the observations was used. The use of a median value severely diminished the number of observations upon which the Seasonal Kendall test based its results. The number of observations decreased from up to 2500 per segment/parameter pair to approximately 65.

COMPARISONS OF TREND TEST RESULTS

The Seasonal Kendall test using four seasons revealed ten segment/parameter pairs with significant trends. They are listed in Table 1 and plotted in Appendix A. [Note: While the methodology employed in the Seasonal Kendall test makes use of only one (the median) observation per season, all recorded data are shown in the plots.] The Seasonal Kendall tau statistic, denoted by Zvalue, and the estimated slope are displayed in the same table.

As a comparison, linear regression was performed on the same segment/parameter pair in two ways. First all the data for the pair was used, and a linear regression line fit through the data was done. In the second case, a linear regression line was calculated using only the median observation for each season. This second case is performed because it represents a linear regression on the exact same data as was used in the Seasonal Kendall test. The results are displayed in Table 1 and 2 along with the Seasonal Kendall test results under the heading LR w/days, and LR w/med/seas. The slope is displayed as is the F-statistic and the number of observations on which the regression was performed. The F-statistic is roughly equivalent to the seasonal Kendall test statistic, with higher values indicating a more highly significant trend. For our sample sizes an F-statistic >~8.0 indicates a significance level of at least .005. Although it is dependent on the sample size, an F-statistic >~4.0 indicates a significance level of at least .05 for our samples. The relationship between the F-statistic and the number of observations is interesting to note.

Also included in the tables are the ten segment/parameter pairs with the most significant trends as determined by both of the linear regressions described above. Three segment/parameter pairs were common to both the Seasonal Kendall Tau most significant trend list, and the list compiled using linear regression with days (Table 1). A much higher number of pairs, seven, were common to the top ten list of Seasonal Kendall and linear regression with seasonal medians. The values of the slopes varied as can be seen in Table 2.

Ten out of seventy pairs have significant slopes according to the Seasonal Kendall test. Forty-five of seventy have significant slopes according to linear regression with days and only four pairs have significant slopes according to linear regression using only the seasonal medians. This difference is marked and highlights the problems of using linear regression. The appearance of only two common segment parameter pairs between the two linear regression techniques, further demonstrates the inconsistencies of using linear regression on non-normal data erratically distributed in time. These results also indicate that the different outcomes between the Seasonal Kendall test and linear regression are not due as much to the different procedures as to the different amounts of data used.

An important distinction between the linear regression and the Seasonal Kendall test method is the amount of data used to assess trend. The Seasonal Kendall test uses only one observation per season where the linear regression uses all the data. The difference is substantial: at most seventy observations versus approximately two and a half thousand. The number of observations plays a large role in assessing the significance of a trend. When using all data in a linear regression, highly significant trends were found for upwards of fifty percent of our segment/parameter pairs.

In analyzing the results of the linear regression, one notes the heavy influence given to the last few years of record due to the preponderance of observations. As was noted earlier, linear regression is based on a number of underlying assumptions, one of which is evenly spaced data. The heavy emphasis given to the last few years of record reaffirms this point. The Seasonal Kendall test does not rest on these assumptions, thus partially explaining the differing results.

SPECIFIC SEGMENT/PARAMETER PAIRS

Segment CB4

The segment/parameter pair with the most significant trend as determined by linear regression over all data values is surface salinity measurements in segment CB4. The F-statistic indicates that there is less than one chance in a million that this pair does not have a trend. The Seasonal Kendall slope for this pair, however, equals zero, showing absolutely no evidence of trend. The F-statistic for a linear regression of the seasonal medians is very low, in close accord with the results of the Seasonal Kendall test.

Segment CB5

For illustrative purposes, a casual look a scatter plot of the segment CB5, for Salinity in the bottom layer, (first plot of Appendix B) is uninformative. However, if a trend analysis is done for the period before 1981 and then for the later monitoring period, 1984-1987, a significant decreasing trend is seen in the first time period. This early trend is highly significant according to both linear regression tests and the Seasonal Kendall test. In the later monitoring period no significant trend was present according to the Seasonal Kendall test or a linear regression of the seasonal medians. This time period showed a highly significant increasing trend according to linear regression using all the data. The accompanying graph (second plot of Appendix B) show regression lines for both monitoring periods and for the entire record.

In studying these results, it is observed that a linear regression over the entire data set is heavily influenced by the last few years of the record because of the bulk of observations during that time. While this overall trend may be of interest, the summary statistic of trend for the entire record is misleading. While there is strong evidence of decreasing trend during the first seventeen years of record, there are mixed predictions for the last four years of record.

Caution must also be taken in looking at the linear regression results because of the seasonality that is in clear evidence. The 1984-1987 data record begins in June 1984 and ends in September 1987. When using linear regression, missing observations or unevenly spaced data, may render the results inaccurate. If salinity is typically low in the winter but there are relatively more observations in other seasons, then the trend will be deceivingly high. Similarly, an abundance of measurements during low salinity periods will give a deceivingly low trend. The Seasonal Kendall test does not have these limitations.

SUMMARY AND CONCLUSIONS

While the emphasis of this report is on a demonstration and comparison of the Seasonal Kendall methodology, it is appropriate to draw some conclusions based on the test results. Seven of the ten significant trends were decreasing trends; two decreasing dissolved oxygen trends, one decreasing Chlorophyll-a trend, three decreasing salinity trends, and one decreasing trend for percent saturated oxygen. There were two decreasing trends in water temperature, and one decreasing trend in Chlorophyll-a.

Perhaps more interesting is the spatial distribution of significant trends. Fully half of the significant trends were found in segment CB1/CB2 (two segments that were combined in this data set). All of these trends are decreasing trends; in dissolved oxygen, in salinity, in percent of oxygen saturation and in Chlorophyll-a. In addition there were no significant trends found in CB6, CB7, or the MOUTH segments of the Bay. These results indicate changing water quality in the upper portions of the Bay, while the lower Bay's water quality does not exhibit a trend with time.

A NOTE OF CAUTION

For interpretation of the Seasonal Kendall test trend results, there are several important points that should be emphasized. Significance is a statistical term that refers to how certain one can be that the data show a trend, that is, a progressive change in values over time. The term does not refer to how rapidly a parameter value is changing. For example, a data set may have a significant Kendall tau statistic when there is a consistent progressive increase (or decrease) in values over time even if the magnitude of change is very small. In addition, the term significance does not relate to whether a parameter is above water quality standards. A parameter may be exhibiting a trend in values even though the values are well within standards.

