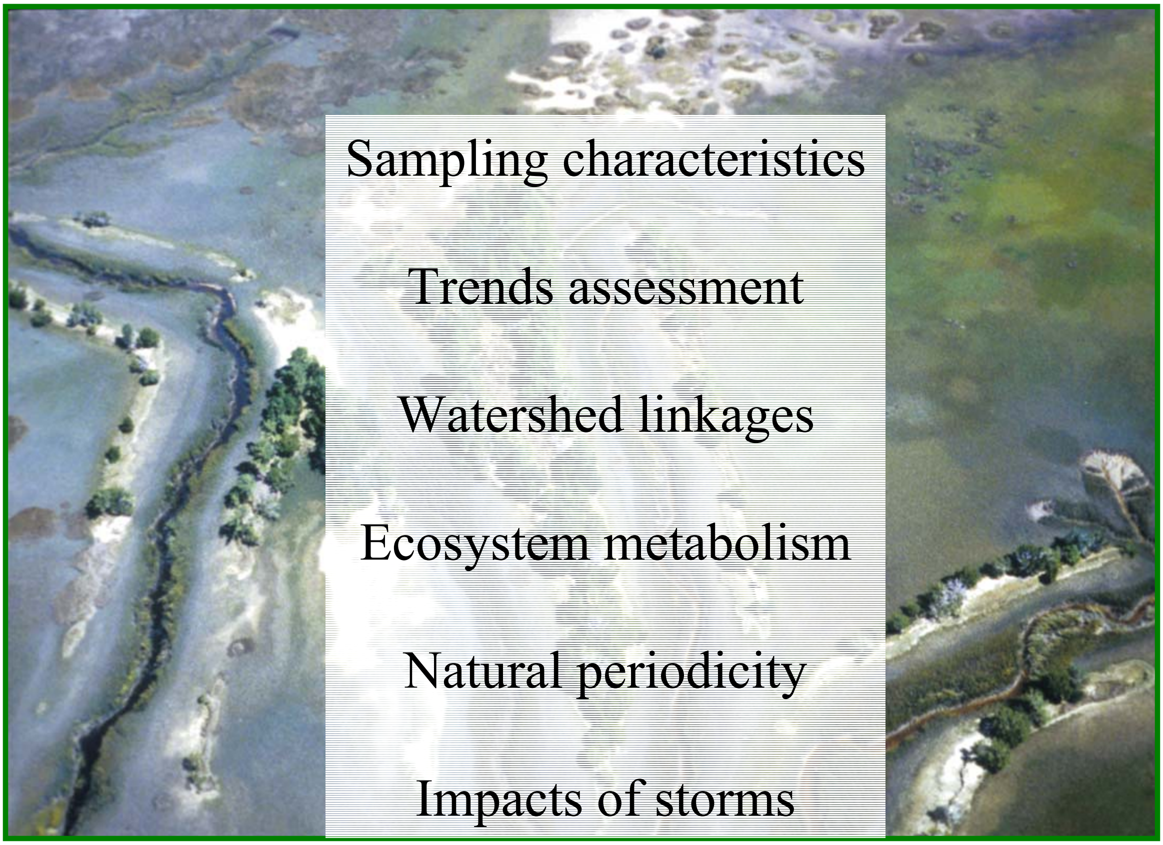
A SYNTHESIS OF WATER QUALITY DATA: NATIONAL ESTUARINE RESEARCH RESERVE SYSTEM-WIDE MONITORING PROGRAM (1995-2000)



Sampling characteristics

Trends assessment

Watershed linkages

Ecosystem metabolism

Natural periodicity

Impacts of storms

Final Report

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NATIONAL
ESTUARINE
RESEARCH
RESERVE
SYSTEM

U.S. Department of Commerce ❧ National Oceanic and Atmospheric Administration ❧ National Ocean Service

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Table of Contents

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This report is South Carolina Department of Natural Resources, Marine Resources Division Contribution Number 500.

List of Tables

List of Figures

List of Appendices

Executive Summary

A total of 4,135 datasonde deployments conducted at 55 monitoring sites during the first six years (1995-2000) of the NERR SWMP were analyzed in this report. Due to the progressive implementation of the SWMP at NERR sites, total deployments in 1995 were substantially lower than the total number of annual deployments for the other four years, which progressively increased with time. Deployments conducted at NERR sites in the Southeast and Mid-Atlantic regions collectively accounted for approximately half of the total deployments analyzed, primarily due to: (1) the initiation of the NERR SWMP at sites in these regions, and (2) climates more favorable to intensive year-round sampling than in other regions. In general, fewer and longer deployments occurred in winter and shorter, more frequent deployments were conducted in summer. This scenario was particularly evident for West Coast, Northeast/Great Lakes, and Mid-Atlantic Reserves.

Most NERR sites collected 70% or more of the maximum possible water temperature observations for a given season or year. Total observations for salinity, depth and pH were similar to the total number of observations for water temperature, but typically observations for these parameters were 3-7% less than for water temperature. Deletion of suspected anomalous data largely accounts for these discrepancies. Similarly, substantially fewer observations for the same period for turbidity and dissolved oxygen data sets largely resulted from the deletion of suspected anomalous data. With regard to dissolved oxygen, increased deployment duration was shown to increase the percent of time with hypoxic conditions (DO <28% sat) and decrease the percent of time with supersaturation (DO > 120% sat) at many sites. These discrepancies were presumed to result from increased bio-fouling as a result of increased deployment duration, which represents a bias for estimating hypoxia and supersaturation at these sites. Increased hypoxia with deployment duration was most evident at West Coast, Mid-Atlantic, and Gulf of Mexico and Caribbean NERRs. Decreased supersaturation with deployment duration was most noticeable at Southeast and Gulf of Mexico and Caribbean NERRs. These trends became progressively more noticeable between 1995 and 2000, coinciding with reduced rainfall and more drought-like conditions at many of these NERRs.

Improved statistical and analytical approaches were included in this report, with much emphasis placed on identifying seasonal and inter-annual variability of parameters. Three-way ANOVA models revealed several significant inter-annual differences for water quality parameters for many sites; however, inter-annual trends with respect to Reserve or region were not readily apparent. Three-way ANOVA models revealed several significant differences for water quality parameters among sites for each Reserve with respect to season. Water temperature, salinity, and hypoxia events were generally greatest in the summer or fall and lowest in the winter or spring, when water temperature and salinity were lowest and supersaturation was greatest. These findings, particularly for salinity, appeared to be related to seasonal precipitation and evapo-transpiration. Furthermore, these patterns were also observed in metabolic analyses, with maximum heterotrophic conditions generally occurring in the summer or fall and minimum heterotrophic or maximum autotrophic conditions typically occurring in winter or spring.

Periodicity analyses primarily focused on daily and tidal cycle influence on water quality, but also determined how the relative contribution of each of these cycles varied seasonally and inter-annually. Water temperature was primarily influenced by the daily solar radiation cycle; however, water temperature in these shallow estuarine systems could also be strongly influenced by low tide events. Water depth was more influenced by tide than by daily cycles; however, daily (i.e., afternoon winds) and seasonal (i.e., prevalent wind direction) solar radiation cycles also appeared to influence water depth periodicity. Furthermore, seasonal precipitation and evapo-transpiration patterns may have influenced water depth in the shallow water bodies monitored by the NERR SWMP. Dissolved oxygen was primarily influenced by daily solar radiation cycles; however, strong tidal influence was also observed for sites located closer to inlets where cooler, more saturated marine waters replenish warmer, oxygen-reduced waters twice daily. This phenomenon was particularly noticeable during summer months when hypoxia was most prevalent, particularly during daytime low tide events.

Four distinct multivariate analyses were used to explore and develop "natural" relationships between climate and land-use patterns within a watershed and subsequent water quality in the downstream monitored water body. A common grouping in two of the four analyses (principal component analysis and non-linear multidimensional scaling) was the primary division of NERRs based on water temperature, followed by a division in salinity. Sites with low salinity were associated with a high percentage of agricultural land in the watershed and high turbidity, whereas sites with high salinity were associated with a lower percentage of agricultural land in the watershed and lower turbidity. The geographic regional distinctions evident from the water temperature division for both principal component analyses and non-linear multi-dimensional scaling were supported by discriminant function analyses, which grouped NERR sites according to geographic region, with a "mis-classification" error of only 6%. Cluster analyses, used previously in the 1996-1998 NERR SWMP data (Wenner et al. 2001) also roughly grouped the NERRs based on geographic region and latitude, further emphasizing the importance of climate and biogeography in controlling water chemistry of shallow water, estuarine systems.

Analysis of associated changes in water quality during the passage of tropical systems revealed only one consistent trend, an abrupt decrease in water temperature prior to storm passage, with increasing cooling effects strongly related to increasing storm intensity. This cooling effect is widely reported for tropical systems in the open ocean where it has been related to upwelling effects (see Chapter 6); however, the occurrence of this phenomenon in shallow water systems, in some instances hundreds of miles away from the storm center, have received little mention in the literature. Short-term changes in salinity resulted in salinity spikes when storms approached from the sea or decreases when storms passed from the west after having made landfall. Long-term changes in salinity resulted from slow-moving systems depositing copious amounts of precipitation, particularly when the precipitation occurred throughout the watershed of water bodies monitored by NERRs. Altered salinity distributions and excessive runoff from these storms subsequently resulted in ecological disturbances in some of these estuaries, with the return to pre-storm conditions requiring several years to achieve (i.e., Pamlico Sound following the passage of Hurricanes Dennis and Floyd in 1999).

General Introduction

The System-wide Monitoring Program (SWMP) of the National Estuarine Research Reserve (NERR) system collects water quality observations at 30-minute intervals at numerous locations throughout the United States. Initiated at two sites in North Carolina in 1994, the NERR SWMP has grown substantially, with 51 active sites at 22 Reserves nationwide at the end of 2000. Given the diverse biogeography and physiography of these sites, the NERR SWMP provides an ideal platform for attempting to characterize the short-term variability and long-term changes in estuarine systems, as well as to document the response of these systems to episodic events such as tropical systems and drought conditions.

A recent report characterized the short-term variability in dissolved oxygen, water temperature, salinity, and depth at 44 sites from 22 Reserves between 1996-1998 (Wenner et al. 2001). The report provided a thorough descriptive examination of water quality observations at each site, net ecosystem metabolic analyses based on dissolved oxygen observations, and characterization of the influence of natural cycles (light-dark, tidal) on water quality. Furthermore, the report provided a critical first analysis of the link between watershed and water body characteristics and subsequent water quality.

In an effort to improve certain aspects of the analytical methods used previously, to increase the length of the time series for trends assessment, and to ensure that all archived data collected by the NERR SWMP since 1995 had been analyzed, a second synthesis project was initiated in fall 2001. Rather than focus on detailed examination of data for each site participating in the NERR SWMP, the intent of the current synthesis project was to examine data at the Reserve and System-level, with particular emphasis on assessing trends in water quality between 1995-2000. To this end, quantification of qualitative attribute data collected in the previous synthesis, and quantification of new attribute data not available in the previous synthesis were primary objectives of the current study. Metabolic analyses for all sites and years were also included in the current study. In addition, several modifications were made to the statistical analyses, the most notably of which was the use of General Additive Models (GAM), rather than Harmonic Models, to characterize the periodic and cyclical nature of water quality observations for individual site deployments. The impetus of the change was to use models that allow the patterns in the data to emerge, rather than forcing the data to fit specific patterns. Lastly, investigation of the effects of tropical systems, discussed briefly in the previous study, was included in this report.

The current report consists of six independent, but inter-related, chapters. The first chapter characterizes seasonal and regional trends in sampling between 1995-2000. A critical first step in our analysis was to evaluate and compare data sets to determine what, if any, sampling bias existed. Disproportionate sampling among sites, regions, seasons and years can complicate interpretation of observed differences in parameters at these levels. This chapter also examines the effects of deployment duration on dissolved oxygen readings. Drift in dissolved oxygen (% sat) due to increased fouling of DO probes with increased deployment duration represents a potential bias in determination of the frequency and duration of hypoxic events. In order to determine if potential drift occurred, and to assess trends in hypoxia and supersaturation at varying time intervals over the entire data set, we re-evaluated potential drift at varying deployment time intervals. The second chapter characterizes seasonal and inter-annual trends for specific water quality variables. This chapter also includes statistical tests for deployment-level differences in DO extremes, salinity, pH, and turbidity among Reserves with respect to site, season, and year.

Chapters 3 through 6 represent applied approaches to characterizing NERR SWMP water quality data. The intent of these chapters is to attempt to document the dominant processes responsible for influencing distributions of water quality parameters and to characterize the response of water quality parameters to both natural cycles and episodic events. Chapter 3 examines the relationship between the watershed, land-use practices within the watershed, and climate in influencing water chemistry at NERR SWMP sites. Several multivariate analyses were used to classify sites and determine general relationships regarding land-water interactions. Trends in production, respiration, and net ecosystem metabolism at 42 sites are provided in chapter 4. Improved techniques for modeling short (diel, tidal) and intermediate (seasonal, inter-annual) periodicity in water quality variables are presented in chapter 5. Chapter 6 examines changes in water quality at NERR SWMP sites associated with the passage of 21 tropical systems by one or more NERRs between 1995-2000.

Data analyzed in this report were collected prior to the publication of the previous synthesis work (Wenner et al. 2001); thus, sampling and design recommendations provided in the previous synthesis could not incorporated into the System Wide Monitoring Program prior to our current analysis. As such, those recommendations are not reiterated here; however, three additional recommendations are suggested as a result of the current synthesis. First, although improved ancillary attribute data were collected for this report, several desired attribute data (SAV/Shellfish Bed cover, freshwater flow, tidal excursion) were unobtainable, were incomplete, or were collected too far away from NERR sites to be meaningful. Furthermore, attribute data that we were successful in obtaining were collected from multiple sources and took over six months to compile for the 51 sites at 22 NERRs. As a result of our experiences, we recommend that each Reserve attempt to maintain current and relevant attribute data for their sites (see Chapter 3), as well as attempt to locate the desired attribute data that could not be included in this report. Second, nutrient data sampling was too sporadic and incomplete to provide meaningful interpretation of data that could be related to metabolic processes (see Chapter 4). We therefore recommend modification of sampling protocols to include increased sampling at more pertinent locations (i.e., along a salinity gradient that encompasses the *sources* of nutrients and the *dilution of nutrients*). Finally, because the objective of this synthesis was to provide a more thorough “big picture” analysis, the details of the site-level processes were not included. Specifically, over 33,000 graphs for deployment-level periodicity analyses were created for the 1995-2000 NERR SWMP dataset, but only examples of these analyses were included in this report. It is our sincere hope that the efforts to model periodicity at each of these sites will be further enhanced by knowledgeable interpretation by experts at each Reserve.

Chapter 1: Characteristics of Sampling

Introduction

A critical first step in evaluating and comparing data sets is to determine what, if any, sampling bias exists. Disproportionate sampling among sites, regions, seasons and years can complicate interpretation of observed differences in parameters at these levels. For example, several NERRs in the Northeast are not monitored during the winter months due to freezing temperatures and ice formation (Wenner et al. 2001). As a result, the annual frequency of occurrence of water temperatures <10°C at these sites are underestimated, and annual occurrence of supersaturation events may also be underestimated. Although it may not be appropriate to adjust values in these types of situations when comparing data sets, it is critical to document their occurrence and provide the necessary caveats for interpretation of results.

Extended deployment duration can lead to potential drift in dissolved oxygen (% sat) due to increased fouling of DO probes, which in turn represents a potential bias in determination of the frequency and duration of hypoxia events. Wenner et al. (2001) evaluated dissolved oxygen drift at NERR SWMP sites at various time intervals during the first 14 days post-deployment; however, the only criteria used to select these deployments was the total duration (≥ 14 days). Because hypoxia at various time intervals was expressed as a percent of the time interval with DO < 28% sat, an additional criteria, the amount of DO data available at each time interval, should be specified to avoid bias. In order to determine if potential drift estimates reported by Wenner et al. (2001) were markedly different than estimates determined using the additional criteria, and to assess trends in hypoxia and supersaturation at varying time intervals over the entire data set, we re-evaluated potential drift at varying deployment time intervals.

Methods

Total deployments and deployment duration were evaluated to determine if sampling was similar among years, regions, and seasons. Deployments were assigned to each season according to the month in which the deployment was initiated. Seasons were defined as winter (January-March), spring (April-June), summer (July-September), and fall (October-December), and these definitions are used throughout this report. Data were plotted and graphically presented using MS Excel.

Total observations for each water quality parameter were determined on an annual and seasonal basis. Total observations were expressed as a percentage of the maximum number of potential 30-min observations for a given year or season. Maximum annual observations were 17,520, except during leap years (1996, 2000) when maximum annual observations increased to 17,568. Maximum observations were 4,368 in spring and 4,416 in summer and fall. Winter observations in leap years (1996, 2000) were 4,368, compared to 4,320 winter observations for other years.

Potential drift in dissolved oxygen (% saturation) due to fouling was evaluated by comparing the percent of time with hypoxia (<28% saturation) and supersaturation (>120% saturation) at various deployment intervals. Two hundred seventy deployments that began in July and August 1995-2000, were at least 14-d in duration, and contained at least 90% of DO (% sat) data for each deployment duration interval (1, 2, 4, 7, and 14-d) were selected for these analyses

Mean hypoxia and mean supersaturation were calculated from deployment-level percent of time observations for 1995-1996 (*n*=73), 1997-1998 (*n*=82), and 1999-2000 (*n*=115). Mean hypoxia and supersaturation for each deployment duration interval were plotted in MS Excel and a polynomial (quadratic) trend line fit to the data.

Regional evaluations of these data were also conducted to determine if differences existed among regions at sites monitored by the NERR SWMP. Mean and standard deviation for hypoxia and supersaturation were calculated from deployment-level percent of time observations between 1995-2000 for each of five geographic regions: West Coast (*n*=70), Northeast/Great Lakes (*n*=75), Mid-Atlantic (*n*=44), Southeast (*n*=36), and the Gulf of Mexico/Caribbean (*n*=45). Mean and standard deviation of the percent of time with hypoxia and supersaturation were plotted for each deployment duration interval.

Results and Discussion

Water quality observations collected by the NERR SWMP between 1995-2000 total 3.18 million records from 55 sites and 22 Reserves. Five sites not included in the previous synthesis report that contained partial or complete 1996-1998 data are included in the current study because these sites were still actively participating in the NERR SWMP at the end of 2000. Six additional sites were added to the NERR SWMP in 1999-2000, three of which replaced sites monitored by these Reserves during 1996-1998 and three of which were added as the third site at their respective Reserves in 1999 and 2000.

During the first six years of the NERR SWMP (1995-2000), a total of 4,135 YSI deployments conducted at 55 monitoring sites were included in analyses for this report. Due to the progressive implementation of the SWMP at NERR sites, total deployments in 1995 (*n*=366) were substantially lower than the total number of annual deployments for the other four years. Similar numbers of total deployments were conducted in 1996 (*n*=626) and 1997 (*n*=691). Similar numbers of deployments were also conducted in 1998 (*n*=796) and 1999 (*n*=783); however, these deployments represented an increase of approximately 15% from 1996-1997 levels. Total deployments in 2000 (*n*=873) were the most observed for a single year between 1995-2000 and represented an increase of approximately 10% from 1998-1999 levels.

Deployments conducted at sites in the Southeast (*n*=988) and Mid-Atlantic (*n*=956) regions collectively accounted for approximately half of the total deployments, and the number of annual deployments per site in each of these regions averaged 19.3 and 18.0, respectively (Figure 1). Similar numbers of deployments were conducted at NERR sites in the Northeast/Great Lakes region (*n*=777) and Gulf of Mexico/Caribbean region (*n*=778); however, relative sampling effort was drastically different at sites within these two regions (11.4 vs. 17.7 annual deployments/site). Substantially fewer deployments were conducted at NERR sites on the West Coast (*n*=636) where relative sampling effort averaged 12.7 annual deployments per site in this region.

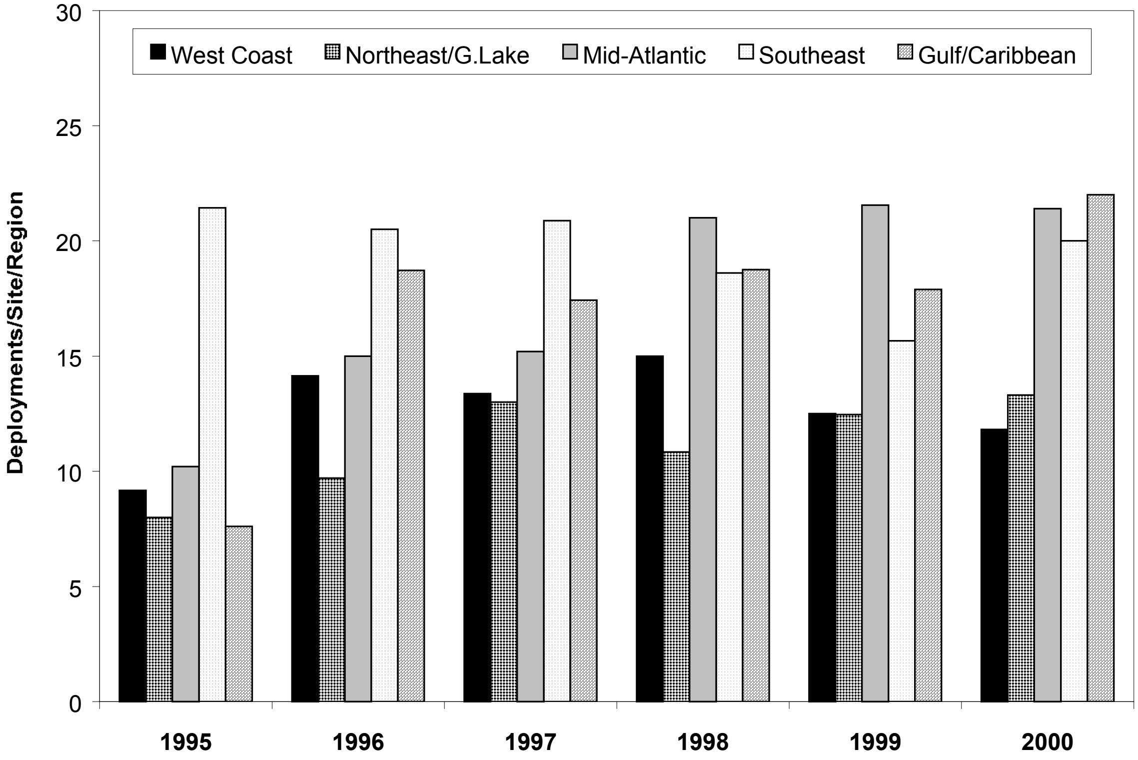

Figure 1. Annual sampling effort among regions, NERR SWMP 1995-2000.

Seasonal variation in deployment frequency (Figure 2) and duration (Figure 3) were apparent. Maximum deployment frequency (3.5 to 6.1 deployments per site) was typical for all regions during summer while minimum deployment frequency (0.6 to 4.3 deployments per site) was typical during winter. Maximum deployment duration (15.2-24.7 d) was typically observed for all regions in winter while minimum deployment duration (12.3-19.3 d) was typically observed in summer. Seasonal deployment (frequency and duration) trends were particularly noticeable for NERRs in the Northeast/Great Lakes, Mid-Atlantic regions, and West Coast regions.

Seasonal deployment trends resulted in variable data collection (Appendices 1-9). Many reserves collected more water quality observations in summer than in winter. This trend was especially pronounced for Great Bay, Hudson River, Old Woman Creek, Waquoit Bay, Wells (Head of Tide), and Chesapeake Bay MD (Appendices 4-9). Inter-annual variability was irregular for a number of sites (Appendices 1-3). Inter-annual variability was most noticeable in years when monitoring sites were either initiated or terminated. As such, the percent of monitoring sites that collected at least 50% of the maximum number of annual observations steadily improved for all water quality parameters between 1995-2000; however, even in year 2000, 7-14 sites (13-27%) did not collect at least 50% of annual data for most water quality parameters (Figure 4).

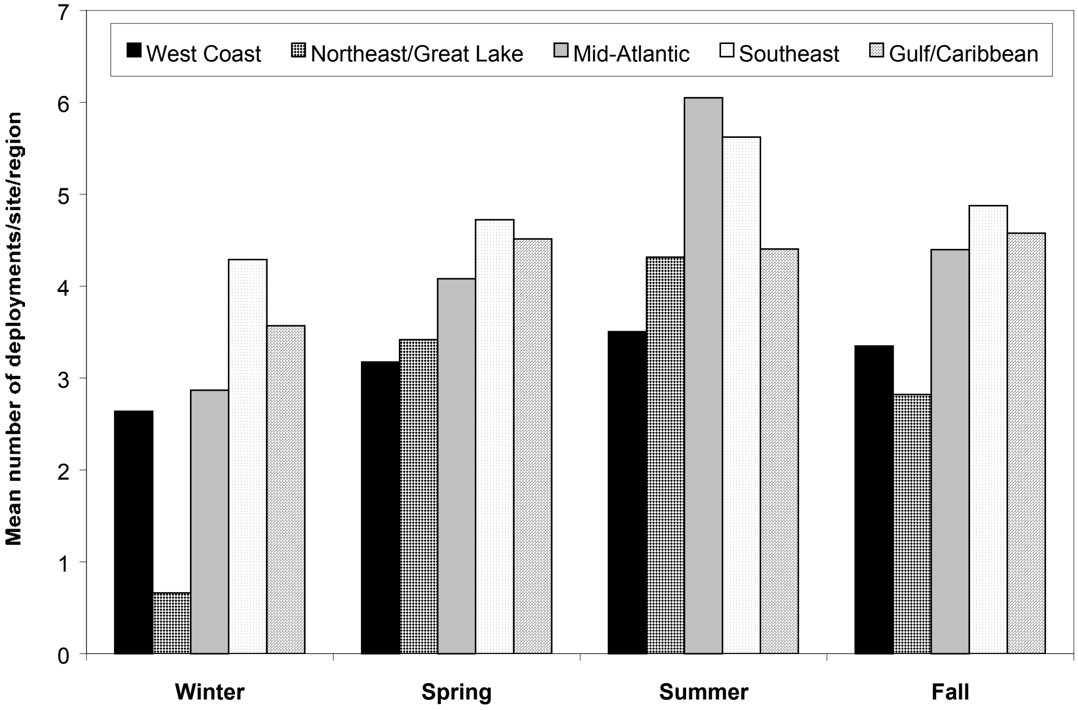

Figure 2. Seasonal sampling effort among regions, NERR SWMP 1995-2000.

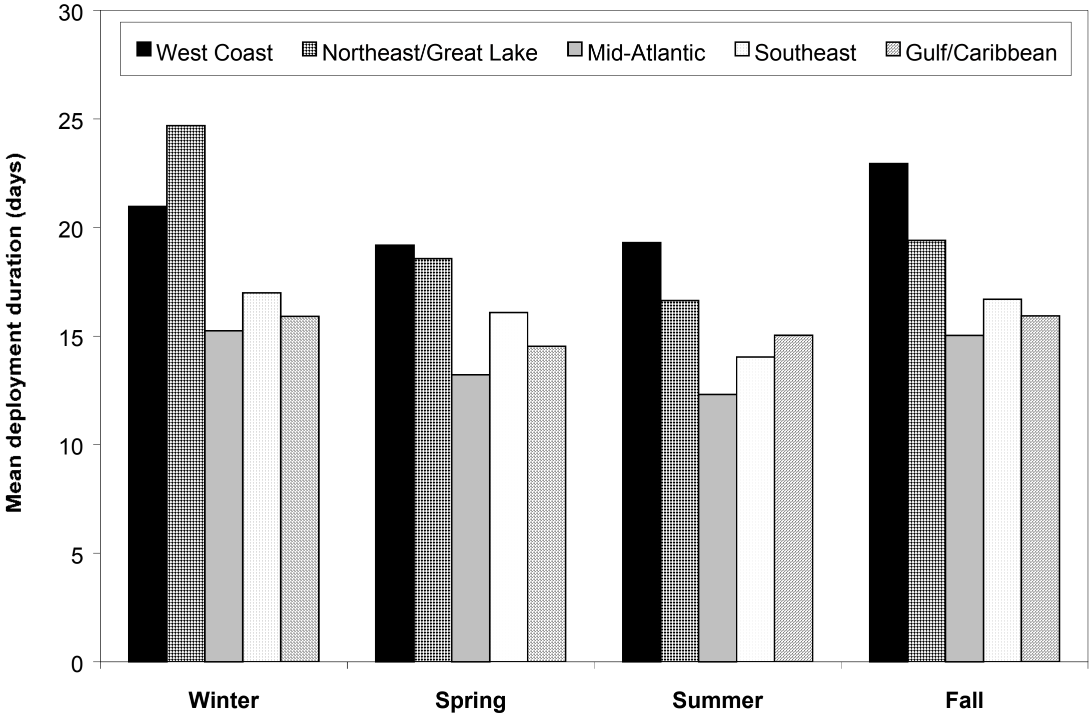

Figure 3. Mean regional and seasonal deployment duration, NERR SWMP 1995-2000.

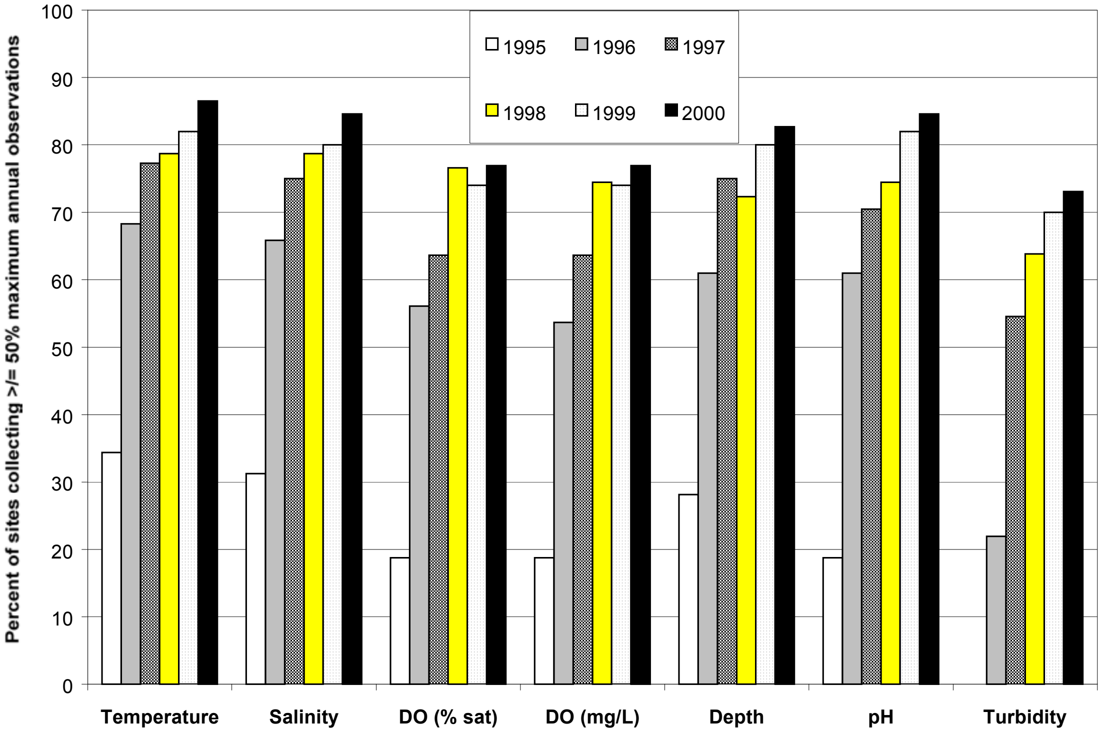

Figure 4. Percent of NERR sites collecting at least 50% of annual water quality data for each parameter by year.

Mean percent of time with hypoxia vs. deployment duration (1, 2, 4, 7, & 14-d intervals) was similar among year groups (quadratic increase, R^2=0.95-0.98, Figure 5). Incidentally, hypoxia at varying post-deployment intervals also progressively increased between biennial groupings. Mean percent of supersaturation vs. deployment duration (1, 2, 4, 7 & 14-d intervals) was also similar among year groups (quadratic decay, R^2=0.98-0.99, Figure 6) and decreased between biennial groupings.

Regional differences in hypoxia and supersaturation at NERR sites were apparent; however, within each region, the overall trends of quadratic increase (hypoxia, Figure 7) and quadratic decrease (supersaturation, Figure 8) with increasing post-deployment duration were observed. Mean percent of hypoxia (and corresponding standard deviation) was lowest at NERR sites located in the Northeast/Great Lakes and Southeast regions. The occurrence of low hypoxia at sites in the Southeast region was perplexing, but likely represents numerous sites located in relatively pristine water bodies. Mean percent of supersaturation was greatest at NERR sites located on the West Coast. Mean percent of supersaturation was lowest (and remarkably similar) for NERR sites located in the Northeast/Great Lakes and Mid-Atlantic regions.

Given these observations, hypoxia and supersaturation analyses were again based only on the first 48-hours post-deployment, consistent with the Wenner et al. (2001) report.

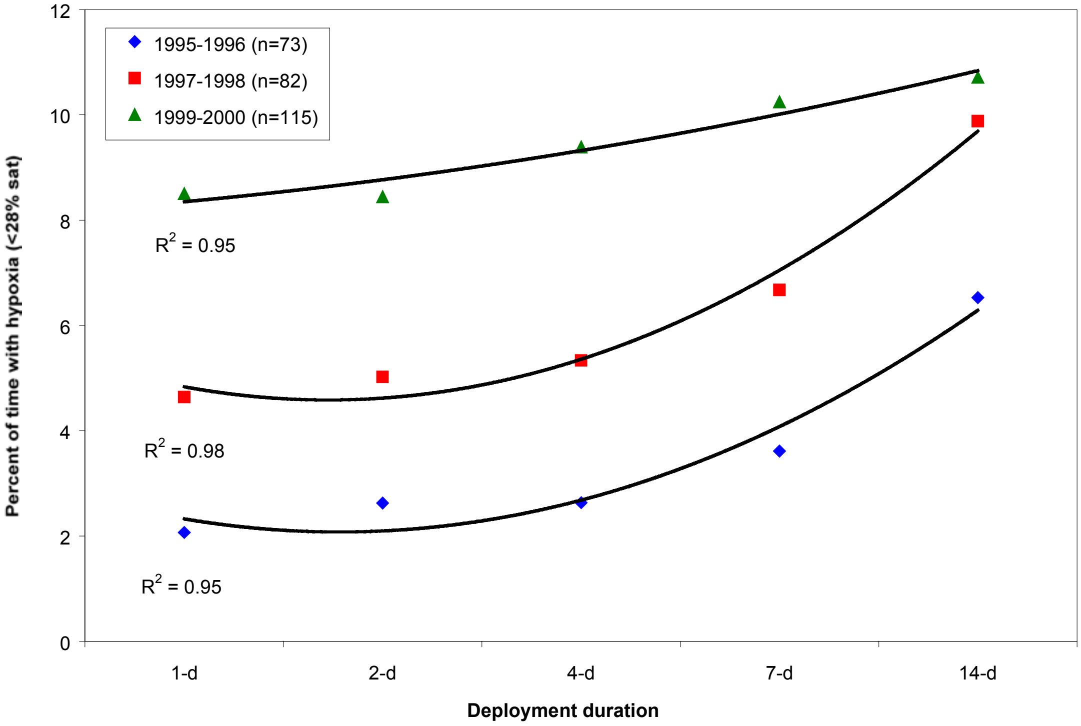

Figure 5. Mean percent of hypoxia versus deployment duration, Jul-Aug 1995-2000.

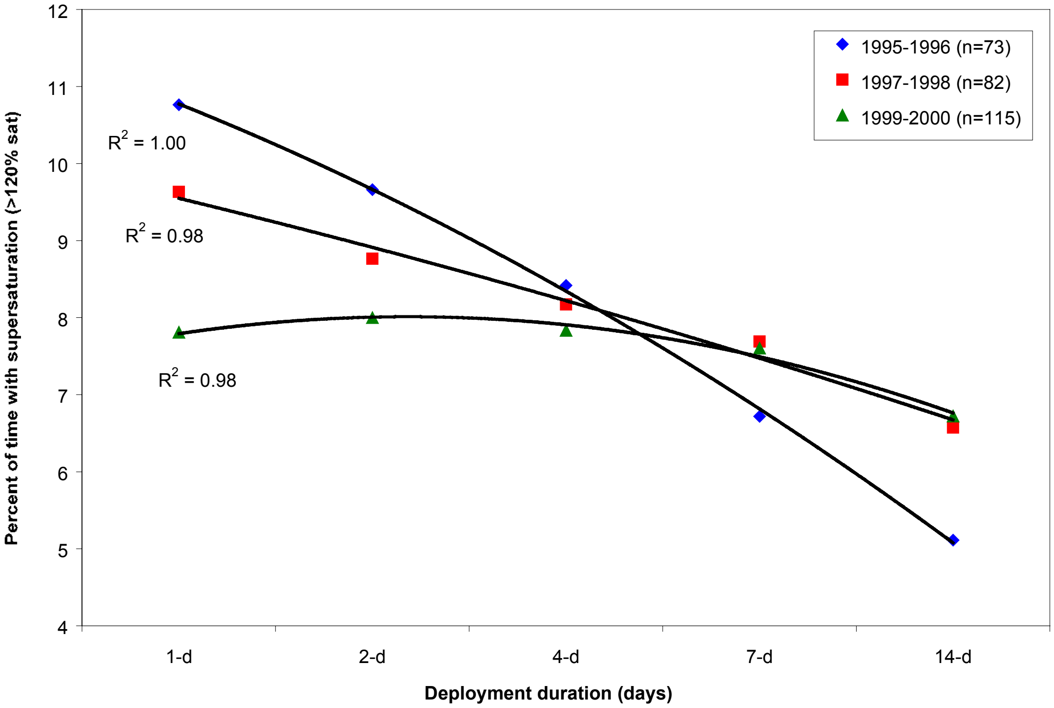

Figure 6. Mean percent of supersaturation vs. deployment duration, Jul-Aug 1995-2000.

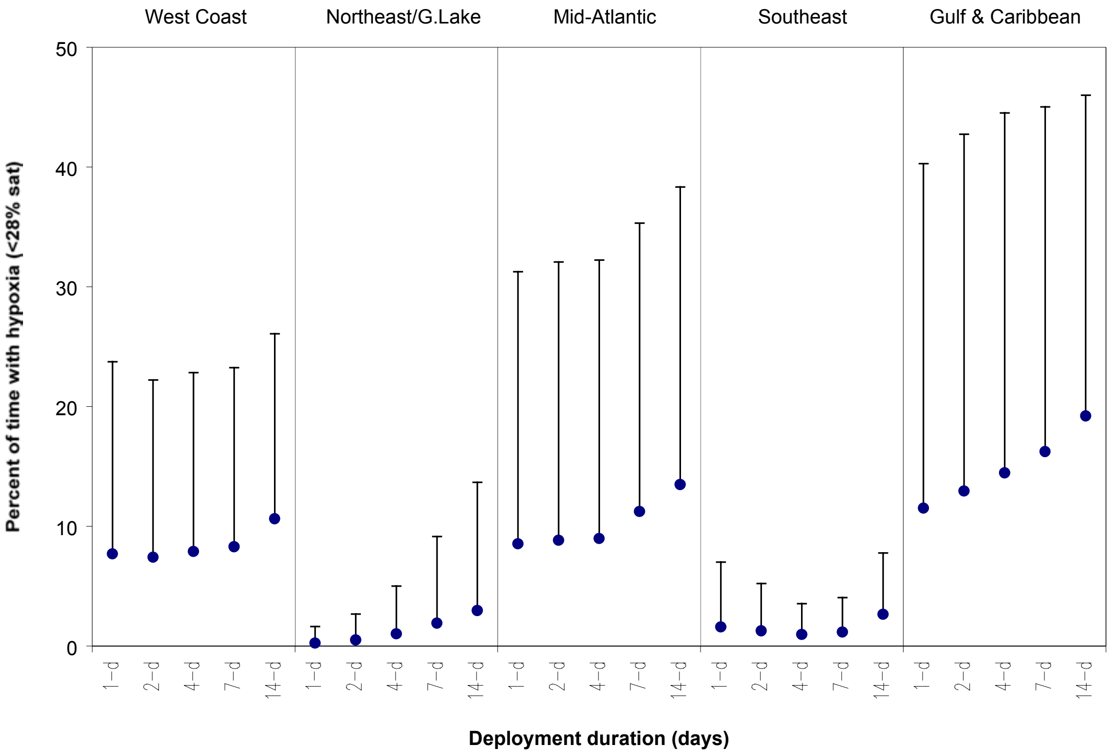

Figure 7. Mean (+ 1 std. dev.) percent of hypoxia vs. deployment duration by region, Jul-Aug 1995-2000.

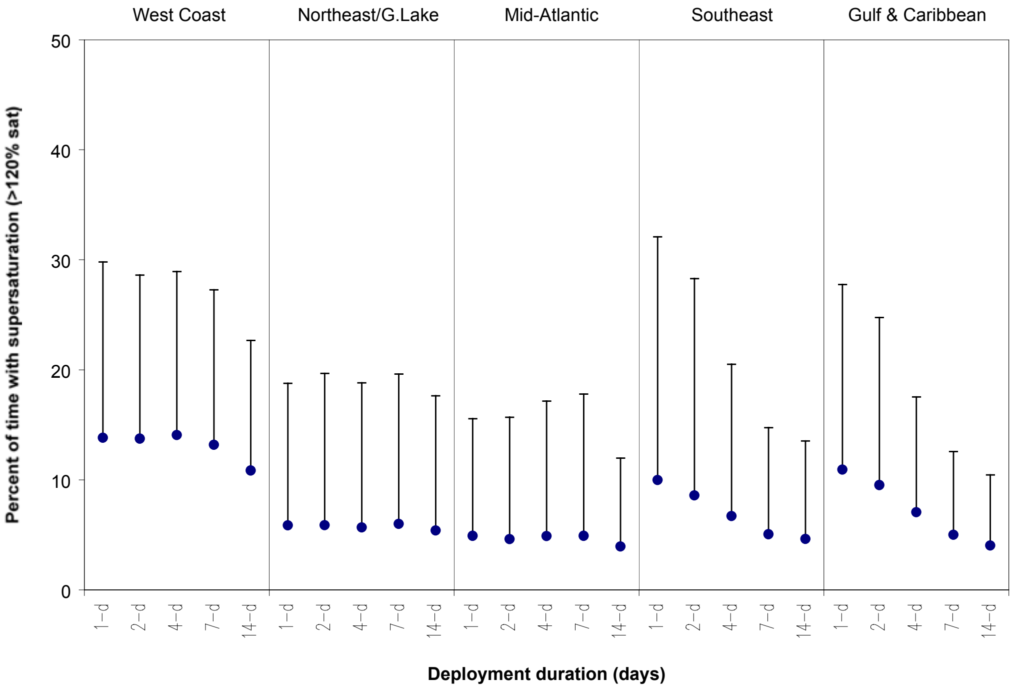

Figure 8. Mean (+ 1 std. dev.) percent of supersaturation vs. deployment duration by region, Jul-Aug 1995-2000

Chapter 2: Characterizing Trends in NERR SWMP Data

Introduction

The principal objectives of the NERR SWMP are to track short-term variability and long-term changes in a suite of water quality variables at representative estuarine ecosystems and coastal watersheds throughout the U.S. (Wenner and Geist 2001). Short-term variability (i.e., tidal and daily cycles) in water quality variables are presented in Chapter 5 of this report. This chapter focuses on characterizing seasonal, intra-seasonal and inter-annual variability in water quality parameters monitored at NERR SWMP sites.

Diverse biogeography and disparities in watershed size, water body dimensions and physiography impede the ability to compare and contrast NERR SWMP sites. To facilitate comparison among sites, representative values (metrics) for each water quality parameter were calculated. Representative values were defined with the intention of characterizing the frequency that sites experience ecologically or physiologically significant extreme values for these parameters on a seasonal or annual basis.

Statistical models used to test for differences between sites within each Reserve were based on deployment-level metrics; however, seasonal and annual trends were assessed. A recent synthesis of NERR SWMP data (Wenner et al. 2001) utilized multiple statistical models to test for differences between two sites within each Reserve. Because eight Reserves in this synthesis now include three replicate sites, and in an effort to improve the ability to statistically compare between Reserves for a given region, we used three-way Analysis of Variance (ANOVA) to test for differences among site, season and year.

Methods

Water Quality Metrics

Two water quality variables, water temperature and DO (% sat), remained unchanged from the previous synthesis project. Metrics for these parameters were defined as the overall percent of time water temperature was <10°C or >25°C and the percent of time (average of the first 48-hours post-deployment) with hypoxia (<28% sat) and supersaturation (>120% sat) during summer (Jul-Sep).

Mean water depth was defined as the mean depth measured by each YSI (from sensor to surface) plus the vertical relief (0.1-1m) between the sensor and the bottom sediment. Where YSI's were mounted to floating objects or distance between the sensor and the bottom could not be determined, mean depth between mean high water (MHW) and mean low water (MLW), obtained from annual metadata or the Wenner et al. (2001) synthesis report, were used instead. Mean daily depth range was also included to represent mean daily tidal range.

Overall mean salinity was again used as a metric, but was complemented by the inclusion of mean daily salinity range. Metrics for pH and turbidity (1999-2000 data only) were added to the current synthesis project and were defined as the overall percent of time pH is <7.0 or >8.0 and the overall percent of time that turbidity is >25 NTU, respectively.

Seasonal and Intra-seasonal variability

Descriptive examination of seasonal and intra-seasonal variability in water temperature, salinity, and precipitation was undertaken on a regional basis. Monthly precipitation data were obtained from the National Climatic Data Center (NCDC). Precipitation data for the nearest NCDC Weather Station were used; however, on occasion, data from multiple NCDC stations were used when data records were incomplete. Seventy percent of NCDC stations were located within 26 km of NERR SWMP sites. Monthly precipitation records from NCDC stations located 26-82 km away (mean = 40 km) were sometimes used because these stations represented the next closest station for which data for months with missing data were available. Two Reserves (NIW, NOC) provided partial precipitation data from stations closer to YSI sites than NCDC stations.

Hypoxic Duration

Duration of annual hypoxic events during the first 48-hours of each deployment were examined to characterize continuous hypoxic events at NERR SWMP sites between 1995-2000. Although deployments from all seasons were considered, only deployments with a full complement of records (96 observations) during the first 48-hours were analyzed. Hypoxic events were sorted into one of seven time classes (<4h, 4-8h, 8-12h, 12-16h, 16-20h, 20-24h, and >24h). To compensate for seasonal and inter-annual sampling variability among sites and regions, observations of hypoxic duration were extrapolated to a predicted annual frequency to facilitate comparisons on a standardized scale. Extrapolation was made using the following general formula: (n deployments) x (97 observations per deployment) ÷ (maximum annual observations). This approach was used by Wenner et al. (2001) to compare duration of hypoxia among NERR SWMP sites.