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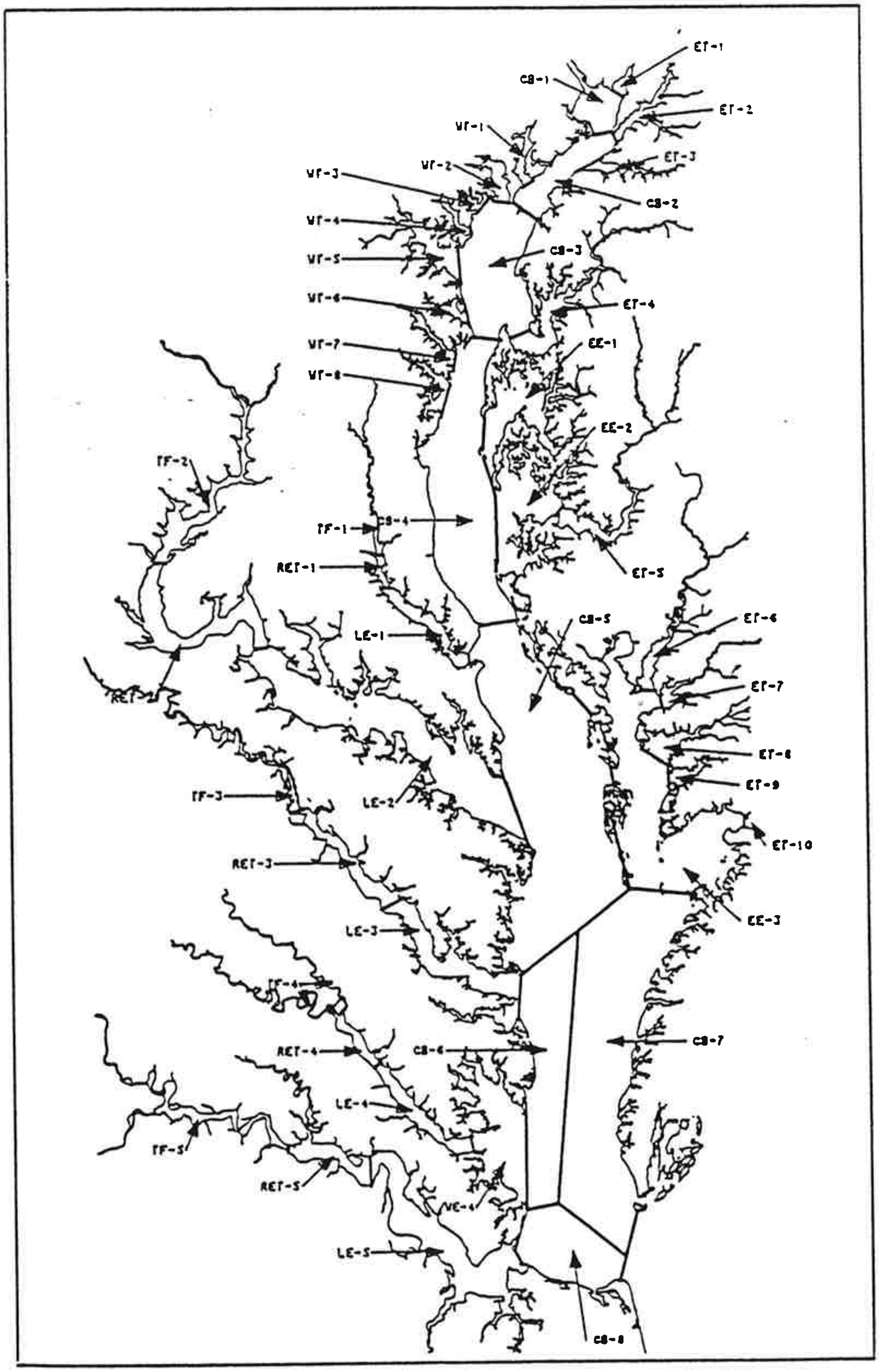


Figure 1. Chesapeake Bay Segments

Table 1.

			Ten Most Significant Trends as Determined by		
Segment	param/layer		Ktau	LR med/seas	LR daily
CB12	DO	BOT	+	+	+
CB12	%OxSat	BOT	+	+	
CB12	Salin	SUR	+	+	+
CB12	Salin	BOT	+	+	
CB12	Chla	SUR		+	
CB12	Chla	BOT	+	+	
CB3	DO	SUR	+		
CB3	Chla	BOT	+	+	
CB4	DO	SUR			+
CB4	%OxSat	SUR			+
CB4	Salin	SUR			+
CB4	Salin	BOT	+	+	
CB4	WtrTmp	BOT	+		+
CB5	%OxSat	SUR			+
CB5	Salin	SUR			+
CB5	Salin	BOT			+
CB5	WtrTmp	BOT	+		
CB6	Salin	SUR		+	
CB7	%OxSat	SUR			+
MOUTH	Chla	BOT		+	

Table 2

COMPARISON OF SEASONAL KENDALL TAU WITH LINEAR REGRESSION MEASURES

The ten trends significant to the .05 level as determined by the Seasonal Kendall test.

	Ktau w/seas		LR w/days			LR w/med/seas		
Segment/param/layer	Slope	Zvalue	Slope	F(1,n-2)	n	Slope	F(1,n-2)	n
CB12 DO BOT	-.06	-2.34	-.07	24.32	552	-.06	2.30	56
CB12 %OxSat BOT	-.47	-2.80	-.36	18.31	536	-.44	5.90	56
CB12 Salin SUR	-.03	-4.48	-.05	25.64	917	-.06	7.05	57
CB12 Salin BOT	-.05	-3.24	-.07	13.68	577	-.08	6.20	56
CB12 Chla BOT	-.38	-2.45	-.23	16.77	332	-.21	2.67	32
CB3 DO SUR	-.04	-1.98	+.01	1.05	1593	+.04	1.16	60
CB3 Chla BOT	+.20	+1.86	+.32	20.24	644	+.25	3.38	40
CB4 Salin BOT	-.13	-3.20	-.02	2.12	1461	-.11	6.18	67
CB4 WtrTmp BOT	+.08	+2.00	+.20	32.11	1460	+.16	1.50	67
CB5 WtrTmp BOT	+.10	+2.04	+.18	16.73	899	+.18	1.84	66

The ten most significant trends as determined using linear regression over the entire data set with daily observations.

	LR w/days			Ktau w/seas		LR w/med/seas		
Segment/param/layer	Slope	F(1,n-2)	n	Slope	ZValue	Slope	F(1,n-2)	n
CB12 DO BOT	-.07	24.32	552	-.06	-2.34	-.06	2.30	56
CB12 Salin SUR	-.05	25.69	917	-.03	-4.48	-.06	7.05	57
CB4 DO SUR	+.04	34.36	2385	-.01	-0.19	0.00	0.00	66
CB4 %OxSat SUR	+.38	68.58	2360	-.01	-0.09	+.01	0.00	66
CB4 Salin SUR	+.11	149.09	2490	0.00	00.00	+.02	0.13	71
CB4 WtrTmp BOT	+.18	32.11	1460	+.08	+2.00	+.16	1.50	67
CB5 %OxSat SUR	+.46	58.31	1394	-.10	-0.28	-.15	0.23	63
CB5 Salin SUR	+.06	26.66	1513	-.07	-1.18	-.01	0.05	68
CB5 Salin BOT	+.09	34.52	894	-.04	-0.80	-.01	0.43	66
CB7 %OxSat SUR	+.43	48.30	353	+.22	+1.22	+.20	1.18	51

The ten most significant trends as determined by linear regression of the seasonal medians