Analysis of Variance

Input data for ANOVAs were modified from last year for several parameters. Summary statistics for mean salinity, pH, and turbidity during the first 7-days of each deployment, rather than mean daily values, were used to decrease overall sample size to a level which would not de facto produce statistically significant results due to an excessively large *n*. Summary statistics for hypoxia and supersaturation were defined as the percent of time during the first 48-hours post-deployment, the same definitions used by Wenner et al. (2001). Data fom 1996-2000 were used for dissolved oxygen, temperature and salinity; however, incomplete data between 1996-1998 prompted us to only use 1999-2000 data for pH and turbidity.

The three-way ANOVA with interaction terms was first used to examine the data. If interaction terms were not significant at $p < 0.05$, they were removed from the model. Data were then tested for Normality (Shapiro-Wilk) and Heterogeneity of Variance (visual observation of residuals vs. predicted values) after placement in the three-way ANOVA model. To evaluate normality when using an ANOVA model, the appropriate test should be conducted for each of the defined groups (SAS 1987). Due to the complexity and difficulty of trying to run normality and homogeneity tests on each of the 16-60 groups, normality and homogeneity were tested on model residuals.

If data were normal and homogeneous, values were not transformed for the model. If data were neither normal nor homogenous, then data were log-transformed (i.e., salinity, turbidity, pH) or arcsine-transformed (i.e., hypoxia, supersaturation) for the model. If data transformation still did not produce normal and homogenous data, then the data were ranked before being analyzed using the three-way ANOVA model. This ranking approach is a viable statistical alternative when assumptions are violated (SAS 1989).

Results and Discussion

Water Quality Metrics

Water temperature <10°C was regularly experienced at monitoring sites in the Pacific Northwest and in the Mid-Atlantic and the Northeast regions (Appendix 10). Sites in these regions typically experienced water temperatures <10°C between 25-60% annually. Exceptions to this observation include sites at five Reserves (South Slough, Great Bay, Hudson River, Old Woman Creek, and Chesapeake Bay MD) that typically do not deploy or scale back deployment of YSI's during the winter months. Conversely, water temperature >25°C was regularly experienced at monitoring sites in the Southeast, Gulf of Mexico, and Puerto Rico (Appendix 11). Sites in these regions typically experienced water temperatures >25°C between 25-60% annually, with sites in Puerto Rico experiencing water temperatures >25°C more than 90% of the year. Two Reserves in California (Tijuana River Estuary and Elkhorn Slough) did not experience either water temperature extreme combined more than 15% annually. Large inter-annual variation in percent of time with water temperature extremes was noted for numerous sites and may have been partially due to the amount of annual data collected at these sites (Appendix 1).

Summertime (Jul-Sep) hypoxia during the first 48-hours post-deployment was highly variable among deployments for a given site between 1995-2000 (Appendix 12). Ten sites regularly experienced hypoxia more than 15% of the first 48-hours post-deployment. Four sites (ELKAP, ELKSM, TJROS, TJRTL) were located on the West Coast, two sites (CBMJB, DELPB) were located in the Mid-Atlantic, one site (SAPHD) was located in the Southeast, and all three sites at the Rookery Bay Reserve in the Gulf of Mexico. Summertime supersaturation during the first 48-hours post-deployment was also highly variable among deployments for a given site between 1995-2000 (Appendix 13). Seven sites regularly experienced supersaturation more than 15% of the first 48-hours post-deployment. Two sites (ELKAP, TJRTL) were located on the West Coast, two sites (WQBCB, WQBMP) were located in the Northeast, two sites (CBMPR, CBVGI) were located in the Mid-Atlantic, and one site (WKBWB) was located in the Gulf of Mexico.

Mean water depth estimates provided here are slightly deeper than previously reported estimates, which reflected the mean depth of water above the sensor, rather than the mean depth of water of the water body where YSI's were located (Wenner et al. 2001). Mean depth for all but two monitoring sites (PDBBY, SOSVI) on the West Coast was less than 2m (Appendix 14). Mean daily depth range at West Coast sites ranged from 0.1m (ELKNM) to 2.3-2.4m (PDBBY, SOSVI). Mean depth at sites in the Northeast ranged from < 2m (*n*=6), 2-4m (*n*=6), and >4m (*n*=2). Mean daily depth range at Northeast sites ranged from 0.1m for three non-tidal freshwater sites (OWCSU, OWCWM, and HUDSK) to 2.2-2.6m for sites at the Great Bay and Wells Reserves. Mean depth for most sites in the Mid-Atlantic, Southeast, and Gulf of Mexico was between 1-2m with depth at seven sites (MULB6, CBMPR, four SAP sites, and WKBFR) between 2-6m. Mean depth at four sites (DELPB, CBMJB, both JOB sites was less than 1m.

Mean salinity at NERR SWMP sites ranged from 0-37 ppt and mean daily salinity range varied from 0-19 ppt (Appendix 15). Mean salinity at all but three sites (SOSSE, SOSWI, PDBJL) on the West Coast was >25 ppt. Mean daily salinity range at West Coast sites varied approximately 2-8 ppt for sites with mean salinity >25 ppt, and 17-19 ppt for three sites with mean salinity ~ 10 ppt. Mean salinity and mean daily salinity range at sites in the Northeast was highly variable. Mean salinity for all but one site (MULB6) in the Mid-Atlantic region was less than 20 ppt, whereas mean salinity for all but one site (NIWTA) in the Southeast region was greater than 20 ppt. Mean daily salinity range at sites in the Mid-Atlantic and Southeast regions was variable and ranged from 0-12 ppt. Mean salinity at sites in the Gulf of Mexico was ≤ 10ppt for two Reserves in the northern Gulf (WKB, APA) and 19-34 ppt for sites at the Rookery Bay Reserve in southwest FL. Minor to moderate daily salinity variation was observed for sites in the Gulf of Mexico. Mean salinity for sites at Jobos Bay, Puerto Rico, was >35 ppt with minor daily variation.

Only NERR sites with mean salinity less than 15 ppt experienced pH values <7.0 at least 25% of the time between 1999-2000 (Appendix 16). Half of NERR sites (11 of 21) with mean salinity <15 ppt experienced pH values <7.0 at least 25% of the time. With the exception of SOSSE and SOSWI, other low salinity sites (PDBJL, WELHT, MULBA, DEL NERR, CBM NERR, and NIWTA) that experienced high frequency of pH <7.0 were typically located upstream with minor to moderate tidal influence. Values of pH <7.0 have been associated with reduced bivalve growth (Ringwood and Keppler 2002), increased fecal coliform survival (Solic and Krstulovic 1992), and increased toxicity of ammonia for certain fish species (Thurston et al. 1981).

NERR sites with a wide salinity range experienced pH values >8.0 at least 25% of the time between 1999-2000 (Appendix 16); however, NERR sites with mean salinity >15 ppt (16 of 33) experienced pH values >8.0 more frequently than NERR sites with mean salinity <15 ppt (4 of 22). The effects of high pH are not well documented; however, pH >9.5 has been reported to increase phosphate uptake and contribute to algal blooms in tidal freshwater reaches of the Potomac River (Seitzinger 1991).

Turbidity >25 NTU, the federal standard for high turbidity (**www.epa.gov)**, was experienced more than 25% of the time in 1999-2000 at several NERR sites (Appendix 17). High turbidity was experienced at one West Coast site (PDBJL), the two Northeast freshwater Reserves (OWC and HUD), and about half of sites in other regions.

Seasonal and Intra-seasonal variability

Seasonal variation in water temperature was apparent for all regions; however, the extent of seasonal variation in water temperature varied among regions (Appendices 18-22). With the exception of PDBJL, mean water temperatures among West Coast sites varied ≤ 10°C between seasons. At NERRs in the Northeast and Mid-Atlantic regions, mean water temperature typically varied 10-20°C between seasons; however, seasonal temperatures were shifted by about 5°C between these regions, such that mean summer temperatures in the Northeast and Mid-Atlantic regions were 20°C and 25°C, respectively. Seasonal temperature variation at NERRs in the Southeast was typically 10-15°C and seasonal temperatures were approximately 5°C warmer with respect to NERRs in the Mid-Atlantic. Seasonal temperature variation at NERRs in the northern Gulf of Mexico (WKB, APA) were similar to seasonal variation observed for NERRs in the Southeast, but seasonal temperatures were also about 5°C warmer. Seasonal temperature variation at the RKB and JOB NERRs were <10°C and <5°C, respectively. Intra-seasonal variation was most pronounced during the first sampling season at sites.

Seasonal salinity patterns between 1995-2000 were evident for most sites throughout the NERR SWMP. Most sites experienced the lowest mean salinity in winter/spring and the greatest mean salinity in summer/fall, regardless of geography (Appendices 23-27). Exceptions to this trend were observed at the Rookery Bay Reserve, where mean salinity in summer/fall was substantially lower than mean salinity in winter/spring. Seasonal variation in salinity was not well defined for seven sites (PDBBY, WQBMP, WELIN, MULB6, NOCMS, JOB09, and JOB10). Overall salinity at these sites was ≥ 28 ppt and most were located in open water systems with minor to moderate daily salinity variation.

Seasonal precipitation patterns were in phase with seasonal salinity patterns for sites on the West Coast and at the Rookery Bay NERR where maximum precipitation and minimum salinity occurred in winter and summer, respectively (Appendices 28 & 32). In contrast, seasonal precipitation for most of the other NERRs was six to nine months out of phase with salinity (Appendices 29-31). Seasonal precipitation was typically greatest in the summer or fall for NERRs in Puerto Rico, the northern Gulf of Mexico, the Southeast, and the Mid-Atlantic. At the WKB and APA NERRs, winter and summer were both wet seasons. Seasonal variability in precipitation was not discernable for NERRs in the Northeast.

Intra-seasonal variability in precipitation between 1995-2000 was noted for many sites and was most pronounced in fall and winter for sites on the West Coast and in summer for sites on the East Coast. Substantially more precipitation was recorded in winters 1995 and 1998 at the TJR, ELK, and SOS NERRs and in fall 1996 at the ELK and SOS NERRs, than during other years (Appendix 28). At NERRs along the Eastern Seaboard, summers 1996 and 1999 were especially wet, as was winter 1998 at NERRs along the Eastern Seaboard and in the northern Gulf of Mexico (Appendices 29-32).

Evapo-transpiration, as well as precipitation, appears to influence seasonal salinity at sites with discernable seasonal patterns. Seasonal variability in water temperature at sites on the West Coast and the Rookery Bay NERR was less pronounced than observed for other NERRs (Appendices 18 & 22); thus, seasonal variability in evapo-transpiration would also be expected to be less severe. At these sites, precipitation may be more important than evapo-transpiration in determining salinity distributions. Seasonal variability in water temperature at sites along the East Coast and northern Gulf of Mexico experience dramatic seasonal variation in water temperature (Appendices 19-22); thus, seasonal variability in evapo-transpiration should reflect this trend. At these sites, maximum precipitation and minimum salinity were out of phase, suggesting that direct precipitation input may not be as important in determining salinity distributions. At these sites, maximum evapo-transpiration in the summer and minimum evapo-transpiration in the winter provides an alternative explanation for seasonal salinity patterns. Seasonal salinity patterns at these sites may also be related to runoff of surface and/or groundwater in the spring.

The effects of precipitation in determining salinity distributions appear to be most pronounced in the summer, during periods of maximum evapo-transpiration. During the summer, salinity at many sites was sustained at the annual maximum and, in some cases, the maximum observed between 1995-2000. During periods of maximum annual salinity, daily salinity variation was usually markedly less than observed during other seasons, and often, less than the mean daily variation for that season. This pattern likely reflects the effects of low precipitation and maximum evapo-transpiration during this time. During these periods, abrupt decreases in salinity are evident from annual scatter plots and may have been related to precipitation activity. Abrupt short-term decreases and sustained long-term decreases in salinity associated with precipitation events were documented during the passage of tropical systems in this report. Although several tropical systems had long-term decreasing effects on salinity (*see Chapter 6*), the immediate effect of these systems on salinity was to restore daily salinity variation patterns at these sites. This scenario was particularly evident for drought-stricken sites at the Great Bay NERR associated with the passage of Hurricane Floyd in 1999.

Hypoxic duration

Duration of hypoxic events during the first 48-hours post-deployment was examined for all 55 sites with data between 1995-2000. On average, 85% (range = 61-100%) of deployments at each site contained the full 48-hour record and were used in these analyses (Table 1). Of the deployments used in these analyses, 16% (range = 0-74%) of all deployments contained at least one hypoxic (DO <28% sat) event. The percent of deployments used in these analyses was similar among geographic regions; however, the percent of deployments with hypoxic events was substantially greater at West Coast and Gulf of Mexico/Puerto Rico sites (22-28%) than observed for the Mid-Atlantic (15%), Southeast (11%), and Northeast (6%) regions.

A total of 1,564 hypoxic events were observed in the deployments examined (Table 2). Thirty-two percent of these events were observed at West Coast NERRs, down 8% from 1996-1998 (Wenner et al 2001). This finding loosely suggests that hypoxic events may have decreased in 1999-2000; however, 11% of West Coast deployments were not examined. Twelve percent of hypoxic events were observed at Northeast NERRs, the same as previously reported. Hypoxic events at Mid-Atlantic, Southeast, and Gulf of Mexico/Puerto Rico NERRs increased 2-4% (12-20% total) from 1996-1998 levels.

Frequency of hypoxic duration for 1995-2000 data was similar to frequency of hypoxic duration in 1996-1998 (Wenner et al. 2001). Hypoxic events lasting less than 4 hours decreased by one percent and were compensated for by hypoxic events lasting 12-16 hours, which subsequently increased by one percent. Ninety-five percent of all hypoxic events lasted less than 12 hours, similar to 1996-1998 estimates (Wenner et al. 2001).

Table 1. Overview of deployments used to examine hypoxic duration.

	Deployments				Hypoxia		
Site	**Total**	**Not Used**	**Used**	**% Used**	**Events**	**Deployments**	**% of Deployments**
tjrmm	3	0	3	100	0	0	0
tjros	102	11	91	89	143	45	49
tjrtl	41	2	39	95	81	27	69
elkap	73	7	66	90	105	49	74
elknm	24	7	17	71	36	10	59
elksm	70	10	60	86	2	1	2
sosse	68	12	56	82	14	7	13
sosvi	22	0	22	100	0	0	0
soswi	73	21	52	71	1	1	2
pdbby	50	2	48	96	0	0	0
pdbjl	109	7	102	94	120	40	39
MEAN				**89**			**28**
welht	49	7	42	86	3	2	5
welin	58	6	52	90	18	6	12
grbgb	64	8	56	88	0	0	0
grblr	17	5	12	71	0	0	0
grbsq	32	4	28	88	0	0	0
wqbcb	28	4	24	86	1	1	4
wqbmp	24	2	22	92	2	1	5
narpc	84	16	68	81	4	3	4
nartw	49	6	43	88	4	2	5
hudsk	68	8	60	88	0	0	0
hudtn	25	3	22	88	0	0	0
hudts	70	7	63	90	9	5	8
owcsu	100	10	90	90	66	18	20
owcwm	109	7	102	94	75	22	22
MEAN				**87**			**6**
mulb6	92	23	69	75	0	0	0
mulba	88	18	70	80	0	0	0
mulcn	86	12	74	86	0	0	0
delbl	124	11	113	91	44	14	12
delpb	96	14	82	85	49	17	21
delsl	122	9	113	93	66	19	17
cbmjb	58	13	45	78	108	33	73
cbmpr	47	16	31	66	5	1	3
cbvgi	107	8	99	93	4	4	4
cbvtc	136	12	124	91	35	22	18
MEAN				**84**			**15**
nocms	130	15	115	88	1	1	1
noczi	115	11	104	90	0	0	0
niwdc	51	2	49	96	9	5	10
niwol	108	11	97	90	8	6	6
niwta	132	16	116	88	49	18	16
acebb	88	18	70	80	21	10	14
acesp	90	17	73	81	34	15	21
sapfd	104	41	63	61	17	10	16
saphd	32	3	29	91	19	7	24
sapld	47	4	43	91	22	7	16
sapml	90	25	65	72	0	0	0
MEAN				**84**			**11**
wkbfr	132	17	115	87	16	4	3
wkbwb	128	16	112	88	6	4	4
apaeb	114	45	69	61	11	2	3
apaes	117	35	82	70	23	9	11
rkbbr	47	5	42	89	85	24	57
rkbmb	26	0	26	100	37	9	35
rkbuh	102	15	87	85	144	32	37
job09	60	19	41	68	52	17	41
job10	52	5	47	90	15	5	11
MEAN				**82**			**22**
			Mean	85		*Mean*	16
			Min	61		*Min*	0
			Max	100		*Max*	74

Table 2. Frequency of occurrence of extended hypoxic events (two consecutive observations with DO < 28% sat) during the first 48-hours post-deployment recorded at NERR sites between 1995-2000. Percent number (%N) represents the regional contribution to the total number of extended hypoxic events observed. Percent (%) values for each duration category are additive within a particular region.

	N	%N	<4 h	%	4-8 h	%	8-12 h	%	12-16h	%	16-20 h	%	20-24 h	%	>24 h	%
West Coast	502	32	318	63	124	25	46	9	10	2	3	1	1	0	0	0
Northeast	182	12	155	85	14	8	7	4	2	1	2	1	1	1	1	1
Mid-Atlantic	311	20	236	76	53	17	6	2	6	2	0	0	0	0	10	3
Southeast	180	12	159	88	15	8	3	2	2	1	0	0	0	0	1	1
Gulf/PR	389	25	286	74	54	14	15	4	10	3	8	2	6	2	10	3
Percent			74		17		5		2		1		1		1	

Frequency of hypoxia >12 hours was similar among geographic regions (2-8%); however, frequency of hypoxia <12 hours was different among regions (Table 2). At NERRs in the Northeast and Southeast, hypoxic events <4 hours in duration accounted for 85-88% of total hypoxic events compared to 74-75% of total hypoxic events in the Gulf of Mexico/Puerto Rico and Mid-Atlantic regions and 63% of total hypoxic events at NERRs on the West Coast. Subsequently, greater percentages of hypoxic events lasting 4-8 hours in duration and 8-12 hours in duration were observed for NERRs on the West Coast, and greater percentages of hypoxic events lasting 4-8 hours, 8-12 hours, and >24 hours were observed for Mid-Atlantic and Gulf of Mexico/Puerto Rico NERRs.

Predicted annual duration of hypoxia based on 1995-2000 data was similar to estimates calculated from 1996-1998 data (Figures 9-13). No hypoxia was observed in deployments examined for 12 sites (Table 1); thus, predicted hypoxia at these sites reflects this lack of input data. Hypoxic events are a naturally occurring phenomenon (Wenner et al. 2001) and hypoxia was observed at these sites in deployments not used for these analyses due to incomplete data sampling during the first 48-hours post-deployment. Given these observations, predicted annual duration of hypoxia from these analyses should be interpreted loosely and not conclusively.

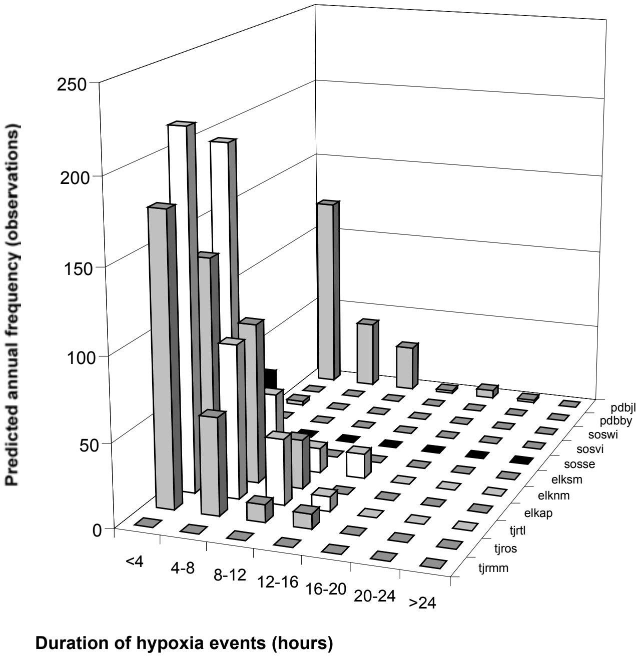

Figure 9. Predicted annual occurrence and duration of hypoxia at West Coast NERRs.

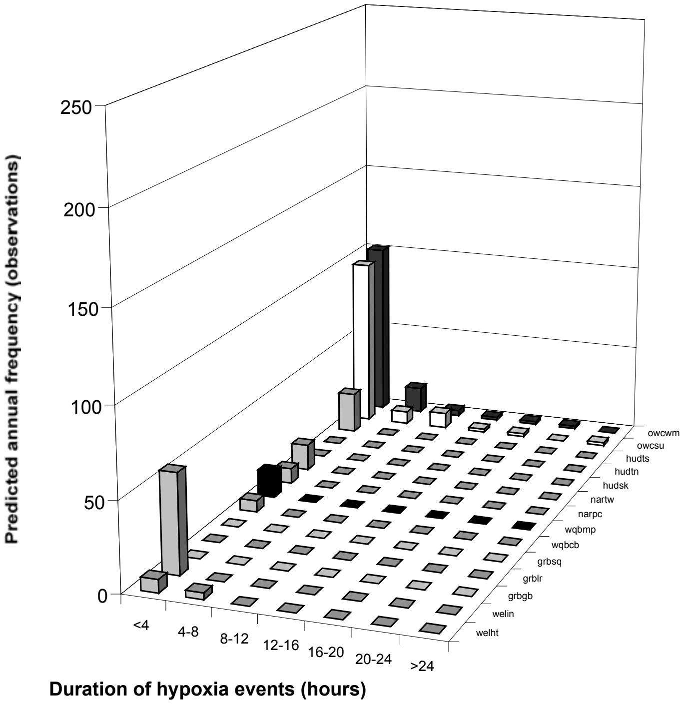

Figure 10. Predicted annual occurrence and duration of hypoxia at Northeast NERRs.

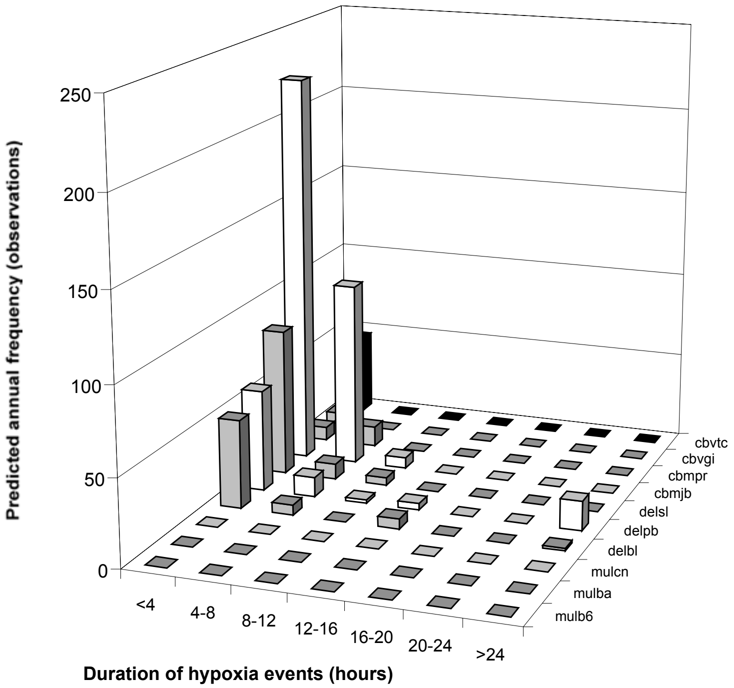

Figure 11. Predicted annual occurrence and duration of hypoxia at Mid-Atlantic NERRs.

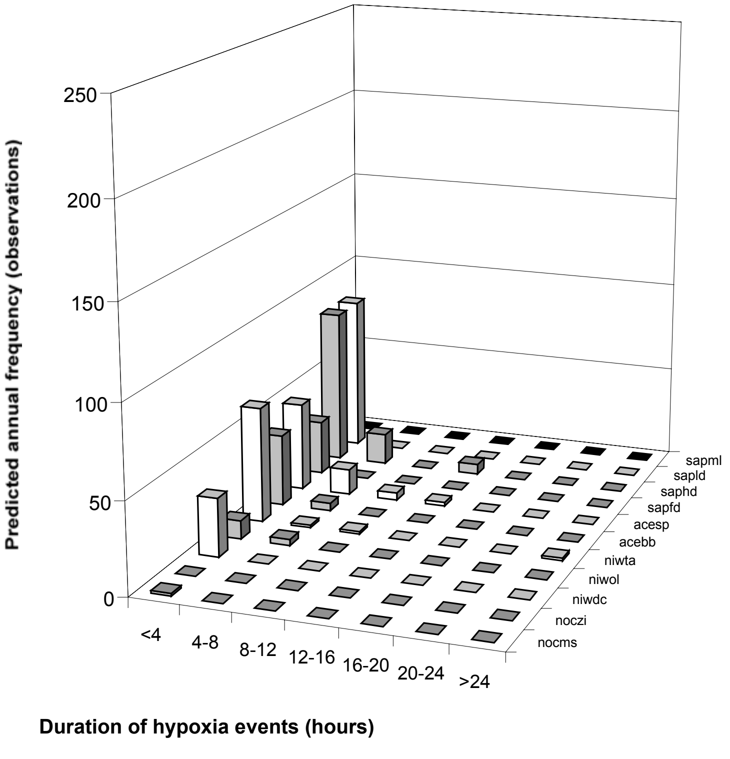

Figure 12. Predicted annual occurrence and duration of hypoxia at Southeast NERRs.

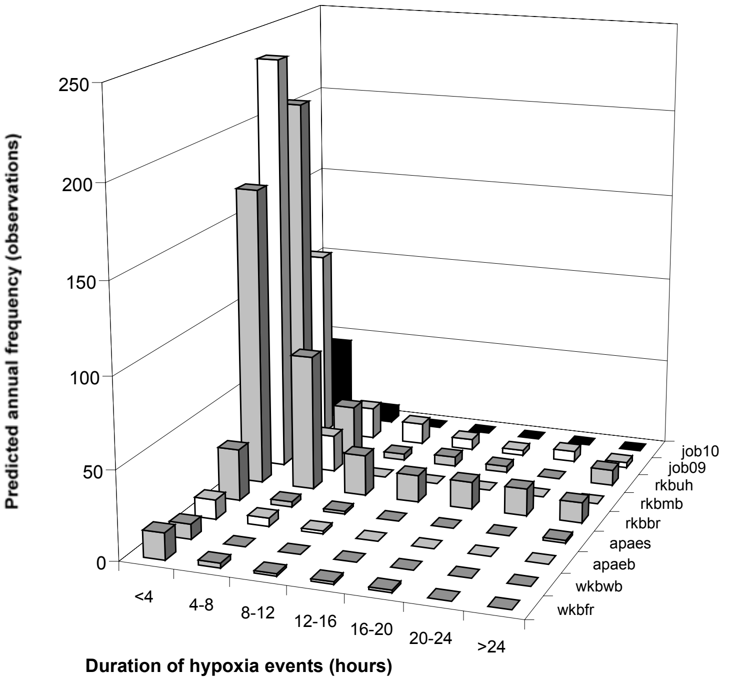

Figure 13. Predicted annual occurrence & duration of hypoxia, Gulf and Caribbean NERRs.

Analysis of Variance
Significant interactions were included in the model, but are not discussed here due to the goal of this synthesis to examine trends among Reserves rather than trends among individual sites. Overall model significance ($p < 0.05$) was used to determine which Reserves to include in the discussion of results; however, presentation and discussion of results is based on least-square mean values.

Hypoxia
Models from the Great Bay, Mullica River, Hudson River, North Carolina, and South Slough NERRs were not interpretable because very few values exceeded 0 or these values occurred in only one site, one season, and one year. Subsequently, these models returned no estimates on least-squares means for at least 2 of the treatments; thus, these Reserves were excluded from hypoxia analyses. Hypoxia models were significant (R^2 = 0.13 to 0.73) for all Reserves except Rookery Bay and Elkhorn Slough (Table 3).

Site differences were observed for two Reserves (Padilla Bay, North Carolina), with Joe Leary Slough having significantly greater percent of time hypoxia than Bayview Channel and Masonboro Island having greater percent of time with hypoxia than Zeke's Island, respectively. Seasonal differences in hypoxia were significant for 11 Reserves. Highest levels of hypoxia were observed in the summer at seven Reserves (Padilla Bay, Waquoit Bay, Old Woman Creek, Chesapeake Bay VA, ACE Basin, Sapelo Island and Apalachicola Bay) and in the spring at four Reserves (Wells, Delaware Bay, Chesapeake Bay MD, and Week's Bay). Lowest levels of hypoxia were observed in winter or fall for most Reserves, except Chesapeake Bay MD, where lowest levels of hypoxia were observed in the summer. Hypoxia was significantly different among years (1996-2000) for 14 Reserves, with no consistent pattern among all Reserves or within a given region. Hypoxia was likely related to a host of factors including elevated temperature, low tide, water mass residence time and nutrient and organic loading (*see Chapters 4 and 5*).

Supersaturation

Models from the Tijuana River Estuary, Hudson River, Mullica River, Sapelo Island, and Rookery Bay NERRs were not interpretable because very few values exceeded 0 or these values occurred in only one site, one season, and one year. Subsequently, these models returned no estimates on least squares means for at least 2 of the treatments; thus, these Reserves were excluded from supersaturation analyses. Supersaturation models were significant (R^2 = 0.08 to 0.68) for all Reserves except Elkhorn Slough and Weeks Bay (Table 4).

Site differences were only observed for one Reserve (Padilla Bay), with Joe Leary having significantly higher levels of supersaturation than Bayview Channel. Seasonal differences in supersaturation were significant for eight Reserves with greatest amount of time with supersaturation observed in summer (Padilla Bay, Great Bay, Narragansett Bay, Waquoit Bay, Old Woman Creek, Chesapeake Bay VA, ACE Basin, and Apalachicola Bay) and in spring at the Chesapeake Bay MD Reserve. The lowest levels of supersaturation were observed in the winter or fall for most Reserves, except Chesapeake Bay MD, where highest supersaturation was observed in winter. Supersaturation was significantly different among years (1996-2000) for 12 Reserves, with no consistent pattern among all Reserves or for Reserves within a given region.

Salinity

Models for salinity were significant (R^2 = 0.07 to 0.84) for 13 Reserves (Table 5). Salinity models were significant for Reserves from all geographic regions, including three freshwater Reserves (Hudson River, Old Woman Creek, and Chesapeake Bay MD). Salinity models were significant at Reserves from all geographic regions, but were proportionally more significant for Southeast Reserves (3 of 4) and Northeast Reserves (4 of 6) than for Reserves from all other regions (2 of 4).

Salinity was significantly different between sites within a Reserve at six Reserves (Padilla Bay, South Slough, Great Bay, Narragansett Bay, ACE Basin, and Weeks Bay). Seasonal differences in salinity were observed at 11 Reserves. Salinity was greatest in the summer at seven Reserves (Padilla Bay, South Slough, Great Bay, Narragansett Bay, Chesapeake Bay VA, North Inlet-Winyah Bay, and ACE Basin) and greatest in fall at four Reserves (Old Woman Creek, North Carolina, Week's Bay, and Jobos Bay). Salinity at these Reserves was lowest in winter or spring, except for Jobos Bay, where salinity was lowest in summer. Salinity was significantly different among years (1996-2000) at 11 Reserves; however, no consistent pattern was observed for maximum salinity among Reserves or for Reserves within a given geographic region.

pH

Models for pH were significant (R^2 = 0.12 to 0.88) for twelve Reserves, approximately half of the Reserves in the NERR SWMP (Table 6). These models were significant for Reserves from all geographic regions, but were proportionally greater for Reserves in the Northeast (5 of 6) than all other regions (1-2 out of 4). Reserves with significant models for pH included Elkhorn Slough, Padilla Bay, Great Bay, Waquoit Bay, Narragansett Bay, Hudson River, Old Woman Creek, Chesapeake Bay VA, North Carolina, North Inlet-Winyah Bay, Rookery Bay and Weeks Bay.

Site differences in pH were observed for all but two Reserves (North Inlet-Winyah Bay and Waquoit Bay). Seasonal differences in pH were observed for all Reserves, with no consistent pattern detected among seasons overall or for Reserves within a given geographic region. Significant differences in pH between 1999-2000 were detected for two Reserves in the Southeast (North Inlet-Winyah Bay and North Carolina) and two Reserves in the Northeast (Old Woman Creek and Waquoit Bay). The two Southeast Reserves had significantly higher pH values in 2000 than in 1999, compared to the two Northeast Reserves, which had significantly higher pH values in 1999 than in 2000.

Turbidity

Models for turbidity were statistically significant (R^2 = 0.15 to 0.84, Table 7) for all but three Reserves (Delaware Bay, Mullica River, and Waquoit Bay). Turbidity data was not available for a fourth Reserve, Chesapeake Bay MD, in 1999-2000.

Site differences in turbidity were observed for nine Reserves and were proportionally greater (3 of 4) for West Coast (Tijuana River, Padilla Bay and South Slough) and Gulf of Mexico/Caribbean Reserves (Apalachicola Bay, Rookery Bay, and Weeks Bay) than for other regions. Seasonal differences in turbidity were observed for 16 Reserves, representing all geographic regions. West Coast NERRs had the highest turbidity in the winter, consistent with maximum precipitation (Appendix 28). Lowest turbidity among West Coast NERRs occurred in the fall, summer or spring depending on the Reserve. Reserves in the Southeast consistently had the lowest turbidity in the winter, when annual precipitation was at a minimum (Appendix 31). Within the Southeast region, highest turbidity values varied among season for the different Reserves. No consistent patterns in seasonal turbidity maximums were observed for other geographic regions. Turbidity was significantly greater in 1999 at two Reserves (Apalachicola Bay and Old Woman Creek) and significantly greater in 2000 for three Reserves (North Inlet-Winyah Bay, North Carolina, and Week’s Bay).

Table 3. Three-way ANOVA for site (n), season (s), and year (y) and least-squares mean for hypoxia during the first 48-hours post-deployment, NERR SWMP 1996-2000. Italicized text indicates non-significant (p >0.05) or non-interpretable results. Shaded lines denote breaks between geographic regions (West Coast, Northeast, Mid-Atlantic, Southeast, Gulf of Mexico/Caribbean). Least-squares mean values are arranged from left to right from highest to lowest. Similarity of least-squares mean values for seasons and years occur when (1) values overlap between rows, or (2) co-occur on the same row.

									Least-squares Mean		
NERR	**Transform**	**n**	**Model p-value**	**Model R2**	**Site p-value**	**Year p-value**	**Season p-value**	**Inter-action**	**Site**	**Year**	**Season**
tjr	Rank	135	0.0349	0.13	0.7439	0.0201	0.218			96 98 97 97 99 00	
elk	*Rank*	*138*	*0.3817*	*0.07*	*0.3565*	*0.3951*	*0.2048*				
sos	*Rank*	*105*	*<.0001*	*0.44*	*0.0152*	*<.0001*	*0.698*	*n*y y*s*			
pdb	Rank	139	<.0001	0.32	<.0001	0.0261	0.0289		jl > by	98 99 99 00 97 96	Su F F Sp W
wel	Rank	72	<.0001	0.64	0.2382	<.0001	0.1231	y*s		96 97 98 00 00 99	Sp W Su W Su F
grb	*Rank*	*92*	*<.0001*		*<.0001*	*<.0001*	*<.0001*	*all*			
wqb	Rank	45	<.0001	0.67	0.9197	<.0001	0.0003			00 97 96 96 98 99	Su F Sp W
nar	Rank	116	<.0001	0.73	0.024	<.0001	0.0004	y*s n*s	pc	00 99 97	
hud	*Rank*	*130*	*<.0001*	*0.75*	*0.3857*	*<.0001*	*<.0001*	*n*y n*s y*s*			
owc	Rank	173	<.0001	0.40	0.3746	<.0001	<.0001			99 98 00 97 97 96	Su Sp F W
mul	*Rank*	*227*	*<.0001*	*0.93*	*<.0001*	*<.0001*	*<.0001*	*all*			
del	Rank	296	0.0014	0.15	0.9042	0.4539	0.0656	y*s			Sp F Su Su W
cbm	Rank	53	0.0007	0.41	0.441	0.0013	0.1022			96 99 98 00 99 98 00	Sp W F Su W F Su
cbv	Rank	221	<.0001	0.52	0.1403	<.0001	<.0001	y*s		00 98 99 96 97	Su Sp F W
noc	Rank	173	<.0001	0.98	<.0001	<.0001	<.0001	all	ms > zi	96 98 00 97 99	F Su Sp W
niw	Rank	239	<.0001	0.42	0.2291	<.0001	0.42	n*y*s		00 98 99	
ace	Rank	119	0.0048	0.18	0.8351	0.0521	0.0075			98 99 97 99 97 96 00	Su F F Sp Sp W
sap	Rank	205	0.0003	0.15	0.2342	0.0004	0.0546			99 97 96 00 97 96 00 98	Su W Sp W Sp F
wkb	Rank	219	<.0001	0.60	0.0085	<.0001	0.0023	all		00 96 96 97 99	Sp W F
apa	Rank	146	<.0001	0.26	0.227	<.0001	0.0002			00 98 98 99 99 97 96	Su Sp Sp W W F
rkb	*Rank*	*160*	*0.7647*	*0.04*	*0.9425*	*0.2352*	*0.9696*				
job	Rank	90	0.0001	0.46	0.4953	0.0007	0.5662	y*s	no est	96 00 00 99 99 98	

Table 4. Three-way ANOVA for site (*n*), season (*s*), and year (*y*) and least-squares mean for supersaturation during the first 48-hours post-deployment, NERR SWMP 1996-2000. Italicized text indicates non-significant or non-interpretable results. Shaded lines denote breaks between geographic regions (West Coast, Northeast, Mid-Atlantic, Southeast, Gulf of Mexico/Caribbean). Least-squares mean values are arranged from left to right from highest to lowest. Similarity of least-squares mean values for seasons and years occur when (1) values overlap between rows, or (2) co-occur on the same row.

									Least-squares Mean		
NERR	**Transform**	***n***	**Model p-value**	**Model r2**	**Site p-value**	**Year p-value**	**Season p-value**	**Inter-action**	**Site**	**Year**	**Season**
tjr	*arcsine*	*135*	*<.0001*	*0.61*	*<.0001*	*0.0003*	*0.2906*	*n*y n*s y*s*			
elk	*Rank*	*138*	*0.5535*	*0.06*	*0.4351*	*0.5092*	*0.2949*				
sos	*Rank*	*105*	*0.2943*	*0.10*	*0.6357*	*0.2109*	*0.2653*				
pdb	Rank	139	<.0001	0.34	<.0001	0.0164	0.0192		jl > by	98 99 00	Su F
										99 00 97	F Sp W
										97 96	
wel	Rank	72	0.001	0.33	0.4204	0.0003	0.3482			96	
										97 98 00	
										98 00 99	
grb	Rank	92	<.0001	0.40	0.3515	<.0001	0.0032			97 96	Su Sp
										96 98 99	F
										00	
wqb	arcsine	45	0.0034	0.45	0.0594	0.3022	0.001				Su Sp W
											W F
nar	Rank	116	0.0128	0.16	0.1081	0.0302	0.0814			00 99 98	Su F W
										99 98 96 97	W Sp
hud	*Rank*	*130*	*<.0001*	*0.68*	*0.6593*	*<.0001*	*0.0001*	*n*y y*s*			
owc	Rank	173	<.0001	0.37	0.3993	<.0001	<.0001			99	Su
										98 00 97	Sp
										96	F W
mul	*Rank*	*227*	*0.0046*	*0.35*	*0.2772*	*0.0138*	*0.0569*	*n*y*s*			
del	*Rank*	*296*	*<.0001*	*0.33*	*0.1258*	*0.0219*	*0.0595*	*y*s n*y*s*			
cbm	Rank	53	0.0035	0.36	0.4886	0.0046	0.1669			96 99 98	Sp W F
										99 98 00	W F Su
cbv	Rank	221	<0.0001	0.21	0.2448	0.0274	<.0001			00 98 99	Su
										99 97	Sp
										97 96	F W
noc	Rank	173	0.0089	0.11	0.1706	0.0041	0.4917			00 96 98 97	
										99	
niw	Rank	239	0.0182	0.08	0.7731	0.0027	0.4018			96 97 00 98	
										99	
ace	Rank	119	0.0002	0.37	0.7397	0.0431	0.0057	y*s		98 99 97	Su F
										99 97 00 96	Sp W
sap	*Rank*	*205*	*<.0001*	*0.39*	*0.0519*	*<.0001*	*0.0112*	*n*s y*s*			
wkb	*Rank*	*219*	*0.5089*	*0.03*	*0.2109*	*0.4374*	*0.7573*				
apa	Rank	146	0.001	0.17	0.3508	0.0047	0.0082			00 98	Su Sp
										98 99 97	Sp W
										99 97 96	W F
rkb	*Rank*	*160*	*<.0001*	*0.33*	*0.0101*	*<.0001*	*0.2283*	*n*y y*s*			
job	Rank	90	0.0013	0.26	0.4541	0.0002	0.2381			96 00	
										00 99	
										99 98 97	

Table 5. Three-way ANOVA for site (*n*), season (*s*), and year (*y*) and least-squares mean for salinity during the first seven days post-deployment, NERR SWMP 1996-2000. Italicized text indicates non-significant or non-interpretable results. Shaded lines denote breaks between geographic regions (West Coast, Northeast, Mid-Atlantic, Southeast, Gulf of Mexico/Caribbean). Least-squares mean values are arranged left to right from highest to lowest. Similarity of least-squares mean values for seasons and years occur when (1) values overlap between rows, or (2) co-occur on the same row.

									Least-squares Mean		
NERR	**Transform**	**n**	**Model p-value**	**Model r2**	**Site p-value**	**Year p-value**	**Season p-value**	**Inter-action**	**Site**	**Year**	**Season**
tjr	*Rank*	*143*	*0.1668*	*0.09*	*0.3856*	*0.8173*	*0.0559*				
elk	*Rank*	*148*	*0.9678*	*0.02*	*0.8800*	*0.7716*	*0.8874*				
sos	No	130	<0.0001	0.84	<0.0001	<0.0001	0.1556		vi>wi=se	00 97 99 98	Su
										97 99 98 96	F
											Sp
											W
pdb	Rank	142	<0.0001	0.25	<0.0001	0.0940	0.1063		jl>by	98 99 00 97	Su F Sp
										99 00 97 96	F Sp W
wel	*Rank*	*81*	*0.0941*	*0.17*	*0.4488*	*0.7057*	*0.0258*				
grb	No	102	<0.0001	0.66	<0.0001	<0.0001	0.0094	s*y	gb>sq>lr	99	Su
										97 00 98 96	F
											Sp
wqb	*No*	*49*	*0.0685*	*0.29*	*0.8400*	*0.1677*	*0.6097*				
nar	No	130	<0.0001	0.74	<0.0001	<0.0001	<0.0001	s*y	tw>pc	00 99	Su F
										99 97	Sp W
										96 98	
hud	Rank	137	<0.0001	0.44	0.7676	0.0254	<0.0001	s*y			
owc	No	179	<0.0001	0.72	<0.0001	<0.0001	<0.0001	n*s s*y			F Sp
											Su
mul	*Rank*	*258*	*0.3046*	*0.04*	*0.4311*	*0.1364*	*0.6771*				
del	*Rank*	*319*	*0.8384*	*0.02*	*0.9831*	*0.3153*	*0.9036*				
cbm	Rank	77	<0.0001	0.38	0.8962	0.7701	<0.0001			96	
										99 00 98 97	
cbv	Rank	235	<0.0001	0.22	0.1979	<0.0001	0.0217			00 98 99	Su
										99 97 96	Sp
											F W
noc	Rank	195	0.0036	0.11	0.7880	0.2137	0.0109			00 97 98 96	F Sp Su
										99	Sp Su W
niw	Rank	257	0.0392	0.07	0.7671	0.0498	0.1191			97 00 96 98	Su W
										96 98 99	W F Sp
ace	No	143	<0.0001	0.69	<0.0001	<0.0001	<0.0001	s*y	bb>sp	00	Su F
										99 97	Sp
										97 96	W
										96 98	
sap	*Rank*	*230*	*0.4076*	*0.05*	*0.6615*	*0.2916*	*0.5308*				
apa	*Rank*	*200*	*0.3051*	*0.05*	*0.8658*	*0.0442*	*0.8530*				
wkb	No	251	<0.0001	0.81	<0.0001	<0.0001	<0.0001	s*y	wb>fr	00	F
										99	Su
										97 98 96	W
											Sp
rkb	*Rank*	*174*	*0.9702*	*0.02*	*0.8979*	*0.7962*	*0.8474*				
job	Rank	92	0.0115	0.21	0.7634	0.0748	0.0254			96 00	F Sp
										00 98 97	Sp W Su
										98 97 99	

Table 6. Three-way ANOVA for site (*n*), season (*s*), and year (*y*) and least-squares mean for pH during the first seven days post-deployment, NERR SWMP 1999-2000. Italicized text indicates non-significant or non-interpretable results. Shaded lines denote breaks between geographic regions (West Coast, Northeast, Mid-Atlantic, Southeast, Gulf of Mexico/Caribbean). Least-squares mean values are arranged left to right from highest to lowest. Similarity of least-squares mean values for seasons and years occur when (1) values overlap between rows, or (2) co-occur on the same row.