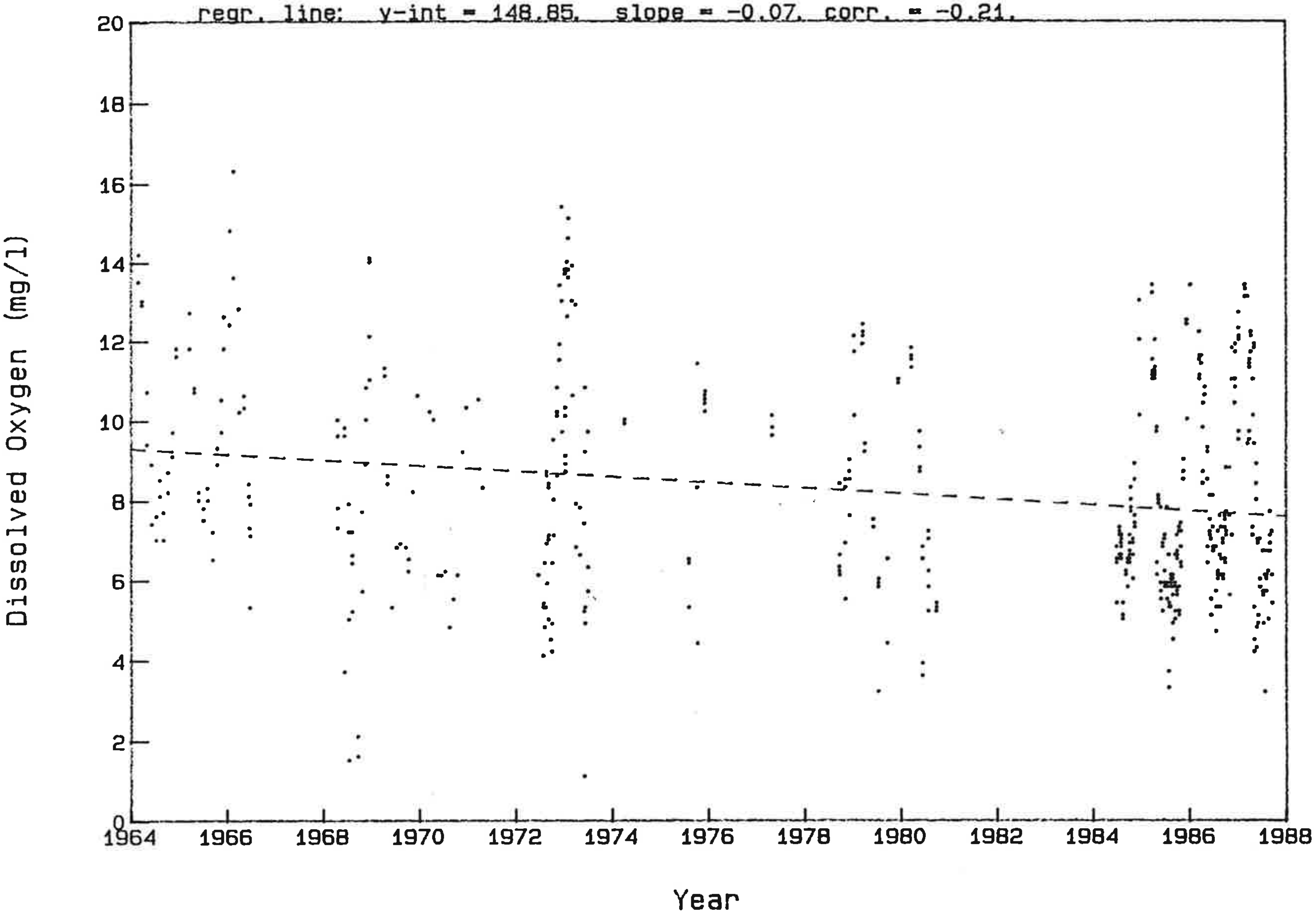
	LR w/med/seas			LR w/days			Ktau w/seas	
Segment/param/layer	Slope	F(1,n-2)	n	Slope	F(1,n-2)	n	Slope	ZValue
CB12 DO BOT	-.06	2.30	56	-.07	24.32	552	-.06	-2.34
CB12 %OxSat BOT	-.44	5.90	56	-.36	18.31	536	-.47	-2.80
CB12 Salin SUR	-.06	7.05	57	-.05	25.69	917	-.03	-4.48
CB12 Salin BOT	-.08	6.20	56	-.07	13.68	577	-.05	-3.24
CB12 Chla SUR	-.21	2.67	32	-.27	21.70	364	-.18	-1.47
CB12 Chla BOT	+.09	3.03	30	-.23	16.77	332	-.38	-2.45
CB3 Chla BOT	+.25	3.38	40	+.32	20.24	644	+.20	+1.86
CB4 Salin BOT	-.11	6.18	67	-.02	2.12	1461	-.13	-3.20
CB6 Salin SUR	+.09	3.17	22	+.01	0.05	361	-.02	-0.43
MOUTH Chla BOT	+.13	2.53	17	-.30	3.73	223	-.25	-0.95

APPENDICES

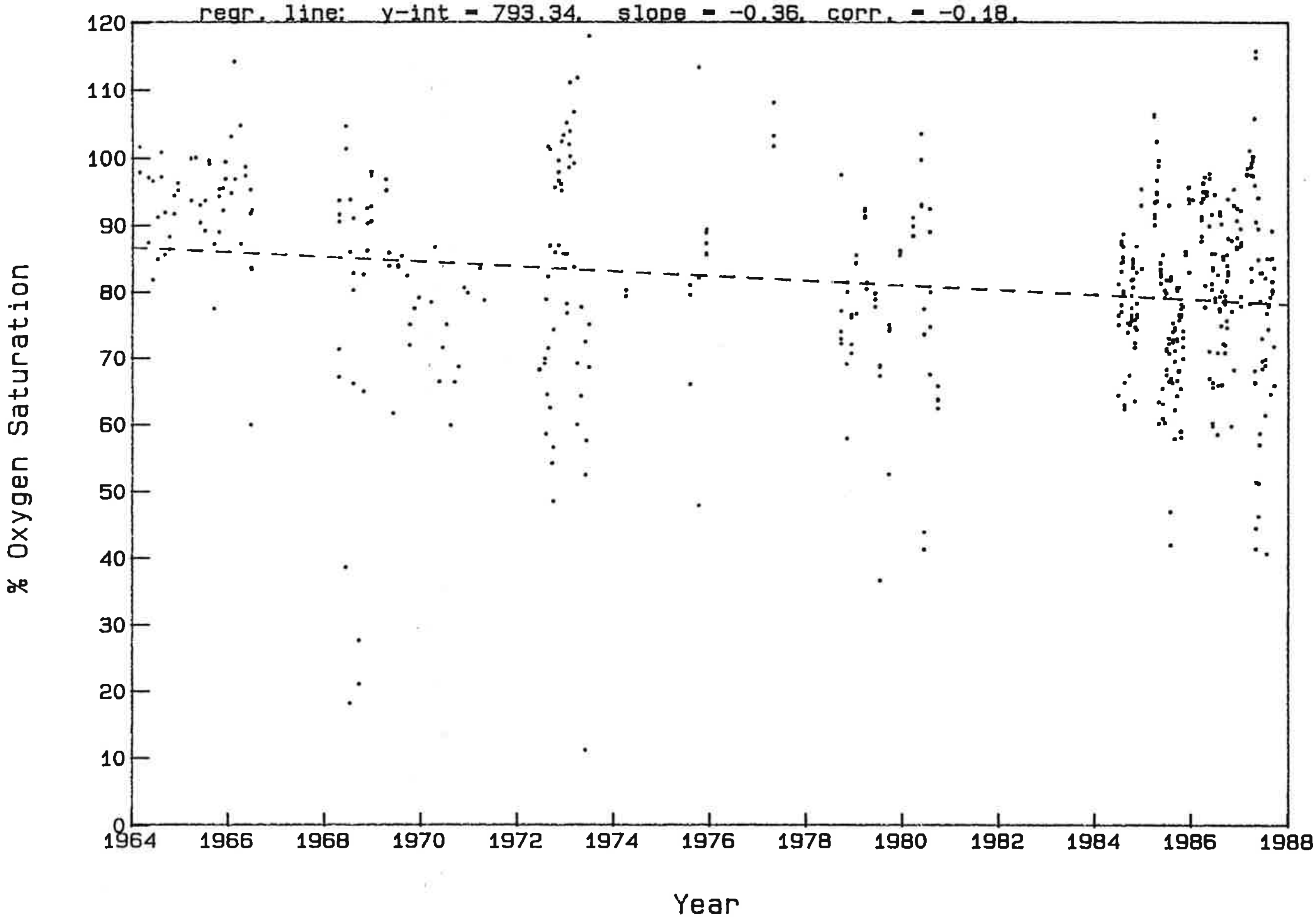
Appendix A

Ten Most Significant Trends

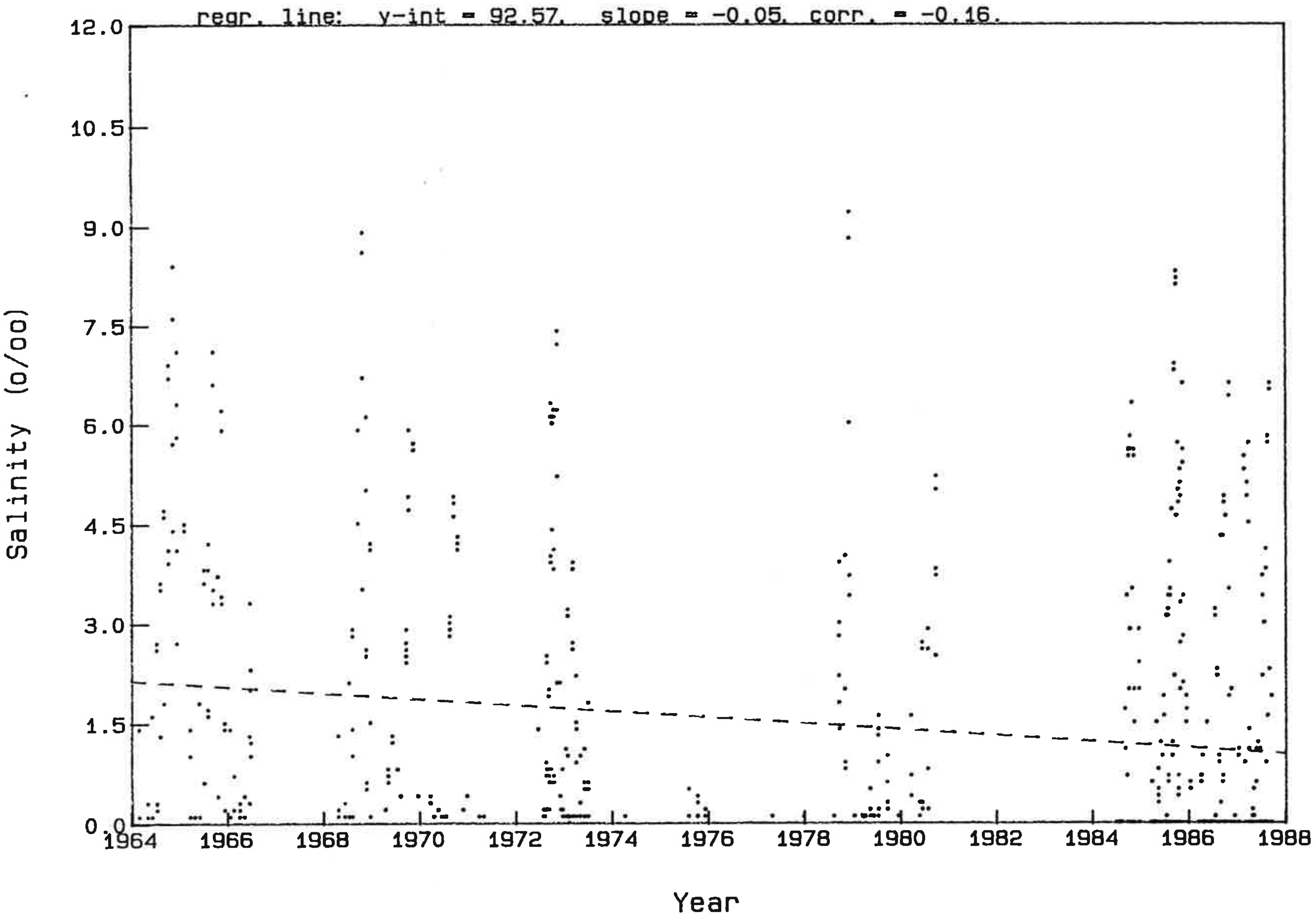
Dissolved Oxygen Trend
Segment CB1-2 of the Chesapeake Bay
Bottom Layer



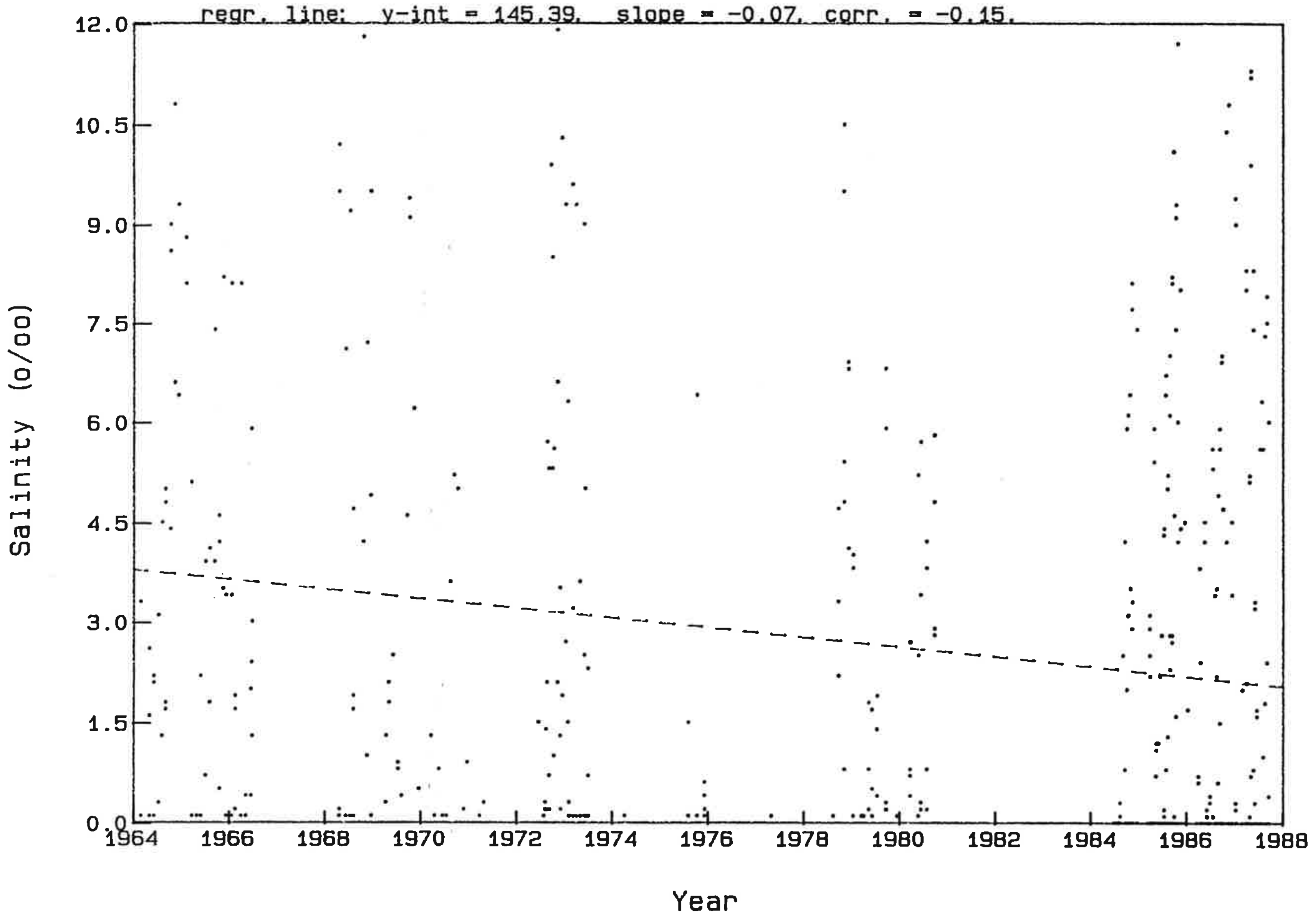
Percent Oxygen Saturation Trend
Segment CB1-2 of the Chesapeake Bay
Bottom Layer