									Least-squares Mean		
NERR	**Transform**	**n**	**Model p-value**	**Model r2**	**Site p-value**	**Year p-value**	**Season p-value**	**Inter-action**	**Site**	**Year**	**Season**
tjr	*Rank*	*30*	*0.9821*	*0.04*	*0.9417*	*0.8886*	*0.8092*				
elk	No	68	<.0001	0.71	0.0003	0.0002	<.0001	n*y n*s y*s	ap > sm		F Sp Su
sos	*Rank*	*78*	*0.8141*	*0.04*	*0.8302*	*0.9539*	*0.4608*				
pdb	No	55	<.0001	0.72	<.0001	0.1877	<.0001		by > jl		W F Sp Su
wel	*Rank*	*25*	*0.9127*	*0.07*	*0.7559*	*0.4638*	*0.8964*				
grb	No	41	<.0001	0.72	<.0001	0.4032	0.0616	y*s	gb > sq > lr		Su F F Sp
wqb	No	22	0.0415	0.43		0.0064	0.125			99 00	Sp W Su W Su F
nar	No	67	<.0001	0.46	0.033	0.4248	<.0001	y*s	tw > pc		W F Sp Su
hud	No	78	<.0001	0.88	<.0001	0.4578	<.0001	n*y*s	sk > ts		F Su
owc	Rank	91	<.0001	0.26	0.7888	0.036	0.0001			99 00	Su Sp W W F
mul	*Rank*	*124*	*0.5807*	*0.04*	*0.1825*	*0.9645*	*0.7379*				
del	*Rank*	*123*	*0.9886*	*0.01*	*0.9198*	*0.5901*	*0.9507*				
cbm	*No*	*15*	*0.782*	*0.09*			*0.8304*				
cbv	No	129	<.0001	0.74	<.0001	0.3045	<.0001	n*s y*s	gi > tc		W F Su Sp
noc	Rank	67	0.0012	0.28	0.0476	0.0039	0.2374		ms > zi	00 99	Sp F Su F Su W
niw	Rank	112	0.0297	0.12	0.98	0.0332	0.0393			00 99	Su Sp Sp F W
ace	*Rank*	*57*	*0.6589*	*0.06*	*0.7598*	*0.9262*	*0.3744*				
sap	*Rank*	*69*	*0.1325*	*0.12*	*0.975*	*0.0212*	*0.3826*				
wkb	No	103	<.0001	0.55	<.0001	0.8069	<.0001	n*s	wb > fr		F W W Su Su Sp
apa	*Rank*	*80*	*0.9503*	*0.02*	*0.8475*	*0.8709*	*0.7805*				
rkb	No	95	<.0001	0.59	<.0001	0.1549	0.0004		mb > uh > br		Sp Su F W
job	*Rank*	*44*	*0.0855*	*0.22*	*0.8164*	*0.1738*	*0.117*				

Table 7. Three-way ANOVA for site (*n*), season (*s*), and year (*y*) and least-squares mean for turbidity during the first seven days post-deployment, NERR SWMP 1999-2000. Italicized text indicates non-significant or non-interpretable results. Shaded lines denote breaks between geographic regions (West Coast, Northeast, Mid-Atlantic, Southeast, Gulf of Mexico/Caribbean). Least-squares mean values are arranged left to right from highest to lowest. Similarity of least-squares mean values for seasons and years occur when (1) values overlap between rows, or (2) co-occur on the same row.

NERR	Transform	*n*	Model p-value	Model r2	Site p-value	Year p-value	Season p-value	Inter-action	Least-squares Mean Site	Least-squares Mean Year	Least-squares Mean Season
tjr	log	34	0.0031	0.4560	0.0054	0.4171	0.0798		tl > os		W Sp F Sp F Su
elk	No	68	0.0014	0.3352	0.9814	0.5843	0.0007	n*y			W Sp Su F
sos	log	72	<0.0001	0.4361	<0.0001	0.1143	0.0599		se > wi > vi		W F Su Su Sp
pdb	No	56	<0.0001	0.8449	<0.0001	0.9849	<0.0001	n*s y*s	jl > by		W F Sp Sp Su
wel	log	25	0.0369	0.4947	0.0090	0.1479	0.7256		in > ht		
grb	No	45	<0.0001	0.5752	<0.0001	0.0716	0.0453		sq > lr > gb		Sp F F Su
wqb	*No*	*22*	*0.9599*	*0.0343*	*N/A*	*0.6921*	*0.9681*				
nar	log	60	0.0183	0.2448	0.0084	0.3207	0.1147		tw > pc		F W Su W Su Sp
hud	rank	78	0.0192	0.1677	0.8109	0.3859	0.0020				Su F F Sp
owc	rank	90	<0.0001	0.2678	0.8729	0.0287	0.0001			99 00	Su Sp W W F
mul	*rank*	*120*	*0.7610*	*0.0289*	*0.2834*	*0.9280*	*0.8535*				
del	*rank*	*121*	*0.8910*	*0.0196*	*0.9364*	*0.4279*	*0.6656*				
cbm	*No Data*	*No Data*	*No Data*	*No Data*	*No Data*	*No Data*	*No Data*				
cbv	rank	129	<0.0001	0.1889	0.1175	0.3442	<0.0001				Su Sp W F
noc	rank	67	0.0009	0.2837	0.0663	0.0020	0.1990			00 99	Sp F Su F Su W
niw	rank	105	0.0111	0.1526	0.9045	0.0453	0.0145			00 99	Su Sp F W
ace	log	36	0.0216	0.6378	0.1323	0.0443	0.3255	n*y*s			
sap	log	27	0.0397	0.4059	0.0090	0.9889	0.1433		ld > hd		Su Sp F Sp F W
wkb	rank	55	0.0258	0.2234	0.2440	0.0145	0.1170			00 99	Sp W F W F Su
apa	log	51	0.0073	0.2893	0.0127	0.4072	0.0089		eb > es	99 00	Sp Su W F
rkb	log	94	0.0034	0.2031	0.0121	0.1213	0.0366		mb > uh > br		F Su W W Sp
job	rank	45	0.0044	0.3444	0.4341	0.3514	0.0112				F W Sp Su

Chapter 3: Classification by Physical, Chemical, Climatic and Land-use Attributes.

Introduction

Previous classification of NERRs based on hierarchical cluster analysis indicated strong regional groupings, suggesting that climate played an important role in controlling water quality (Wenner et al. 2001). Because critical input attribute data used in these cluster analyses were not standardized to the watershed relative to the water body monitored by NERRs, classification of NERRs according to physical and chemical water quality indices and adjacent land-use practices was included in this synthesis. In addition to standardization and refinement of attribute data, 11 NERRs not evaluated by Wenner et al. (2001) were included, thus, substantially increasing the scope of this classification.

The principal objectives of this chapter are to (1) explore relationships among water quality, habitat and soil variables and detect groupings for the NERR sites based on the input variables, and (2) discriminate the groupings and geographic regions that were used to group the reserves. In order to detect the presence of natural groupings and to provide a baseline for comparison of the results with the new techniques and the 1996-1998 analyses (Wenner et al. 2001), hierarchical cluster analysis and correlation analyses were again utilized. In addition to these analyses, three additional analytical techniques (i.e., principal components analysis (PCA), nonlinear multidimensional scaling and discriminant analysis) were also included. Principal components analysis extracted independent and conceptually meaningful factors from correlated variables (Kleinbaum and Kupper 1978); thus, this technique reduced the dimensionality of the data to facilitate understanding of the complex nature behind the interrelated attributes. Multidimensional scaling was similar to PCA, but established the nonlinear relationship among variables to reduce the dimensionality. Discriminant analyses were performed to differentiate the NERR sites based on water quality and habitat characteristics. The stepwise discriminant analyses were used to select the differentiating variables.

Methods

Data

Eleven physical and chemical attributes represented half of the input data used in these analyses (Table 8). These data primarily consisted of site-specific summary statistics from the 1995-2000 NERR SWMP database. Physical data included mean water depth and mean water body width. Mean daily water depth was determined from the NERR SWMP database for all sites, except for three sites where YSI loggers were attached to floating platforms. At these sites (SAPML, SAPFD, GRBGB), depth was determined from the respective site metadata. Water body width was also determined from the site metadata; however, manual determination using Global Information System (GIS) technology was required in some instances when these data were not included in the site metadata. Six additional water quality variables [daily mean salinity, daily salinity range, hypoxia frequency, supersaturation frequency, frequency of cold water temperature (≤ 10°C), frequency of warm water temperature (≥ 25°C)] were calculated using the data between 1995-2000. Frequency of high turbidity (>25 NTU) and frequencies of extreme pH values (<7 and >8) were calculated using the data between 1999-2000.

Nine land-use and climatic data attributes represented the remaining input data used in these analyses (Table 9). Land-use data were derived from a Geographic Information System (GIS) database. Water quality sampling locations were first digitized using ArcView® software (Environmental System Research Institute, Inc., California). After digitization, the correctness of each location was compared to descriptions in the metadata, and with the GIS files provided by the National Oceanographic and Atmospheric Administration, Estuarine Reserves Division (NOAA ERD, Gunnar Lauenstein, pers. comm.). Watershed boundaries were delineated for each sampling location using digital raster data within NERRs, nationwide elevation, drainage basins, 8-digit HUC (Hydrological Unit Codes), creek, shoreline, and/or river data (Table 10). Watershed boundaries were delineated based on the area where waters were drained to a shared destination bound by topographic features and height of land. The majority of digital data was downloaded from the Coastal Assessment & Data Synthesis (CA&DS) system (Table 10), a national- and regional-level database and mapping analysis tool under development by the NOS Special Projects Office, in cooperation with other NOS offices. We quantified the watershed sizes after research coordinators had confirmed the delineation of watershed boundaries. ArcView extensions (i.e., Geo-processing and X-tools) were used to quantify seven habitat and soil attributes within each watershed for each sampling location including permeability (inches/hour), clay (%), agricultural land (% of area), forest land (% of area), wetland (% of area), urban/developed (% of area), and shellfish bed (% of area). GIS files of land use and soil were obtained through FTP server of the CA&DS System. Four major classes (agriculture, forest, wetland and urban) of the seven categorized land use types provided in the files were included in the analyses. Because the resolution of three data types (barren" and "range" land; water) was not acceptable for small watersheds, they were excluded from the analyses. Total precipitation (cm) between 1995-2000 from the nearest NCDC weather stations was used, except partial data provided from closer stations at North Inlet-Winyah Bay and North Carolina NERRs.

Analyses

A total of 51 sites in the NERR system were included in the analyses. Two Jobos Bay NERR sites were not included in the multivariate analyses due to unavailability of the land use information in GIS. The Model Marsh (Tijuana River Estuary NERR) site was excluded from analyses because of insufficient water quality data given the recent inclusion (Dec 2000) in the NERR SWMP. Lastly, the Lower Duplin (Sapelo Island NERR) site was excluded from analyses because this site is essentially located on top of the Marsh Landing site. The Lower Duplin site was created in 1999 in close proximity to the Marsh Landing site to provide a long-term reference after the responsibility for maintaining the Marsh Landing site changed custody.

Pair-wise correlations were calculated to detect the linear correlation between each of the variables. Pair-wise correlations were necessary to evaluate if variables were auto-correlated and to help in the interpretation of the multivariate analyses described below.

Table 8. Physical and chemical attributes used to classify NERR sites. With the exception of depth range, all parameters were determined based on frequency distributions.

Site	Temp < 10°C	Temp >25°C	Hypoxia	Supersaturation	Depth Range	Width	Salinity	SalRange	pH<7.0	pH>8.0	Turb>25
tjros	0.28	6.04	25.18	1.18	0.86	20.00	31.03	3.86	0.71	34.68	3.51
tjrtl	1.81	20.34	30.20	19.25	0.78	5.00	27.23	7.55	0.00	32.53	8.03
elkap	5.56	8.36	18.99	29.47	0.36	6.00	30.48	2.94	4.51	26.83	6.66
elknm	1.65	1.82	23.51	14.06	0.07	19.00	33.23	4.89	0.25	44.17	10.23
elksm	1.24	0.00	0.10	0.52	1.59	27.00	29.82	2.07	0.00	17.32	4.17
sosse	35.17	0.09	1.03	7.17	1.45	150.00	10.83	17.59	41.29	0.33	6.97
sosvi	16.37	0.00	0.00	7.86	2.26	364.00	27.80	6.83	0.20	21.18	0.89
soswi	33.56	0.00	0.07	6.19	1.81	30.00	10.74	19.14	34.24	0.42	4.42
pdbby	45.84	0.00	0.00	9.36	2.39	50.00	28.26	1.66	0.00	39.92	2.39
pdbjl	36.68	0.92	2.98	14.89	0.84	30.00	10.54	19.39	26.26	19.36	48.08
welht	36.60	0.10	1.27	0.56	0.40	8.50	3.44	5.72	87.75	0.00	7.96
welin	52.01	0.00	2.48	0.97	2.60	500.00	31.01	3.54	3.94	10.50	12.56
grbgb	20.97	0.37	0.00	12.16	2.25	3,567.00	23.27	2.88	0.00	5.78	2.01
grblr	31.78	5.80	0.00	1.55	2.29	80.00	14.42	11.80	14.92	0.00	1.77
grbsq	17.71	2.53	0.00	4.41	2.23	140.00	19.00	12.11	1.70	1.65	21.32
wqbcb	38.35	3.46	0.00	33.62	0.54	1,500.00	29.73	1.29	0.00	47.37	
wqbmp	52.11	3.23	0.39	33.75	0.52	1,500.00	30.29	1.23	0.00	49.43	0.37
narpc	52.50	0.32	0.54	4.95	1.37	419.00	28.18	1.50	0.11	25.14	0.39
nartw	39.89	0.01	0.34	1.99	1.29	9,911.00	29.62	1.42	0.00	24.58	6.19
hudsk	20.22	1.92	0.00	2.15	0.07	7.00	0.16	0.01	0.00	61.17	4.32
hudtn	20.92	12.02	0.00	0.00	1.31	1,428.00	0.10	0.00	0.57	0.27	46.53
hudts	19.13	14.29	0.36	0.20	1.31	1,284.00	0.10	0.00	7.59	3.50	29.64
owcsu	11.40	9.57	3.71	6.32	0.10	8.00	0.28	0.02	0.00	6.00	66.52
owcwm	8.34	19.27	4.22	3.21	0.10	30.00	0.20	0.05	0.05	16.71	73.22
mulb6	39.38	3.15	0.00	11.16	1.10	3,500.00	29.04	4.97	0.05	50.97	15.43
mulba	39.14	16.53	0.00	0.82	1.01	290.00	2.58	4.76	89.24	0.00	38.55
mulcn	32.02	13.46	0.17	0.64	0.98	250.00	14.51	8.10	8.72	0.06	5.66
delbl	28.92	26.52	9.51	3.39	1.14	110.00	2.18	1.34	35.21	4.27	94.20
delpb	33.45	0.01	19.88	0.00	0.07	5.00	0.04	0.01	87.52	2.86	20.60
delsl	31.29	20.27	3.66	1.78	1.25	40.00	10.79	12.17	25.06	1.02	80.18
cbmjb	13.18	35.00	24.39	12.19	0.68	5.00	0.17	0.03	42.46	2.01	
cbmpr	9.66	38.46	2.49	16.56	0.78	50.00	0.19	0.13	26.01	0.98	
cbvgi	33.90	22.83	0.09	18.80	0.73	7,472.00	20.50	0.75	0.00	34.46	6.46
cbvtc	34.00	19.78	0.94	8.94	0.87	20.00	10.18	7.83	5.00	7.28	90.80
nocms	8.59	27.16	0.06	9.09	1.32	20.00	28.15	5.88	2.48	46.58	13.51
noczi	10.35	29.33	0.00	9.72	1.10	299.00	21.99	3.63	2.70	39.21	12.46
niwdc	7.19	35.90	0.63	9.36	1.54	70.00	30.85	5.56	0.87	46.73	9.98
niwol	8.89	32.24	4.26	7.47	1.58	90.00	30.14	6.05	0.60	27.43	11.85
niwta	13.11	30.67	3.36	3.88	1.21	10.00	5.98	4.01	27.19	6.78	80.21
acebb	6.10	33.38	3.31	2.88	1.89	3.10	30.41	6.01	0.09	13.22	39.95
acesp	6.07	31.69	7.23	0.15	2.01	18.00	27.71	6.97	0.56	11.13	41.79
sapfd	2.47	42.68	0.92	0.69	2.40	20.00	21.63	1.25	11.12	0.00	
saphd	4.03	47.63	22.76	0.48	2.16	141.00	26.21	0.92	1.30	3.33	3.38
sapml	2.18	45.85	0.00	0.00	2.40	130.00	24.42	7.79	0.00	0.47	
wkbfr	1.59	41.79	2.94	2.10	0.46	120.00	6.62	2.64	21.85	34.65	21.60
wkbwb	5.55	42.70	0.07	27.16	0.43	400.00	10.04	4.91	0.77	62.18	37.37
apaeb	1.60	49.09	1.28	14.49	0.62	1,131.00	9.99	3.05	2.21	18.90	25.17
apaes	2.23	46.61	8.38	3.94	0.60	1,131.00	8.40	3.07	4.87	28.75	12.06
rkbbm	0.00	30.71	20.27	0.00	1.04	423.00	33.77	4.10	0.09	7.44	16.43
rkbbr	0.00	61.77	77.97	0.00	0.83	35.00	21.40	6.06	1.05	0.00	16.15
rkbuh	0.00	57.45	35.51	0.22	0.78	40.00	19.22	7.80	7.01	0.41	12.83

Table 9. Land-use, habitat and climate variables used to classify NERR sites.

Site	Perm	Watershed (HA)	Clay	Agricultural Land	Forest Land	Urban /Built-up	Wetland	Shellfish	’95 -’00 Precipitation (cm)
tjros	1.62	308.61	31.85	0.00	0.00	96.48	0.00	0.00	141.35
tjrtl	4.78	3.94	12.50	0.00	0.00	100.00	0.00	0.00	141.35
elkap	1.31	39.05	33.90	26.22	0.00	0.00	73.78	0.00	455.98
elknm	6.22	148.60	18.79	31.20	28.32	14.59	25.89	0.00	455.98
elksm	1.04	92.40	34.72	83.63	7.12	0.00	3.33	0.00	455.98
sosse	1.17	563.16	25.80	0.00	100.00	0.00	0.00	0.02	1,064.18
sosvi	1.80	2,635.14	24.46	0.00	98.25	0.06	1.69	0.03	1,064.18
soswi	2.07	5,697.52	23.91	0.00	94.52	0.66	0.90	3.75	1,064.18
pdbby	1.65	235.88	34.00	0.35	0.01	0.00	0.00	0.00	451.76
pdbjl	4.48	3,793.63	18.20	76.40	15.35	4.65	0.00	0.00	451.76
welht	10.11	1,581.63	5.51	2.89	76.05	15.55	0.38	0.00	764.51
welin	11.00	496.79	6.08	0.00	40.26	42.33	17.08	2.57	764.51
grbgb	6.41	90,811.47	8.44	10.01	77.38	7.53	3.18	1.85	762.53
grblr	5.97	49,831.36	7.53	5.76	85.02	4.13	3.14	0.00	659.00
grbsq	6.82	32,540.07	8.89	12.84	75.72	7.42	2.85	0.16	762.53
wqbcb	3.41	6,109.89	25.28	1.59	54.86	20.83	0.21	12.07	756.67
wqbmp	3.41	6,109.89	25.28	1.59	54.86	20.83	0.21	12.07	756.67
narpc	5.66	470,774.07	4.89	4.68	45.32	35.88	1.45	9.38	674.55
nartw	5.66	431,110.44	4.89	5.11	49.49	39.18	1.58	10.25	715.70
hudsk	4.99	5,194.99	7.25	40.84	46.26	12.41	0.00	0.00	762.43
hudtn	2.82	1,775,638.00	14.24	31.92	53.92	10.14	1.14	0.00	668.43
hudts	2.82	1,776,154.00	14.24	31.92	53.92	10.14	1.14	0.00	762.43
owcsu	1.91	6,574.42	26.11	95.51	1.81	2.60	0.00	0.00	610.16
owcwm	1.95	6,853.85	25.79	93.96	2.68	2.53	0.00	0.00	610.16
mulb6	9.78	349,595.41	7.92	6.96	44.03	18.22	18.09	10.04	658.09
mulba	10.19	66,789.06	7.87	17.00	43.05	10.53	28.09	0.00	643.08
mulcn	10.17	136,170.00	7.65	11.52	55.16	6.49	24.63	0.30	643.08
delbl	5.30	4,963.55	14.95	46.26	46.99	4.04	2.28	0.35	722.96
delpb	4.95	614.49	16.10	42.65	34.44	13.04	9.87	0.00	722.96
delsl	5.73	19,797.50	15.04	40.89	11.56	39.88	6.63	0.67	722.96
cbmjb	4.46	252.48	12.84	38.63	52.47	7.47	0.14	0.00	676.68
cbmpr	2.77	135,561.90	18.50	35.72	21.32	39.13	2.02	0.00	676.68
cbvgi	3.41	721,148.46	25.28	23.25	66.93	4.48	2.70	6.77	770.43
cbvtc	4.83	939.91	18.04	24.79	73.26	0.00	1.94	0.30	773.81
nocms	13.32	37.56	17.20	0.00	0.00	0.00	78.90	57.22	926.44
noczi	5.23	1,120,315.48	17.99	25.05	42.80	3.08	27.14	0.72	1,017.30
niwdc	7.62	2,230.00	17.38	0.00	72.30	0.40	20.36	2.09	802.67
niwol	10.19	1,524.00	6.67	0.00	80.48	0.00	7.36	0.48	802.67
niwta	1.16	164.03	41.40	0.00	35.13	0.00	64.87	0.26	802.67
acebb	2.07	328.94	40.67	0.00	30.75	1.71	58.26	10.66	677.60
acesp	0.42	83.09	47.40	0.00	12.71	0.00	87.29	4.80	677.60
sapfd	3.96	314.30	29.88	0.00	4.86	0.00	41.01	1.16	706.40
saphd	2.85	440.57	34.79	0.00	3.46	0.00	56.21	2.90	706.40
sapml	2.96	1,983.80	34.34	3.73	15.35	0.00	58.59	9.92	706.40
wkbfr	3.21	38,273.24	24.33	60.35	34.57	3.56	0.24	0.01	1,077.24
wkbwb	3.30	53,707.21	24.09	62.10	30.80	3.89	0.77	1.32	1,077.24
apaeb	9.70	26,929.17	10.48	0.08	82.81	0.01	15.18	1.78	867.51
apaes	9.70	26,929.17	10.48	0.08	82.81	0.01	15.18	1.78	867.51
rkbbm	9.07	36,218.85	8.10	38.33	14.29	10.27	23.50	10.62	877.11
rkbbr	7.65	442.36	8.62	0.00	11.03	0.00	88.97	0.39	877.11
rkbuh	9.04	7,180.16	9.21	60.58	24.26	3.83	11.26	0.08	786.41

Table 10. Summary of sources of GIS data obtained for multivariate analyses.

	GIS sources or website	GIS data
1	The Coastal Assessment & Data Synthesis (CA&DS) system: ftp://sposerver.nos.noaa.gov/datasets/CADS/GIS_Files/ShapeFiles	Land use, shellfish, elevation, shoreline, soil, drainage basin
2	NOAA Coastal Service Center, Charleston, SC	NERR base maps, digital raster data within NERR sites
3	San Diego State University Geospatial Data Clearinghouse: http://hurricane.sdsu.edu/tj/physdata_trw.html	Sub-basin boundary, soil, land use data for Tijuana River Estuary Reserve
4	U. S. Environmental Protection Agency http://www.epa.gov/nsdi/projects/rf1_meta.html	Rivers
5	USGS http://water.usgs.gov/lookup/getspatial?huc250k	8-digit HUCs (Hydrological Unit Codes)

Hierarchical cluster analysis was used to detect groupings among NERR sites. Euclidean distance was used as the measure for clustering sites, and the method of average linkage was used. These two analyses were carried out using Community Analysis Package (Pisces Conservation LTD, UK). A resulting dendrogram indicated how the clusters were formed and provided a measure of the linkage distance for clustering. On the resulting dendrogram, the clusters observed at the linkage distance previously established were identified using an amalgamation schedule provided by STATISTICA (StatSoft, Inc., Tulsa, OK). An amalgamation schedule, which indicates linkage distances across the consecutive steps in a clustering process, was used to detect distance where a discontinuity among distinctive groupings could be observed.

Principal components analysis (PCA) was performed to explore the relationship among water quality, habitat, and climatic characteristics. This analysis resulted in the computation of principal components (PCs) scores for each of the NERR sites. A scree plot was evaluated to determine if a clear breaking point was observed. A relationship between the first two principal components and the twenty variables was plotted to determine the orientation of each variable. The first two principal components were then plotted against each other by NERR site to evaluate if groups of sites were observed.

Non-linear multi-dimensional scaling was performed using an auto-associated Artificial Neural Network (ANN). Almeida (2002) states, "The use of ANNs has gained increasing popularity for applications where a mechanistic description of the dependency between dependent and independent variables is either unknown or very complex". ANN is a method that deconvolutes complex signals by allowing the data to take on the shape of any unbroken curve. The curve fitting occurs over and over allowing the model to learn the data and develop a predictive model (Almeida 2002). A variable number of hidden nodes were used and activation values of the hidden nodes for each case defined the reduced coordinate system.

Discriminant analysis was performed using SAS (SAS Institute, Inc., Cary, NC) to differentiate five geographic regions previously classified in the report using these twenty sites attributes. The distinguishing variables used to separate the groupings were selected using stepwise, forward, and backward discriminant analyses. Significance levels to include and/or remove for these analyses were set at 0.15 as the default values. Box plots for the selected attributes were graphed to visualize the differences among regions using STATA (Stata Corp, TX).

No turbidity data were collected during 1999-2000 at five (CBMJB, CBMPR, SAPFD, SAPML, WQBCB) sites. The two most common methods, "complete case analyses" (excluding all data from the five sites), and "mean substitution method" (substituting the missing data with the mean value) were used to handle missing data for multivariate analyses. Complete case analysis and the mean substitution method yielded very similar results for cluster analyses, discriminant analyses, and PCA. Only the results using the mean substitution method were provided here in order to be inclusive but succinct.

Results and Discussion

Correlation

Soils rich in clay content were positively associated with low soil permeability ($r = -0.76$, $p < 0.0001$) and wetland area ($r = 0.393$, $p = 0.004$). Wetland areas were negatively correlated with the amount of forested land ($r = -0.404$, $p = 0.003$), agriculture ($r = -0.332$, $p = 0.02$), and urban ($r = -0.285$, $p = 0.04$) land uses. Watersheds with a large percentage of functional wetlands were associated with abundant shellfish beds ($r = 0.363$, $p = 0.009$), which primarily occurred in areas with high salinity ($r = 0.34$, $p = 0.01$) and high pH ($r = 0.304$, $p = 0.03$). Wetland areas were also associated with warm water temperature ($r = 0.458$, $p = 0.007$) and high occurrences of summer hypoxia ($r = 0.358$, $p = 0.01$), but negatively correlated with cool water temperature ($r = -0.398$, $p = 0.004$).

In contrast, the amount of forested land was positively correlated with cool water temperature ($r = 0.352$, $p = 0.01$) and high precipitation ($r = 0.527$, $p = 0.0001$), but negatively correlated with high summer hypoxia frequencies ($r = -0.366$, $p = 0.008$). Furthermore, the amount of agricultural land was negatively correlated with the amount of forested land ($r = -0.35$, $p = 0.01$), salinity ($r = -0.458$, $r = 0.0007$), and range in depth ($r = -0.49$, $p = 0.0003$). It appeared that sites with lower salinity water and reduced tidal influence would have a higher percent of land available for agricultural purposes. Sites with a large percentage of agricultural land were also positively associated with high turbidity ($r = 0.423$, $p = 0.002$).

Salinity was positively correlated with alkaline waters ($r = 0.373$, $p = 0.07$) and daily depth range ($r = 0.404$, $p = 0.003$), but negatively associated with turbidity ($r =-0.5$, $p = 0.0002$). Cold water was positively correlated with more acidic waters ($r = 0.3$, $p = 0.03$) and negatively correlated with hypoxia ($r = -0.408$, $p = 0.003$). Supersaturation was associated with more alkaline waters ($r = 0.561$, $p < 0.0001$) and small daily depth range ($r =-0.336$, $p = 0.01$), which implied sites were either located in non- or small-tidal areas.

Cluster Analysis

Cluster analysis was used to group 51 sites in the NERR SWMP according to physical, chemical, land use, climatic, and soil attributes (Tables 8-9). A Euclidean linkage distance of approximately 5.8 was used as the grouping criteria based on the amalgamation schedule (Figure 14). Four distinct groupings of NERRs were identified, with the exception of eight sites (TJROS, TJRTL, HUDTS, HUDTN, NARTW, HUDTS, NARTW, CBVGI, RKBBR, NOCMS) that were not easily classified (Figure 15). Groups two and four appeared to correspond to geographical region and latitude. Sites belonging to group two were primarily located in South Carolina, except for two sites along the West Coast (ELKSM and PDBBY). In contrast, group four was a large grouping, primarily consisting of sites with cooler water temperature located in the Northeast/Great Lakes and the Mid-Atlantic regions (Figure 15). One West Coast site, PDBJL, located at similar latitude as other sites in this group, was also included. Group three was also a large grouping, primarily consisting of sites associated with more saline and less turbid water than the group two sites. The smallest grouping was group one, consisting of two Elkhorn Slough sites (ELKNM, ELKAP) and both Waquoit Bay sites.

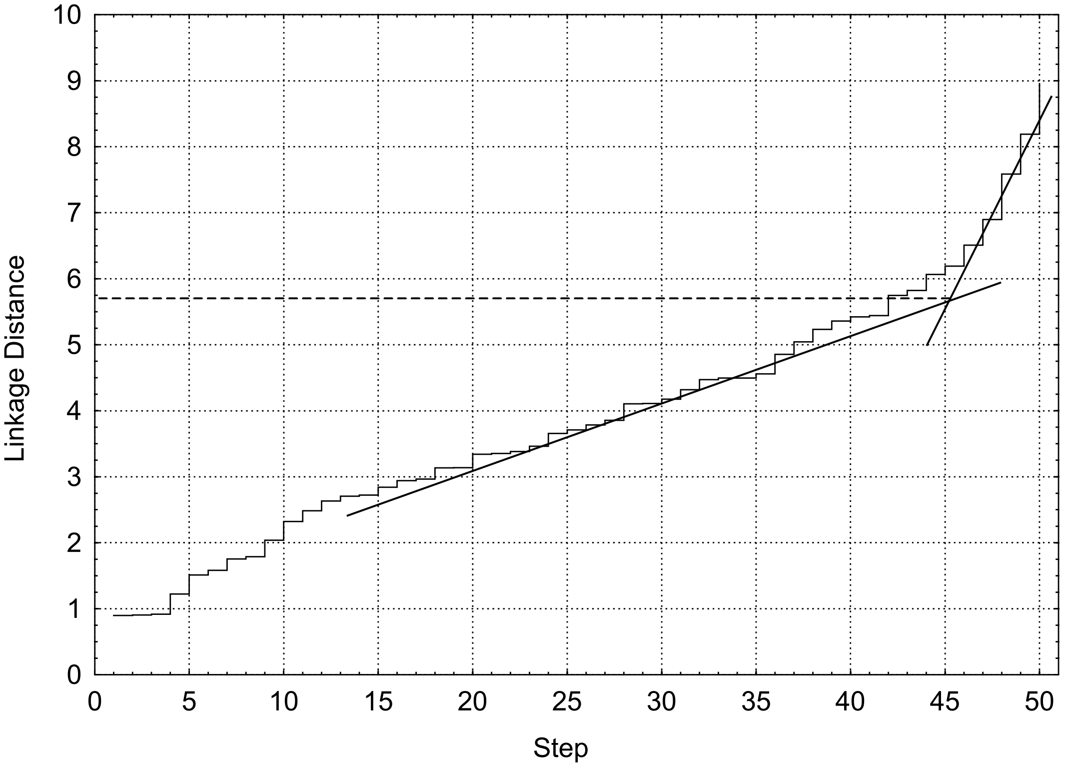

Figure 14. Amalgamation schedule used to identify groupings among 51 NERR sites. The two straight lines indicate the linkage distance.

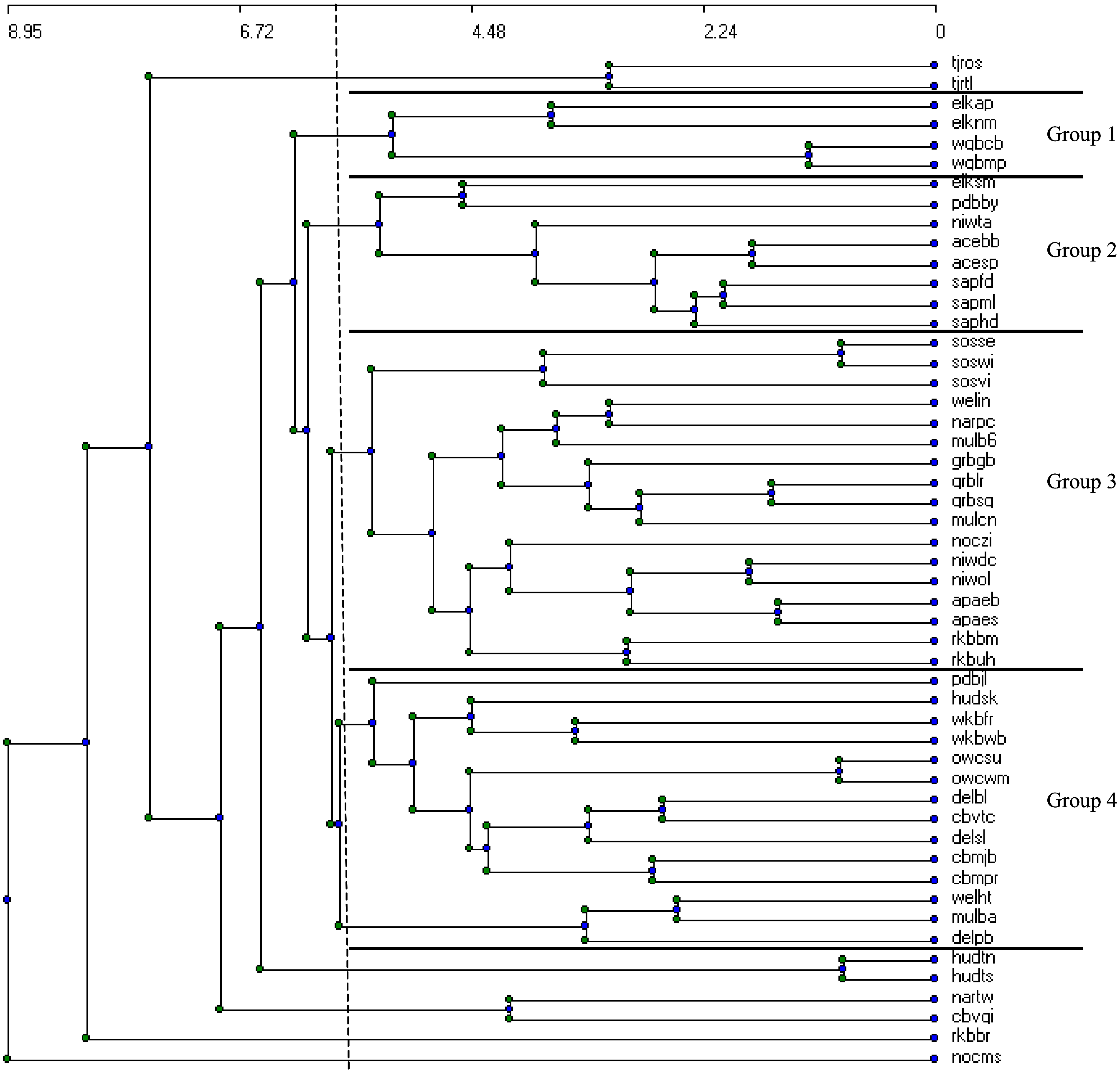

Figure 15. Dendrogram of 51 NERR sites based on habitat and water quality characteristics.

Eight sites did not fit into one of the four major groups (Figure 15). Masonboro Island in the North Carolina Reserve was very dissimilar to other sites because of its small watershed, high permeability, and high percentage of wetland and shellfish. High temperature and summer hypoxia occurrences differentiated Blackwater River in the Rookery Bay Reserve from other sites. Two sites in the Tijuana River Estuary NERR with 100% urban/developed land and extremely low precipitation were also very dissimilar from other NERR sites. Large watersheds at NARTW and CBVGI distinguished these two sites from others. Similarly, the extremely large watershed sizes at HUDTS and HUDTN distinguished these sites from other NERR sites. With the exception of nine reserves (Padilla Bay, Wells, Narragansett Bay, Mullica River, North Inlet-Winyah Bay, North Carolina, Chesapeake Bay-Virginia, Delaware, and Weeks Bay), at least two sites within each reserve were more similar to each other than to sites located in other Reserves.

The dendrogram of site attributes produced four major groupings (Figure 16). Within group one, hypoxia, warm water temperature, and wetland area were most similar, which reinforces the correlative relationship noted previously. Among the sites within group 2, supersaturation and more alkaline water were most similar. Among the sites within group 3, agricultural land and turbidity were similar. Among the sites within group 4, the amount of forested land and precipitation were most similar. These findings were consistent with the results from the correlation analyses.

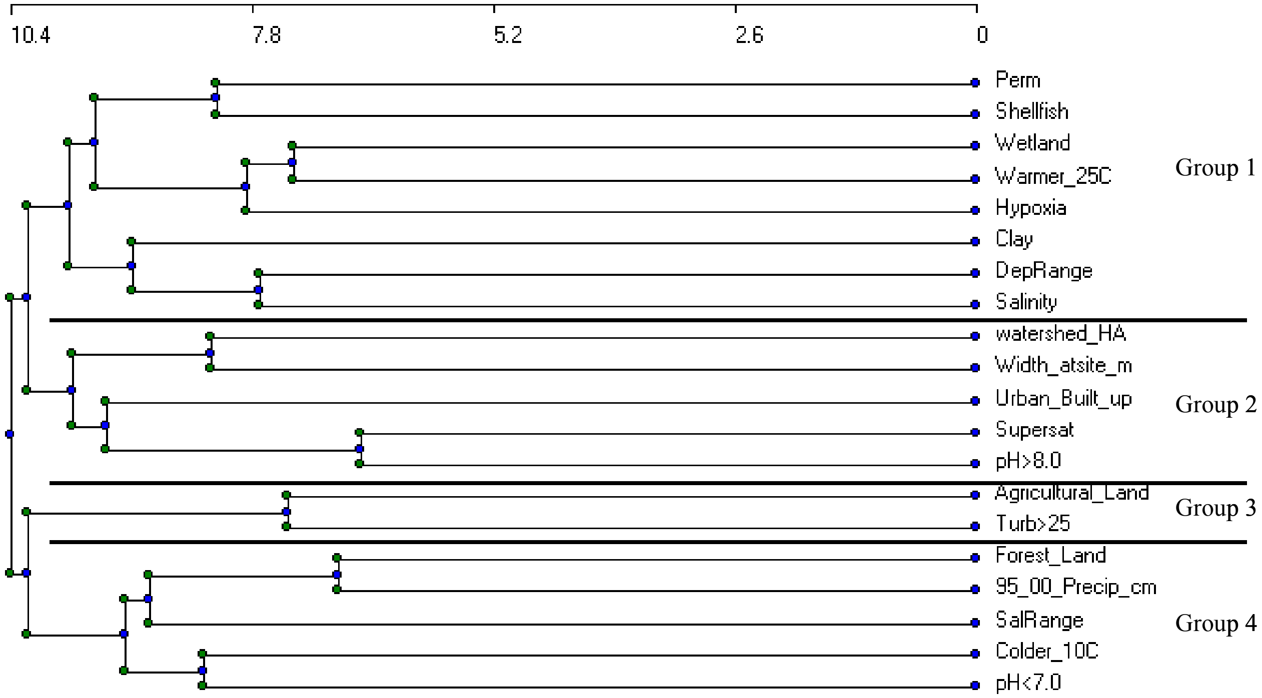

Figure 16. Dendrogram of site attributes for 51 NERRs examined using cluster analysis.

Principal components analysis
No clear breaking point in the scree plot was observed (Figure 17); thus, eigenvalues greater than 1 were used to select the first 7 principal components. Seventy-six percent of the variance was explained by these seven components (Appendices 33-34). This large number of PCs weakened the purpose of dimension reduction and made it difficult to interpret the abstract PCs. The large number of PCs also emphasized the high variability among water quality and habitat characteristics of interest.

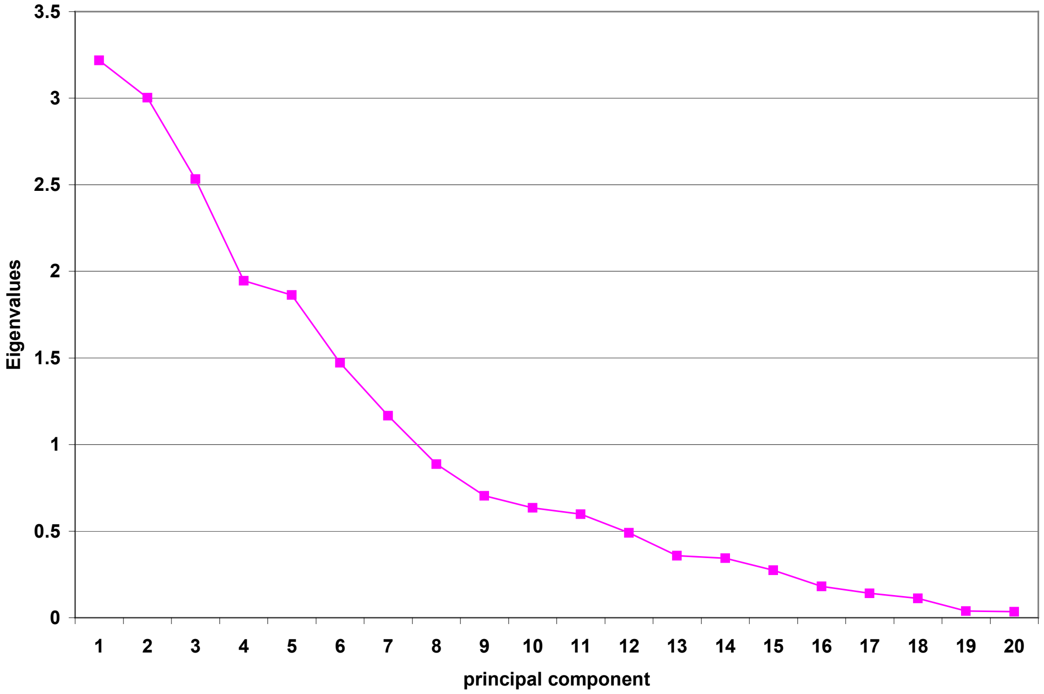

Figure 17. Scree plot of principal components analysis.

The first three principal components explained 44% of the total variation in all variables, and are briefly discussed here. The first principal component distinguished two major groups based on water temperature and habitat (i.e., warm wetland vs. cold forest) and explained 16% of the original variation (Figures 18-19). Warm water NERR sites with high wetland components were primarily located in the Southeast, Gulf of Mexico, and California, while cold water, predominantly forested NERR sites were located in the Northeast, Mid-Atlantic, and the northern West Coast. The second PC explained 15% of the original variation and illustrated salinity regime and land use influence (Figure 19). Specifically, high percent of agricultural land was associated with low salinity and high turbidity, as determined using correlation and cluster analyses. Examples of low salinity, high agricultural NERRs include Old Woman Creek, Delaware Bay, and both Chesapeake Bay Reserves. Examples of high salinity, low agricultural NERRs include Reserves located along the Southeast Coast and within California. These findings were consistent with correlation and cluster analyses (Figure 20). The third component accounted for 13% of the variance (Appendix 34) and represented precipitation and mean daily range in depth. No distinct boundaries between the groupings were identified.

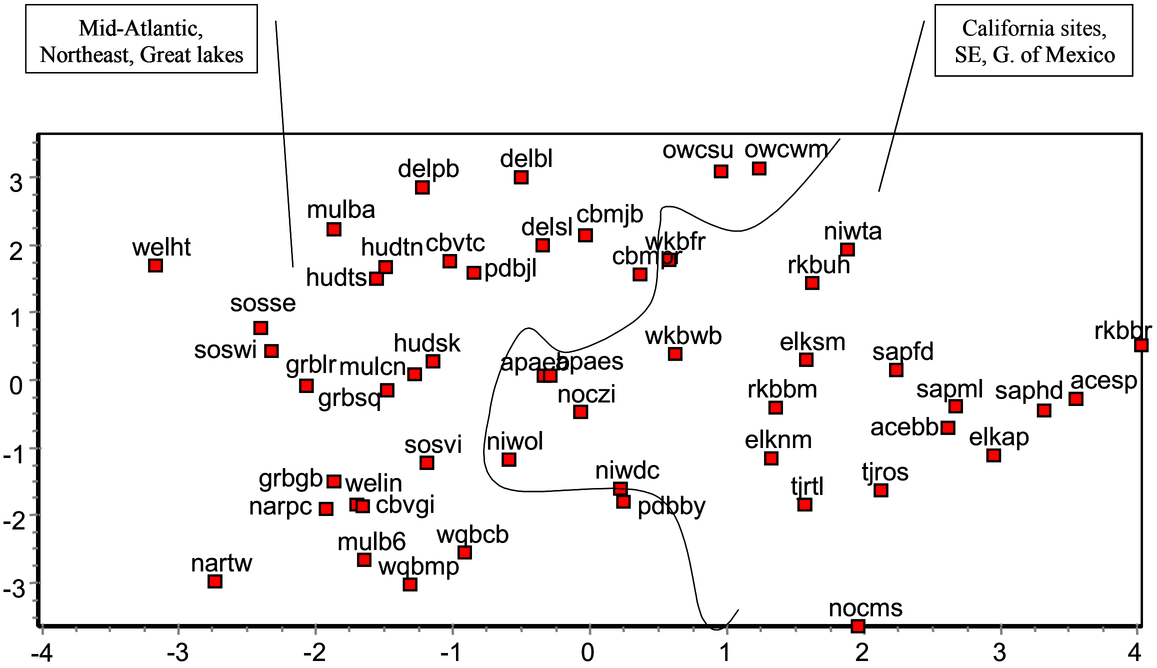

Figure 18. Relationship between the PC 1(x-axis) & PC 2 (y-axis) and 51 NERR sites.

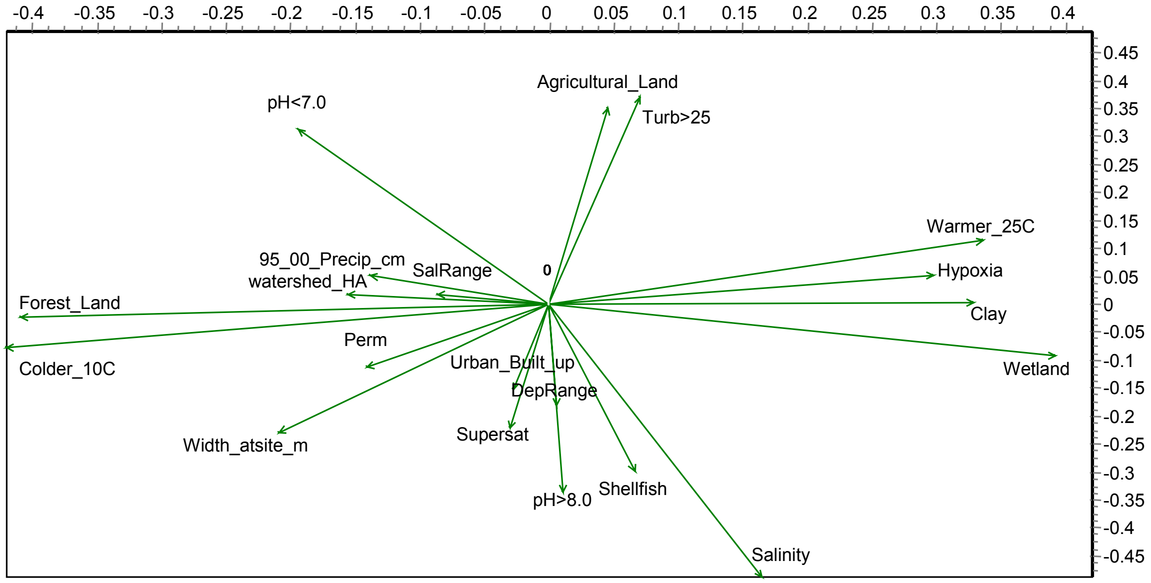

Figure 19. The relationship between PC 1 (x-axis) & PC 2 (y-axis) and attribute variables.