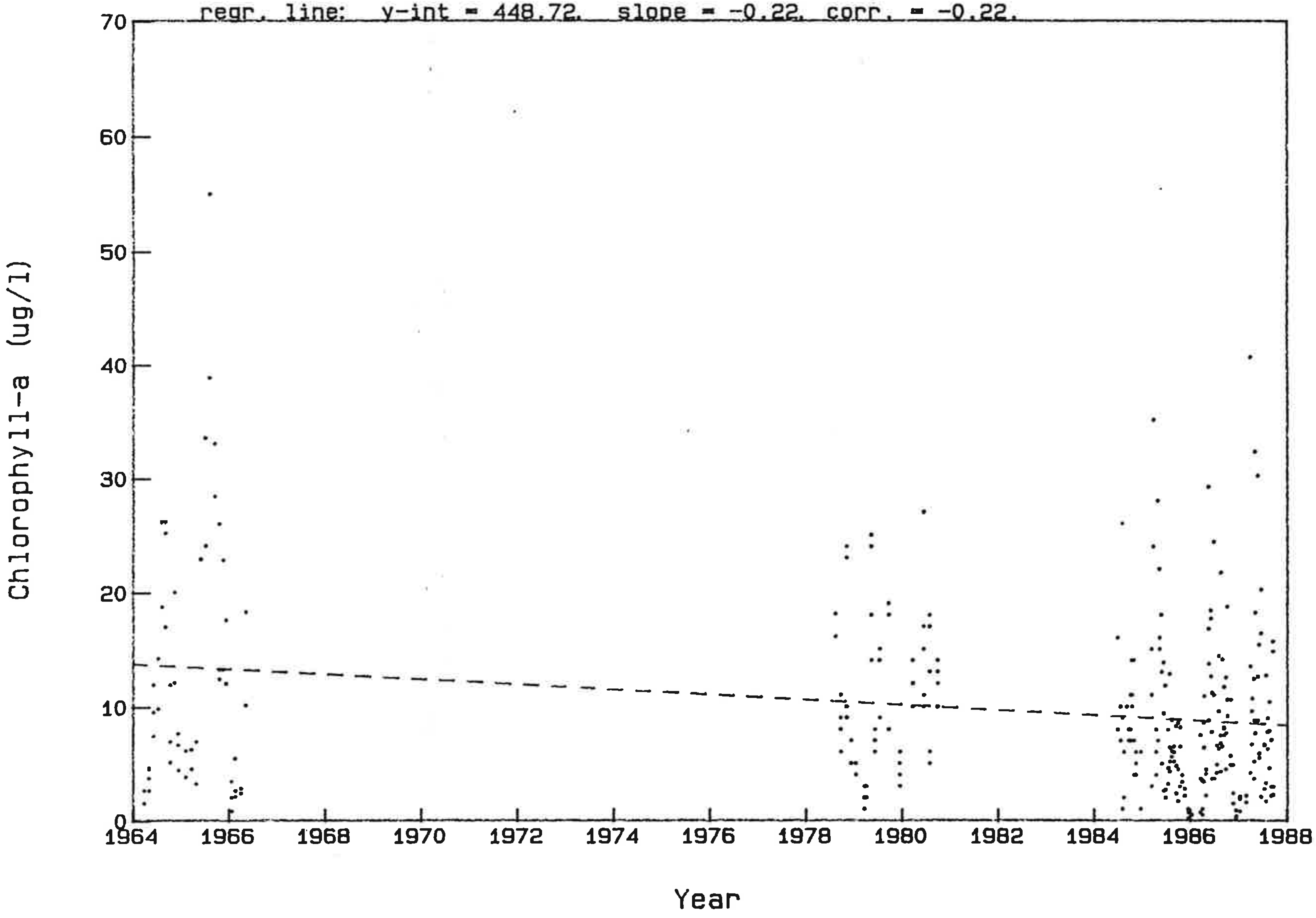
Salinity Trend
Segment CB1-2 of the Chesapeake Bay
Surface Layer