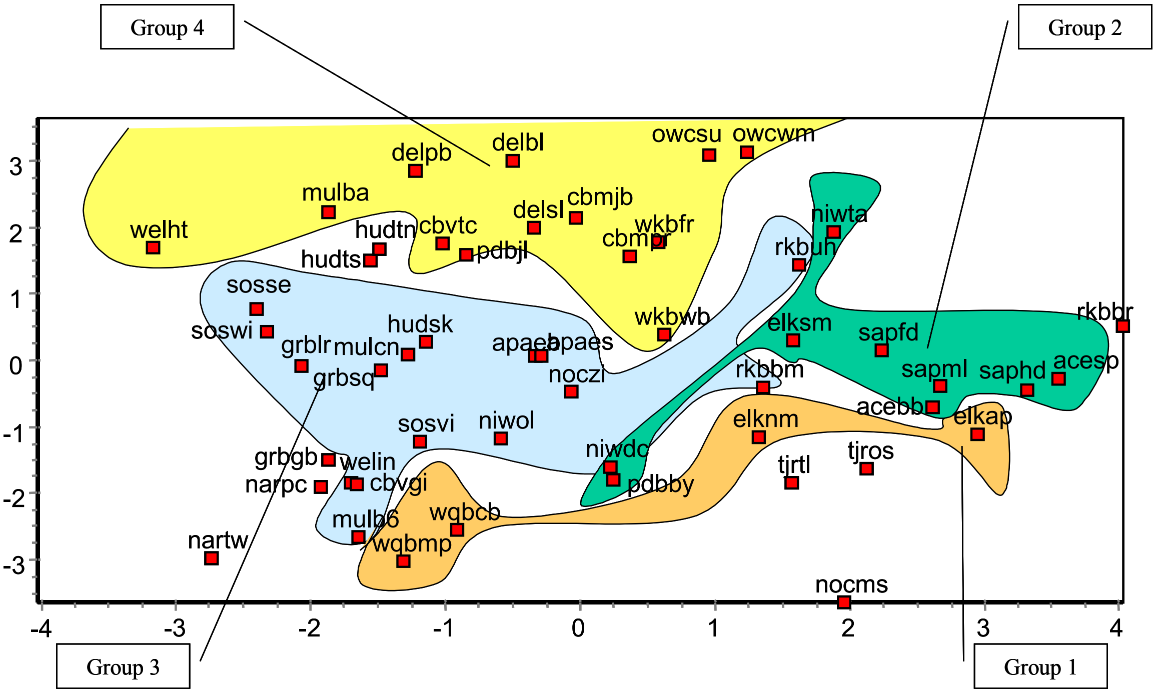

Figure 20. Major groupings of 51 NERR sites identified by cluster analysis were plotted against the first two PC axes using PCA.

Nonlinear multidimensional scaling using artificial neural networks

More total variance was explained by nonlinear multidimensional scaling compared to PCA with the same numbers of components/dimensions before reaching 20 components (Appendix 34). For example, 13% more variance was explained by the first three components using multidimensional scaling than was explained by the first three components using PCA. This scenario indicated the existence of non-linearity in the relationship among these site attributes. Similar trends of explained variance were generally observed in both PCA and multidimensional scaling; however, ten PCA components were needed to account for more than 85% of total variance, compared to only six multidimensional scaling components to account for similar amounts of variance (Figure 21). Subsequently, the relationships among these variables were complex and were not reducible to lower dimensions as we had hoped, a similar conclusion reached using PCA and cluster analysis.

Fifty-one sites were spatially mapped to the first two dimensions, which was parallel to the method used to examine the pattern of NERR sites using PCA (Figure 22). The distribution pattern of the sites was very similar to the result using PCA, with the reversal of both axes. For instance, the group on the upper right of the PCA map was located on the lower left corner of this new map. Again, the sites with more distinctive features, such as RKBBR, NOCMS, HUDTS, HUDTN, NARTW, and CBVGI, consistently occurred on the edge of the map. The sites with warmer water separated from the others along the first dimension while the second axis differentiated the sites using salinity, turbidity, and percent area of agricultural land. These predominant natural trends were similar to the first two dimensions from the PCA.

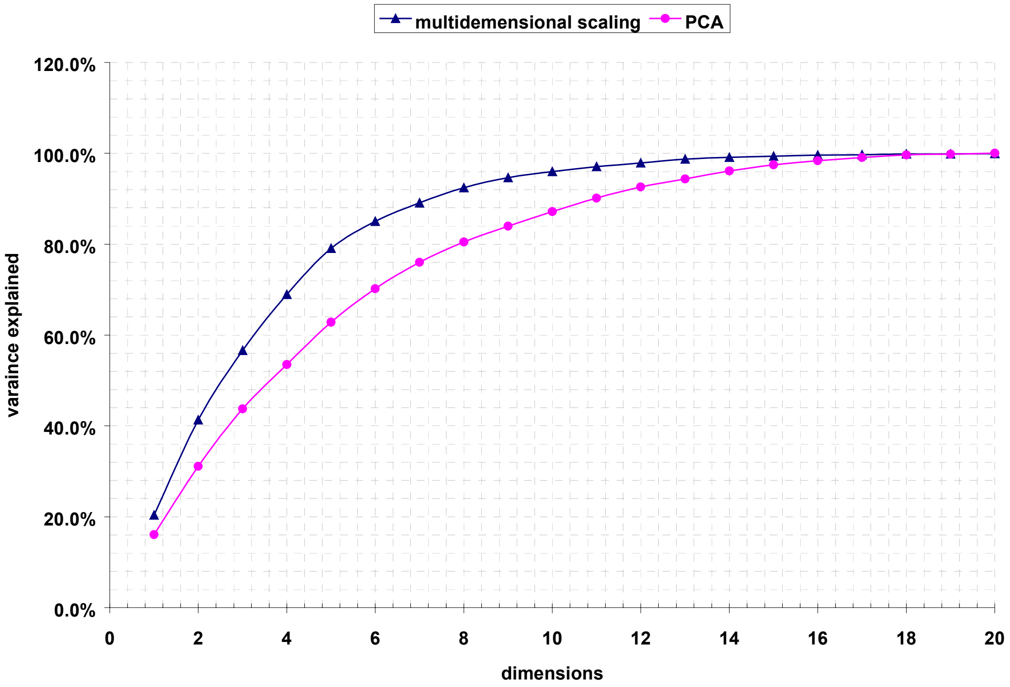

Figure 21. Comparison of variance explained by the reduced dimensions using PCA and nonlinear multidimensional scaling.

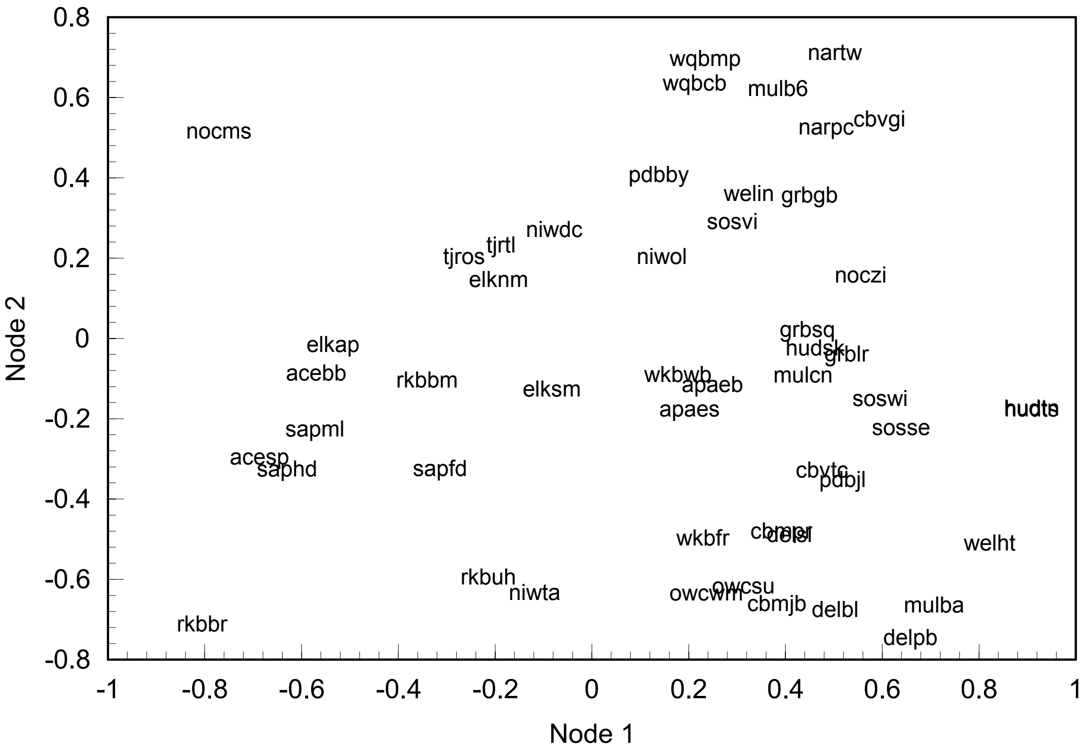

Figure 22. NERR sites were mapped with respective to two dimensions of autoassociated neural networks.

Discriminant analysis

Discriminant analyses successfully differentiated the five geographic regions with the error rate of 6% (Table 11). Two Mid-Atlantic sites and one West Coast site were grouped with sites in the Northeast region, and one site located in the Northeast was grouped with sites in the Mid-Atlantic region. Attributes were most different between the West Coast and the Gulf of Mexico using the generalized square distance (Table 12). Attributes were most similar between the Northeast and the Mid-Atlantic. The Southeast and the Gulf of Mexico were also fairly similar when compared to other regions.

Differentiating attributes (Figure 23) were selected using three distinct stepwise discriminant analysis methods (stepwise, forward selection, and backward elimination, (Table 13). Stepwise and forward selection kept the same ten attributes in the model: warm water temperature (≥ 25°C), cold water temperature (≤10°C), pH <7, pH >8, clay, permeability, turbidity, precipitation, salinity range, and mean range in depth. Backward elimination was in general agreement with these two methods.

Table 11. Results of discriminant analysis of data from 51 NERR sites.

Error rates for Region

	West Coast	Northeast	Mid-Atl.	Southeast	G. of Mex.	Total
Rate	0.0000	0.2143	0.1000	0.0000	0.0000	0.0629
Priors	0.2000	0.2000	0.2000	0.2000	0.2000	

Discriminant functions for five geographic regions.

Attribute	West Coast	Northeast	Mid-Atlantic	Southeast	Gulf of Mexico
Constant	-10.74175	-9.53057	-3.60198	-18.65224	-21.07932
Watershed size	0.56332	-1.27959	-0.89539	1.77580	0.49671
Clay	1.50113	-3.89460	-1.60179	2.76667	3.98061
Agricultural Land	-1.51924	3.45665	3.39300	-4.62589	-2.98169
Forest Land	-1.22088	3.48660	3.20365	-3.61050	-4.64787
Urban Built-up	-0.90648	3.01824	2.25837	-3.76018	-2.59606
Wetland	-3.61723	1.25984	1.89716	1.06694	-1.58664
Shellfish	0.33203	1.45973	0.60462	-0.99846	-2.83115
Width at site	-0.40327	0.11864	0.71454	-0.91005	0.61813
Precipitation	-3.41186	-3.03165	-1.43486	3.60699	7.83432
Cold (<10oC)	-3.01713	4.41422	4.33346	-5.42449	-2.95964
Warm (>25oC)	-13.86439	-12.68825	-0.58623	18.15026	20.09128
Hypoxia	3.91375	2.10568	0.32169	-5.38441	-2.56996
Supersatutation	2.84222	3.28388	1.12462	-5.28405	-4.68603
Depth Range	2.05674	1.44691	0.31626	-1.46052	-4.19737
Salinity	-3.20406	-6.91758	-2.43461	10.09876	7.46359
Salinity Range	2.90932	-3.58488	-2.66735	3.20249	2.24909
pH<7	-1.01116	-5.09796	-0.82732	6.67713	3.28356
pH>8	-0.54280	-4.67166	-2.03469	6.30697	4.01550
Turbidity >25	-1.85558	-1.38186	0.45295	2.47769	1.22792
Perm	-1.88249	-2.52701	0.10663	1.23079	5.83271

Table 12. Dissimilarity between regions using generalized squared distance.

Region	West Coast	Northeast	Mid-Atlantic	Southeast	Gulf of Mexico
West Coast	0	24.98634	36.16749	86.52786	105.82605
Northeast	24.98634	0	13.15349	105.83015	107.75766
Mid-Atlantic	36.16749	13.15349	0	62.87010	59.25187
Southeast	86.52786	105.83015	62.87010	0	21.25898
Gulf of Mexico	105.82605	107.75766	59.25187	21.25898	0

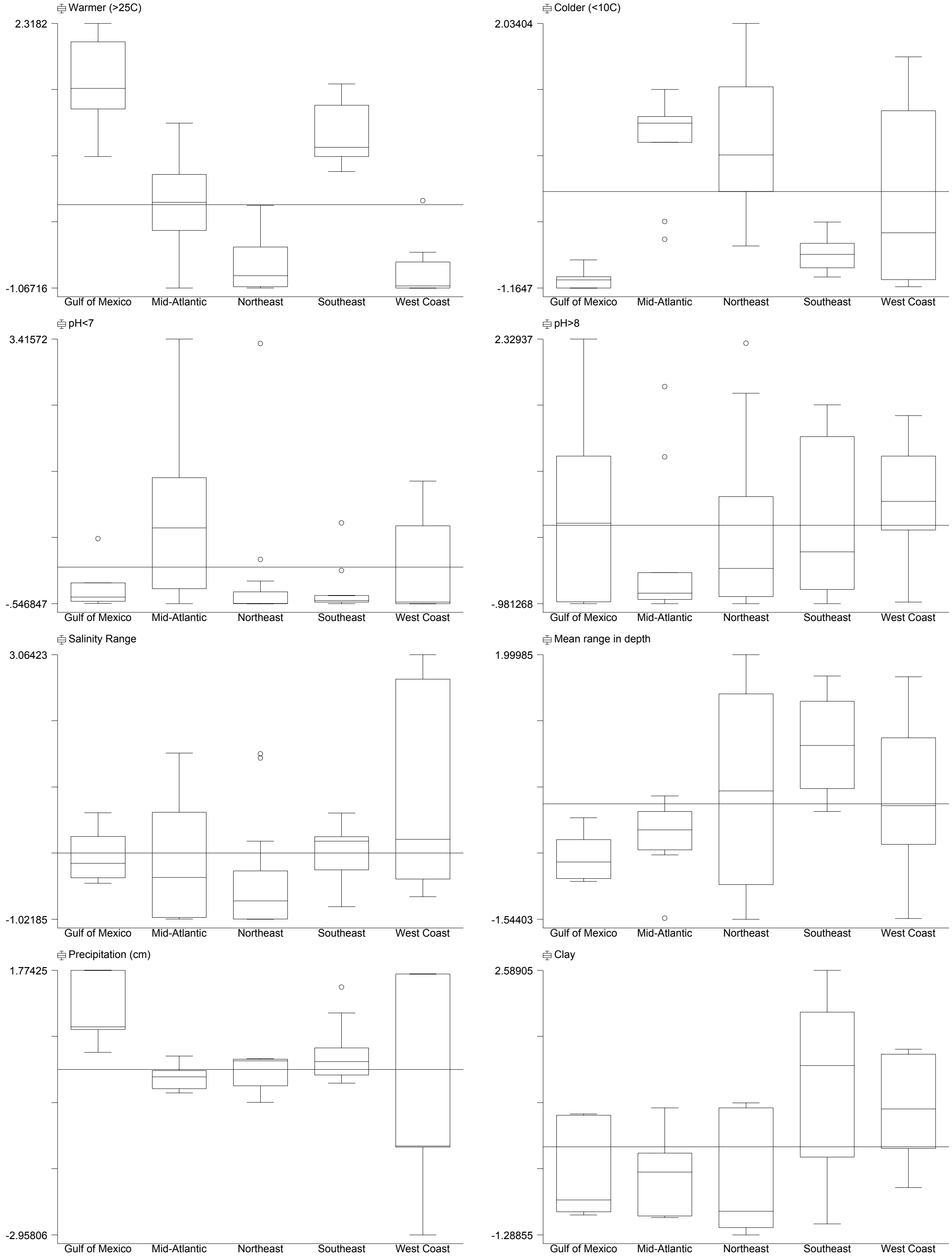

Figure 23. Box plots of differentiating attributes among five geographic regions. Each variable was standardized (with mean 0 and variance 1).

Table 13. Differentiating attributes for separating five geographic regions were selected using the stepwise discriminant analysis with three methods: stepwise selection, forward selection, and backward elimination (significance levels set at SAS default value of 0.15).

Summary of Stepwise selection

```
          Number                                                Partial
  Step        In  Entered                Removed              R-Square  F Value   Pr > F
     1         1  Warmer_25C                                   0.7991    45.74  <.0001
     2         2  Clay                                         0.3899     7.19  0.0001
     3         3  Perm                                         0.3973     7.25  0.0001
     4         4  95_00_Precip_cm                              0.3421     5.59  0.0010
     5         5  SalRange                                     0.2907     4.30  0.0052
     6         6  Colder_10C                                   0.3139     4.69  0.0033
     7         7  Turb_25                                      0.2803     3.89  0.0092
     8         8  DepRange                                     0.2274     2.87  0.0355
     9         9  pH_8_0                                       0.1665     1.90  0.1309
    10        10  pH_7_0                                       0.2009     2.32  0.0745
```

Summary of forward selection

```
          Number                   Partial
  Step        In Entered          R-Square F Value Pr > F
     1         1 Warmer_25C        0.7991    45.74 <.0001
     2         2 Clay              0.3899     7.19 0.0001
     3         3 Perm              0.3973     7.25 0.0001
     4         4 95_00_Precip_cm   0.3421     5.59 0.0010
     5         5 SalRange          0.2907     4.30 0.0052
     6         6 Colder_10C        0.3139     4.69 0.0033
     7         7 Turb_25           0.2803     3.89 0.0092
     8         8 DepRange          0.2274     2.87 0.0355
     9         9 pH_8_0            0.1665     1.90 0.1309
    10        10 pH_7_0            0.2009     2.32 0.0745
```

Summary of backward elimination

```
          Number                  Partial
  Step        In Removed         R-Square F Value Pr > F
     0        20                   .         .    .
     1        19 Width_atsite_m    0.0599    0.43 0.7858
     2        18 Perm              0.0751    0.57 0.6879
     3        17 Shellfish         0.0558    0.43 0.7868
     4        16 watershed_HA      0.0892    0.73 0.5754
     5        15 Forest_Land       0.1077    0.94 0.4566
     6        14 Agricultural_Land 0.0494    0.42 0.7962
     7        13 Urban_Built_up    0.0580    0.51 0.7304
     8        12 Turb_25           0.1309    1.28 0.2971
```

Conclusions

In summary, eight distinguishing attributes were consistently important factors for all four methods including warm water temperature (≥ 25^{o}C), cold water temperature (≤10^{o}C), pH <7, pH >8, clay, precipitation, salinity range, and mean range in depth. As expected, temperature is the most distinguishing characteristic. Water temperature was very warm at sites in the Gulf of Mexico and fairly warm in the Southeast while water temperature in the Mid-Atlantic and the Northeast was cooler. Water was more acidic in the Mid-Atlantic when compared with other regions, where most sites were more oceanic and alkaline. Tidal dynamics (mean daily in depth, and salinity range) seemed greater in the Southeast and the West Coast than at sites in the Gulf of Mexico and the Mid-Atlantic. However, the variation of these attributes was large within the West Coast, so no clear-cut conclusion could be drawn. Precipitation was excessive in the Gulf of Mexico, and the proportion of clay was high in the Southeast and the West Coast.

Chapter 4: Production, Respiration and Net Ecosystem Metabolism

Introduction

While no single index has emerged that captures all the complex processes and trophic interactions that occur within estuaries, net ecosystem metabolism is a particularly useful indicator because it integrates the system level processes of primary production and respiration within the estuary. Net ecosystem metabolism may be particularly useful for assessing nutrient enrichment and eutrophication at different locations because this approach provides an index of how well balanced the ecosystem is and appears to reflect the loading of organic matter or dissolved inorganic nutrients to the system (Kemp et al. 1997). Strongly net autotrophic systems like portions of Waquoit Bay (D'Avanzo et al. 1996) and the MERL mesocosms (Oviatt et al. 1986) are dominated by inorganic nitrogen loading, while net heterotrophic systems like Tomales Bay (Smith and Hollibaugh 1993, 1997) are dominated by organic carbon loading. In addition, seasonal changes in metabolic rates, particularly those associated with phytoplankton blooms, can result in changes of net ecosystem metabolism from autotrophy during bloom conditions to heterotrophy during non-bloom conditions (Caffrey et al. 1998).

NERR sites have been selected to be representative of the coastal bioregions of the U.S. and are characterized by a variety of plant communities including phytoplankton, salt marsh, seagrass, mangrove and freshwater macrophyte. Results from the first synthesis (Wenner et al. 2001) demonstrated that metabolic rates were influenced by habitats adjacent to the deployment sites. Sites near mangrove forests and in some salt marsh creeks had exceptionally high respiration rates and were exceedingly heterotrophic. Three sites, located in either eelgrass beds or above macroalgae mats, were autotrophic. Temperature was the single most important factor controlling metabolic rates at individual sites, although salinity was also important at about half the sites. On an annual basis, respiration exceeded gross primary production demonstrating that all but 4 of the 28 NERR sites examined were heterotrophic. Freshwater fill time and nitrogen loading to the different estuaries may explain much of the variance in net ecosystem metabolism.

Data from 42 sites participating in the National Estuarine Research Reserve's System Wide Monitoring Program (NERR SWMP) between 1995-2000 were analyzed to estimate an integrated index of ecosystem level processes (production, respiration and net ecosystem metabolism). This chapter summarizes how these processes change over a seasonal and annual basis and whether long term trends in the data exist. Relationships among metabolic rates, physical, chemical and biological factors are compared at several Reserves with extensive ancillary nutrient and chlorophyll *a* data, as well as with literature values from other estuaries.

Methods

Dissolved oxygen (% saturation) data from NERR sites were analyzed following extensive quality control and quality assurance as described in Wenner et al. (2001). For presentation of results, sites were categorized based on the dominant habitat near the deployment site (Table 14).

Table 14. Data availability, habitat, and estuarine surface area (km^2) of NERR sites.

Region/Reserve	Site	Days of Data Available	Habitat Type	Estuarine Surface Area (km^2)
West Coast				
Padilla Bay	Bay View Channel (PDBBY)	947	SAV	3 E+01
South Slough	Stengstacken Arm (SOSSE)	909	marsh	3 E-01
South Slough	Winchester Arm (SOSWI)	859	marsh	6 E-01
Elkhorn Slough	Azevedo Pond (ELKAP)	1656	marsh	4 E-03
Elkhorn Slough	South Marsh (ELKSM)	1195	marsh	4 E-02
Tijuana River	Oneonta Slough (TJROS)	1045	marsh	4 E-02
Tijuana River	Tidal Linkage (TJRTL)	509	marsh	8 E-03
Northeast				
Wells	Head of Tide (WELHT)	274	marsh	2 E-02
Wells	Inlet (WELIN)	1099	SAV	1 E+00
Great Bay	Great Bay Buoy (GRBGB)	785	SAV	2 E+01
Great Bay	Squamscott River (GRBSQ)	430	open water	1 E+00
Waquoit Bay	Central Basin (WQBCB)	316	SAV	4 E+00
Waquoit Bay	Metoxit Point (WQBMP)	305	SAV	4 E+00
Narragansett Bay	Potters Cove (NARPC)	973	open water	3 E-01
Narragansett Bay	T-wharf (NARTW)	519	open water	4 E+02
Hudson River	Tivoli South (HUDTS)	855	marsh	7 E-01
Old Woman Creek	State Route 2 (OWSSU)	827	open water	6 E-02
Old Woman Creek	State Route 6 (OWCWM)	790	open water	6 E-02
Mid Atlantic				
JC – Mullica River	Buoy 126 (MULB6)	781	open water	5 E+01
JC – Mullica River	Lower Bank (MULBA)	627	open water	1 E+01
Delaware Bay	Blackwater Landing (DELBL)	1377	marsh	2 E+00
Delaware Bay	Scotton Landing (DELSL)	1043	marsh	1 E+00
Chesapeake Bay Md	Jug Bay (CBMJB)	424	marsh	5 E-03
Chesapeake Bay Md	Patuxent Park (CBMPR)	243	marsh	5 E-02
Chesapeake Bay Va	Goodwin Island (CBVGI)	926	SAV	1 E+00
Chesapeake Bay Va	Taskinas Creek (CBVTC)	1296	marsh	6 E-02
Southeast				
North Carolina	Masonboro Inlet (NOCMS)	1496	marsh	1 E-02
North Carolina	Zeke's Island (NOCZI)	1514	marsh	4 E-02
North Inlet-Winyah Bay	Oyster Landing (NIWOL)	1187	marsh	8 E-02
North Inlet-Winyah Bay	Thousand Acre Creek (NIWTA)	1201	marsh	1 E-02
ACE Basin	Big Bay Creek (ACEBB)	888	marsh	3 E-03
ACE Basin	St Pierre Creek (ACESP)	871	marsh	2 E-02
Sapelo Island	Flume Dock (SAPFD)	752	marsh	2 E-01
Sapelo Island	Marsh Landing (SAPML)	721	marsh	2 E+00
Gulf & Caribbean				
Jobos Bay	Station 10 (JOB10)	562	mangrove	9 E-02
Jobos Bay	Station 09 (JOB09)	528	mangrove	3 E-02
Rookery Bay	Blackwater River (RKBBR)	419	mangrove	3 E-01
Rookery Bay	Upper Henderson (RKBUH)	1106	mangrove	2 E-01
Apalachicola	Bottom (APAEB)	784	open water	1 E+01
Apalachicola	Surface (APAES)	1057	open water	1 E+01
Weeks Bay	Fish River (WKBFR)	1168	open water	6 E+00
Weeks Bay	Weeks Bay (WKBWB)	1191	open water	5 E+00

The method used here assumes that water masses are laterally and vertically homogenous (i.e., they have the same metabolic history); thus, in areas where physical processes such as advection and diffusion dominate over biological processes, metabolic rates may be either underestimated or overestimated (Kemp and Boynton 1980). Because previous analyses at two sites (Hudson River, Sawkill site, and Padilla Bay, Joe Leary site) suggested physical forces usually overwhelmed biological activity at these locations (Caffrey 2003), analyses for these two sites were not included in this report. For all other Reserves, data from two sites per Reserve were analyzed.

Oxygen is produced as a by-product of photosynthesis and consumed by respiration. In aquatic environments, oxygen concentrations usually exhibit a characteristic diurnal pattern, with concentrations increasing from morning into mid-afternoon as photosynthesis exceeds respiration. Declining oxygen concentrations occur during the late afternoon or evening in response to decreasing photosynthetic rates and continue to decrease throughout the night when photosynthesis does not occur. In addition to these biological processes, physical processes can also affect oxygen concentrations. Diffusion of oxygen across the air-water interface can increase or decrease water column concentrations, with diffusion from the air into the water occurring when the water is under saturated and vice versa when the water is supersaturated.

The diffusion, or air-sea exchange, was estimated by equation (1) below where ($DO_{sat,t1}$ $DO_{sat,t2}$) are the oxygen concentrations (units -%) for t1 and t2 and dt is the time difference, in hours, between t2 and t1. The time interval for all data was 0.5 hours. A coefficient of 0.5g O_2 m^{-2} hr^{-1} at zero O_2 was used to estimate the rate of air-sea exchange (J. Hagy and W.R. Boynton, pers. comm.). The units for air-sea exchange are g O_2 m^{-2}. Thus, when the average oxygen concentration for the time interval (($DO_{sat,t1}$ +$DO_{sat,t2}$)/200) is under saturated, air-sea exchange is positive and oxygen diffuses from the air into the water. If oxygen concentrations are supersaturated, air-sea exchange is negative and oxygen diffuses out of the water into the air.

$$\text{Air-sea exchange} = \left(1 - \frac{DO_{\text{sat,t2}} + DO_{sat,t1}}{200}\right) * 0.5 * \text{dt} \qquad (1)$$

This approach may underestimate exchange during periods of high winds and overestimate exchange during calm periods, since previous research has shown that the rate of diffusion is dependent on wind speed (Copeland and Duffer 1964, Hartman and Hammond 1984, Marino and Howarth 1993).

For each time interval, air-sea exchange was subtracted from the change in oxygen concentrations (DO) in g O_2 m^{-2} multiplied by water depth (m) to give oxygen flux (g O_2 m^{-2}) as described in equation (2) below.

$$\text{Oxygen flux} = (DO_{t2} - DO_{t1})\text{*water depth} - \text{air-sea exchange} \qquad (2)$$

Oxygen fluxes during daylight hours were combined to give net production. Similarly, oxygen fluxes from night were combined to determine night oxygen flux. Respiration is defined as a positive quantity; thus, night oxygen fluxes were multiplied by "–1" to give a night respiration rate. Gross production and total (day + night) respiration rate were calculated using net production and night respiration values. Assuming a constant respiration during the day and night, night respiration divided by hours of night equals the hourly respiration rate (g O_2 m^{-2} h^{-1}). Total respiration equals the hourly respiration rate multiplied by 24 h (g O_2 m^{-2} d^{-1}). Gross production is the net production plus the respiration occurring during daylight hours and was calculated by adding net production to the hourly respiration multiplied by the daylight hours. Net ecosystem metabolism was calculated by subtracting total respiration from gross production, or more directly by net production minus night respiration. Production rates were converted from oxygen to carbon assuming a photosynthetic quotient of 1.2 (O_2:CO_2 molar).

Daily metabolic rate data were averaged by month and then by season, defined as winter (December-February), spring (March-May), summer (June-August), and fall (September-November). Means and standard errors of means were calculated for annual data. Seven sites (ACEBB, ELKAP, ELKSM, GRBGB, GRBSQ, NIWOL and NIWTA) had monthly nutrient data for most of the years between 1995 – 2000 and four of these sites (GRBGB, GRBSQ, NIWOL, NIWTA) had monthly chlorophyll *a* data for the same period. North Inlet sites (NIWTA, NIWOL) also collected dissolved organic carbon (DOC) measurements. Relationships among metabolic rates and temperature, salinity, precipitation, the percent deviation of rainfall from average rainfall, nutrient, chlorophyll *a* and DOC concentrations were examined using stepwise linear multiple regression analysis. Correlation analysis between annual net ecosystem metabolism and estuarine surface area was performed among habitat groups. All statistical analyses were performed using SYSTAT.

Results

Average annual rates of gross primary production ranged from a low of 2.3 g O_2 m^{-2} d^{-1} at Old Woman Creek SU to a high of 28.1 g O_2 m^{-2} d^{-1} at Tijuana River Tidal Linkage (Table 15). The Tidal Linkage site also had the highest total respiration rate as well (32.3 g O_2 m^{-2} d^{-1}) while Elkhorn Slough South Marsh had the lowest respiration rate (4.4 g O_2 m^{-2} d^{-1}, Table 16). Most sites were heterotrophic, with Rookery Bay Blackwater River being the most heterotrophic (7.6 g O_2 m^{-2} d^{-1}). Three sites (Chesapeake Bay VA Goodwin Island, Wells Inlet, and Waquoit Bay Central Basin) were slightly autotrophic.

Spatial and Seasonal Trends by Region

Reserve sites exhibited a strong seasonal pattern of high rates of gross primary production and total respiration in the summer and low rates in the winter, with a few exceptions. Blackbird Landing in Delaware provides a good example of strong seasonal differences (Figure 24). In contrast, seasonal trends at Jobos were very muted with little distinction between winter and summer (Figure 25), perhaps due to the relatively small range in temperature (22-32°C). Net ecosystem metabolism rates also exhibited seasonal patterns, although seasonal patterns for net ecosystem metabolism were weaker than seasonal patterns for production and respiration at most Reserves.

Table 15. Mean (+/- s.e.) annual rates of gross primary production, total respiration, and net ecosystem metabolism (NEM) in g O_2 m^{-2} d^{-1} at NERR sites.

Region/Reserve/Site	Production		Respiration		NEM	
	mean	s.e.	mean	s.e.	mean	s.e.
Pacific						
Padilla Bay BY	11.36	1.13	11.71	1.00	-0.35	0.21
South Slough SE	14.40	1.39	16.49	1.45	-2.08	0.25
South Slough WI	10.03	0.86	11.30	0.96	-1.27	0.18
Elkhorn Slough AP	10.95	0.54	13.26	0.50	-2.21	0.21
Elkhorn Slough SM	2.99	0.18	4.36	0.24	-1.37	0.15
Tijuana River OS	15.10	0.92	19.07	1.04	-3.96	0.32
Tijuana River TL	28.07	2.38	32.31	2.31	-4.14	0.45
Northeast						
Wells HT	3.28	0.42	6.91	0.79	-3.62	0.53
Wells IN	5.08	0.54	4.94	0.51	0.92	0.34
Great Bay GB	7.59	0.65	7.78	0.62	-0.19	0.17
Great Bay GB	6.49	0.57	7.13	0.71	-0.64	0.26
Waquoit Bay CB	6.59	0.29	8.75	0.41	0.31	0.24
Waquoit Bay MP	5.58	0.41	7.16	0.54	-0.12	0.39
Narragansett Bay PC	8.20	0.57	9.86	0.79	-1.66	0.30
Narragansett Bay TW	8.05	0.96	9.35	1.22	-1.30	0.42
Hudson River TS	3.04	0.31	4.63	0.42	-1.59	0.20
Old Woman Creek SU	2.31	0.20	6.41	0.33	-4.10	0.29
Old Woman Creek WM	2.68	0.20	6.32	0.35	-3.65	0.26
Mid Atlantic						
Mullica River B6	5.81	0.58	5.94	0.60	-0.03	0.19
Mullica River BA	2.74	0.31	4.82	0.46	-2.08	0.34
Delaware Bay BL	11.24	1.02	13.94	1.17	-2.69	0.25
Delaware Bay SL	9.39	0.94	10.96	1.13	-1.57	0.36
Chesapeake Bay MD JB	6.76	0.52	12.32	0.59	-5.57	0.36
Chesapeake Bay MD PR	8.23	1.63	10.20	1.41	-1.97	0.39
Chesapeake Bay VA GI	5.15	0.42	4.68	0.52	0.48	0.16
Chesapeake Bay VA TC	8.88	0.64	8.52	0.67	-2.07	0.21
Southeast						
North Carolina MS	5.51	0.33	7.72	0.48	-0.93	0.18
North Carolina ZI	3.46	0.31	6.44	0.40	-0.86	0.17
North Inlet-Winyah Bay OL	6.97	0.33	7.91	0.42	-2.21	0.26
North Inlet-Winyah Bay TA	4.68	0.27	5.55	0.34	-2.99	0.18
ACE BB	12.42	0.67	17.92	0.91	-5.36	0.69
ACESP	11.97	0.65	14.73	0.80	-2.62	0.30
Sapelo FD	18.40	1.49	22.12	1.66	-3.72	0.34
Sapelo ML	9.18	0.85	11.09	1.00	-1.91	0.34
Gulf and Caribbean						
Jobos Bay 10	4.21	0.29	6.79	0.46	-2.58	0.36
Jobos Bay 09	5.70	0.35	10.02	0.55	-4.32	0.38
Rookery Bay BR	3.88	0.37	11.49	0.45	-7.61	0.32
Rookery Bay UH	5.64	0.28	11.56	0.35	-5.92	0.26
Apalachicola EB	3.11	0.22	5.64	0.40	-1.56	0.23
Apalachicola ES	2.84	0.17	4.40	0.34	-2.53	0.26
Weeks Bay FR	7.73	0.91	7.41	0.96	-2.16	0.28
Weeks Bay WB	6.91	1.29	7.04	1.17	-2.03	0.26

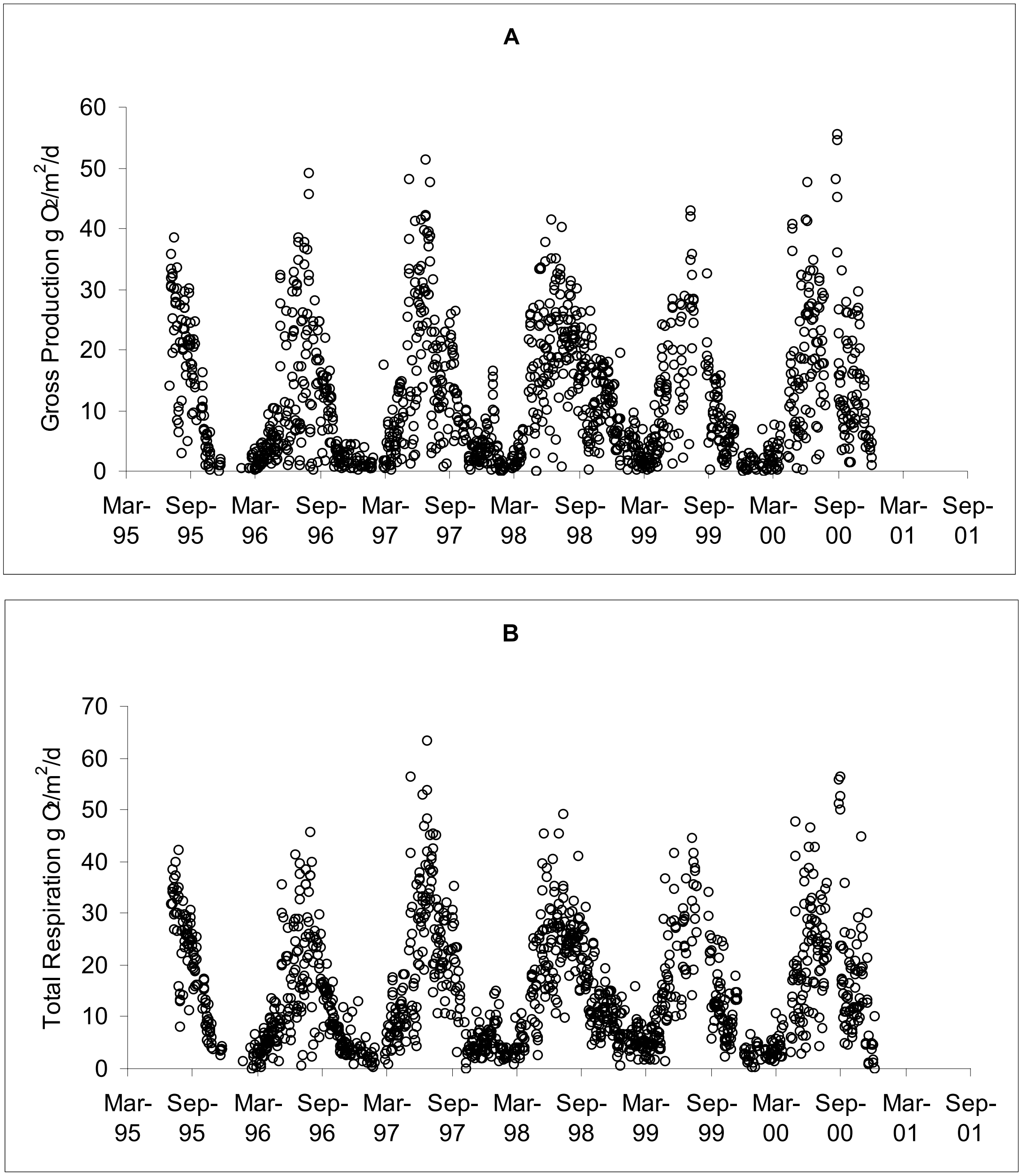

Figure 24. Seasonal patterns in production (A) and respiration (B) at Blackbird Landing (Delaware Bay NERR) between 1995-2000.

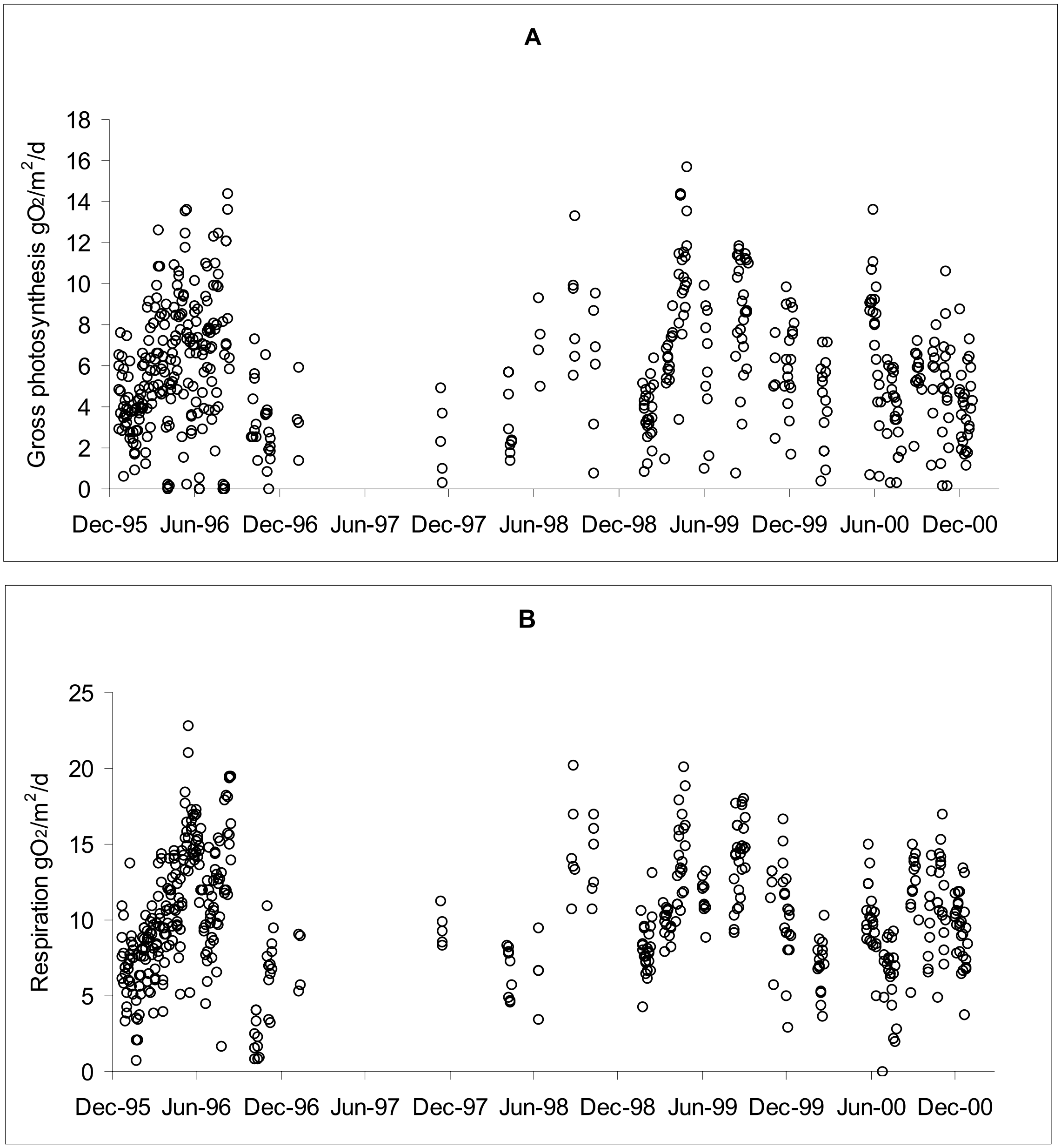

Figure 25. Lack of well-defined seasonal patterns in production (A) and respiration (B) at Station 9 (Jobos Bay NERR) between 1995-2000.

Gross primary production “P” and respiration “R” are discussed in the following sections; however, only production plots are shown given consistent P:R trends at all Reserve sites.

West Coast

Reserves in this region span the greatest geographical and climatic gradients in the Reserve system, so it is not surprising that seasonal or inter-annual patterns were not consistent among these Reserves. The South Slough Reserve exhibited the typical summer peak in production and respiration rates, while the Tijuana River Reserve and Bayview Channel (Padilla Bay NERR) had peak rates in the spring (Figure 26a). Elkhorn Slough sites did not show any consistent seasonal trends. Rates were highest at the Tijuana River Tidal Linkage site and least at the Elkhorn Slough South Marsh site (Figure 26a). Elkhorn Slough and Tijuana River did exhibit some inter-annual trends in production and respiration rates, although they were not consistent between the two Reserves. The Reserves in this region were usually most heterotrophic in the summer, except for Padilla Bay (Bayview Channel) and Elkhorn Slough (Azevedo Pond), which were most heterotrophic in the fall (Figure 26b). Padilla Bay (Bayview Channel) was consistently autotrophic in the spring and often autotrophic in the summer.

Northeast

Peak production and respiration rates for all Reserves in this region occurred during summer (Figure 27a). Few Reserves collected data during winter months due to ice cover, but where data were available (e.g. Wells), rates were often near zero. The high winter primary production rate from Great Bay (Squamscott River) should be interpreted with caution because it represents just three days worth of data from a single year. Production and respiration rates were lowest, usually less than 5 $gO_2\ m^{-2}\ d^{-1}$, at the Old Woman Creek Reserve and the Wells (Head of Tide) site (Figure 27a). Three sites in this region (Waquoit Bay, Wells Inlet site and Great Bay GB) were usually balanced or autotrophic with inconsistent seasonal variation (Figure 27b). Net ecosystem metabolism at other sites was heterotrophic, often with maximum effects in summer. Inter-annual variation in production and respiration in this region was minimal and inconsistent between sites and among Reserves; however, the Wells Inlet site was somewhat autotrophic in 1996-1997, strongly autotrophic in summer 1998, and then strongly heterotrophic during spring and summer 1999-2000 (Figure 28).

Mid-Atlantic

All sites within this region exhibited consistent seasonal trends in production and respiration, except for the Chesapeake Bay Maryland sites where limited sampling makes interpretations difficult. Summer production and respiration rates were often 1.5 to 2 times higher than rates in the other seasons (Figure 29a). Production and respiration rates ranged from being relatively low at Mullica River (Lower Bank) to high at both Delaware Bay sites (Figure 29a). Interannual variation in production and respiration was minimal in this region. Net ecosystem metabolism showed seasonal and spatial variation among Reserve sites. Maximum heterotrophy during the summer was a consistent pattern across all sites (excluding Chesapeake Bay MD). Chesapeake Bay VA (Goodwin Island) and Mullica River (Buoy 126) sites were usually autotrophic or balanced during the other seasons. Conditions at the Delaware Bay and Mullica River (Lower Bank) sites changed from generally balanced in 1996-1998 to heterotrophic in 1999-2000 (Figure 30).

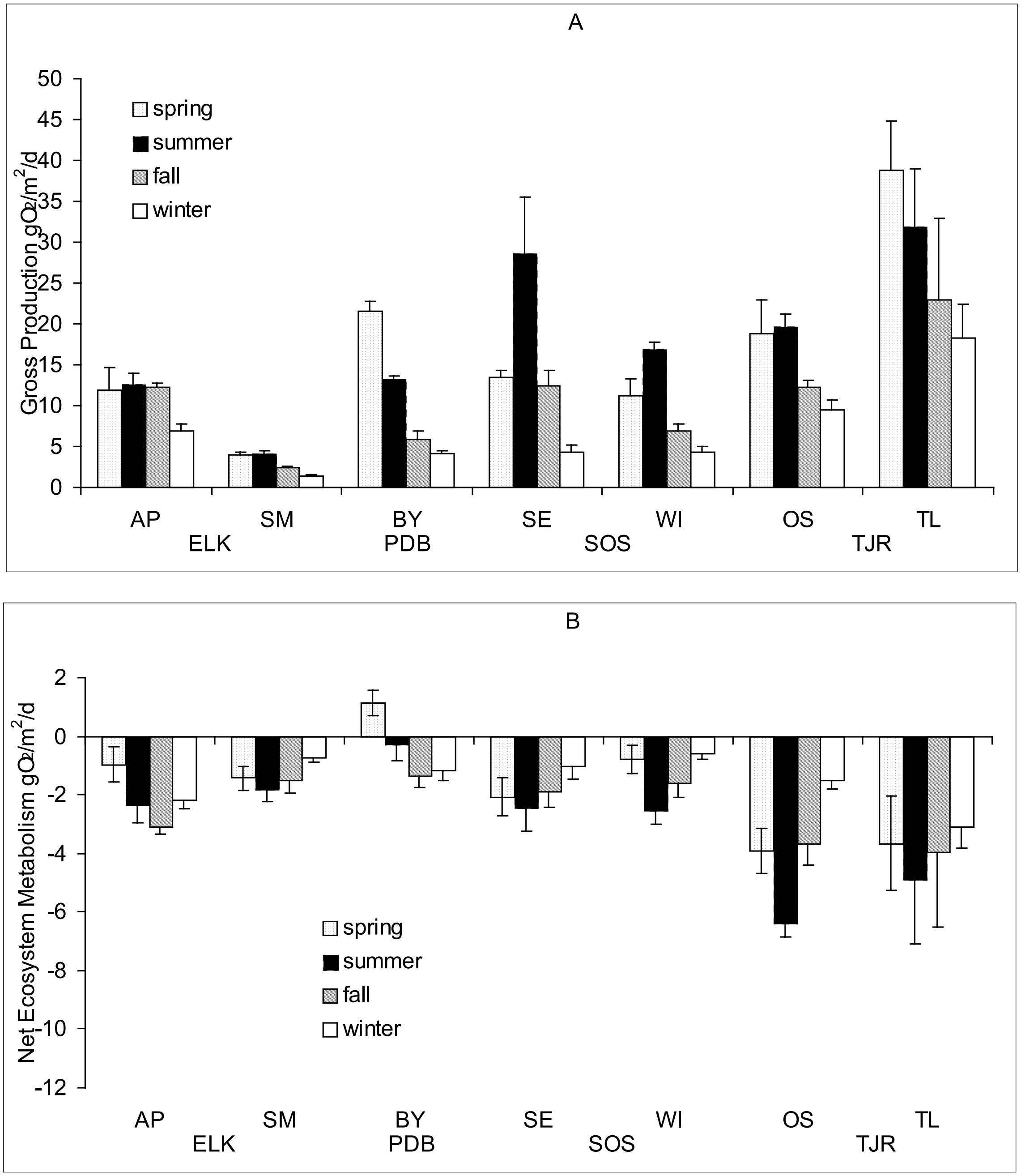

Figure 26. Gross production (A) and net ecosystem metabolism (B) rates for West Coast NERR sites evaluated, 1995-2000.

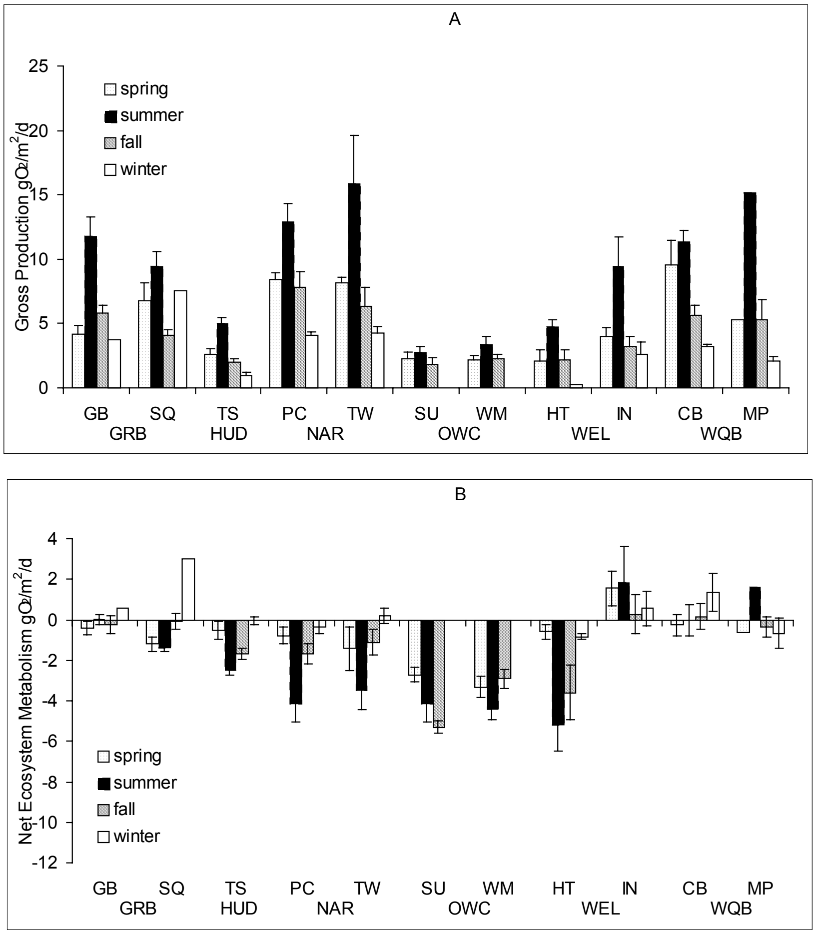

Figure 27. Gross production (A) and net ecosystem metabolism (B) rates for Northeast NERR sites evaluated, 1995-2000.

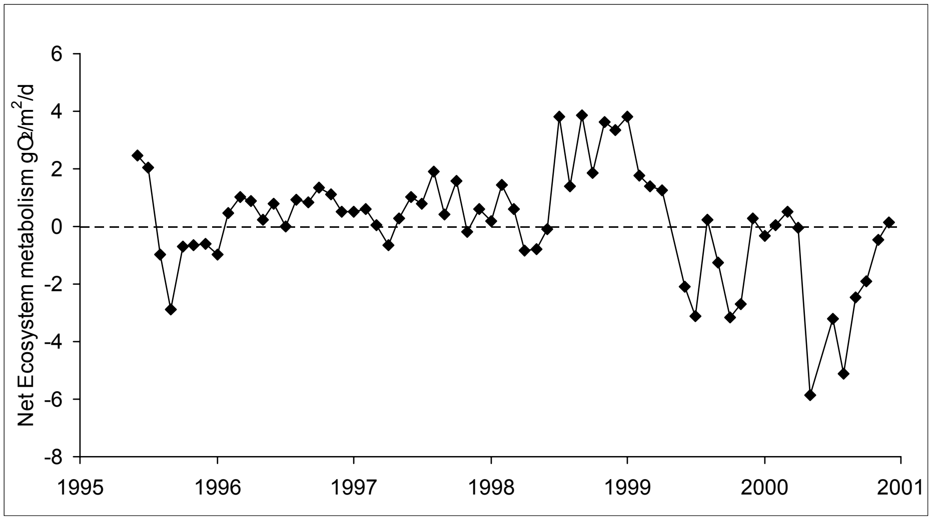

Figure 28. Monthly net ecosystem metabolism at the Wells Inlet site, 1995-2000.

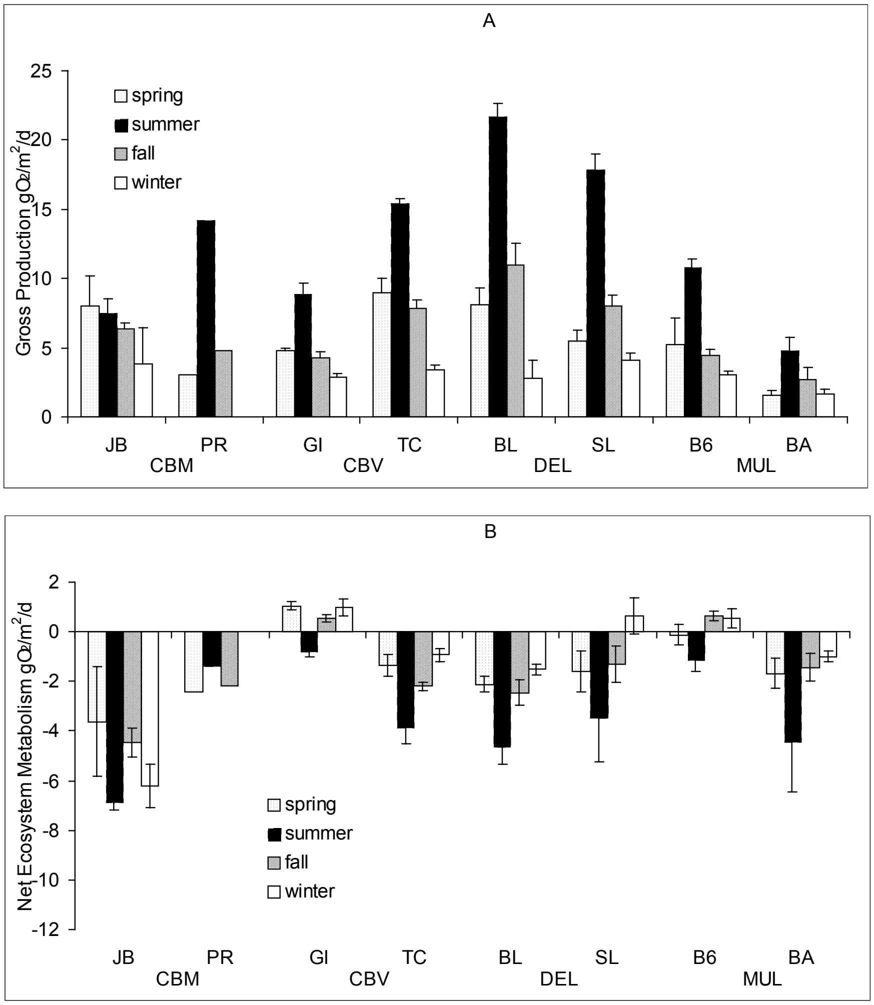

Figure 29. Gross Production (A) and Net Ecosystem Metabolism (B) rates for NERR sites evaluated in the Mid-Atlantic region, 1995-2000.

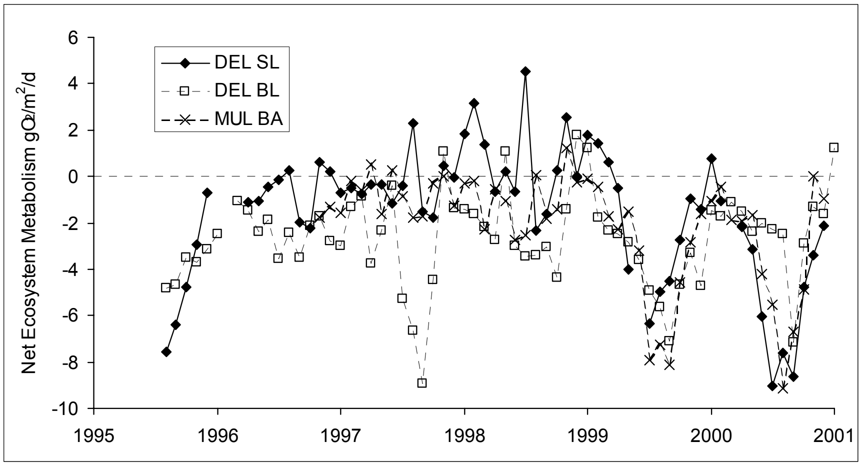

Figure 30. Monthly net ecosystem metabolism at Delaware Bay Scotton Landing (DELSL), Delaware Bay Blackbird Landing (DELBL) and Mullica River Lower Bank (MULBA), 1995-2000.

Southeast

Production and respiration rates in the Southeast region were greatest at the Sapelo Island sites and decreased moving north into North Carolina (Figure 31a). Most sites had peak rates in summer, except for ACE Basin St Pierre where peak rates occurred in spring. Production and respiration in North Carolina often had a bimodal pattern, with peaks in both March and April and again in June-Aug (Figure 32a). Inter-annual variation in metabolic rates was inconsistent among Reserves in this region. The highest production and respiration rates occurred in 1996 at ACE Basin (Big Bay) and in 1999 at North Inlet (Oyster Landing), but no clear trends were observed for other sites. Similar to the Gulf and Caribbean Reserves, net ecosystem metabolism had a consistent seasonal pattern and was almost always heterotrophic at all sites (Figure 31b). ACE Basin (Big Bay) was the most heterotrophic site in this region, while the North Carolina sites were the least heterotrophic. Net ecosystem metabolism was most heterotrophic during the summer and balanced or slightly autotrophic in the winter, except at ACE Basin (St Pierre) and Sapelo Island (Marsh Landing), which were most heterotophic during spring (Figure 31b). North Carolina sites, particularly Zeke's Island, were autotrophic or balanced during fall and winter months (Figure 32b). North Inlet (Oyster Landing) also became autotrophic (or balanced) every January or February (data not shown).

Gulf of Mexico and Caribbean

Reserves in the Gulf of Mexico and Caribbean exhibited several different seasonal patterns of production and respiration (Figure 33a). Apalachicola Bay sites and the Weeks Bay-Weeks Bay (WB) site had peak rates in summer, typical of most Reserve sites. Rookery Bay sites and Jobos Bay (site 9) had peak rates in the spring, while rates at both Jobos Bay site 10 and Weeks Bay Fish River showed little seasonal variation (Figure 33a). Metabolic rates were lowest at Apalachicola Bay compared to the other Reserves in this region. Rates within Reserves were generally quite similar, suggesting few differences between control and impact sites. Interannual variation in metabolic rates at all Reserve sites was minimal. In fact, the Blackwater River site in Rookery Bay was autotrophic only 1 day over the entire record. In contrast with the production and respiration rates, net ecosystem metabolism exhibited a consistent seasonal pattern of greater heterotrophy during the summer, except Jobos Bay, which was most heterotrophic during the fall (Figure 33b). All sites from this region were strongly heterotrophic, particularly Rookery Bay sites (Figure 34).

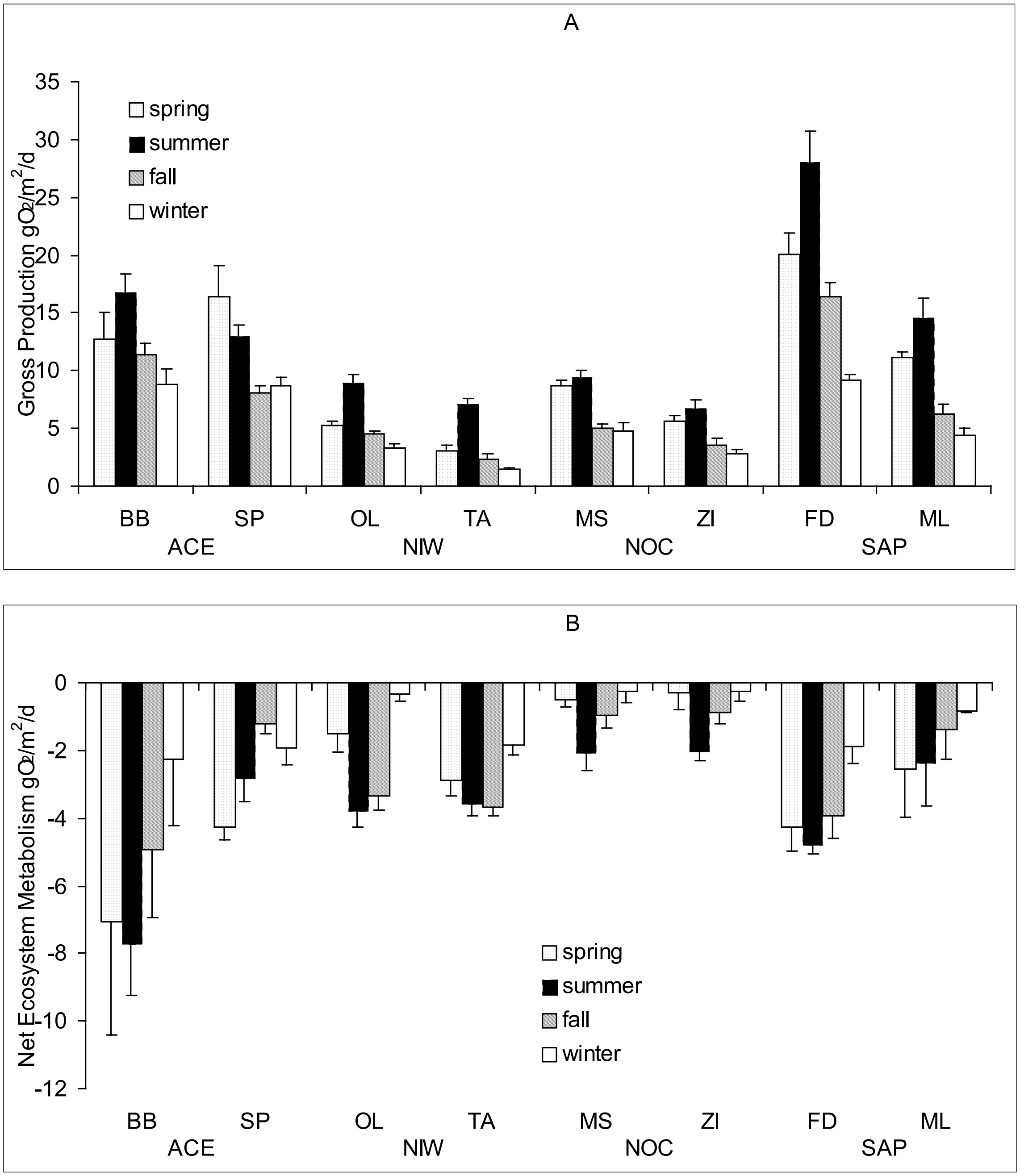

Figure 31. Gross production (A) and net ecosystem metabolism (B) rates for NERR sites evaluated in the Southeast, 1995-2000.

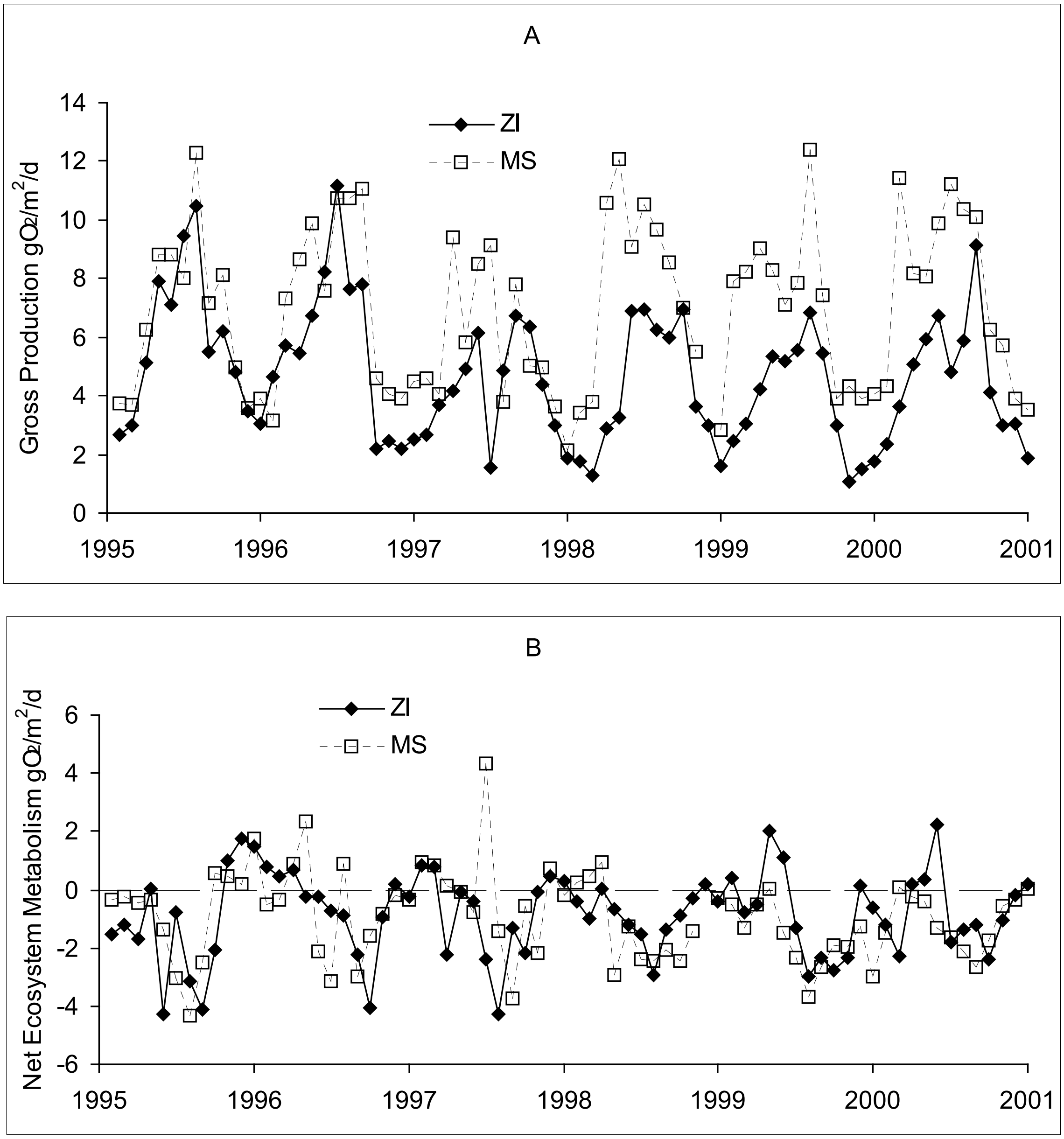

Figure 32. Gross production (A) and net ecosystem metabolism (B) rates for North Carolina Zeke's Island (ZI) and Masonboro Island (MS) sites, 1995-2000.

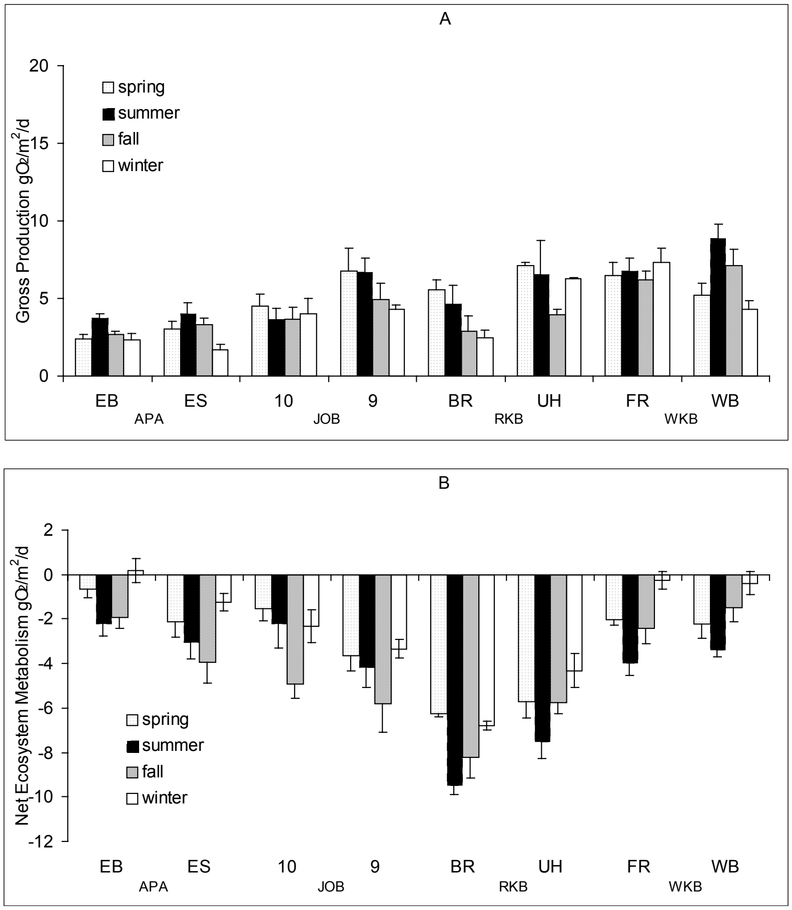

Figure 33. Gross production (A) and net ecosystem metabolism (B) rates for NERR sites evaluated in the Gulf of Mexico and Caribbean, 1995-2000.

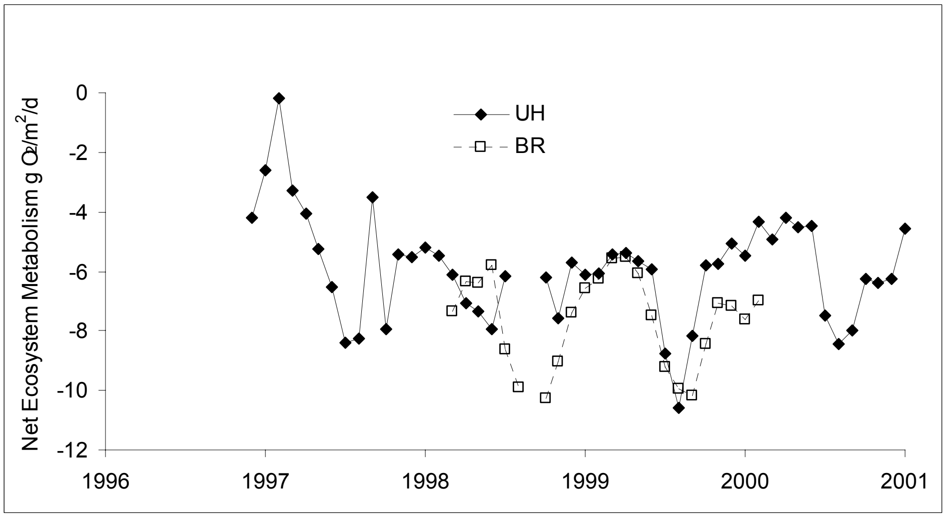

Figure 34. Monthly net ecosystem metabolism at the Rookery Bay Upper Henderson (UH) and Blackwater River (BR) sites, 1997-2000.

Factors controlling metabolic rates

Analysis of the 1996-1998 data indicated that temperature and salinity were important factors controlling metabolic rates at the sites. Nutrient data from some of the Reserves suggested that nutrient concentrations and inputs might also be important in controlling metabolic rates. The seasonally averaged data shown in Figures 26, 27, 29, 31 and 33 confirm the importance of temperature for the entire dataset. Stepwise multiple regression was used to examine how metabolic rates (gross production, respiration, and net ecosystem metabolism) were related to physical (temperature, salinity, rainfall, deviation from normal rainfall), chemical (DIN, DIP, TN, TP, DOC) and biological (chlorophyll *a*) variables. Regression models for all metabolic rates at the seven Reserves were significant, except for net ecosystem metabolism at the Great Bay GB site (Table 16). The regression models could explain 20-90% of the variation in metabolic rates. R-squared values were generally higher for gross production and respiration than net ecosystem metabolism. Temperature was a significant factor in all the models except for net ecosystem metabolism at both Elkhorn Slough sites. Nutrient concentrations were a significant factor in 5 out of 6 net ecosystem metabolism models, but were significant in only 3 out of 7 gross production or respiration models (Table 16).

Table 16. Significant regression models of gross production, respiration, and net ecosystem metabolism at NERR sites. Physical parameters include temperature (T), salinity (S), precipitation (Pr), and percent deviation from normal precipitation (Pd). Chemical parameters include dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), total nitrogen (TN), total phosphorus (TP), and dissolved organic carbon (DOC). Chlorophyll *a* (C) was the biological parameter.

Site	Gross production		Respiration	
	r^2	significant factors	r^2	significant factors
ACEBB	0.27	T	0.56	T, S, DIN
ELKAP	0.43	T, DIN, DIP	0.43	T, S
ELKSM	0.30	T, Pr	0.40	T, Pr
GRBGB	0.65	T	0.72	T
GRBSQ	0.71	T,S,Pr, C	0.76	T, C
NIWOL	0.79	T, Pr, TP, DOC, C	0.89	T, Pd, DOC, C
NIWTA	0.82	T, TN, DOC, C	0.78	T, S, Pr, Pd, DIN, C

Site	Net ecosystem metabolism		Chemical and biological factors included in model
	r^2	significant factors	
ACEBB	0.56	T, S, DIN	DIN, DIP
ELKAP	0.26	S, DIN, DIP	DIN, DIP
ELKSM	0.17	S, Pd	DIN, DIP
GRBGB	0.06	DIN	DIN, DIP, C
GRBSQ	0.56	T, DIN	DIN, DIP, C
NIWOL	0.69	T, TP, C	DIN, DIP, TN, TP, DOC, C
NIWTA	0.41	T, Pr, Pd, DIN	DIN, DIP, TN, TP, DOC, C

While nutrient concentrations are most likely important in controlling metabolic rates, monthly grab samples (or a monthly diurnal set of samples) may not adequately capture water column nutrient concentrations. Even with hourly sampling of nutrients, the relationship between nutrient concentration and metabolic rates are difficult to interpret (Figure 35). Sampling at Elkhorn Slough (Azevedo Pond) provides a good example of this situation. Although higher nutrient concentrations should lead to increased gross production, increased production generally lagged peak nitrate concentrations by two to ten days in January and March (Figure 35). Furthermore, April peaks in gross production appeared to be unrelated to nitrate concentrations (Figure 35).

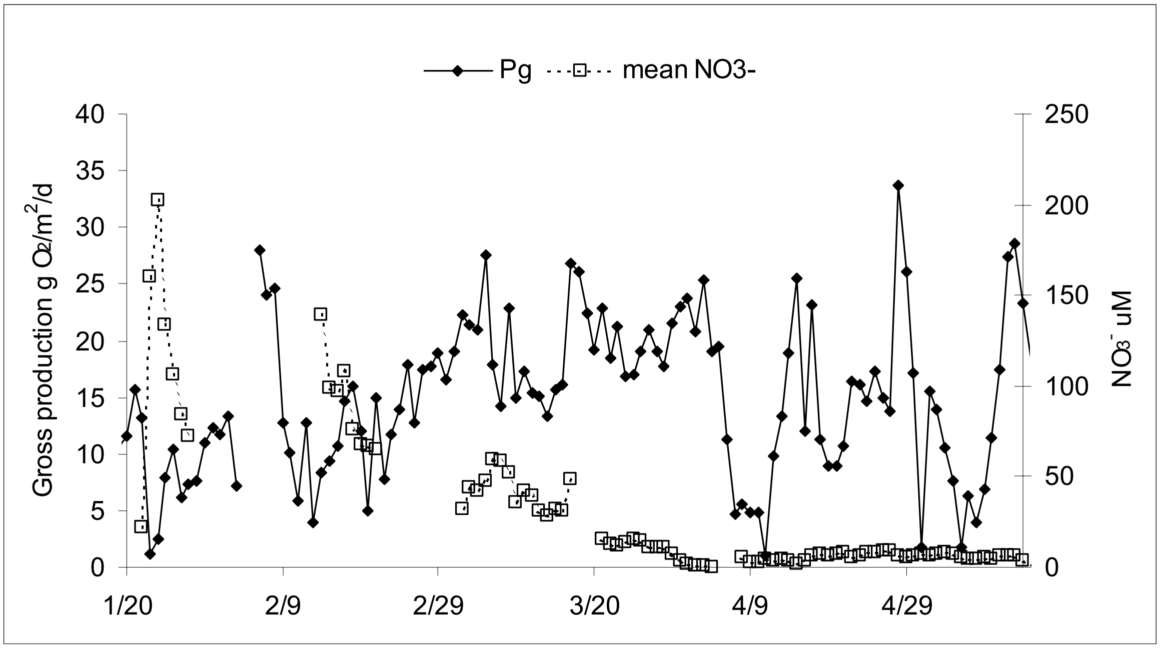

Figure 35. Gross production (Pg) versus mean nitrate (NO_3^-) at Elkhorn Slough, Azevedo Pond in winter and spring.

Discussion

Analysis of the 1996-1998 data suggested that the habitat adjacent to the monitoring site could explain some of the general trends in net ecosystem metabolism among the different sites. Sites adjacent to mangroves or in marsh creeks were heterotrophic, often strongly heterotrophic. In contrast, sites adjacent to SAV (eelgrass or macroalgal beds) were either autotrophic or nearly balanced. Open water sites were generally heterotrophic, although the variation between sites could be large.

Estuarine surface area was estimated for each site and compared with net ecosystem metabolism for each habitat type (Figure 36). As estuarine surface area increased, open water sites and marsh creeks became significantly more autotrophic, with a correlation coefficient of $r = 0.70$ ($p<0.02$) at open water sites and $r = 0.40$ ($p<0.10$) at marsh creeks. The converse was true for SAV and mangrove sites, where small sites were more autotrophic than larger sites. The correlation for the SAV sites was $r = –0.87$ ($p<0.02$), while the correlation at mangrove sites, $r = -0.69$ and was not significant.

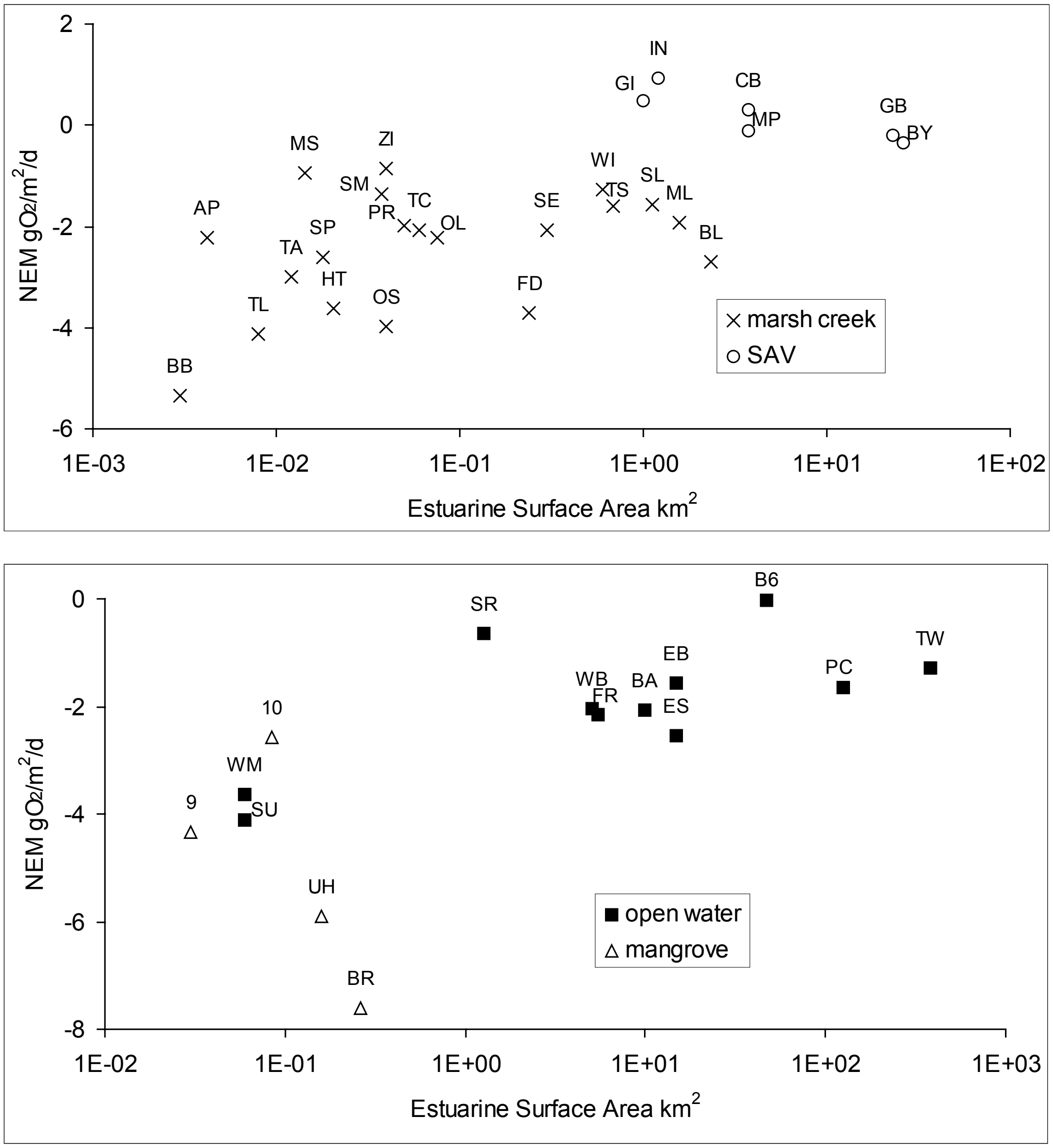

Figure 36. Relationships between net ecosystem metabolism, habitat type, and estimated estuarine surface area (km^2) for NERR SWMP sites.

Several factors may be contributing to the patterns between net ecosystem metabolism and estuarine surface area such as residence time, nutrient and organic loading. In the marsh creeks and open water sites, nutrient inputs supporting phytoplankton production may become more important than allochthonous organic inputs from the marsh or uplands as systems get bigger. The pattern for SAV sites was quite different, suggesting that as area increases, systems become more heterotrophic. The relative balance between SAV, plankton production and organic loading may explain this pattern. While the relationship between estuarine surface area and net ecosystem metabolism is interesting, it does not provide a direct mechanism that could explain these patterns. Further studies to estimate residence time, nutrient and organic loading rates for these sites are necessary.

The results of this study were compared to other metabolic rates in estuarine and coastal systems. Net ecosystem metabolism was estimated for a variety of locations, seven of them at or near NERR sites (Table 17, Figure 37). There was good agreement between estimates at three of the sites (Waquoit Bay, Apalachicola Bay, and Elkhorn Slough). The estimate from Central Basin and Metoxit Point is bracketed by the measurements in the three sub-watersheds of Waquoit Bay (D'Avanzo et al. 1996). Summer measurements of metabolic rates in East Bay by Boynton (1975) were similar to the Reserve measurements. However, the estimate of net ecosystem metabolism in Apalachicola Bay as a whole based on a biogeochemical budget suggests that the bay is autotrophic. Elkhorn Slough South Marsh site was quite similar to the Slough-wide estimate based on a biogeochemical budget. Net ecosystem metabolism from the other four Reserve sites (Narragansett Bay, Hudson River, Patuxent River, and Weeks Bay) were all more heterotrophic than literature estimates (Table 17). This is not surprising given that literature estimates were for the entire system, or large reaches in the case of the Hudson (i.e., the oligohaline section). The shallow Reserve sites can potentially support a greater production and respiration, than deep systems having lower light penetration and thus reduced production.

Smith and Hollibaugh (1993) summarized the metabolic results from 27 marsh, estuarine and coastal systems. They observed that estuarine and coastal systems generally became more heterotrophic as gross primary production increased (Figure 36). The results from the NERR sites generally followed this trend, although the rates of production and net ecosystem metabolism were two to five times greater than the systems summarized in Smith and Hollibaugh (1993). The Reserve sites were much shallower and represented smaller areas than most estuarine studies, which focus on large, deep open water areas.

Table 17. Comparison of SWMP and literature values for net ecosystem metabolism.

Reserve	SWMP	other study	citation
	g C m^{-2} y^{-1}		
Waquoit Bay	-154	-397 to +18	D'Avanzo et al. 1996
Narragansett Bay	-388	80	Smith and Hollibaugh 1995
		26 to 43	Nixon et al. 1995
		14	LOICZ
Hudson	-287	-30	Howarth, pers. comm.
Patuxent River (Patuxent Park)	-458	-15	LOICZ
Apalachicola Bay	-348	-366	Boynton 1975 (East Bay only)
		13.1	LOICZ
Weeks Bay (Weeks Bay)	-344	-31	LOICZ (Mobile Bay)
Elkhorn Slough (South Marsh)	-257	-219	LOICZ

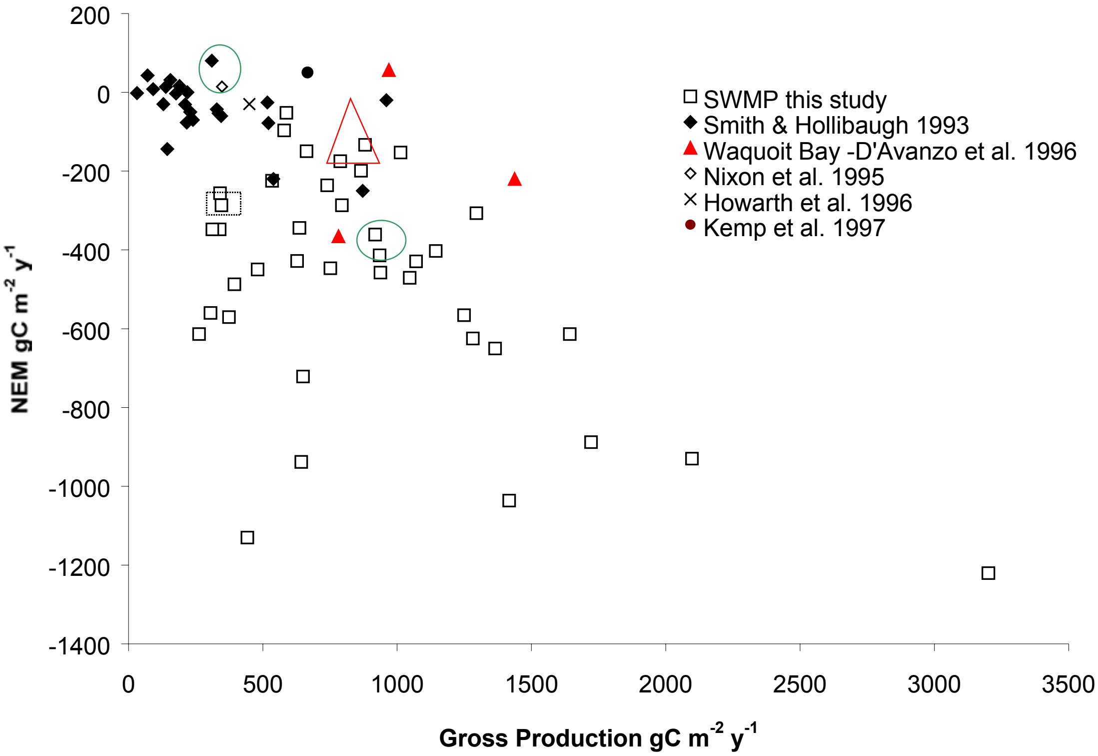

Figure 37. Net ecosystem metabolism (g C m^{-2} y^{-1}) versus gross primary production (g C m^{-2} y^{-1}) for Reserve SWMP sites, and literature values. Open squares represent SWMP data, filled diamonds are from the Smith and Hollibaugh 1993 review, filled triangles are from D'Avanzo et al. 1996 for Waquoit Bay. The SWMP Waquoit Bay values are enclosed by an open triangle. Narragansett Bay values are enclosed by ovals. Hudson River SWMP data is enclosed by a dashed rectangle for comparison with Howarth et al. (1996) estimate for the upper Hudson.

Chapter 5: Tidal and Diel Periodicity in NERR-SWMP Water Quality Data

Introduction

Water chemistry measures in NERR estuaries are highly periodic in nature. Preliminary analyses (Wenner et al. 2001) using classical harmonic regression techniques found that, for the vast majority of NERR sites, between 70% and 90% of the short-term variability in dissolved oxygen was explainable using only tidal (24.84 h) and diel (24.00 h) model components with corrections for trend. The percent of variance attributed to these two cycles was typically 80-95% for water temperature and salinity and greater than 90% for water depth. Effects of other natural or anthropogenic influences and disturbances will ride atop this "roller coaster" of diel and tidal periodicity. To carefully detect, measure and understand atypical influences and disturbances, we must first fully understand the typical variability, the periodic fluctuations in data. This portion of the synthesis of NERR water quality data quantifies this periodicity, in particular the relative importance of diel vs. tidal influences, in water quality measurements.

Methods

The available data at each of the 55 sites were time series of 8 water quality measurements made by a YSI meter every half-hour for the study's 3-6 year duration. Meters were to be redeployed approximately fortnightly, although QA/QC "deployments" across all sites ranged in length from less than a day to several months. A cursory inspection of the data revealed that deployment of a meter often resulted in an abrupt change in the mean level of any observed water quality measure. More seriously, there are clear indications that the observed amplitudes of periodic fluctuations at times also changed dramatically with new deployments. Together with the realization that the duration of daylight, and hence in all probability the shape of any diel signature, will change over each 12-month period, these "deployment effects" have led us to take a two-phase approach to quantification of periodicity in the water quality indices:

1. Fit periodic regression models to deployment-length segments of data (7-30 days), obtaining graphical and numerical descriptives of tidal and diel signatures, and then
2. Analyze deployment-level summaries for annual periodicity, and compare and contrast mean levels between the 55 sites for summaries of interest.

Deployments less than 7 days in duration were not used in these analyses. Furthermore, deployments greater than 30 days duration were split into multiple sub-series of duration less than 30 days each. Turbidity (NTU) values crossed several orders of magnitude, so these were transformed to $\log_{10}$(turbidity +0.5) prior to phase 1 analysis.

Phase 1: Periodic regression models for deployment-level data

Technical details provided in this section are conceptually summarized as an example of the graphical presentation of each deployment's harmonic model fit in Figure 38 (p. 67). The graphical summaries of each deployment's data have been captured into Powerpoint® presentations for each available combination of the 55 sites and 8 variables, and are available for review by contacting Dr. Don Edwards (edwards@math.sc.edu).

Classical harmonic regression techniques model periodicity due to tidal gravitational potential using weighted sums of sine functions whose periods have historically been deduced from the movements of the earth, moon, and sun. These methods have a rich scientific history dating back to the work of Newton and LaPlace in the 17th and 18th centuries, with contributions by Darwin, Lord Kelvin and many others. Our principal references, based on the advice of Blanton (2001), are Defant (1958) and Foreman and Henry (1989), whose recommendations are based on Godin's (1972) work.

The deep-water tide-generating forces can be grouped into constituents, each of which owns a sine wave in the classical harmonic regression model. The most important constituents are shown in Table 18, modified from Defant (1958, p. 48). There are many other classical tidal constituents, but these are either of much less importance, of longer duration, or are inseparable from the above constituents for series 7-30 days in duration.