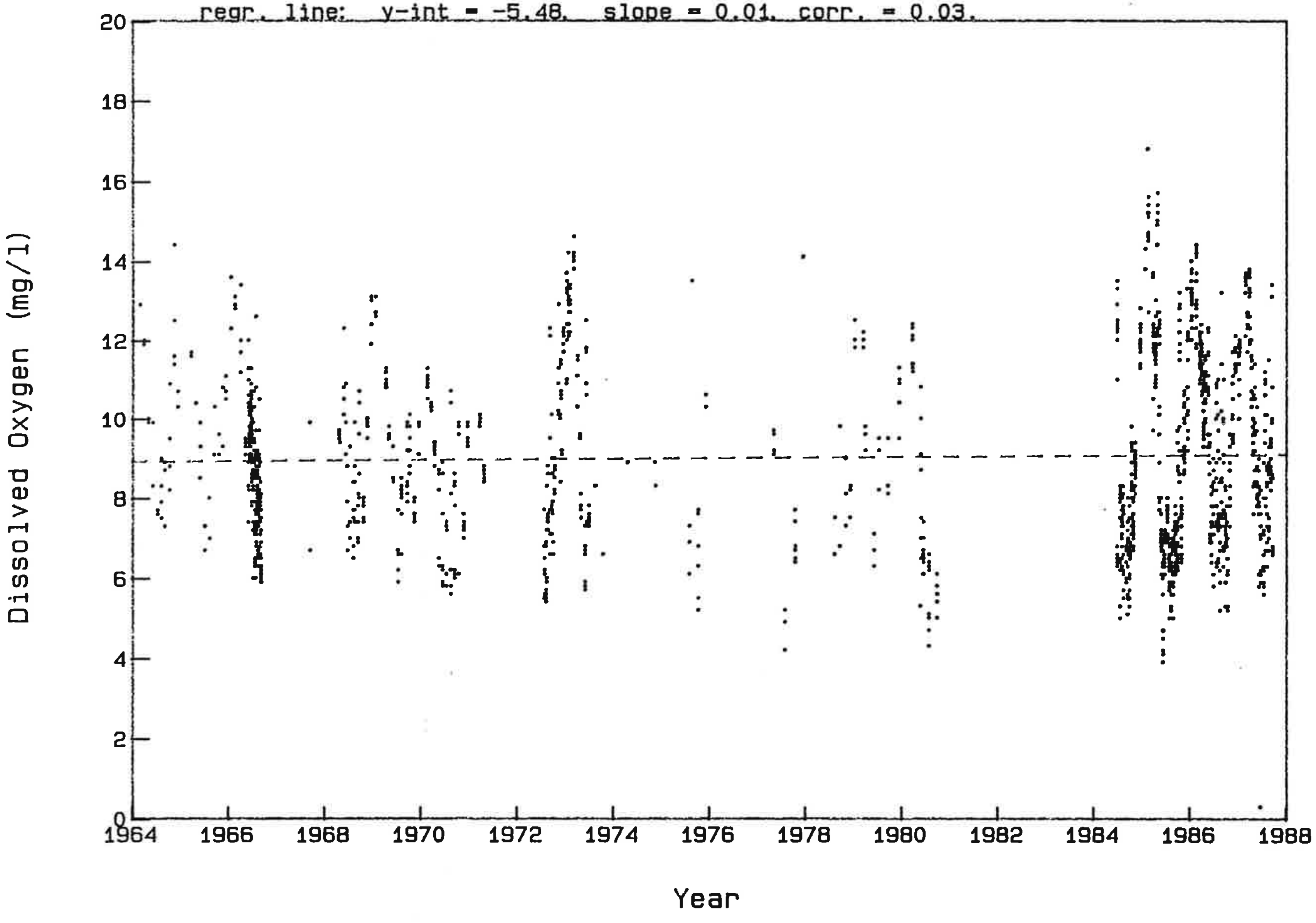


Salinity Trend
Segment CB1-2 of the Chesapeake Bay
Bottom Layer



Chlorophyll-a Trend
Segment CB1-2 of the Chesapeake Bay
Bottom Layer

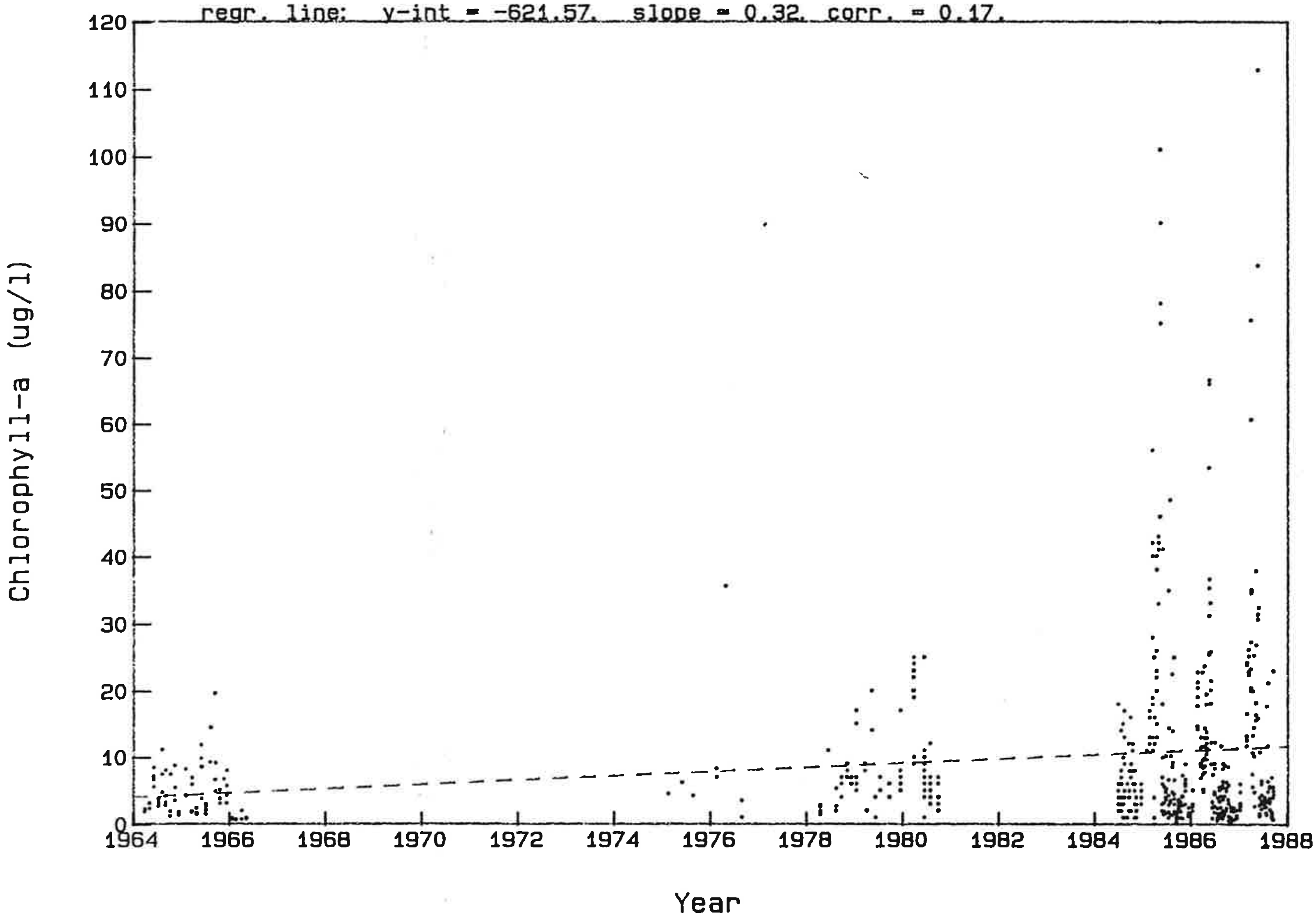