Table 18. Important Constituents of Tide-Generating Forces (modified from Defant 1958).

	Symbol	Period (Solar hours)	Mean amplitude (ratio to M_2)	Description
Semidiurnal Tides	M_2	12.4206012	1.000	Main lunar (semidiurnal) constituent
	S_2	12.0000000	0.466	Main solar (semidiurnal) constituent
	N_2	12.6583482	0.191	Lunar const. due to monthly variation in Moon distance
	K_2	11.9672349	0.127	Soli-lunar const. for changes in sun and moon declination
Diurnal Tides	K_1	23.9344697	0.584	Soli-lunar constituent
	O_1	25.8193417	0.415	Main lunar (diurnal) const.
	P_1	24.0658902	0.193	Main solar (diurnal) constituent
Long-Period Tides	M_t	327.86 (18.66 d)	0.172	Moon's fortnightly constituent

Water quality variables are also potentially strongly influenced by solar energy; thus, we introduced a diel term (period = 24 hours), herein referred to as the "D" constituent. Simulation studies conducted during this project, as well as published literature (Foreman & Henry 1989), confirm that this constituent is not distinguishable from K_1 or P_1 for series 7-30 days in duration because their periods are too similar, nor from K_2 or S_2, whose periods are approximately or exactly D/2. Subsequently, the deployment-level model extracts four periodic signatures from the data as follows:

(1) D (in sum with K_1, P_1, K_2, and S_2),
(2) M_2,
(3) N_2, and
(4) O_1.

By far the most consistently important among these are D and M_2. The additional terms N_2 and O_1 are rarely of great importance, but the addition of these to the model is theoretically necessary and seemed to lead to better model fits and greater consistency for the D and M_2 patterns. The model used here also included a trend term, which would remove the effects of the main long-period constituent M_t and other constituents whose periods are on the order of a few days to a month.

Classical harmonic regression analyses of water level (depth) typically fit the data remarkably well and provide near-perfect predictions. Occasionally, shallow-water settings create complexities in tidal signatures that are not well modeled by a weighted-sum of sine waves using the classical constituents (Defant 1958). Moreover, "noisier" variables like dissolved oxygen and salinity require a much more flexible approach than the classical sine-wave-based models, and there is certainly no reason to believe that the very important diel signature will be well approximated by sine waves for any variable. These considerations, and an unusual abundance of data, have led us to use a nonparametric regression approach to the deployment-level harmonic analyses, using a relatively new statistical technology called "generalized additive models" (Hastie and Tibshirani 1990). For a measurement made at a time t, we can identify the stage of each of the four major cycles: X_D, X_{M2}, X_{N2}, and X_{O1}, defining each X to be 0 at midnight on the first day of the data collection. The model hypothesizes that the measured water quality variable Y can be well approximated during the deployment by the sum of a slowly-changing trend term and four smooth, repeating cyclic functions:

$$Y \approx f_0(t) + f_D(X_D) + f_{M2}(X_{M2}) + f_{N2}(X_{N2}) + f_{O1}(X_{O1}) \qquad (1)$$

Here, f_D, f_{M2}, f_{N2}, and f_{O1} are smooth but flexible nonparametric "profiles" or "signatures" describing the diel and tidal periodicities in Y, and $f_0(t)$ is a term designed to remove within-deployment trend (analogous to using a low-order polynomial with a time series). The above model fits the noisier variables much better than a classical sine-based model, and is very competitive for modeling depth (Winterton 2002). Despite its complexity, it lends itself very well to graphical depiction, which is key for interpretation.

The generalized additive model (1) also lends itself readily to deployment-level numerical descriptives (Table 19). Deployment descriptives were used for studying annual periodicity and site comparisons in phase 2. These quantities are self explanatory except for the "Pure Error" terms, which are the error sum of squares and degrees of freedom from a "saturated" smooth-curve fit.

Table 19. Deployment-level model descriptives calculated for phase 1 analyses.

Site	Variable	Deployment number
Start date/time	End date/time	Number of observations
Model R^2	Range of fitted values	Mean of fitted values
Model RMSE	Pure Error Sum of Squares	Model Sum of Squares
Df for Error	Df for Model	Df for Pure Error
Diel Signature Range	Diel Signature SS	Diel Signature df
M2 Signature Range	M2 Signature SS	M2 Signature df
N2 Signature Range	N2 Signature SS	N2 Signature df
O1 Signature Range	O1 Signature SS	O1 Signature df

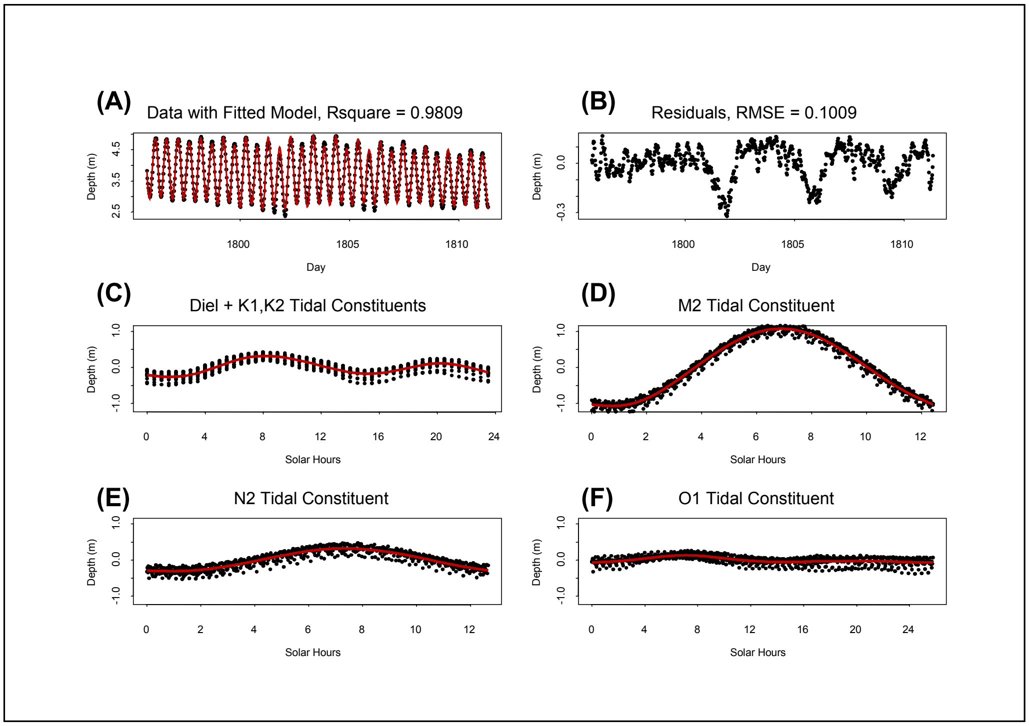

Figure 38. Component plots of deployment-level analyses for water depth at the Lower Duplin site (Sapelo Island NERR) for the period 11/30/1999 to 12/16/1999.

Figure 38 provides a graphical summary of how the model works. Panel (A) depicts the goodness of fit between the observed data and the predicted curve. Panel (B) plots the residuals from the fit of the observed data to the predicted curve, as well as the Root Mean Square for Error (RMSE). Panel (B) is useful for identifying episodic events and irregularities in the data distribution. In this particular example, two to three low-depth events, each approximately 24 hours in duration, were apparent in the plot of the residuals, but were not apparent in panel (A), due to some extent because of differential scaling of the y-axis between these two panels. The x-axis for panels A&B is expressed as days since 1/1/1995, the first date with data in this study. Panel (C) compares the residuals in panel (B) with the predicted 24-hour (diel) signature intended to gauge the influence of solar energy on subsequent water quality parameters. Among deployments lasting 7-30 days in duration, diel signatures were confounded with some of the lesser tidal constituents (K_1, P_1, K_2 and S_2). As a result, the "double bump" curve in panel (C) represents the sum of the diel signature and these (usually) small tidal signatures. This shape is atypical and, in this case, probably represents effects of K_2 and/or S_2 on depth at this site. Panel (D) depicts the main tidal constituent (M_2) with a periodicity of 12.42 hours versus the residuals from panel (B). It is especially important to note the occurrence of daily high and low tides in this cycle when interpreting M_2 patterns, which are also seen in other variables (i.e., minimum DO during the main tidal cycle). Panels (E) and (F) depict the influence of two other tidal constituents, N_2 and O_1, with periods 12.66 h and 25.82 h, respectively. Although observed in this example, these constituents were rarely substantial. More examples and suggestions for interpretation of deployment-level plots are provided in the Results section.

Phase 2: Removing Annual Periodicity; Site Comparisons

In phase 2 of the analysis, for each site and variable with at least 30 fitted deployments from phase 1, key numerical summaries of each deployment (Table 20) were checked for presence of an annual (365.24 d) periodicity. Once again, a nonparametric approach was used to estimate the annual signature for each deployment summary across all available site and variable combinations. The p-value of an approximate F-test for significance of the annual periodicity was calculated for each fit. Because these are approximate tests, and because there could be as many as 440 such tests performed for each summary measure, the annual periodicity was considered statistically significant only if the p-value for this test was less than 0.05/500 = 0.0001. In this case, an estimate of the range and mean level of the fitted annual periodic function was computed and a graphical summary created (e.g., Figure 39).

Table 20. Key deployment summary measures.

- A. Model Performance Measures
    1. Model R^2
    2. Model Root Mean Square for Error (RMSE)
    3. Lack-of-Fit Ratio (MSE/MSPE)
- B. General Model Characteristics
    4. Ratio of Sum of Squares of all Periodic Terms to Model SS (R^2 periodic)
    5. Mean of Model Fitted Values
    6. Range of Model Fitted Values
- C. Diel-Tidal Summaries
    7. Ratio of Diel Mean Square to Model Mean Square (Proportion of Variance Diel)
    8. Ratio of M_2 Mean Square to Model Mean Square (Proportion of Variance M_2)
    9. Ratio of Diel Variance to M_2 Variance

The time series of key summary values (each point corresponds to an analyzed deployment from phase 1) in Figure 39a is presented with respect to the fitted annually periodic nonparametric curve. Residual points plotted by Julian day and the fitted annual curve, with the approximate P-value for the hypothesis of no annual signature (in this case, P is less than 10^{-12}) are presented in Figure 39b. This particular example shows that, for salinity at the Joe Leary Slough site in the Padilla Bay NERR, the diel profile's variance is typically greater than the main tidal (M_2) variance, but the ratio varies seasonally. At this site, diel signals dominate tidal signals in controlling salinity; however, the relative importance of diel signals doubles in winter (ratio ≈ 10) relative to summer (ratio ≈ 5). In the spring months, diel signals continue to be slightly more important influences on salinity than tidal signals; however, in the fall months the two signals are almost equally important (log-ratio ≈ 0).

Because data were not as plentiful for this phase of the analysis, these fitted seasonal curves in some cases are discontinuous from December to January. Also, it appears to us that the approximate F test for annual periodicity is fairly liberal. The remaining aspects of phase 2 involved graphical presentations and comparisons of the mean values of key deployment summary measures between sites.

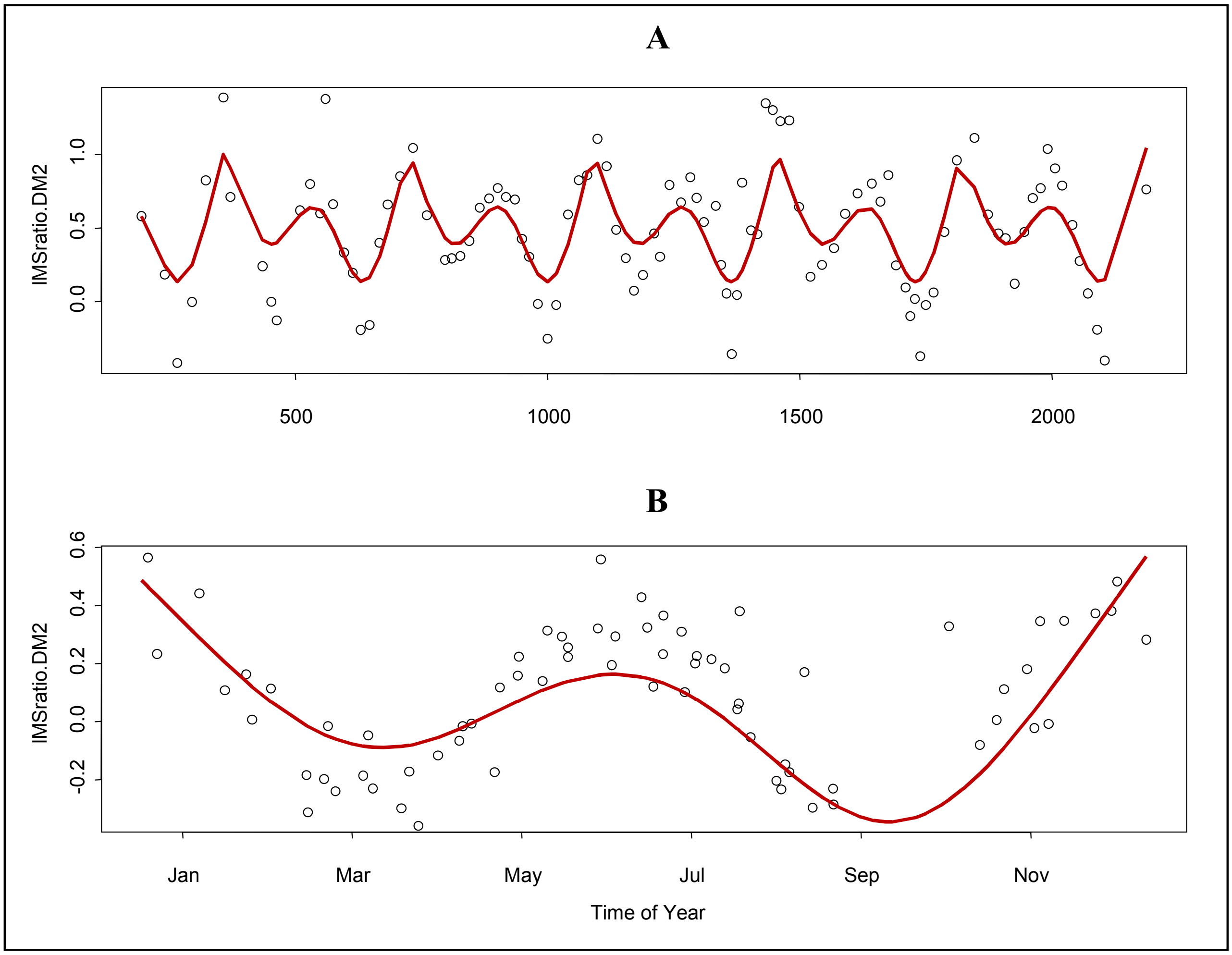

Figure 39. Annual periodicity in salinity based on the logarithm base 10 of the ratio of Diel to M2 variance at Joe Leary Slough (Padilla Bay NERR), 1995-2000. Panel (A) depicts this log-ratio relative to the sampling period (Jan 1995-Dec 2000), whereas panel (B) depicts the seasonal signal of this log-ratio across all sampling years ($p = 1.462e^{-013}$).

Results and Discussion

Phase 1, Deployment fits

The following graphs (Appendices 35-39) provide examples of patterns that appeared in the deployment level analyses. These examples are not exhaustive and are included mainly to inspire exploration of the 3-6 year records available in Powerpoint "movies" for each of the 8 variables at 55 NERR sites (with a few exceptions). Specifically, we hope that scientists familiar with the dynamics of any given site(s) will spend time inspecting these Powerpoint images for these site(s) in order to help generate explanations for patterns that may emerge. The images themselves are at times noisy, and fitted curves may not always correspond to real patterns, especially if the residual scatter in a constituent's plot is substantial. We recommend that any particular pattern in a constituent "signature" be taken seriously only if it recurs in similar form across several consecutive deployments, or across several years at a similar time of year, or if a reasonable scientific explanation for the pattern can be offered.

Phase 2, Removing Annual Periodicity

For site/variable combinations with 30 or more analyzed deployments from phase 1, the key deployment summary measures shown in Table 20 were checked for annual periodicity. Table 21 shows, for each of the 8 variables, the number of sites analyzed and for each key measure the number of sites where annual periodicity was detected at significance level $p < 0.0001$ (0.05/500). For example, the model R^2 for water temperature was found to vary with a repeating annual pattern in only 1 of 45 sites tested. The mean temperature for the fitted values was, in contrast (and not surprisingly), found to be annually periodic for all 45 sites.

Ecological interpretation of Table 21 is difficult. This table is provided to emphasize that mean values of key summary measures may, in some cases, not be representative of a measure for a given site and variable (i.e., if averages of values are strongly seasonal). It is important to note also that a small p-value for this test doesn't necessarily indicate strong seasonal patterns; with large enough sample sizes, even a minor seasonal pattern may produce a statistically significant result. Fewer analyzed deployments (i.e., smaller sample sizes) may be partially responsible for the smaller pH, turbidity, and specific conductivity values in Table 21. We recommend thorough inspection of the individual deployment plots (e.g., Figure 38), and seasonal plots (e.g., Figure 39) to gain the deepest understanding possible of these water quality variable dynamics at the NERR sites, rather than depending completely on overall averages.

Table 21. Key deployment measures, including variable, number of sites analyzed, and number of sites found to be annually periodic.

	Depth	DO mgl	DO %	Temp	Sal	pH	Turb	SpCond
	44	44	44	45	41	35	29	37
A. Model Performance Measures								
1. Model R^2	19	2	4	1	9	4	1	7
2. Model Root Mean Square for Error (RMSE)	20	9	23	24	11	6	2	8
3. Lack-of-Fit Ratio (MSE/MSPE)	7	10	8	15	5	1	3	3
B. General Model Characteristics								
4. Ratio of Sum of Squares of all Periodic Terms to Model SS (R^2 periodic)	11	7	5	26	4	1	1	2
5. Mean of Model Fitted Values	15	40	20	45	17	5	6	11
6. Range of Model Fitted Values	9	16	31	17	6	9	1	1
C. Diel-Tidal Summaries								
7. Ratio of Diel Mean Square to Model Mean Square (Proportion of Variance Diel)	28	12	12	26	9	8	1	4
8. Ratio of M_2 Mean Square to Model Mean Square (Proportion of Variance M_2)	6	5	6	16	3	2	2	3
9. Ratio of Diel Variance to M_2 Variance	15	4	4	11	4	3	1	3

Phase 2, Site Comparisons

All comparisons presented in this section use averages of key deployment summaries as described in Tables 20-21 across all analyzed deployments. The first sub-section, evaluation of model performance, briefly discusses the merits of the GAM approach in characterizing water quality periodicity in the NERR SWMP. The second sub-section, site characteristics, addresses the general patterns observed in the data sets evaluated. The final sub-section deals with the comparison of diel and tidal importance in influencing each of the variables analyzed.

Model Performance

The Generalized Additive Model (GAM) typically provided a better approach for characterizing periodicity in water quality observations at NERR SWMP sites than the harmonic models used in the previous synthesis (Wenner et al. 2001). Data for most site and variable combinations fit the predicted curve very well. Root Mean Square for Error (RMSE) and R-squared values for all site and variable combinations are depicted in Figure 40. Sites with low values of mean R^2 or high values of mean RMSE are identified by site abbreviation. Regarding water depth, R^2 values were near or above 0.90 for all but 8 sites, which had mean R^2 values between 0.65 and 0.8 (Figure 40). For all other variables except turbidity ($R^2 = 0.4$ to 0.8), mean R^2 values typically exceeded 0.7.

Sites with little explainable variance (i.e., little natural variation in depth) may have a lower R^2 value even if the model predicts the data well. In these instances, RMSE, which measures the accuracy with which individual values would be predicted using the fitted model, provides a better measure of overall model performance than R-squared. For example, in all but five sites, mean RMSE for depth is near or below 0.1 m. Hence, the harmonic regression model at the vast majority of sites typically predicts 95% of depth values to an accuracy of ± 0.2 m, which is twice the RMSE. Average RMSE values for all but four sites were less than 1.5 ppt for salinity, 3 mS/cm for conductivity and ≤1 mg/l (15% sat) for dissolved oxygen. Average RMSE values for water temperature was less than 1° C at all but two sites and less than 0.2 for pH at all sites. Average RMSE for turbidity at all but four sites was < 0.25 NTU; thus, transformed turbidity at most sites are predicted to an accuracy of ± 0.5 NTU. Applying the anti-log base 10 to this result we obtain 3.16; thus, un-transformed turbidity is predicted at most sites within a multiple of approximately 3 or less. Relative to un-transformed turbidity variation of a factor of 100 in the same deployment, transformed variability is minor and acceptable.

Poor RMSE performance was occasionally observed (Figure 40). Poor RMSE performance for water temperature was observed at Azevedo Pond (Elkhorn Slough NERR), Jug Bay (Chesapeake Bay MD NERR) and Old Woman Creek (State Route 6). Poor RMSE performance for dissolved oxygen was observed for both Elkhorn Slough NERR sites, Jug Bay, and the Tidal Linkage site (Tijuana River Estuary NERR). Poor RMSE performance for salinity and specific conductivity were observed for both South Slough NERR sites, Joe Leary Slough (Padilla Bay NERR), and Lamprey River (Great Bay NERR). Poor RMSE performance for pH was observed for both Weeks Bay NERR sites and Joe Leary Slough. Poor RMSE performance for turbidity was observed at Lower Duplin (Sapelo Island NERR) and station 10 (Jobos Bay NERR).

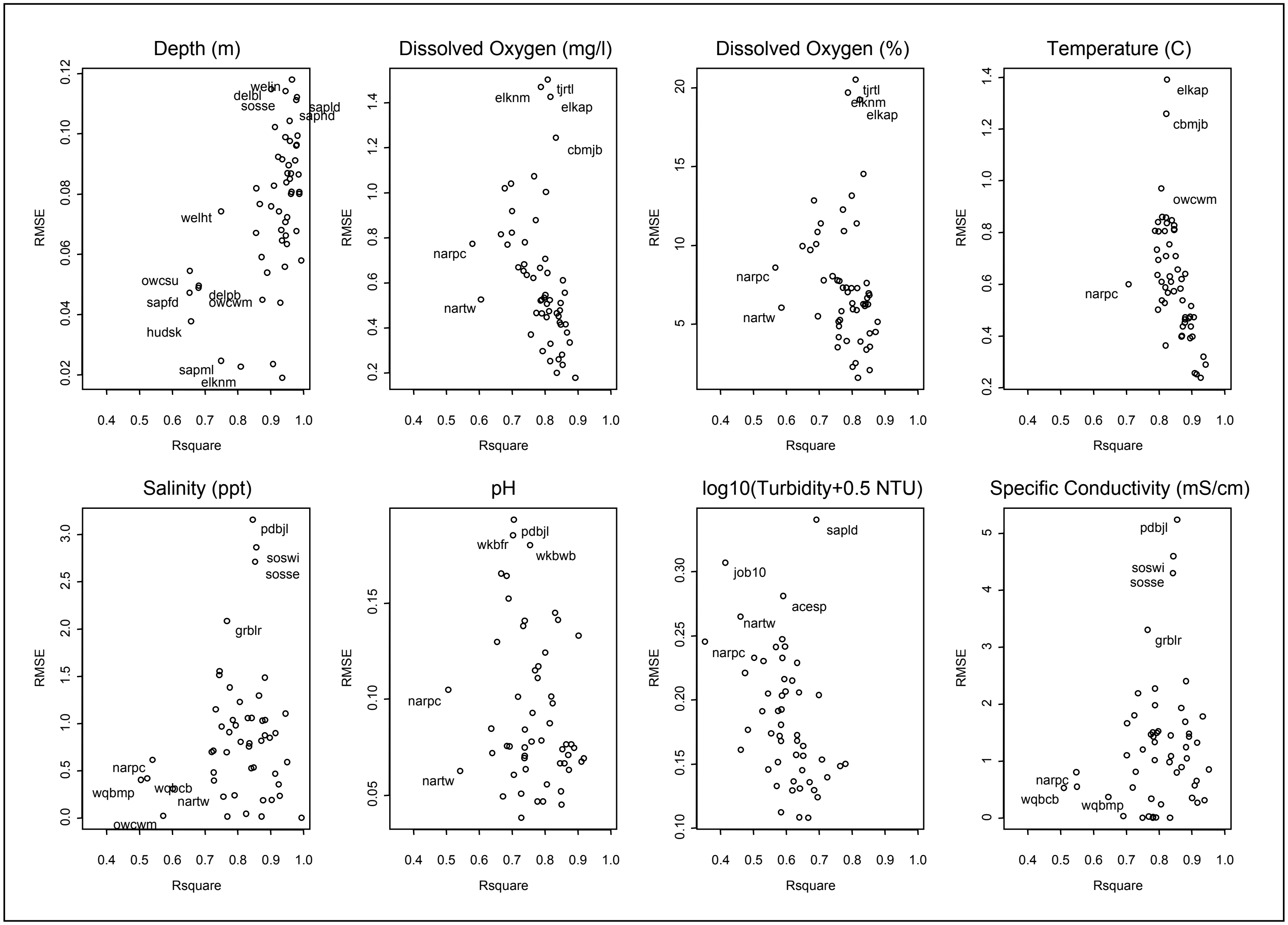

Figure 40. Deployment harmonic regression model performance for all site and variable combinations. See preceeding text for detailed explanation of trends and outlying conditions**.**

Site Characteristics

Although the uniqueness of each of the 55 NERR SWMP sites evaluated often inhibited the task of comparing sites, a few general patterns did emerge. For several parameters, the mean value was positively correlated with the average range. Specifically, sites with extreme low or high mean values for salinity (specific conductivity) and water depth also demonstrate relatively small variability in these values.

Figure 41 shows a plot of the mean range of model fitted values versus the mean model fitted value for each of the eight variables, with some of the more extreme points labeled.

- Points at left in each plot represent sites with relatively low mean fitted values for that variable, for example: the Rookery Bay sites for dissolved oxygen; the Wells – Inlet and Padilla Bay – Bayview Channel sites for temperature; the Old Woman Creek – State Route 2, Hudson River, Chesapeake Bay Maryland, and Mullica River – Lower Bank sites for salinity and specific conductivity; the Mullica River – Lower Bank, Wells – Head of Tide, and Delaware – Penrose Branch sites for pH; and the Narragansett Bay, Waquoit Bay, and Wells – Head of Tide sites for turbidity.

- Points at right in each plot are sites with relatively high mean fitted value for that variable, for example: the Hudson River – Saw Kill, Wells – Head of Tide, Chesapeake Bay Virginia - Goodwin Islands, and Waquoit Bay – Central Basin sites for dissolved oxygen; the Jobos Bay sites for temperature, salinity, and specific conductivity; The Waquoit Bay, Hudson River – Saw Kill, Elkhorn Slough – North Marsh, Weeks Bay – Weeks Bay, and North Carolina – Masonboro Island sites for pH; and the Old Woman Creek, Delaware, Chesapeake Bay Virginia – Taskinas Creek, and North Inlet – Thousand Acre sites for turbidity.

- Points high on each plot are sites that have the largest range of fitted values for that variable, on average, within their deployments. For example: the Wells – Inlet site for depth; the Elkhorn Slough, Tijuana River – Tidal Linkage and Chesapeake Bay Maryland – Jug Bay sites for DO and/or temperature; the South Slough and Padilla Bay – Joe Leary Slough sites for salinity and temperature; the Mullica River – Lower Bank site for pH; and the Sapelo Island – Lower Duplin site for turbidity.

- Points low on each plot are sites that have the smallest range of fitted values for that variable, on average, within their deployments. For example: the Hudson River – Saw Kill site for dissolved oxygen; the Narragansett Bay, Sapelo Island, and Jobos Bay – 10 sites for temperature; the Old Woman Creek – State Route 2, Hudson River, and Chesapeake Bay Maryland sites for salinity and specific conductivity.

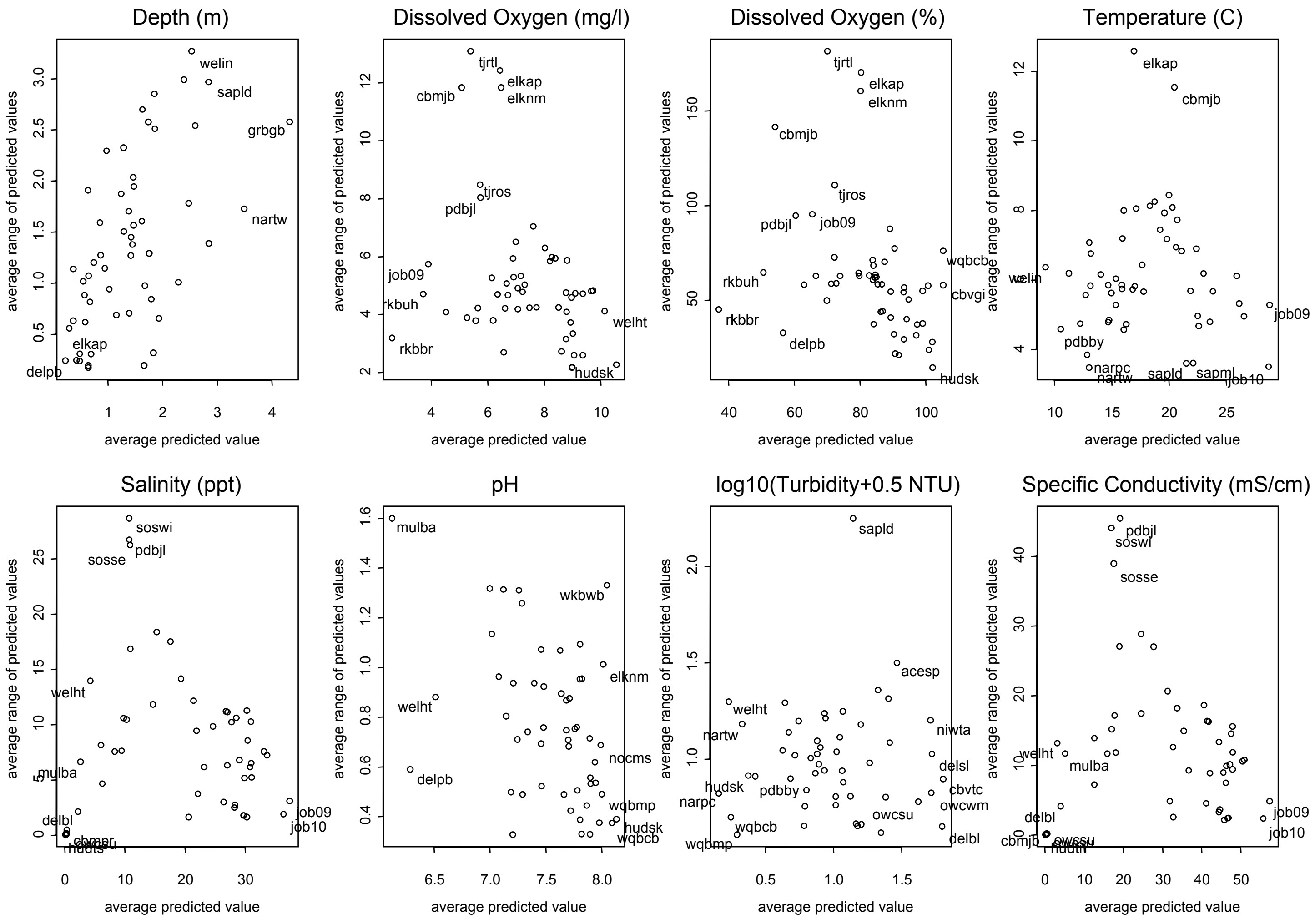

Figure 41. Mean and range of model predicted values. Explanation of trends and outlying conditions are provided in the text.

Diel vs. Tidal Influence

Discussion of the average relative importance of the diel and tidal cycles examines the average ratios of certain mean squares from the phase 1 analyses (Figures 42-47). Throughout this section, we define the “strength of the diel profile” as the ratio of the diel mean square to the model mean square. When this ratio is large, a substantial proportion of the variation explained by the model (if any) is attributable to the diel profile. Similarly, we define the “strength of the tidal (M2) profile” as the ratio of the M_2 mean square to the model mean square. Other tidal constituents (N2 and O1) were not included in the comparisons presented here, as these terms were so often of little importance that their inclusion “watered down” the apparent effects of tide. Sites plotted near the 45° line in each figure represent sites where diel and tidal (M_2) forces were equally (if at all) important in influencing the parameter of interest. Points located near the origin correspond to sites for which neither diel nor tidal (M_2) components played a substantial role in the model. Where necessary, plotted labels have been shifted slightly for readability.

An overview of the results shows great heterogeneity in tidal vs. diel dominance among these sites; neither tidal (M_2) nor diel forces are completely dominant over all sites for any variable. Though there are several notable exceptions for each statement below, it seems apparent that

- More sites are tidally-dominated for depth and salinity than are diel-dominated.

- More sites are diel-dominated for dissolved oxygen and temperature than are tidally dominated.

- Sites split fairly evenly with respect to tidal vs. diel dominance for pH and turbidity, though less data is available for these variables.

This section continues with a detailed discussion of tidal versus diel effects for each variable, on the following pages (Figures 42-47).

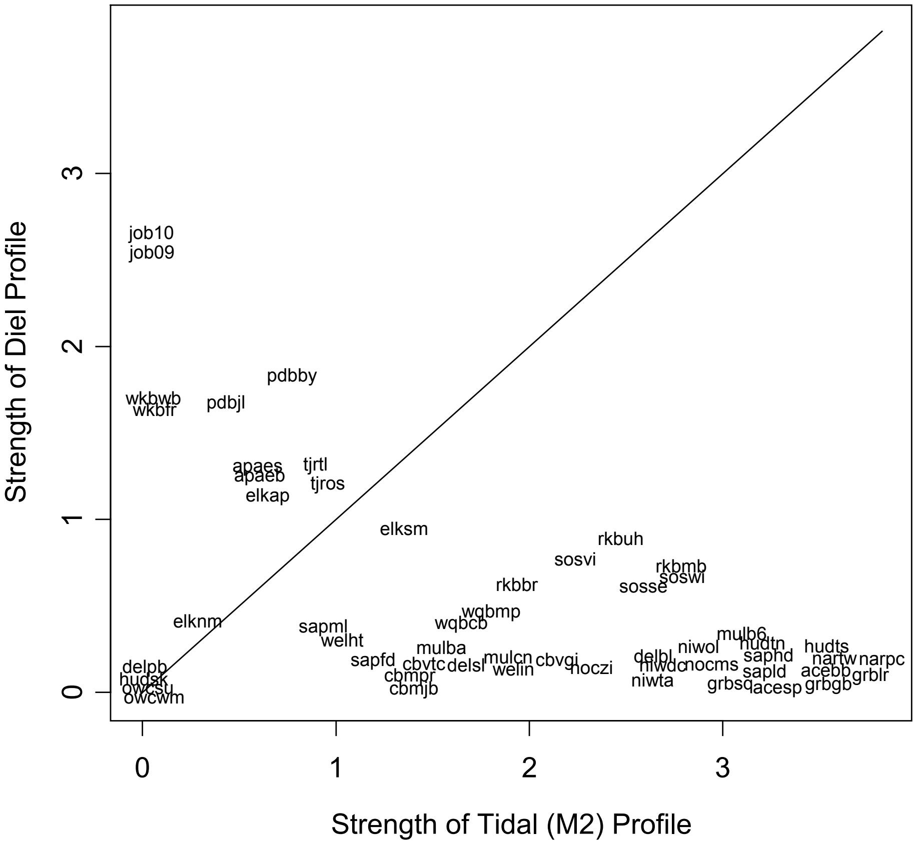

Figure 42. Diel vs. tidal force influence on water depth, NERR SWMP 1995-2000.

Sites from the same reserve tend to cluster with respect to the importance of diel vs. tidal forces in influencing water depth (Figure 42). The Jobos Bay, Padilla Bay, Weeks Bay, Apalachicola Bay and Tijuana River sites lie above the "equal importance" line, suggesting that water depth is driven more by solar influences than tidal ones at these reserves. The Elkhorn Slough sites straddle the line. Water depth at all other sites seems to be more strongly influenced by tidal forces than diel forces.

Water depth was not strongly influenced by either diel or tidal cycles at four freshwater sites, specifically: both Old Woman Creek NERR sites, Hudson River-Saw Kill, and Delaware Bay-Penrose Branch. These sites also had low average R^2 values for depth, as their depth did not vary with any substantial cyclic regularity.

The most extreme sites along both axes in Figure 42 approach or exceed "strength" values of 3. Depth is unusual among the variables in this respect, probably because it is so cleanly cyclic at so many sites. For most other variables, the largest "strength" values are closer to 2.0.

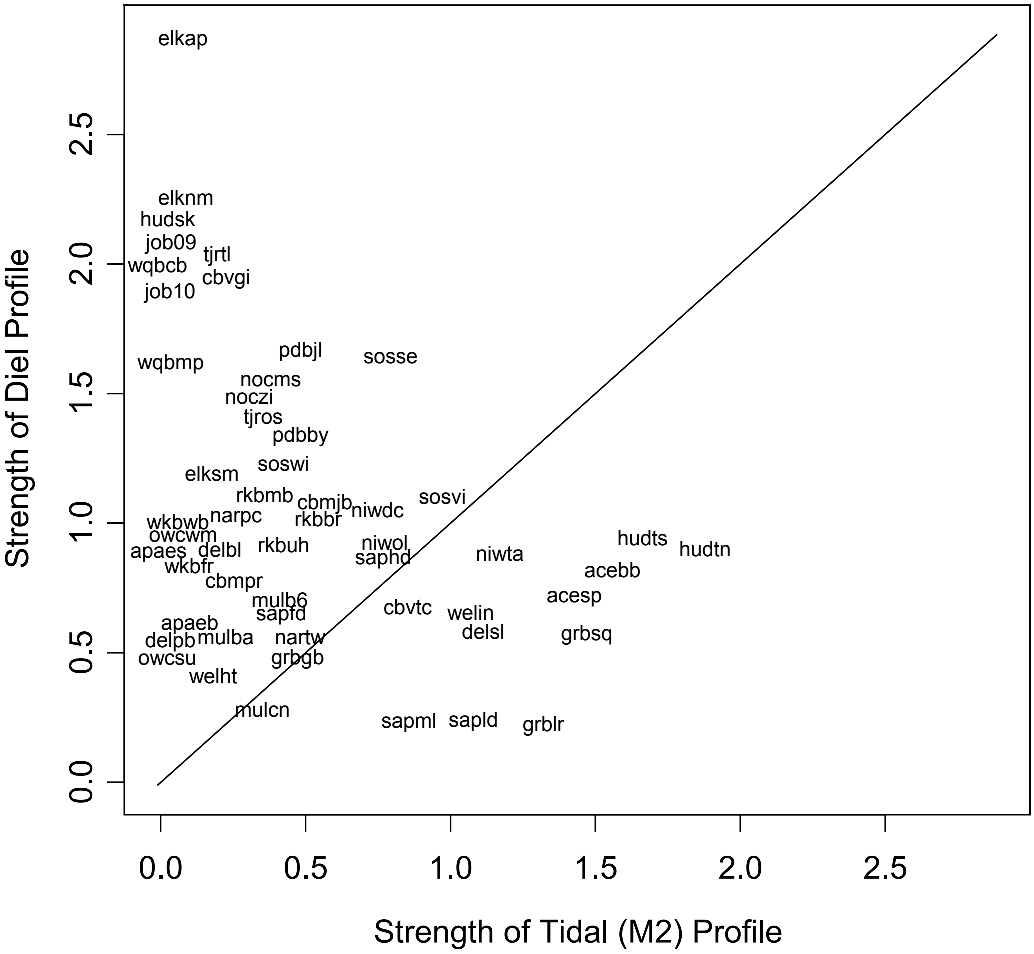

Figure 43. Diel vs. tidal force influence on DO (% sat), NERR SWMP 1995-2000.

A handful of sites lie below the 45° line, suggesting that DO (% sat) at these sites is at least somewhat tidally dominated (Figure 43). Sites where DO (% sat) appears to be primarily tidally influenced include both ACE Basin NERR sites and two Great Bay NERR and two Sapelo Island NERR sites (for both of these reserves, remaining sites lie near the line of equal importance). The Hudson River sites at Tivoli Bay (HUDTN and HUDTS) also appear to be tidally-dominated; however, the Hudson River – Saw Kill site lies far to the upper left, making it one of the most extremely diel-dominated sites for DO (% sat). Other sites either lie near the line of equal importance or show a much stronger diel than tidal influence; of these, the Elkhorn Slough, Jobos Bay and Waquoit Bay sites stand out at extreme upper left, along with the Chesapeake Bay Virginia – Goodwin Islands and Tijuana River – Tidal Linkage sites.

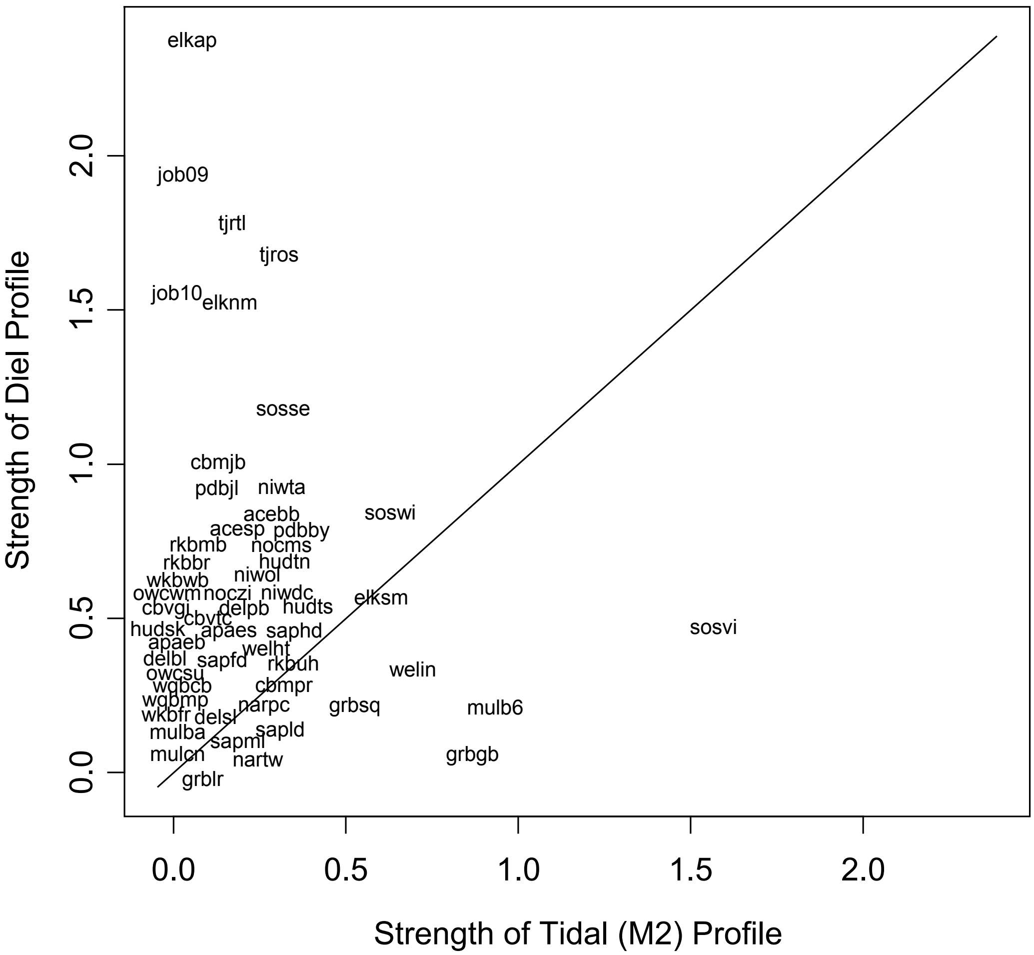

Figure 44. Diel vs. tidal force influence on water temperature, NERR SWMP 1995-2000.

Not surprisingly, temperature is dominated by diel influences in all but a handful of the sites (Figure 44). The most extreme example of tidal influence on water temperature occurs at Valino Island site (South Slough NERR). Additional sites where temperature seems to be somewhat more tidally driven include the Mullica River – Buoy 126, Wells – Inlet site, and two of the three Great Bay sites (Great Bay and Squamscott River). The third Great Bay site, Lamprey River, lies near the origin in this plot, and so shows no great cyclical pattern in temperature. Sites which are extremely dominated by diel effects for temperature include the Elkhorn Slough – Azevedo Pond and North Marsh sites, and the Jobos Bay and Tijuana River sites.

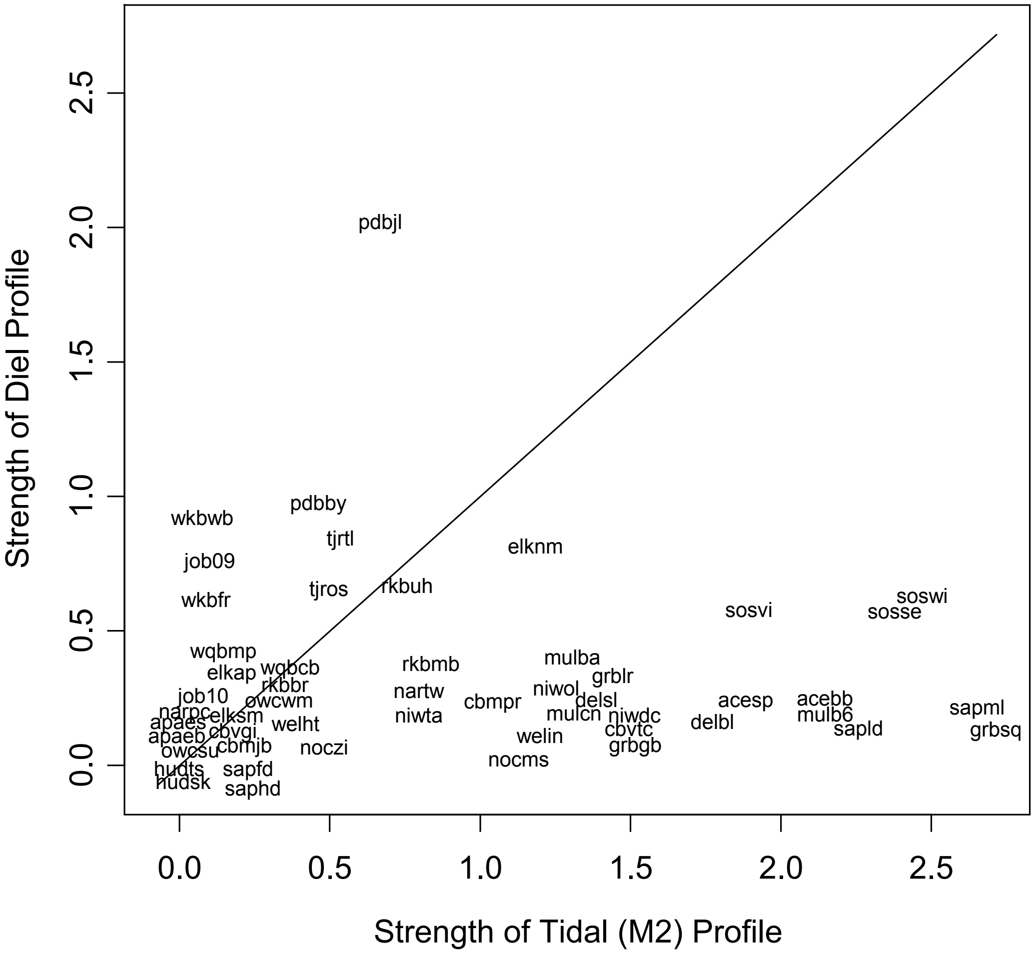

Figure 45. Diel vs. tidal force influence on salinity, NERR SWMP 1995-2000.

Three sites were excluded from this comparison due to shortage of data (Figure 45). Recall that the salinity analyses from phase one should be interpreted cautiously due to frequent freshwater intrusion events that create inconsistencies in the cyclic fluctuations at some sites. A large number of sites lie near the origin in this plot, suggesting that salinity is not very consistently cyclic at these sites. Salinity at a handful of sites seems to be more influenced by diel influences than tidal forces; these sites include the Padilla Bay, Weeks Bay, and Tijuana River sites, and the Jobos Bay – 09 site. Not surprisingly, more sites seem to be tidally-dominated for salinity; among these, the most extreme examples of strong tidal influence on salinity include the Great Bay – Squamscott River site, the South Slough and ACE Basin sites, the Sapelo Island Marsh Landing and Lower Duplin sites, and the Mullica River – Buoy 126 site.

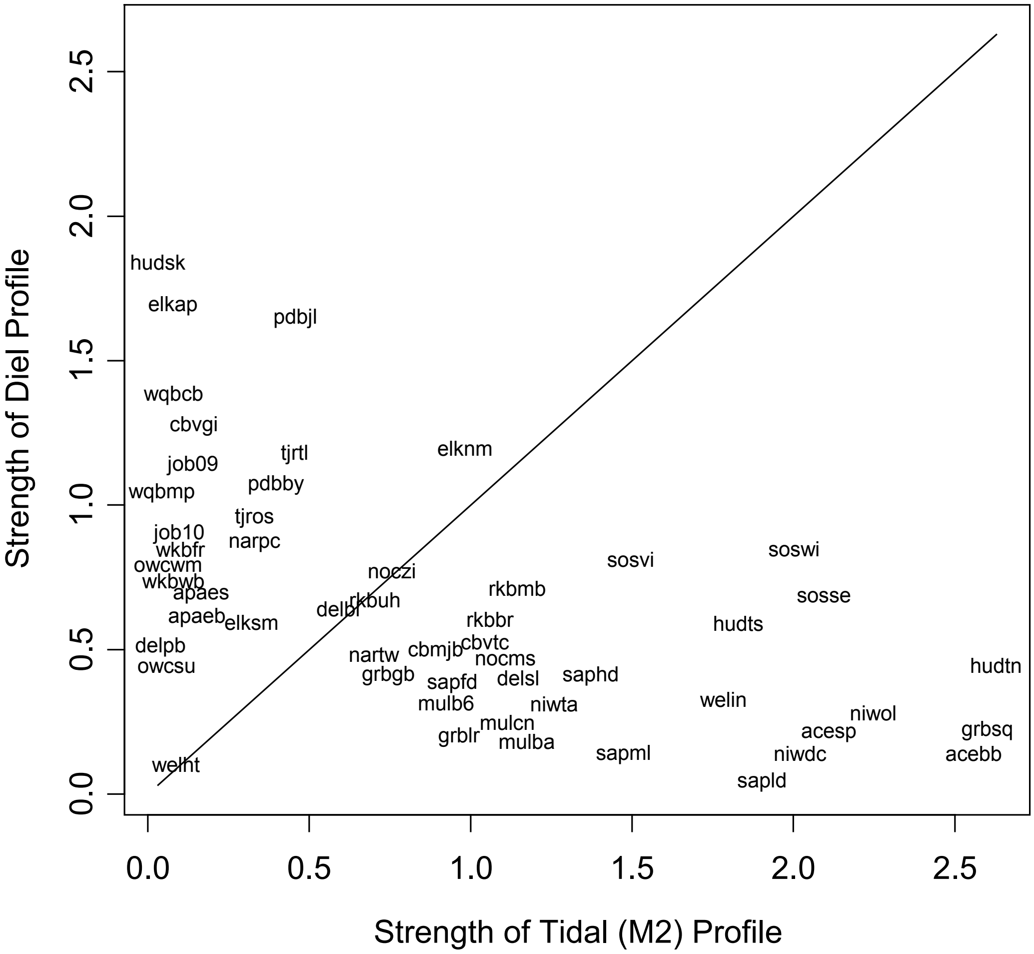

Figure 46. Diel vs. tidal force influence on pH, NERR SWMP 1999-2000.

Two sites were excluded from this comparison due to shortage of data, and data on pH were typically only two years in duration, as opposed to 5-6 years for previously discussed variables, so patterns may not be as well defined for pH as for preceding variables (Figure 46). Sites evaluated were almost evenly divided between the tidal- and diel-dominant groups. Sites with strong tidal influence on pH include Hudson River – Tivoli Bay sites, Great Bay - Squamscott River, both ACE Basin sites, the North Inlet – Winyah Bay sites, the South Slough sites, the Wells – Inlet site, and all four Sapelo Island sites. Sites representing the most extreme diel influence on pH include the Hudson River – Sawkill site, the Elkhorn Slough – Azevedo Pond site, The Chesepeake Bay Virginia – Goodwin Island site, and the Padilla Bay, Waquoit Bay, Tijuana River, and Jobos Bay sites.

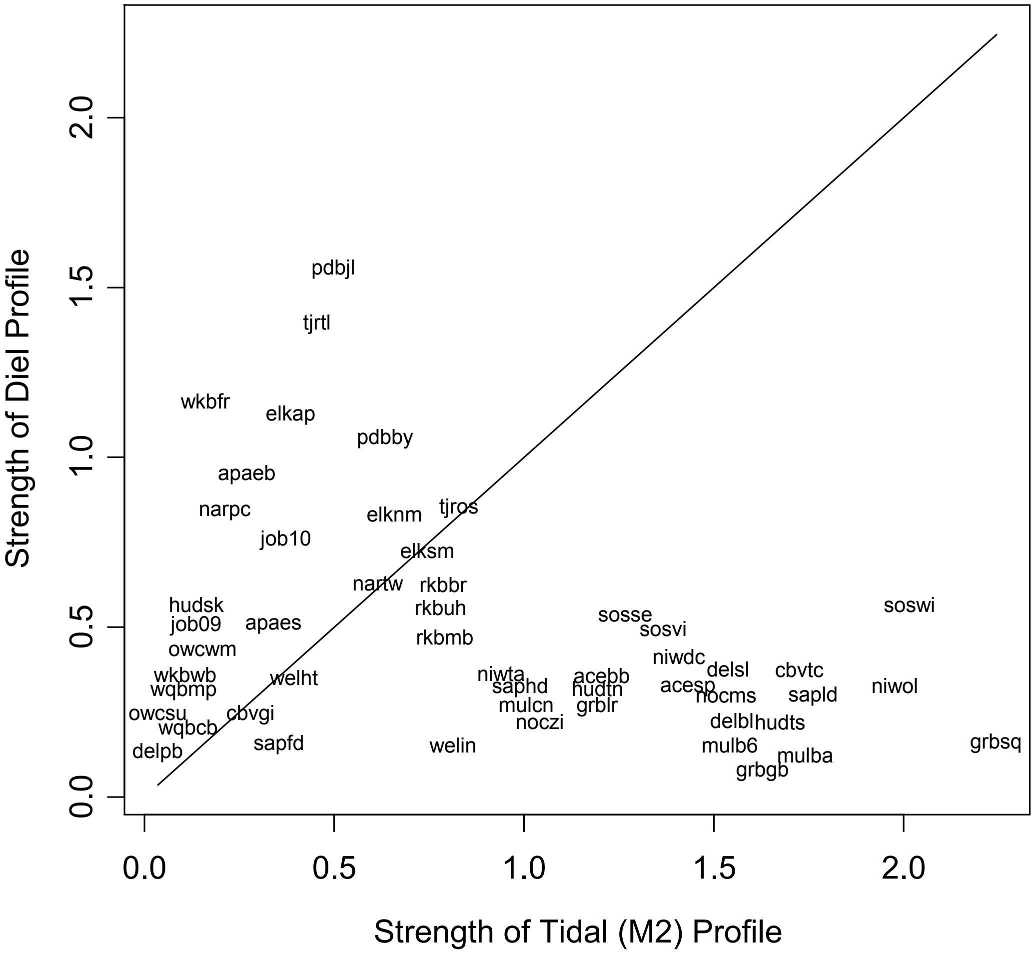

Figure 47. Diel vs. tidal force influence on turbidity, NERR SWMP 1999-2000.

Similar to pH, turbidity data sets spanned a shorter time frame (1999-2000) and were less uniform than data sets for depth, DO, and temperature variables. Four sites are excluded due to lack of data. Figure 47 suggests that there are more tidally dominated sites than diel-dominated ones, but there are a number of sites in both categories. The sites which seem most extremely diel-dominated for turbidity include the Padilla Bay sites as well as the Tijuana River – Tidal Linkage, Weeks Bay – Fish River, Elkhorn Slough – Azevedo Pond, Apalachicola Bay – East Bay Bottom, and Narragansett Bay – Potters Cove sites. Sites which seem most extremely tidally-dominated for turbidity are Great Bay – Squamscott River, South Slough - Winchester Arm, North Inlet – Oyster Landing, and a host of others.

Chapter 6: Impacts of Tropical Systems on Water Quality Data, 1995-2000.

Introduction

Water chemistry of estuaries is invariably related to weather patterns at daily, seasonal, and inter-annual time scales. Precipitation affects water chemistry through the direct input of freshwater as well as the transport of sediments, nutrients, and contaminants into estuarine systems. Evapo-transpiration provides a mechanism for the removal of freshwater from estuarine systems. Changes in barometric pressure and heat exchange generate wind and waves that result in turbulent mixing, de-stratification of the water column, and input of terrestrial matter through the erosion of shorelines. Wind and wave forcing also create currents that transport water, sediments, nutrients, and contaminants into and out of estuarine systems.

Seasonal weather patterns fall into two general categories: (1) fronts that form over land and pass over the coast on their way out to sea, and (2) storms that form at sea and move toward the coast. On the Pacific Coast of North America, weather systems that affect the coast form at sea and move towards land. During the tropical season (15 May – 30 Nov), storms that form in the East Pacific Ocean rarely make landfall in the United States. During the non-tropical season, storms that form in the East Pacific Ocean often pass over the coast and can drop considerable amounts of precipitation, particularly in the northwest. During the tropical season (1 Jun – 30 Nov) on the eastern seaboard of North America, fast-moving tropical systems frequently make landfall in the United States, often depositing considerable localized precipitation and causing substantial erosion. Fronts that move slowly across the eastern seaboard, usually produce less precipitation than tropical systems, and then move out to sea, typify weather patterns that affect estuarine systems along this coast during the non-tropical season.

During the tropical seasons that occurred between 1995 and 2000, 75 named tropical systems were observed in the Eastern Pacific Ocean and 80 named tropical systems were observed in the Western Atlantic Ocean. None of the tropical systems in the Eastern Pacific Ocean made landfall on U.S. soil, compared to 25 tropical systems (31% of total named storms) that made landfall on U.S. soil from the Western Atlantic Ocean. Subsequently, 24 tropical systems passed directly over or close to at least one water quality monitoring site in the National Estuarine Research Reserve's System-wide Monitoring Program. Due to the unique positioning of NERR SWMP sites and the movement patterns of these storms, multiple NERR SWMP sites were affected by the same storm on numerous occasions. Changes in and subsequent recovery of water chemistry at NERR sites in association with these storms is herein examined.

Methods

Movement patterns of tropical systems between 1995-2000 were obtained from the National Hurricane Center (**www.nhc.noaa.gov)** in order to determine the frequency, duration, and intensity of tropical systems that potentially impacted water quality parameters at NERR SWMP sites.

Daily mean and range of water quality variables [temperature, salinity, depth, turbidity, DO (% sat), and pH] two weeks prior to and four weeks following storm passage were plotted in MS Excel in order to visually examine the effects of each storm on the respective water quality parameters at each site. These plots were then sent to the respective NERR Research Coordinator for review and comment.

Short-term and long-term effects of each storm were quantified for each parameter at each site impacted by a tropical system. Short-term effects for water temperature, depth, and turbidity were calculated as the maximum one-day shift in daily mean values as the storm approached or passed over the NERR site. Short-term effects for salinity and pH were calculated as the maximum difference and duration of change in mean daily values between storm passage and the onset of recovery to pre-storm conditions. Long-term effects for salinity and pH were calculated as the total number of days required in order for mean daily values for these parameters to return to pre-storm conditions. Short-term effects using mean daily values for dissolved oxygen (% saturation) were less informative given large (40-80% saturation) daily ranges for this parameter; thus, daily range values for periods of noticeable departure from pre-storm conditions were used instead.

Frequency distributions of short-term effects (one-day change in mean daily values or daily range) were created in order to place the short-term effects of each tropical system into perspective. Water quality data were queried using a relational database (MS Access) and the resulting output data processed using the Histogram function in Microsoft Excel. Annual scatter pots of mean daily values were created in order to place the long-term effects of tropical systems into perspective.

Results

Between 1995 and 2000, 24 tropical systems passed over one or more Reserves in the National Estuarine Research Reserve program (Table 22). Similar numbers of tropical systems were encountered by NERRs in the Gulf of Mexico (*n*=19), Southeast (*n*=20), and Mid-Atlantic (*n*=17) regions (Figure 48). Seventy-eight percent of tropical systems that affected Jobos Bay were hurricane intensity. Eighty-four percent of tropical systems affecting NERRs in the Gulf of Mexico were tropical storm or hurricane intensity, more than double the percentage of systems of the same intensity that affected NERRs in the Southeast. Similarly, the percentage of tropical depressions or extra-tropical systems that passed over the Southeast NERRs (35%) was more than double the percentage of tropical depressions and extra-tropical systems that passed over the Gulf of Mexico NERRs. This discrepancy is attributed to five tropical storm and hurricane systems that affected NERRs in the Gulf of Mexico, made landfall, then moved up the eastern seaboard, steadily losing intensity. All tropical systems that affected Mid-Atlantic and Northeast NERRs also affected NERRs in the Southeast and/or Gulf of Mexico.

No data were collected for two hurricanes (Marilyn and Hortense) that only affected sites at the Jobos Bay Reserve in Puerto Rico. With these exceptions, data were collected for at least one NERR SWMP site for each of the remaining 22 tropical systems (Table 22). In all, 128 data sets from NERR SWMP sites monitored during tropical system events were examined for changes in water quality observations associated with storm passage.

Table 22. Temporal and spatial distribution of tropical systems affecting NERRs between 1995-2000. ET = extra-tropical; TD = tropical depression; TS = tropical storm; H = hurricane. Shaded box indicates no data available.

	PR	Gulf			Southeast				Mid-Atlantic				Interior		Northeast			
	JOB	RKB	WKB	APA	SAP	ACE	NIW	NOC	CBV	CBM	DEL	MUL	OWC	HUD	NAR	WQB	GRB	WEL
1995																		
Hurricane Allison				TS	TD	ET	ET	ET										
Hurricane Erin			H	H														
Tropical Storm Jerry				TD														
Hurricane Opal			H	H									ET	ET				
Hurricane Marilyn	H																	
1996																		
Tropical Storm Arthur								TS										
Hurricane Bertha	H							H	TS	TS	TS	TS			TS	TS	TS	TS
Hurricane Fran							H	H					TD	ET				
Hurricane Hortense	H																	
Tropical Storm Josephine				TS	ET	ET	ET	ET							ET	ET		
1997																		
Hurricane Danny			H						TS									
1998																		
Hurricane Bonnie	H							H	H									
Hurricane Earl				H		ET	ET	ET	ET									
Hurricane Georges	H	H	TD	TD														
Hurricane Mitch		TS																
1999																		
Hurricane Dennis								H	H					ET				
Hurricane Floyd								H	H	H	TS	TS			TS	TS	TS	ET
Tropical Storm Harvey		TS																
Hurricane Irene		H																
Hurricane Jose	TS																	
Hurricane Lenny	H																	
2000																		
Hurricane Debby	H																	
Hurricane Gordon		H		TS	TD	ET			ET	ET	ET	ET			ET	ET		
Tropical Storm Helene	TD		TS	TS					ET									

Since no noticeable changes in parameters monitored or data were not collected for a total of 29 data sets, these data sets were excluded from analyses. No data were collected for an additional 3 data sets for water temperature, 3 data sets for salinity, 2 data sets for depth, 24 data sets for turbidity, 11 data sets for DO, and 6 data sets for pH (Table 23).

Noticeable changes were observed for at least one parameter in 99 data sets. Noticeable changes in water temperature were observed in 71 data sets (74%), salinity in 56 data sets (58%), depth in 65 data sets (67%), turbidity in 39 data sets (52%), DO in 23 data sets (26%), and pH in 37 data sets (40%). In 80% of the data sets, effects from tropical systems were observed one day prior to the system passing the NERR or on the day of passage (range = 5 days before to 2 days after).

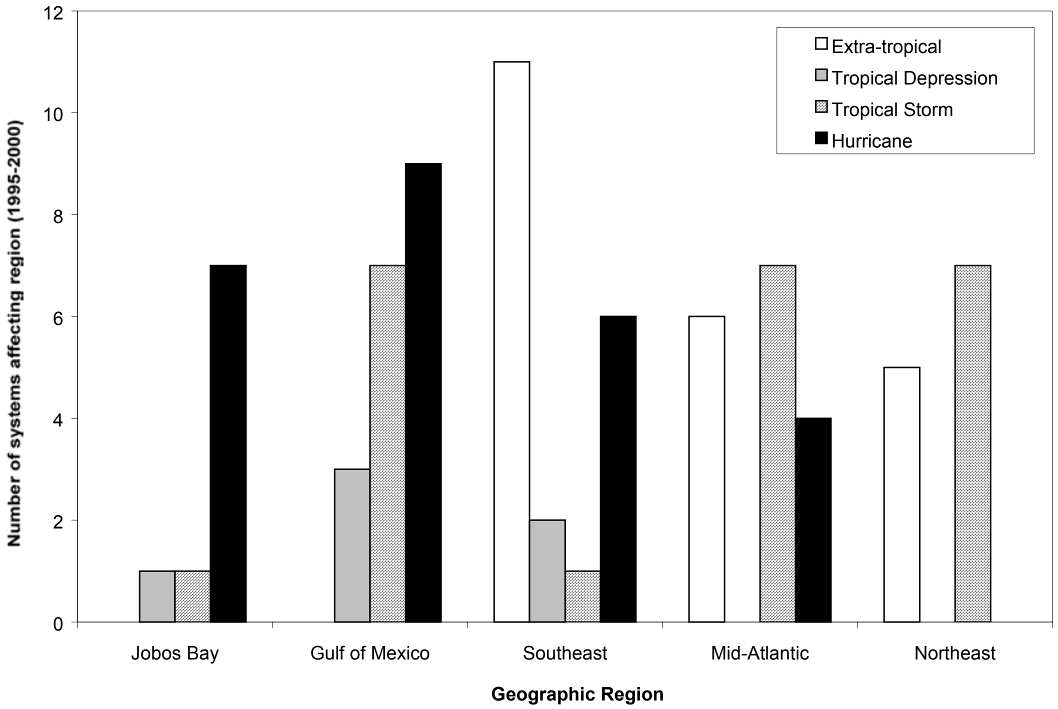

Figure 48. Distribution and intensity of tropical systems affecting NERRs, 1995-2000.

Table 23. Summary of 29 data sets with no noticeable change in any water quality parameter or where data were not collected during the passage of tropical systems.

Storm	Site	Intensity	Pass Over/By	Temp	Sal	Depth	Turb	DO	pH
Allison	apaes	TS	6/5/95	No Data	No Data	No Data	No Data	No Data	No Data
Allison	sapfd	TD	6/5/95	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
Allison	sapml	TD	6/5/95	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
Allison	noczi	ET	6/6/95	No Chng	No Chng	No Chng	No Data	No Chng	No Chng
Opal	apaeb	H	10/4/95	No Data	No Data	No Data	No Data	No Data	No Data
Opal	hudsk	ET	10/6/95	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
Opal	hudts	ET	10/6/95	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
Bertha	cbmjb	TS	7/13/96	No Chng	No Data	No Chng	No Data	No Chng	No Chng
Bertha	cmbpr	TS	7/13/96	No Chng	No Data	No Chng	No Data	No Chng	No Chng
Bertha	narpc	TS	7/13/96	No Chng	No Chng	No Chng	No Data	No Data	No Chng
Fran	hudts	TD	9/8/96	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
TS Josephine	nocms	ET	10/8/96	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
TS Josephine	noczi	ET	10/8/96	No Chng	No Chng	No Chng	No Chng	No Data	No Chng
TS Josephine	narpc	ET	10/9/96	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
TS Josephine	nartw	ET	10/9/96	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
Georges	rkbbr	H	9/26/98	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
Dennis	hudtn	ET	9/7/99	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
Dennis	hudts	ET	9/7/99	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
Floyd	welin	ET	9/17/99	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
Gordon	cbvgi	ET	9/19/00	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
Gordon	cbvtc	ET	9/19/00	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
Gordon	cbmjb	ET	9/19/00	No Chng	No Data	No Chng	No Data	No Chng	No Chng
Gordon	delpb	ET	9/19/00	No Data	No Data	No Data	No Data	No Data	No Data
Gordon	mulb6	ET	9/19/00	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
Gordon	mulba	ET	9/19/00	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
Gordon	mulcn	ET	9/19/00	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
Gordon	nartw	ET	9/19/00	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng
Gordon	narpc	ET	9/19/00	No Chng	No Chng	No Chng	No Data	No Data	No Chng
TS Helene	cbvgi	TS	9/23/00	No Chng	No Chng	No Chng	No Chng	No Chng	No Chng

A strong negative linear relationship (R^2=0.97) existed between the mean one-day change in mean daily water temperature and storm intensity (Figure 49). Similarly, a strong negative quadratic relationship (R^2=0.99) was also observed for the maximum observed one-day change in mean daily water temperature (Figure 49). Decreases in mean daily water temperature less than or equal to -1.5°C were observed for 70% of hurricanes, 47-50% of tropical storms and tropical depressions, and 29% of extra-tropical systems examined. Overall, tropical systems accounted for less than 0.5% of these precipitous drops in mean daily water temperature (≤ -1.5°C) between consecutive days in data sets collected at NERR SWMP sites between 1995-2000 (Figure 50).

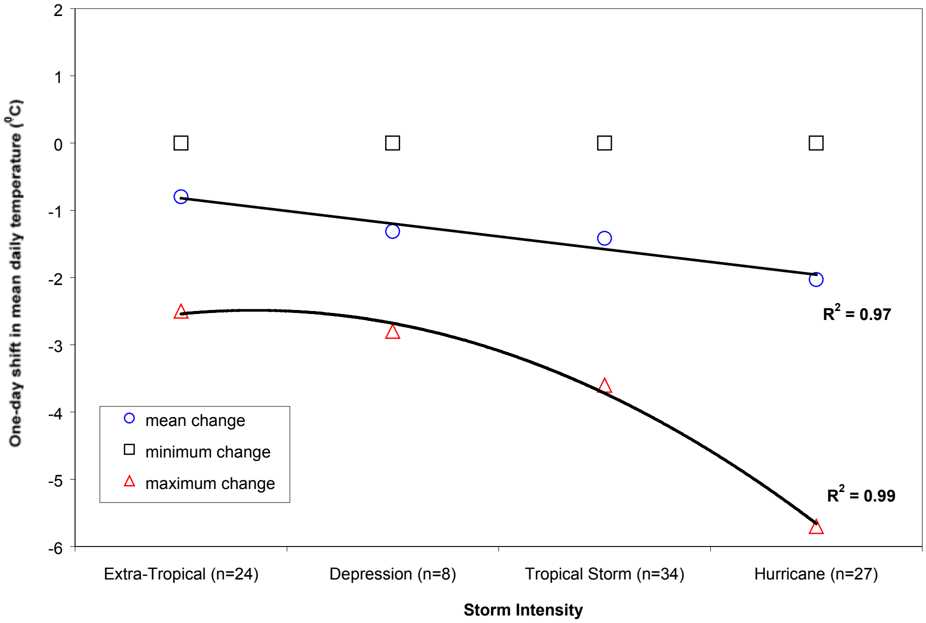

Figure 49. Storm intensity vs. one-day shift in mean daily water temperature.

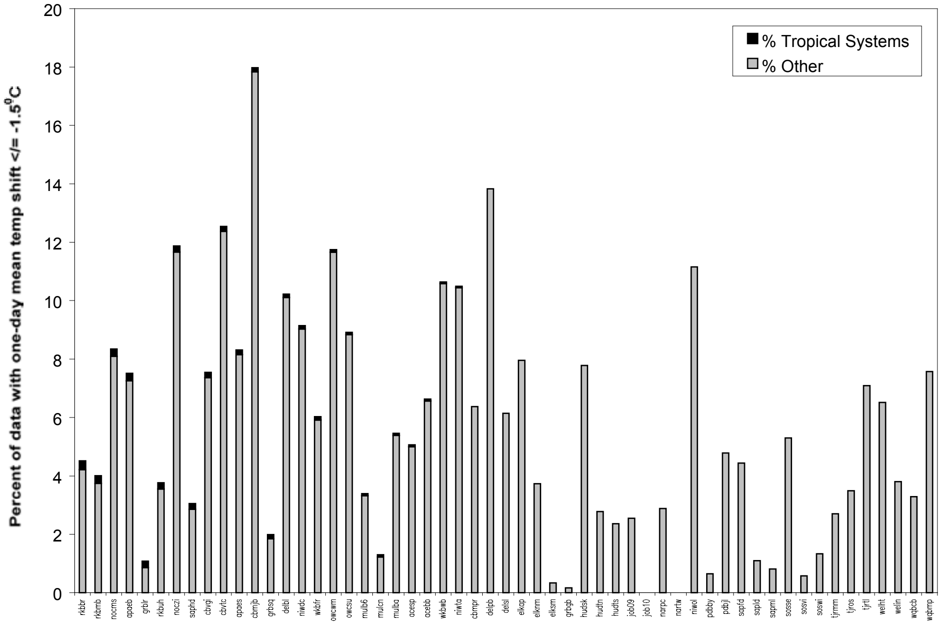

Figure 50. Frequency of one-day shifts in daily mean water temperature ≥ -1.5°C.

No relationship between storm intensity and short-term change in salinity was evident (Figure 51). Six storm systems (Bertha, Fran, Bonnie, Georges, Dennis, and Floyd) drastically altered mean daily salinity, and these altered patterns persisted for 0.5 to 3.5 months at multiple NERRs (Figures 52-56).

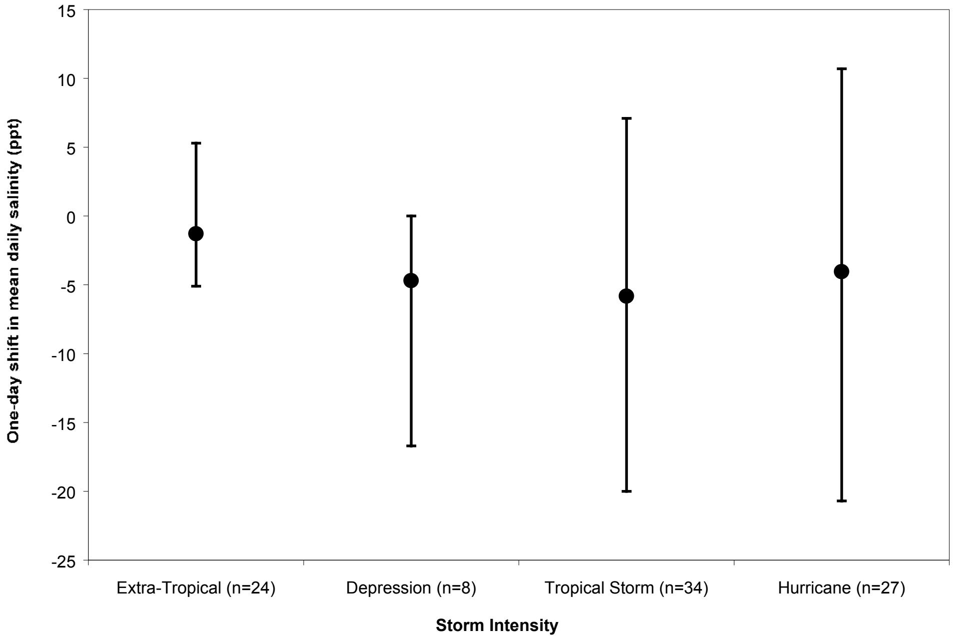

Figure 51. Storm intensity vs. maximum shift in mean daily salinity.

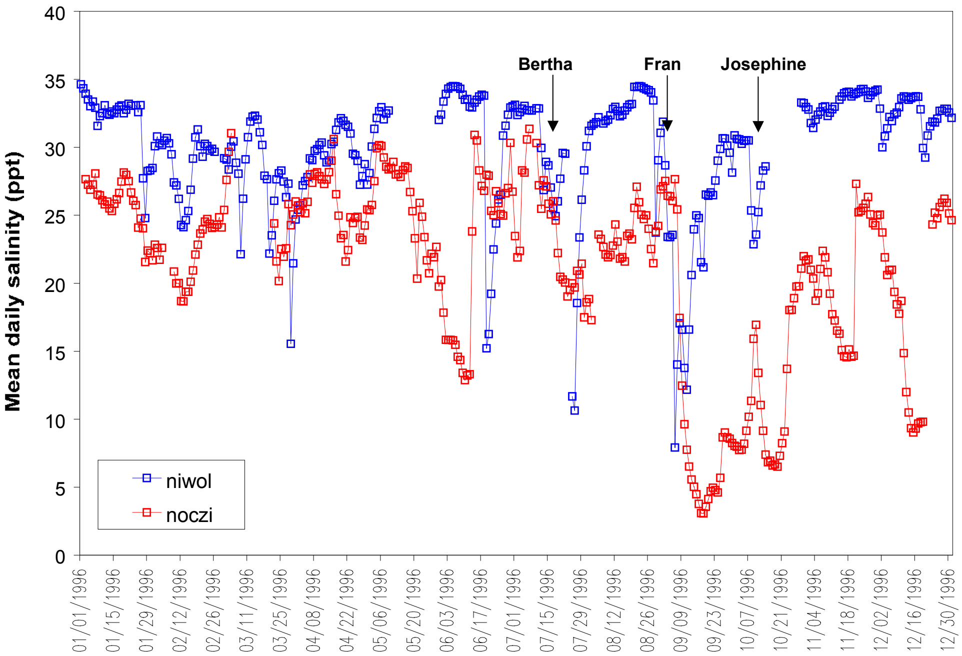

Figure 52. Sustained effects on mean daily salinity, NOC and NIW NERRs, 1996.

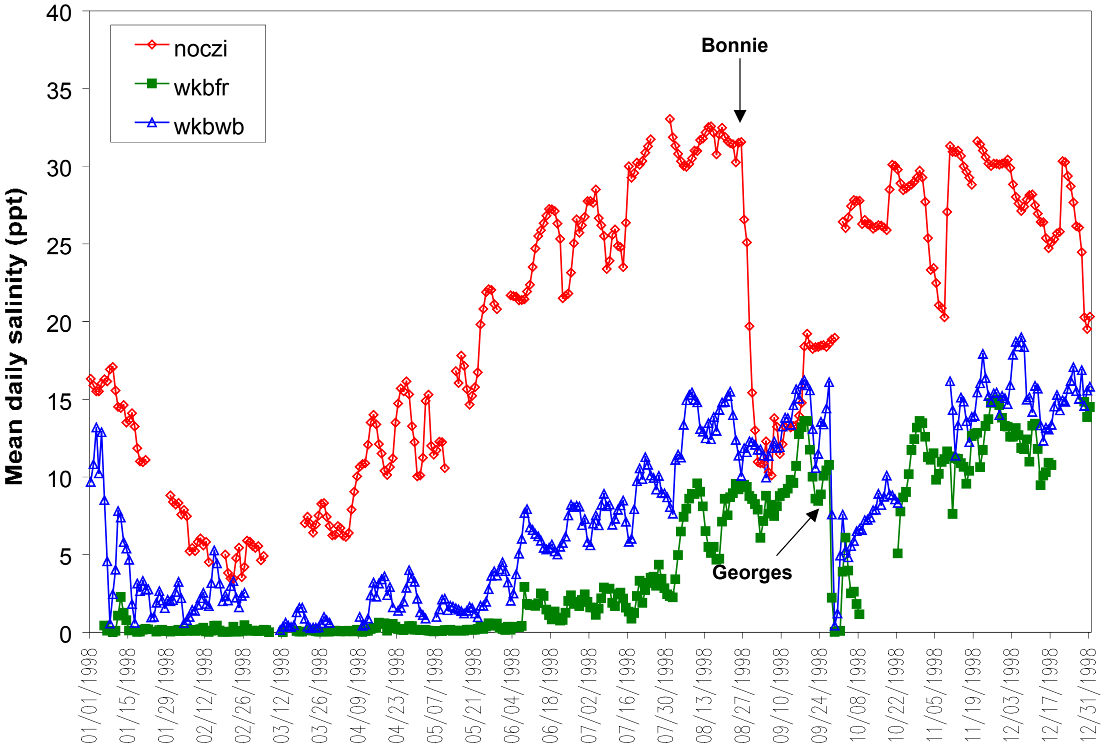

Figure 53. Sustained effects on mean daily salinity, NOC and WKB NERRs, 1998.

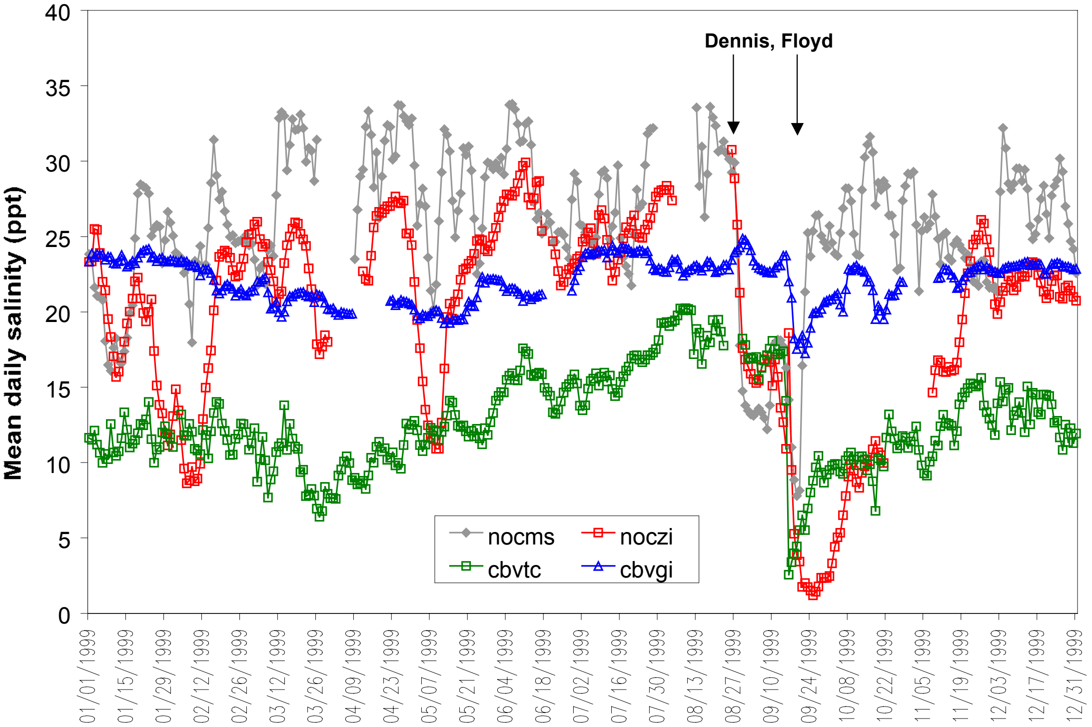

Figure 54. Sustained effects on mean daily salinity, NOC and CBV NERRs, 1999.

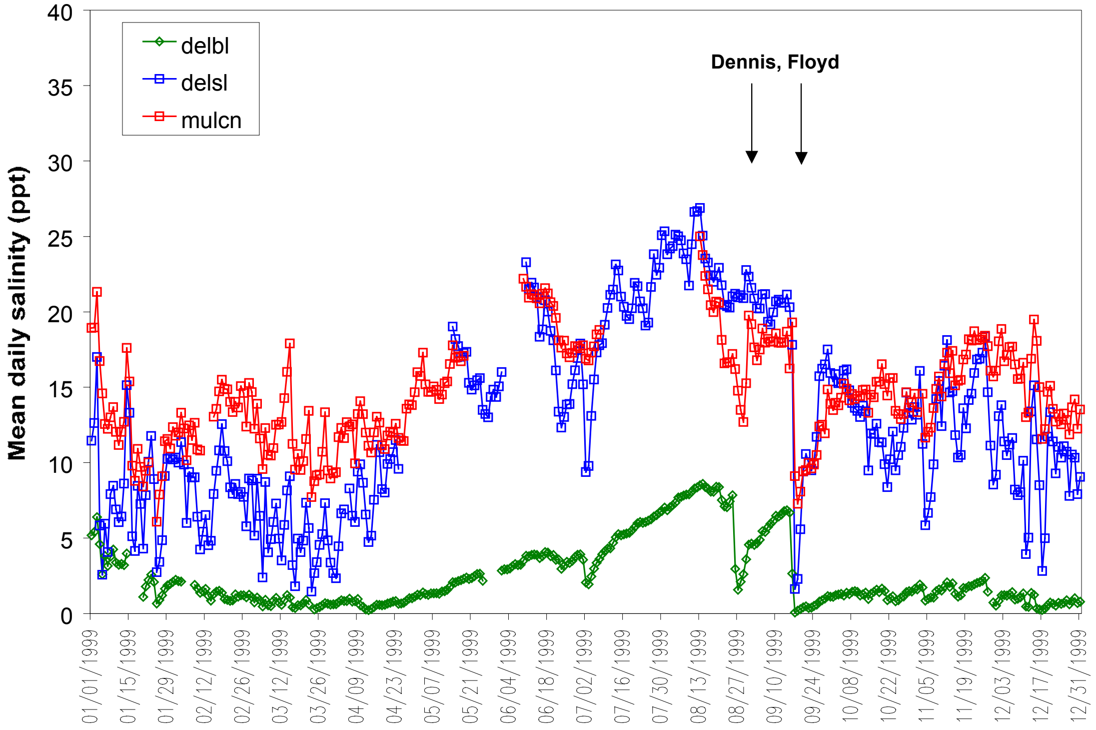

Figure 55. Sustained effects on mean daily salinity, DEL and MUL NERRs, 1999.

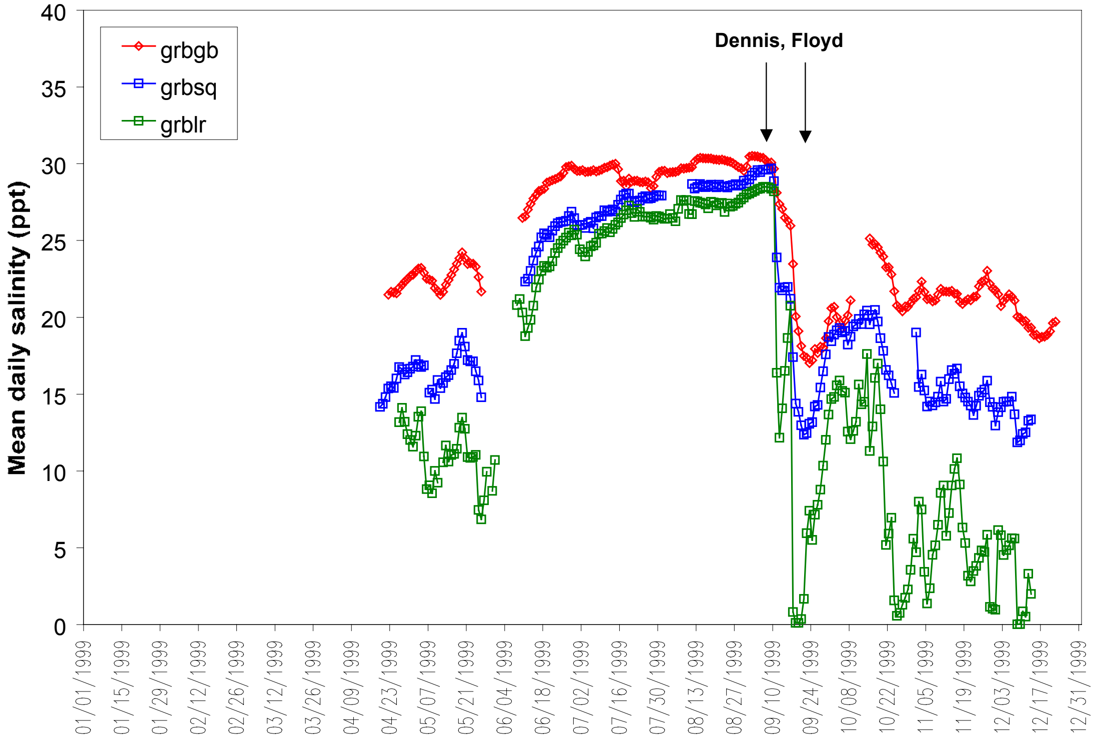

Figure 56. Sustained effects on mean daily salinity, GRB NERR, 1999.

No relationships between storm intensity and water depth and turbidity were evident (Figures 57-58). Changes in pH and DO occurred in less than 50% of the data sets examined, but were observed in at least one data set for 16 of the 21 tropical systems examined. Changes in both pH and DO occurred in 13 data sets from nine tropical systems (Table 24).

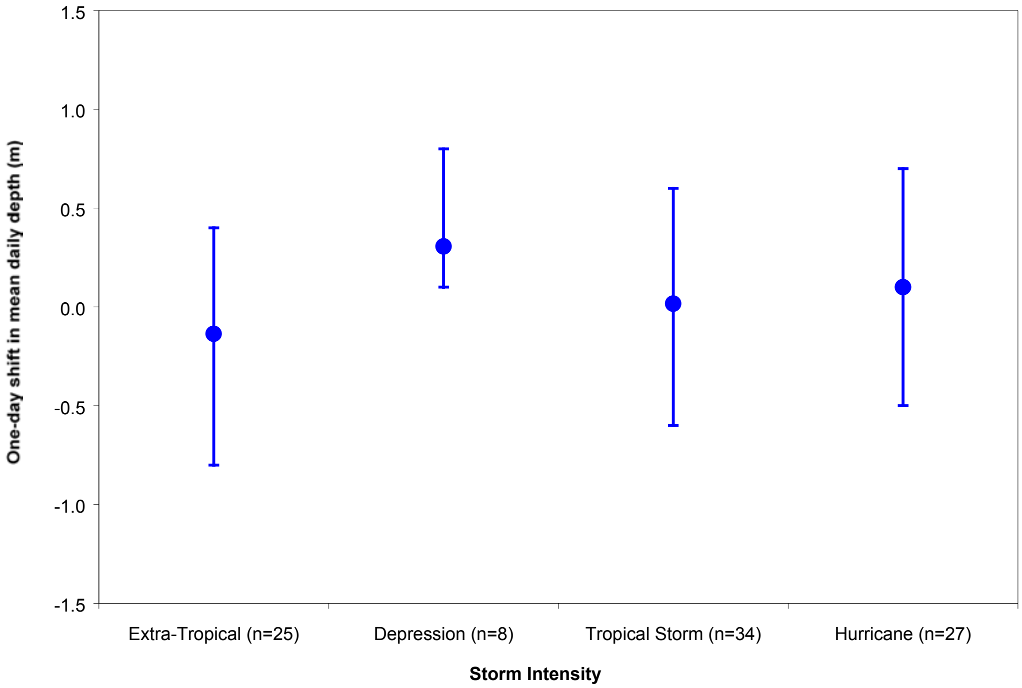

Figure 57. Storm intensity vs. shift (mean and range) in daily water depth.

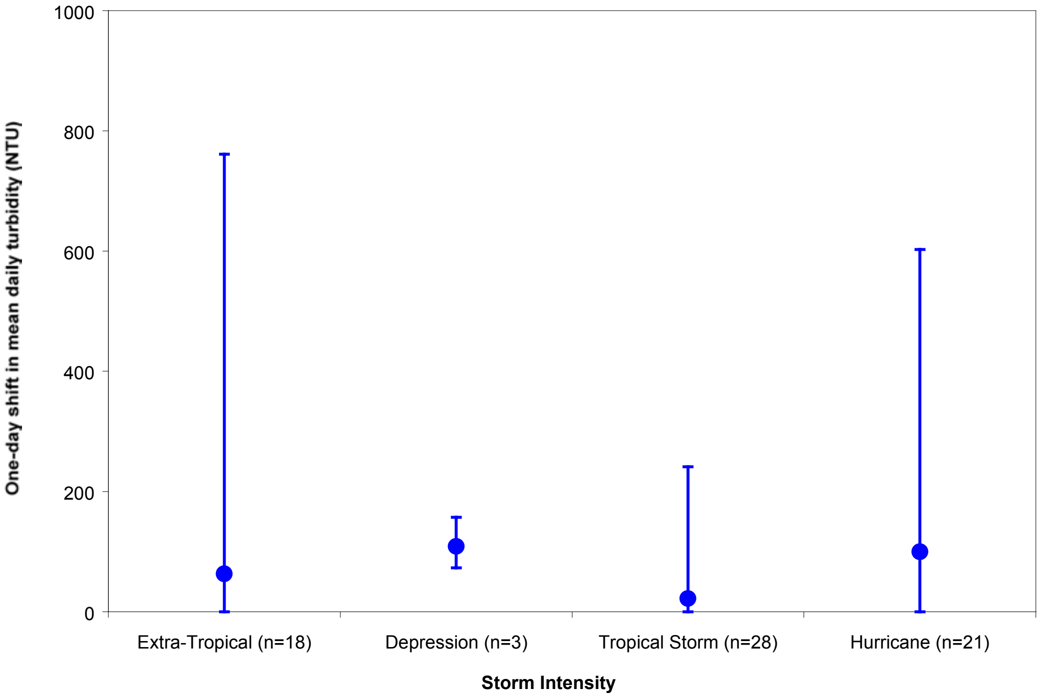

Figure 58. Storm intensity vs. shift (mean and range) in daily turbidity.

Table 24. Summary of observed changes in Dissolved Oxygen (% sat) and pH. Changes in DO and pH were only observed in 40% and 26% of data sets examined, respectively. Empty cells indicate no change was observed.