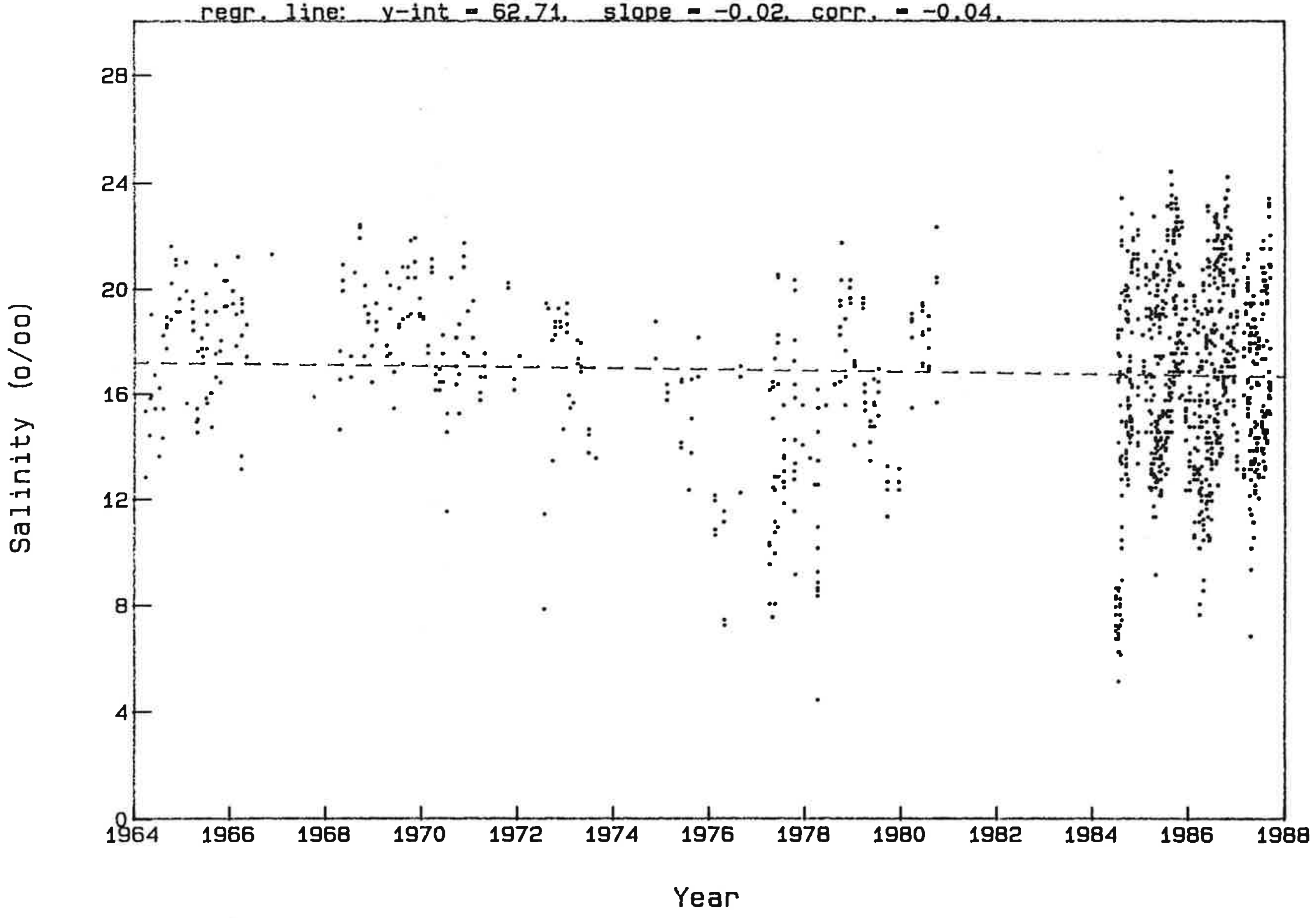
Dissolved Oxygen Trend
Segment CB3 of the Chesapeake Bay
Surface Layer

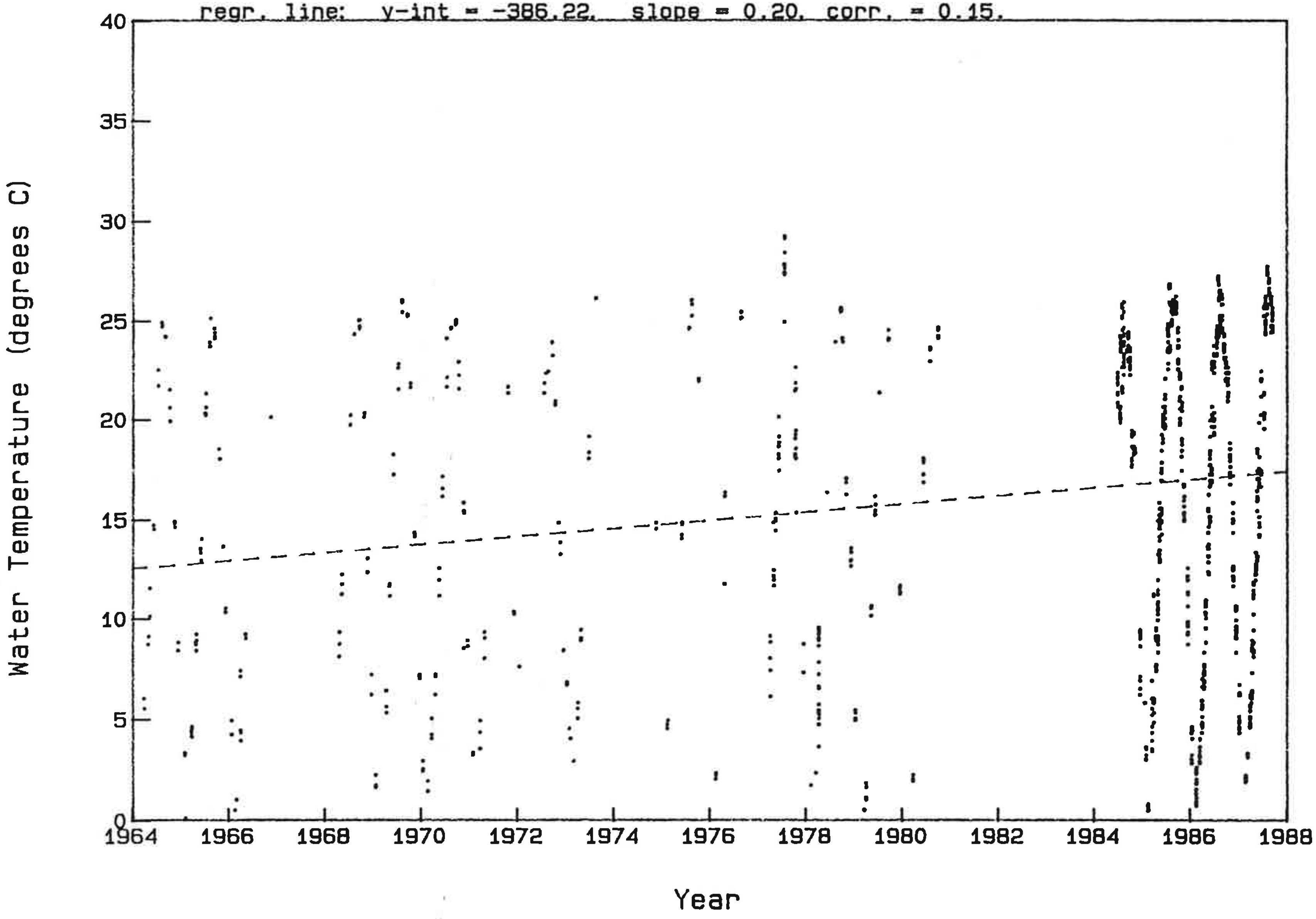
regr. line: y-int = -5.48, slope = 0.01, corr. = 0.03.

Chlorophyll-a Trend
Segment CB3 of the Chesapeake Bay
Bottom Layer



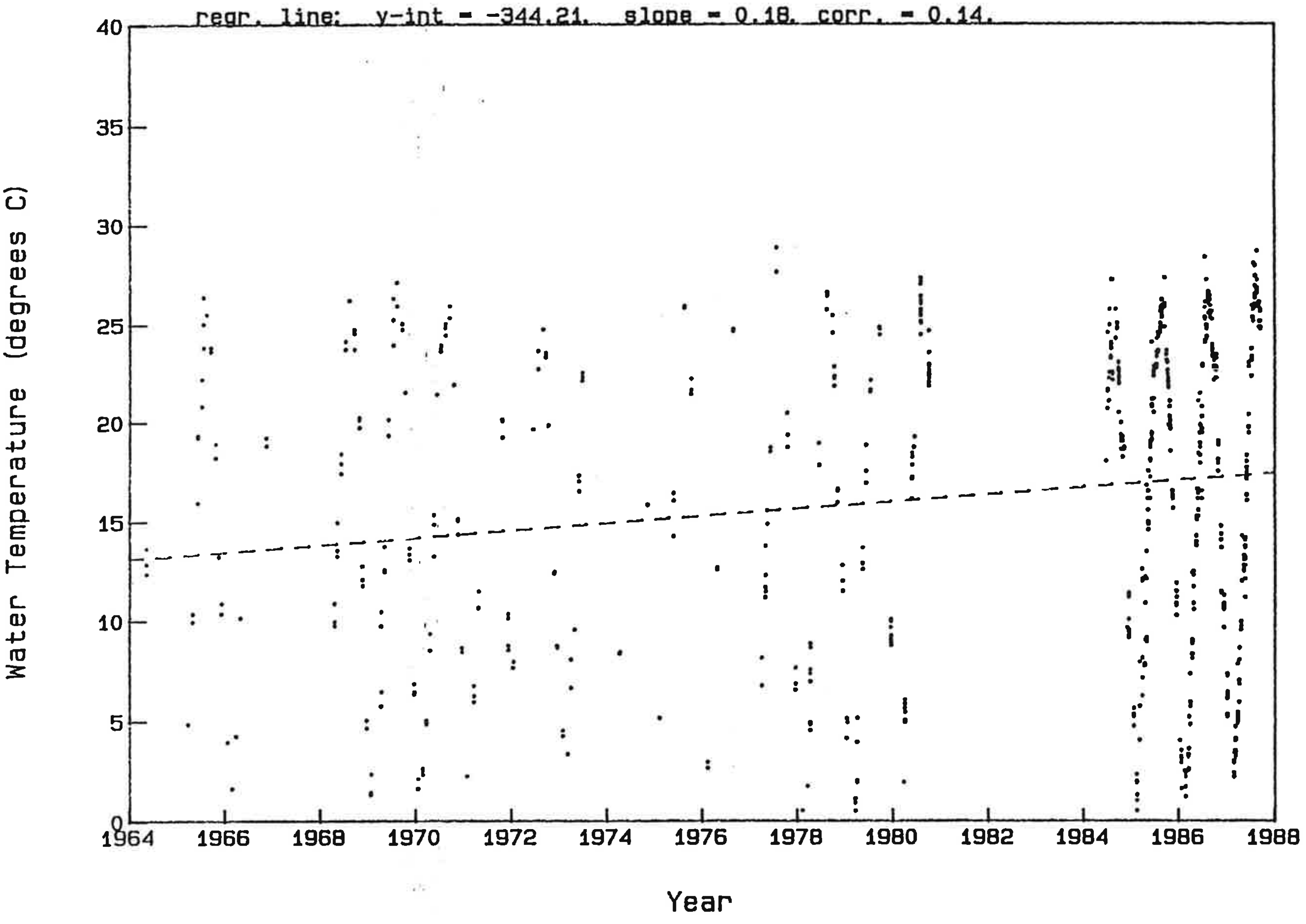
Salinity Trend
Segment CB4 of the Chesapeake Bay
Bottom Layer





Water Temperature Trend
Segment CB4 of the Chesapeake Bay
Bottom Layer

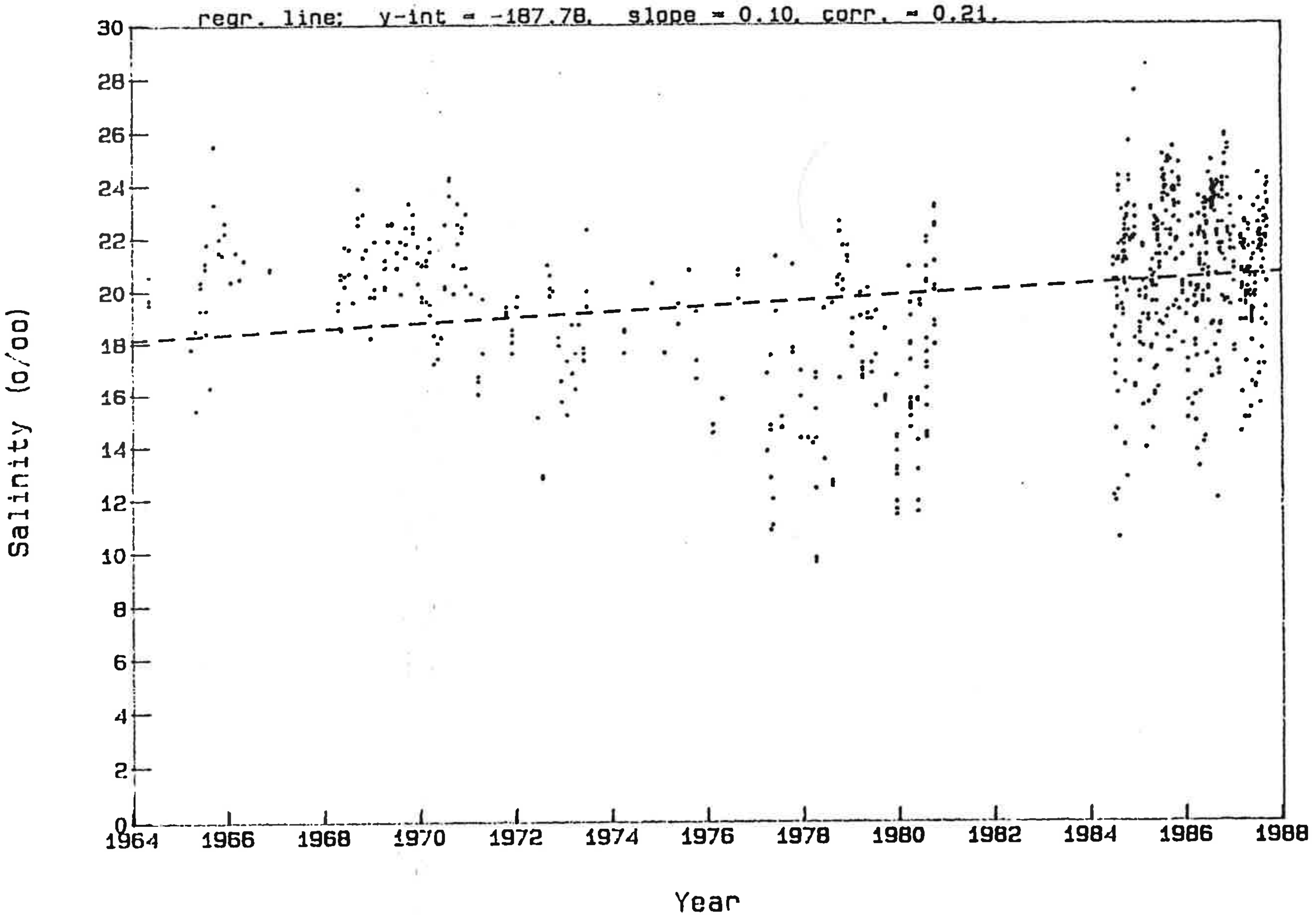
Water Temperature Trend
Segment CB5 of the Chesapeake Bay
Bottom Layer



Appendix B

One Specific Pair

Salinity Trend
Segment CB5 of the Chesapeake Bay
Bottom Layer



Salinity Trend
Segment CB5 of the Chesapeake Bay
Bottom Layer