		DO	DO	pH	pH	pH
Storm	**Site**	**Mean Daily Range**	**Days Present**	**Mean Change**	**Days**	**Daily Rate**
Allison	apaeb			1	5	0.2
Erin	apaes			-2.5	2	-1.3
Erin	apaeb	8.3	1	-0.6	4	-0.2
Opal	apaes	8.4	1	-1.7	2	-0.9
Bertha	job09	50.2	1			
Bertha	job10	22	1			
Bertha	delbl	26.7	3	-0.7	2	-0.4
Bertha	delsl	43.9	4	-0.6	2	-0.3
Bertha	mulcn	8.3	1			
Bertha	nocms	15.1	1			
Bertha	noczi	14.5	1			
Bertha	welht			-1.5	1	-1.5
Bertha	wqbcb			-0.3	1	-0.3
Fran	noczi	26.9	4	-1.1	9	-0.1
Fran	niwol			-0.7	1	-0.7
Fran	niwta			-0.2	1	-0.2
Fran	owcsu			-0.5	2	-0.3
Fran	owcwm			0.3	1	0.3
TS Josephine	apaeb	19.3	2	0.3	1	0.3
TS Josephine	apaes	17.1	2	-0.7	6	-0.1
TS Josephine	niwta	76.2	1	-2	4	-0.5
Danny	wkbfr	11.3	5	-0.7	3	-0.2
Bonnie	cbvgi			-0.7	3	-0.2
Bonnie	nocms			-0.4	1	-0.4
Bonnie	noczi			-0.3	2	-0.2
Earl	apaeb			1	2	0.5
Earl	apaes			1.5	2	0.8
Georges	wkbwb	18.7	3	-1.8	2	-0.9
Dennis	cbvgi	12.6	5	-0.4	6	-0.1
Dennis	nocms			-1.4	2	-0.7
Floyd	noczi			0.2	1	0.2
Floyd	cbvgi	11.4	1	-0.2	1	-0.2
Floyd	cbvtc	27.2	1	-0.6	1	-0.6
Floyd	delbl			-0.9	2	-0.5
Floyd	delpb			-0.8	2	-0.4
Floyd	mulb6			-0.2	1	-0.2
Floyd	mulba			-0.1	1	-0.1
Floyd	mulcn			-0.4	1	-0.4
Floyd	grblr			-0.7	3	-0.2
Floyd	grbgb	5.2	1			
TS Harvey	rkbbr	16.6	7			
TS Harvey	rkbuh	14.2	8			
Irene	rkbbr	14.6	1			
Irene	rkbuh	8	1			
Gordon	acesp	42.8	1			
Gordon	wqbmp	15.2	1			
TS Helene	apaeb			-2.4	4	-0.6
TS Helene	apaes			-2.4	4	-0.6

Discussion

Abrupt decreases in water temperature prior to storm passage were consistently observed in data sets, with increasing cooling effects strongly related to increasing storm intensity. Changes in water temperature were not observed for 25 data sets. In one instance (Zeke's Island during Hurricane Fran), mean daily water temperature showed no change during storm passage, but increased slightly (3.2°C) during the four days following storm passage. This pattern may have been related to excessive biological oxygen demand (BOD) levels in the Cape Fear River (Mallin et al. 1999). Minor changes in all water quality parameters were observed for the remaining 24 data sets. The lack of noticeable changes in water temperature and other parameters for these data sets were probably due to (1) storms passing to the west of the NERRs, (2) large distances between storms and NERRs and (3) rapid deterioration of storm intensity and subsequent short-term exposure (<12 hours) to storms due to rapid movement past NERRs.

The phenomenon of sea surface temperature cooling related to hurricanes in the open ocean has been extensively studied (Beckle 1974, Price 1983, Greatbach 1985, Sanford et al. 1987, Cornillon et al. 1987, Shay et al. 1989, Sakaida et al. 1998). In the open ocean, sea surface temperature cooling of 2-9°C associated with the maximum sustained winds of hurricanes has been reported. As cool waters below the thermocline are brought to the surface via upwelling, warm surface waters are replaced by cold water in the wake of the storm, which effectively creates a cold water 'footprint' of the storm track. Although wind mixing and subsequent upwelling are the primary mechanisms responsible for sea surface cooling, the magnitude of the cooling effect depends on the initial thermal stratification in the ocean and storm mobility (Chang and Anthes 1978). Localized mixing occurs over longer periods in slow moving storms; thus, greater sea surface temperature cooling should occur.

Water temperature cooling associated with hurricanes in the open ocean has received much attention; however, documentation of similar changes in water temperature associated with storm passage in coastal and estuarine water bodies is sparse. The mechanism of water temperature cooling may be related to wind mixing and/or heat exchange at the air-water interface, but is unknown at the present time. Detailed examination of these potential mechanisms may be possible during future tropical system events with the incorporation of weather station data into the NERR SWMP.

During Hurricane Dennis, Arendt et al. (2001) observed the same water temperature cooling response in 18m of water in lower Chesapeake Bay as documented at the Chesapeake Bay Virginia, Goodwin Islands site, on the opposite side of the Bay. Coincident with this water temperature cooling, Arendt et al. (2001) observed a three-day period of inactivity for several adult tautog, *Tautoga onitis*, at a shipwreck continuously monitored using ultrasonic telemetry equipment. These authors also observed similar changes in detection patterns of adult tautog at all monitored sites coincident with abrupt decreases and increases in daily mean water temperature between Nov 1998 and Sep 1999 (Arendt et al. 2001). At a minimum, these findings suggest that abrupt changes in water temperature may serve as indicators of change in other physical or chemical parameters that have short-term ecological consequences in certain habitats.

Habitats monitored by the NERR SWMP largely consist of shallow (mean depth = 2m), tidal creeks. Daily temperature variation in many of these systems can reach up to 10°C. Although large daily temperature variation is regularly experienced, abrupt shifts in mean daily water temperature (≤ -1.5°C), similar to shifts observed during the passage of tropical systems in NERR data sets between 1995-2000, are less common and occur less than 6% of the time at most sites. Furthermore, the abrupt shifts in mean daily temperature observed during the passage of tropical systems represent <0.5% of the total occurrence of these types of temperature changes (Figure 50).

If wind mixing is also responsible for these additional shifts in mean daily water temperature, then shifts in mean daily water temperature may be useful as indicators of the frequency of strong wind mixing events at NERR SWMP sites. The primary ecological ramification of strong mixing events is the breakdown of water column stratification, which can lead to increases in hypoxia. Given the small size of the water bodies monitored by the NERR SWMP and the strong tidal amplitudes experienced at these sites, wind mixing effects may be masked by the twice daily flushing effects of tidal cycles at these sites. Wind mixing may, however, play an important role in controlling the magnitude of the daily variation in DO (% sat). Although changes to DO were only observed in 27% of the data sets examined, strong wind forcing during several storms appeared to drastically reduce daily variation (to less than 20%) in DO for several days.

Short-term changes to salinity and depth during the passage of tropical systems were variable and dependent on the fetch of approaching storms. Tropical systems approaching from open water were usually associated with an initial increase in depth and salinity due to storm surge, followed by a decrease in salinity and depth after storm passage due to precipitation and strong winds pushing water down the estuary. This scenario was particularly evident in data sets from NERRs in the Gulf of Mexico (APA, RKB, WKB) and the North Carolina NERR. Extra-tropical and tropical storm systems that moved up the coast after making landfall were frequently associated with decreases in salinity and depth as a result of precipitation and strong winds pushing water down the estuary. With the exception of the NOC NERR, these types of systems constituted the majority of systems encountered by NERRs on the eastern seaboard (Table 22).

With a few exceptions for salinity, changes to water quality parameters monitored by the NERR SWMP during the passage of tropical systems between 1995-2000 were abrupt, and short-lived. Long-term changes in salinity were evident for only a few storms (Figures 80-84). Altered salinity distributions and excessive runoff from these storms subsequently resulted in ecological disturbances in some of these estuaries. Following Hurricanes Fran (1996) and Bonnie (1998), biological oxygen demand (BOD) loads caused large-scale fish kills in the Cape Fear and Neuse River estuaries (Mallin et al. 1999, Burkholder et al. 1999). Co-occurrence of Hurricane's Dennis and Floyd in September 1999 produced record precipitation and flushed many fish populations into sounds and coastal waters (Mallin et al. 2000). More than two years after Hurricanes Dennis and Floyd, the distribution of some estuarine fish and invertebrate assemblages have still not returned to pre-hurricane levels (L. Crowder, pers. comm.).

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Appendix 1. Inter-annual variability (% annual data) in water temperature and salinity, NERR SWMP 1995-2000.

			Water Temperature (^{0}C)							**Salinity (ppt)**				
Site	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**
elkap	34	90	89	98	85	90	81	34	84	89	97	85	90	80
elknm					61	100	80					61	93	77
elksm	38	92	86	91	79	100	81	38	92	86	91	72	92	78
pdbby	24	85	77	93	88	100	78	24	35	77	91	88	98	69
pdbjl	38	76	92	99	98	79	80	38	76	92	99	98	79	80
sosse	46	64	50	15	82	96	59	46	64	50	2	82	96	57
sosvi					47	89	66					47	89	62
soswi	63	59	40	35	89	96	64	51	59	36	25	89	96	61
tjrmm						10	10						10	10
tjros		91	71	90	93	70	83		87	71	90	86	65	80
tjrtl			38	85	10	22	39			38	81	10	22	38
mean							**66**							**63**
grbgb	26	58	59	58	62	56	53	26	58	59	58	61	52	52
grblr				12	60	54	40				12	60	54	40
grbsq			34	48	60	47	52			34	48	55	47	50
hudsk	48	17	58	73	64	57	53	48	17	32	73	64	57	49
hudtn					36	52	44					36	52	44
hudts	49	47	48	70	64	52	55	49	27	35	70	64	52	49
narpc	4	83	88	89	96	82	74	4	80	88	89	96	81	73
nartw		24	87		66	90	67		24	87		66	84	65
owcsu	38	38	55	59	66	75	55	38	37	55	59	63	71	54
owcwm	41	43	55	57	60	71	54	40	43	55	57	56	71	54
welht	68	61	69	66	48	45	59	68	61	69	66	48	45	59
welin	49	93	93	78	75	88	79	49	93	93	78	75	88	79
wqbcb	13	19	48	26			27	9	19	48	26			25
wqbmp				12	21	71	35				12	21	71	35
mean							**55**							**52**
cbmjb	35	37	18	19	32	49	31	35	37	18	19	32	49	31
cbmpr	37	39	26	14		26	28	37	39	26	14		26	28
cbvgi			19	97	89	93	74			19	97	89	93	74
cbvtc	22	80	89	95	97	96	80	22	76	81	95	97	96	78
delbl	32	84	87	84	91	83	77	29	84	84	84	91	83	76
delpb		40	82	92	57	64	67		37	82	92	57	64	66
delsl	41	75	88	88	90	81	77	41	75	88	88	90	81	77
mulb6		38	76	78	86	94	74		38	75	75	78	94	72
mulba		22	89	85	94	93	77		22	89	85	94	93	77
mulcn		46	79	86	79	82	74		46	79	86	79	82	74
mean							**66**							**65**
acebb	56	61	89	75	85	77	74	49	61	89	75	80	77	72
acesp	60	59	79	72	79	76	71	60	59	54	64	74	71	64
niwdc				76	74	86	79				63	74	86	74
niwol		82	84	90	90	83	86		82	84	75	90	83	83
niwta	87	84	79	93	83	88	85	84	84	79	89	83	88	84
nocms	76	84	79	90	91	99	86	76	84	76	86	91	99	85
noczi	84	94	71	89	84	86	85	82	89	71	85	84	83	82
sapfd	75	90	98	98			90	75	90	97	98			90
saphd					41	79	60					41	79	60
sapld					98	97	98					92	97	94
sapml	51	93	98	95			84	51	93	98	95			84
mean							**82**							**79**
apaeb	53	87	100	99	100	95	89	53	87	100	99	95	93	88
apaes	63	94	95	80	99	99	88	63	94	95	78	99	99	88
job09	3	85	34	24	52	55	42	3	80	24	15	40	49	35
job10		77	15	20	30	71	43		77	1	6	22	58	33
rkbbr				85	96	1	61				85	96	1	61
rkbmb					3	95	49					3	95	49
rkbuh		15	94	95	100	89	79		12	94	95	100	89	78
wkbfr	17	97	94	94	92	97	82	17	97	94	90	92	97	81
wkbwb	18	99	86	86	91	92	79	18	99	86	86	91	92	79
mean							**68**							**66**

Appendix 2. Inter-annual variability (% annual data) in dissolved oxygen (% sat and mg/L), NERR SWMP 1995-2000.

		Dissolved Oxygen (% sat)							Dissolved Oxygen (mg/L)					
Site	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**
elkap	34	83	79	96	83	86	77	34	77	79	96	83	86	76
elknm					53	63	58					53	63	58
elksm	37	82	43	70	68	73	62	37	82	43	70	68	73	62
pdbby	24	76	69	89	63	67	65	24	35	69	89	63	67	58
pdbjl	38	51	80	99	94	71	72	38	51	80	99	94	71	72
sosse	45	40	40	7	76	93	50	45	40	40		76	93	59
sosvi					47	85	65					47	85	64
soswi	63	31	17		83	96	57	59	31	17		83	96	57
tjrmm						10	10						10	10
tjros		76	58	80	69	67	70		72	58	80	69	67	69
tjrtl			38	80	10	22	38			38	80	10	22	38
mean							**57**							**57**
grbgb	26	52	59	58	61	43	50	26	52	59	58	61	43	50
grblr				12	35	51	33				12	35	51	33
grbsq			34	41	56	44	47			34	41	56	44	47
hudsk	48	17	38	73	60	57	49	48	17	38	73	60	57	49
hudtn					34	48	41					34	48	41
hudts	49	47	27	59	64	52	49	49	47	27	59	64	52	49
narpc	4	60	71	71	93	50	58	4	57	71	71	93	50	58
nartw		21	69		45	76	53		21	69		45	76	53
owcsu	38	25	51	55	64	75	51	38	25	55	55	64	71	52
owcwm	41	32	47	50	60	70	50	41	32	47	50	56	70	49
welht	59	54	51	58	42	45	51	59	54	51	58	42	45	51
welin	49	93	85	78	75	52	72	49	93	85	78	75	52	72
wqbcb	13	15	47	24			25	13	15	47	24			25
wqbmp				12	21	60	31				12	21	56	30
mean							**47**							**47**
cbmjb	35	31		15	25	34	28	35	31		15	25	34	28
cbmpr	37	31				10	26	37	31				10	26
cbvgi			19	95	79	82	69			19	95	79	82	69
cbvtc	15	71	70	88	93	88	71	15	67	70	88	93	88	70
delbl	29	84	83	84	71	78	72	29	84	81	84	71	78	71
delpb		40	82	87	44	53	61		40	82	87	44	53	61
delsl	38	66	82	78	77	77	70	38	66	82	78	77	77	70
mulb6		37	68	64	62	80	62		37	62	62	58	80	60
mulba		16	73	70	71	77	61		16	70	70	71	77	61
mulcn		46	79	82	69	75	70		46	68	86	69	75	69
mean							**59**							**58**
acebb	46	37	66	64	57	49	53	39	37	66	64	53	49	51
acesp	52	41	41	52	61	48	49	52	41	37	52	57	48	48
niwdc				76	69	77	74				63	69	77	70
niwol		79	70	89	74	74	77		79	70	74	74	74	74
niwta	81	76	75	79	53	81	74	81	76	75	76	53	81	74
nocms	72	77	55	75	77	83	73	72	77	55	71	77	83	72
noczi	80	79	59	71	77	72	73	76	79	59	75	77	71	73
sapfd		81	81	75			79	19	80	81	75			64
saphd					36	78	57					36	73	55
sapld					86	97	92					86	88	87
sapml	4	76	94	69			61	10	76	94	69			62
mean							**69**							**66**
apaeb	17	37	47	70	70	80	53	31	37	46	65	80	80	56
apaes	38	68	64	72	63	84	65	38	68	64	74	63	84	65
job09	3	65	9	9	39	44	28	3	65	3	18	33	41	27
job10		75	12	10	22	65	37		75	3	10	22	54	33
rkbbr				56	96	1	51				48	96	1	48
rkbmb					3	94	48					3	94	48
rkbuh		15	77	65	100	75	66		15	77	65	100	75	66
wkbfr	17	92	91	63	63	89	69	17	92	91	63	63	89	69
wkbwb	13	88	74	67	80	76	66	13	88	74	67	80	76	66
mean							**54**							**53**

Appendix 3. Inter-annual variability (% annual data) in water depth, pH and turbidity, NERR SWMP 1995-2000.

			Water Depth (m)							pH							Turbidity (NTU)				
Site	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**
elkap	34	90	89	98	85	87	80	34	90	89	98	82	59	75	0		42	98	77	81	60
elknm					59	99	79					62	87	75					49	61	55
elksm	34	92	86	91	83	100	81	20	92	86	91	83	83	76			17	63	83	93	64
pdbby	24	85	77	93	88	100	78	24	85	77	93	86	91	76		50	59	93	77	100	75
pdbjl	28	76	92	99	98	79	79	18	69	92	99	91	79	75		58	78	89	85	77	77
sosse	46	64	50	22	82	96	60	18	20	12		76	96	44		5	9		76	96	47
sosvi					47	89	66					47	89	55					24	87	55
soswi	63	53	39	25	77	96	58	28	31	8		83	96	55		4	3		65	96	42
tjrmm						10	10						10	10							
tjros		87	71	90	93	70	82		53	45	74	57	53	56		38	63	70	89	46	61
tjrtl			35	85	10	22	38			32	50	3	17	25			28	21	8	22	20
mean							**65**							**57**							**56**
grbgb	19	57	59		58	46	48	21	43	48	58	58	37	44				8	62	55	42
grblr				12	60	54	40				12	60	53	40				5	57	53	39
grbsq			34	48	60	47	52			34	48	58	30	45				15	60	7	28
hudsk	48	17	65	73	64	57	54	41	17	65	73	61	57	52		8	65	73	62	57	53
hudtn					36	48	42					36	52	44					30	52	41
hudts	49	47	54	70	64	52	56	42	47	54	70	64	52	55		38	54	68	60	52	54
narpc	4	83	88	89	96	82	74	4	83	88	89	96	78	73		20	43	56	93	70	56
nartw		24	87		66	90	67		24	87		63	87	66		6	35		40	65	37
owcsu	38	42	55	59	66	75	56	38	42	55	59	66	75	56		37	55	52	66	75	57
owcwm	39	42	55	57	60	71	54	41	43	55	57	60	71	54		40	51	57	60	67	55
welht	68	61	69	66	48	45	59	52	61	69	66	48	45	57		54	69	66	48	45	56
welin	49	93	95	78	75	88	80	42	93	93	76	71	88	77		72	95	70	68	74	76
wqbcb	13	19	48	26			27	13	19	48	26			26		19	44	25			29
wqbmp				12	21	71	35				12	21	71	35				12	21	71	35
mean							**53**							**52**							**47**
cbmjb	35	37	18	19	32	49	31	35	26	18	19	7	49	26							
cbmpr	37	39	26	16		26	29	33	33	26	14			26							
cbvgi			19	97	87	93	74			19	97	89	93	74			19	94	89	93	74
cbvtc	18	72	84	98	97	96	78	15	80	89	95	97	96	79		34	62	97	97	96	77
delbl	32	84	87	87	91	83	77	32	84	79	84	91	83	76		58	79	80	84	81	76
delpb		38	62	70	40	69	56		40	78	92	57	72	68		37	82	92	57	80	70
delsl	41	75	88	88	90	81	77	41	75	88	84	90	81	76		53	88	85	90	81	79
mulb6		38	81	78	86	94	75		38	81	78	86	90	75		38	75	70	78	89	70
mulba		22	92	85	94	93	77		22	92	85	94	93	77		22	86	68	86	83	69
mulcn		46	96	89	79	82	78		46	96	89	75	82	78		40	91	67	74	83	71
mean							**65**							**65**							**73**
acebb	56	46	89	75	86	77	72	34	53	50	28	78	72	52		43	70	64	57	32	53
acesp	60	59	82	65	93	76	73	22	51	82	51	73	76	59		42	69	70	57	52	58
niwdc				72	74	86	77				72	74	84	77				70	74	63	69
niwol		79	84	90	90	83	85		81	84	88	87	75	83		71	84	90	90	67	81
niwta	85	84	79	93	83	88	85	33	74	72	93	75	88	72	3	69	72	93	66	85	65
nocms	76	84	74	90	91	99	86	68	80	77	90	85	99	83		62	66	87	81	99	79
noczi	75	94	71	89	84	86	83	84	94	55	89	84	86	82		52	57	89	83	86	73
sapfd		42					42	75	90	97	81			86		14	15	19			16
saphd					45	79	62					45	60	53					21	51	36
sapld					98	97	98					94	80	87					11	37	24
sapml		44					44	45	93	97	88			81		10	12	4			9
mean							**73**							**74**							**51**
apaeb	53	83	100	94	100	95	87	53	87	100	99	94	82	86			9			44	26
apaes	63	96	97	79	98	100	89	59	94	90	75	99	91	85		4	95	80	91	93	73
job09	3	85	34	24	52	53	42	3	85	34	24	52	55	42	3		34	24	49	49	32
job10		77	15	20	30	71	43		77	8	20	24	65	39			15	20	20	37	23
rkbbr				85	96	1	61				85	96	1	61				85	92	1	59
rkbmb					3	87	45					3	92	47					3	84	43
rkbuh		15	94	95	100	89	79		15	94	95	100	71	75		15	94	95	96	70	74
wkbfr	17	97	94	94	84	97	80	17	97	75	90	92	97	78				33	57	82	57
wkbwb	18	99	86	86	91	92	79	18	99	86	62	91	92	75				8	25	29	20
mean							**67**							**65**							**45**

Appendix 4. Seasonal and inter-annual variability in percent of water temperature data collected, NERR SWMP 1995-2000.

	Winter							Spring							Summer							Fall						
Site	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**
elkap		91	68	92	63	98	82	4	91	89	99	99	77	77	68	92	99	100	83	86	88	61	87	99	100	95	97	90
elknm						100	100					68	100	84					86	100	93					88	99	94
elksm		98	99	99	84	99	96	4	94	89	98	55	100	73	97	96	73	81	82	99	88	49	79	83	85	97	100	82
pdbby		59	40	92	98	100	78		84	100	100	89	100	95	25	98	99	77	67	100	78	70	98	60	97	100	100	87
pdbjl		48	83	100	100	94	85	12	61	88	99	99	100	77	62	100	98	100	100	100	93	76	93	99	96	95	24	81
sosse		100	43	32	93	94	72	32	79	77		92	97	75	71	77			47	95	73	80		82	29	97	96	77
sosvi						69	69					28	96	62					64	95	79					96	97	97
soswi		95	27	48	93	94	72	78	87	52	2	85	97	67	73	54		29	83	95	67	99		82	59	97	97	87
tjrmm																											41	41
tjros		96	81	86	96	85	89		96	88	90	79	85	88		93	66	90	100	66	83		78	47	94	99	46	73
tjrtl				87	10	20	39			40	86		59	62			42	82		12	45			70	86	31		62
mean							**78**							**76**							**79**							**79**
grbgb									71	96	79	60	71	75	60	94	78	87	100	100	86	44	66	61	65	89	54	63
grblr						80	80					59	49	54					100	99	100				48		66	57
grbsq											66	70	35	57			73	76	100	87	84			60	48	71	64	61
hudsk								46	55	52	100	84	48	64	90	12	90	100	82	99	79	56		89	91	90	80	81
hudtn													45	45					71	91	81					71	70	70
hudts								45	61	35	99	76	41	59	90	84	87	90	94	98	90	58	42	71	90	85	69	69
narpc		77	73	93	100	76	84		73	100	93	87	75	85		83	77	87	100	98	89	15	100	100	85	99	78	79
nartw			100		14	100	71			96		78	75	83		12	55		98	87	63		85	100		71	100	89
owcsu						34	34	41	36	88	100	100	100	78	99	83	100	100	100	100	97	12	33	33	34	64	66	40
owcwm						34	34	41	72	100	94	80	88	79	99	66	89	100	100	95	92	21	33	30	34	61	66	41
welht			1		23		12	92	86	98	88	98	86	91	99	87	93	97	11	86	79	77	70	81	80	61	7	63
welin		90	90	78	63	99	84	35	97	100	85	51	82	75	63	90	85	68	97	72	79	99	97	96	80	89	99	93
wqbcb									61	50				56		16	78	37			44	52		62	65			60
wqbmp						2	2						100	100					11	89	50				48	71	94	71
mean							**50**							**72**							**79**							**67**
cbmjb						43	43		71		8		69	49	88	76	53	66	48	83	69	52		16		79		49
cbmpr						13	13		73		8		38	40	93	83	65	48		53	68	52		38				45
cbvgi				97	99	82	93				90	72	97	86				100	100	100	100			74	100	85	93	88
cbvtc		67	100	99	96	99	92		78	69	100	100	100	89	16	85	91	95	93	83	77	71	89	95	85	100	100	90
delbl		63	79	74	81	91	77		89	87	75	91	75	83	81	87	88	93	98	81	88	48	98	92	93	96	83	85
delpb			60	87	8	94	62		27	74	96	37	91	65		42	96	85	86	55	73		90	98	98	98	17	80
delsl		62	59	76	98	79	75		81	97	88	66	97	86	94	85	97	97	98	67	89	70	71	98	93	98	80	85
mulb6			95	69	78	77	80			96	80	84	100	90		60	58	88	92	100	80		89	56	73	90	100	82
mulba			78	61	89	77	76			100	91	88	100	95			100	88	100	100	97			78	99	100	94	93
mulcn			86	73	89	69	79		6	100	92	74	95	73		100	55	83	57	81	75		77	76	95	95	84	85
mean							**69**							**76**							**82**							**78**
acebb	30	61	88	80	74	88	70	58	57	93	56	89	63	69	60	43	86	79	88	90	74	77	84	88	86	91	69	82
acesp	27	60	91	80	78	89	71	64	62	93	62	90	59	72	67	58	39	68	73	86	65	76	57	93	77	75	71	75
niwdc				29	90	83	67				86	77	73	79				97	69	92	86				91	62	94	82
niwol		89	79	84	91	84	85		72	92	97	89	82	86		88	80	87	88	77	84		79	85	92	93	89	88
niwta	96	88	66	92	84	84	85	83	83	74	99	89	81	85	95	91	84	87	87	92	89	72	75	90	93	73	94	83
nocms	61	74	92	90	94	100	85	95	97	77	79	91	100	90	65	63	66	97	82	97	78	81	97	81	95	99	100	92
noczi	60	91	62	83	97	96	82	80	97	64	89	83	51	77	97	93	79	90	75	96	88	99	94	79	95	80	100	91
sapfd	50	83	100	93			81	68	85	100	100			88	98	100	100	100			99	84	93	94	100			93
saphd						88	88						77	77					91	82	86					74	68	71
sapld					100	89	95					100	100	100					98	100	99				16	95	100	70
sapml		82	100	83			88	40	99	100	100			85	93	93	100	98			96	71	100	92	100			91
mean							**82**							**82**							**86**							**83**
apaeb		69	100	100	100	79	90	51	80	100	100	100	100	89	80	100	100	100	100	100	97	81	100	99	98	100	99	96
apaes		97	99	65	96	99	91	65	97	99	80	99	100	90	84	84	96	93	100	100	93	99	99	86	81	99	99	94
job09		99	64		44	38	61		94	46	26	50	58	55		59		11	69	46	46	12	88	28	59	44	80	52
job10		65		32	45	67	52		95	48		35	84	65		82		18	38	42	45		65	13	28		93	50
rkbbr				38	100	5	48				100	100		100				100	84		92				100	100		100
rkbmb						100	100						84	84						100	100					26	100	63
rkbuh			77	100	100	85	90			100	100	100	100	100			100	100	100	100	100		59	100	80	100	72	82
wkbfr		99	98	93	99	95	97		99	99	99	86	97	96		99	99	98	84	99	96	69	88	80	84	99	98	86
wkbwb		99	88	83	87	82	88		99	98	83	82	85	89		100	77	98	96	100	94	70	100	83	78	99	99	88
mean							**80**							**85**							**85**							**79**

Appendix 5. Seasonal and inter-annual variability in percent of salinity data collected, NERR SWMP 1995-2000.

	Winter							Spring							Summer							Fall						
Site	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**
elkap		67	68	92	63	98	78	4	91	89	98	99	77	76	68	92	99	100	83	86	88	61	87	99	100	95	97	90
elknm						100	100					68	100	84					86	100	93					88	71	79
elksm		98	99	99	84	99	96	4	94	89	98	55	100	73	97	96	73	81	63	99	85	49	79	83	85	85	71	75
pdbby		22	40	92	98	100	70		52	100	100	89	100	88	25	0	99	73	67	100	61	70	66	60	97	100	92	81
pdbjl		48	83	100	100	94	85	12	61	88	99	99	100	77	62	100	98	100	100	100	93	76	93	99	96	95	24	81
sosse		100	77		93	94	91	32	79			92	97	75	71	77	82		47	95	74	80	43	8	0	97	96	54
sosvi						69	69					28	96	62					64	95	79					96	97	97
soswi		95	52		93	94	84	63	87		2	85	97	67	49	54	66	0	83	95	58	90	27	40	59	97	97	68
tjrmm																											41	41
tjros		79	81	86	96	78	84		96	88	90	79	85	88		93	66	90	95	66	82		78	47	94	76	30	65
tjrtl				87	10	20	39			40	86		59	62			42	82		12	45			70	67	31		56
mean							**80**							**75**							**76**							**71**
grbgb									71	96	79	60	67	75	60	94	78	87	100	100	86	44	66	61	65	82	42	60
grblr												59	49	54					100	99	100				48	80	66	65
grbsq											66	59	35	53			73	76	88	87	81			60	48	71	64	61
hudsk								46	55	31	100	84	48	61	90	12	42	100	82	99	71	56		56	91	90	80	75
hudtn													45	45					71	91	81					71	70	70
hudts								45	61	5	99	76	41	55	90	46	72	90	94	98	82	58	0	62	90	85	69	61
narpc		64	73	93	100	76	81		73	100	93	87	72	85		83	77	87	100	98	89	15	100	100	85	99	78	79
nartw			100		14	100	71			96		78	71	81		12	55		98	67	58		85	100		71	100	89
owcsu						34	34	41	32	88	100	100	85	74	99	83	100	100	100	100	97	12	33	33	34	52	66	38
owcwm						34	34	41	72	100	94	80	87	79	98	66	89	100	99	95	91	21	33	30	34	44	66	38
welht			1		23		12	92	86	98	88	98	86	91	99	87	93	97	11	86	79	77	70	81	80	61	7	63
welin		90	90	78	63	99	84	35	97	100	85	51	82	75	63	90	85	68	97	72	79	99	97	96	80	89	99	93
wqbcb									59	50				54		16	78	37			44	37		62	65			54
wqbmp						2	2						100	100					11	89	50				48	71	94	71
mean							**45**							**70**							**78**							**66**
cbmjb						43	43		71		8		69	49	88	76	53	66	48	83	69	52		16		79		49
cbmpr					38	13	25		73		8	53	38	43	93	83	65	48		53	68	52		38	13			34
cbvgi				97	99	82	93				90	72	97	86				100	100	100	100			74	100	85	93	88
cbvtc		67	76	99	96	99	88		78	61	100	100	100	88	16	85	91	95	93	83	77	71	72	95	85	100	100	87
delbl		63	79	74	81	91	77		89	87	75	91	75	83	76	87	88	93	98	81	87	38	98	84	93	96	83	82
delpb			60	87	8	94	62		14	74	96	37	91	62		42	96	85	86	55	73		90	98	98	98	17	80
delsl		62	59	76	98	79	75		81	97	88	66	97	86	94	85	97	97	98	67	89	70	71	98	93	98	80	85
mulb6			95	69	78	77	80			96	80	61	100	84		60	56	79	85	100	76		89	56	73	90	100	82
mulba			78	61	89	77	76			100	91	88	100	95			100	88	100	100	97		88	78	99	100	94	92
mulcn			86	73	89	69	79		6	100	92	74	95	73		100	55	83	57	81	75		77	76	95	95	84	85
mean							**70**							**75**							**81**							**76**
acebb	11	61	88	80	74	88	67	48	57	93	56	89	63	67	60	43	86	79	66	90	71	77	84	88	86	91	69	82
acesp	27	60	48	50	78	69	55	64	62	67	62	90	59	67	67	58	33	68	73	86	64	76	57	67	77	57	71	68
niwdc				29	90	83	67				47	77	73	66				97	69	92	86				78	62	94	78
niwol		89	79	82	91	84	85		72	92	54	89	82	78		88	80	87	88	77	84		79	85	79	93	89	85
niwta	96	88	66	92	84	84	85	71	83	74	86	89	81	81	95	91	84	87	87	92	89	72	75	90	93	73	94	83
nocms	61	74	92	90	94	100	85	95	97	75	79	91	99	89	65	63	56	97	82	97	77	81	97	81	79	99	100	90
noczi	60	71	62	67	97	96	75	80	97	64	89	83	50	77	97	93	79	90	75	85	87	92	94	79	95	80	100	90
sapfd	50	83	100	93			81	68	85	100	100			88	98	99	96	100			98	84	92	94	100			93
saphd						88	88						77	77					89	82	86					73	68	71
sapld					100	89	95					100	100	100					93	100	96				16	74	100	63
sapml	40	99	100	100			85	93	93	100	98			96	71	100	92	100			91	82	100	83				88
mean							**79**							**81**							**84**							**81**
apaeb		69	100	100	100	72	88	51	80	100	100	100	100	89	80	100	100	100	100	100	97	81	100	99	98	81	99	93
apaes		97	99	57	96	99	90	65	97	99	80	99	100	90	84	84	96	93	100	100	93	99	99	86	81	99	99	94
job09		81	64		44	38	57		94	4	26	44	37	41		59		11	29	46	36	12	88	28	25	44	74	45
job10		65		0	45	65	44		95	0		28	37	40		82		8	16	42	37		65	4	15		87	43
rkbbr				38	100	5	48				100	100		100				100	84		92				100	100		100
rkbmb						100	100						84	84						100	100					26	100	63
rkbuh			77	100	100	85	90			100	100	100	100	100			100	100	100	100	100		47	100	80	100	72	80
wkbfr		99	98	93	99	95	97		99	99	99	86	97	96		99	99	98	84	99	96	69	88	80	71	99	98	84
wkbwb		99	88	83	87	82	88		99	98	83	82	85	89		100	77	98	96	100	94	70	100	83	78	99	99	88
mean							**78**							**81**							**83**							**77**

Appendix 6. Seasonal and inter-annual variability in percent of dissolved oxygen (% sat) data collected, NERR SWMP 1995-2000.

	Winter							Spring							Summer							Fall						
Site	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**
elkap		91	67	92	63	98	82	4	84	54	94	93	74	67	68	82	94	97	81	78	83	61	74	99	100	93	93	87
elknm						86	86					40	66	53					85	54	69					85	48	66
elksm		98	43	80	86	98	81	4	90	16	52	55	66	47	95	70	46	81	47	81	70	49	70	68	65	82	47	63
pdbby		22	40	92	45	65	53		84	95	100	89	99	93	25	98	75	77	67	22	61	70	98	60	83	50	80	74
pdbjl		36	70	100	100	94	80	12	46	71	99	80	82	65	62	75	83	100	100	85	84	76	48	97	96	95	24	73
sosse		62	12	0	93	94	52	32	44	65		92	97	66	71	55			45	95	67	74		82	29	75	85	69
sosvi						69	69					28	96	62					64	78	71					96	97	97
soswi		60	0	0	93	94	49	78	32	23	0	85	97	53	73	32		0	57	95	51	99		43	0	97	97	67
tjrmm																											41	41
tjros		96	81	86	96	84	89		95	57	85	31	75	69		41	49	70	74	62	59		72	47	80	76	46	64
tjrtl				87	10	20	39			40	85		59	61			42	75		12	43			70	75	31		59
mean							**68**							**64**							**66**							**69**
grbgb									71	96	79	56	67	74	60	72	78	86	98	78	79	44	66	61	65	89	27	59
grblr												34	40	37					31	99	65				47	73	66	62
grbsq											45	59	35	46			73	73	93	75	79			60	48	71	64	61
hudsk								46	55	35	100	84	48	61	90	12	61	100	65	99	71	56		56	91	90	80	75
hudtn													36	36					65	83	74					71	70	70
hudts								45	61	0	90	76	41	52	90	84	37	70	93	98	79	58	42	71	74	85	69	66
narpc		77	73	93	100	45	78		48	91	87	87	70	77		25	37	32	88	23	41	15	89	83	72	99	63	70
nartw			100		1	100	67			39		23	66	43		12	47		92	45	49		71	90		62	92	79
owcsu						34	34	41	36	70	85	100	100	72	99	32	100	100	100	100	88	12	33	33	34	57	66	39
owcwm						31	31	41	48	100	64	80	88	70	99	62	57	100	99	95	85	21	18	30	34	61	66	38
welht			0		23		11	83	58	73	52	98	86	75	99	86	69	97	0	86	73	51	70	62	80	45	7	53
welin		90	90	78	63	99	84	35	97	100	85	51	35	67	63	90	85	68	97	67	78	99	97	63	79	89	9	73
wqbcb									61	50				56		0	75	29			35	52		62	65			60
wqbmp						2	2						86	86					11	58	35				48	71	94	71
mean							**44**							**61**							**67**							**63**
cbmjb						43	43		71		0		64	45	88	54	0	58	46	27	45	52		0		55		36
cbmpr						13	13		66		0		24	30	93	58	0	0		3	31	52		0				26
cbvgi				97	84	82	88				90	70	93	84				93	91	89	91			74	100	70	66	77
cbvtc		67	78	99	96	99	88		63	49	82	89	100	77	3	85	65	86	87	54	63	57	69	89	85	100	100	83
delbl		63	63	74	81	91	74		89	87	75	77	75	81	76	87	88	93	49	64	76	38	98	92	93	79	83	80
delpb			60	87	8	94	62		27	74	96	16	91	61		42	96	68	54	12	54		90	98	98	98	17	80
delsl		29	59	76	98	64	65		81	97	77	26	97	76	79	85	73	84	98	67	81	70	71	98	75	84	80	80
mulb6			91	69	78	72	77			58	65	55	100	70		60	63	68	72	68	66		87	59	53	43	83	65
mulba			71	61	57	77	66			81	76	72	86	79			75	80	70	100	81		66	66	63	85	44	65
mulcn			86	57	89	62	73		6	63	92	67	95	65		100	92	83	35	81	78		76	76	95	84	64	79
mean							**65**							**67**							**67**							**67**
acebb	30	48	69	80	66	78	62	39	10	91	52	65	39	50	46	24	18	60	24	9	30	70	67	84	64	73	69	71
acesp	27	60	15	43	78	51	46	51	12	53	42	54	30	40	50	33	46	68	55	40	49	75	57	48	54	59	71	61
niwdc				29	90	61	60				86	64	73	74				96	61	80	79				91	62	94	82
niwol		87	79	84	91	82	85		72	92	94	67	82	81		88	39	86	65	62	68		69	69	92	74	70	75
niwta	96	88	66	90	65	84	81	59	64	60	83	15	67	58	95	78	84	66	61	81	78	72	75	90	76	73	94	80
nocms	47	74	92	85	94	59	75	95	95	44	62	64	97	76	65	58	33	97	50	90	65	81	81	50	57	99	88	76
noczi	59	72	62	51	97	56	66	71	78	64	89	58	50	68	89	85	56	82	75	83	78	99	80	54	62	80	100	79
sapfd	0	76	97	93			67	0	71	88	70			57	0	85	70	74			57	0	90	69	62			55
saphd						88	88						74	74					77	82	80					67	68	68
sapld					81	89	85					100	100	100					68	100	84				16	95	100	70
sapml		53	100	68			74	0	61	100	53			53	0	90	86	77			63	15	99	92	79			71
mean							**72**							**67**							**66**							**72**
apaeb		31	24	83	39	55	47	17	49	39	100	74	94	62	29	43	65	76	84	100	66	21	23	59	23	81	71	46
apaes		97	63	57	64	98	76	48	78	61	56	54	80	63	60	44	62	92	47	99	68	43	55	71	81	86	61	66
job09		99	6		44	16	41		94	23	15	38	37	41		43		10	47	41	35	12	28	6	12	27	80	27
job10		65		19	45	67	49		95	37		29	59	55		82		8	16	42	37		58	11	14		92	44
rkbbr				38	100	5	48				47	100		73				39	84		61				100	100		100
rkbmb						100	100						84	84						93	93					26	100	63
rkbuh			63	92	100	80	84			100	66	100	84	88			83	23	100	64	68		59	61	80	100	72	74
wkbfr		99	85	93	36	88	80		99	99	85	56	97	87		99	99	1	60	93	71	69	71	80	76	99	80	79
wkbwb		81	88	77	81	82	82		99	78	68	82	68	79		86	62	57	59	94	72	53	85	68	65	99	61	72
mean							**67**							**70**							**63**							**64**

Appendix 7. Seasonal and inter-annual variability in percent of water depth data collected, NERR SWMP 1995-2000.

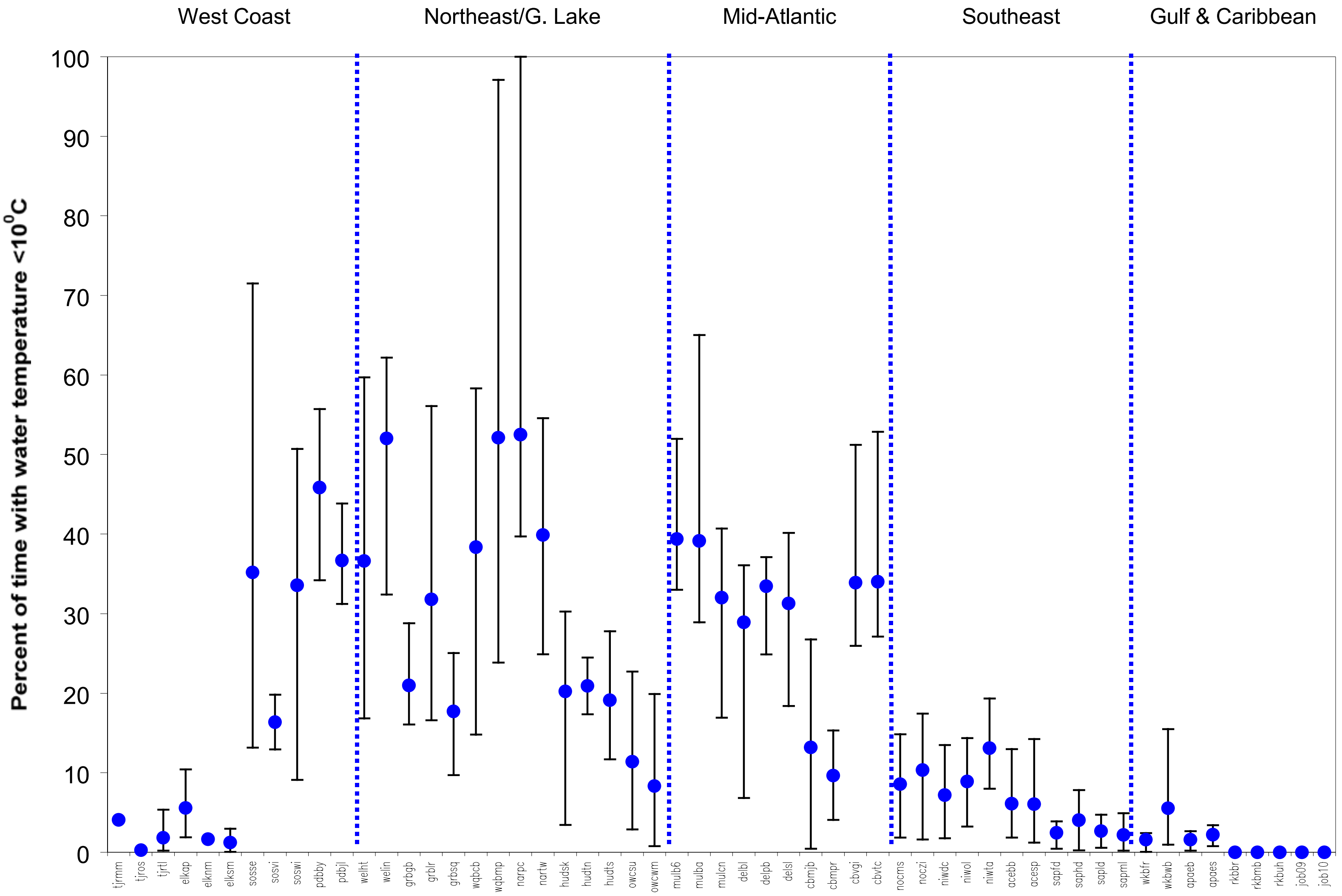
	Winter							Spring							Summer							Fall						
Site	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**
elkap		91	68	92	63	98	82	4	91	89	99	99	65	75	68	92	99	100	83	86	88	61	87	99	100	95	97	90
elknm						100	100					72	99	86					86	100	93					75	99	87
elksm		98	99	99	97	99	99	0	94	89	98	55	100	73	87	96	73	81	82	99	86	49	79	83	85	97	100	82
pdbby		59	40	92	98	100	78		84	100	100	89	100	95	25	98	99	77	67	100	78	70	98	60	97	100	100	87
pdbjl		48	83	100	100	94	85	12	61	88	99	99	100	77	43	100	98	100	100	99	90	56	93	99	96	95	24	77
sosse		100	43	32	93	94	72	32	79	77		92	97	75	71	77			47	95	73	80		82	58	97	96	83
sosvi						69	69					28	96	62					64	95	79					96	97	97
soswi		95	27	40	42	94	60	78	87	61	2	85	97	68	73	32		0	83	95	57	99		66	59	97	97	83
tjrmm																											41	41
tjros		80	81	86	96	85	86		96	88	90	79	85	88		93	66	90	100	66	83		78	47	94	99	46	73
tjrtl				87	10	20	39			40	86		59	62			42	82		12	45			55	86	31		57
mean							**77**							**76**							**77**							**78**
grbgb		71	78	0	33		45		92	61	56	87		74	30	66	0	100	64		52	44	96	0	75			54
grblr												59	49	54					100	99	99				48	80	66	65
grbsq											66	70	35	57			73	76	100	87	84			60	48	71	64	61
hudsk								46	55	75	100	84	48	68	90	12	97	100	82	99	80	56		89	91	90	80	81
hudtn						36	36						84	84					71	70	70					71		71
hudts								45	61	58	99	76	41	63	90	84	87	90	94	98	90	58	42	71	90	85	68	69
narpc		77	73	93	100	76	84		73	100	93	87	75	85		83	77	87	100	98	89	15	100	100	85	99	78	79
nartw			100		14	100	71			96		78	75	83		12	55		98	87	63		85	100		71	100	89
owcsu						34	34	41	52	88	100	100	100	80	99	83	100	100	100	100	97	12	33	33	34	64	66	40
owcwm						34	34	41	67	100	94	80	88	78	99	66	89	100	100	95	92	15	33	30	34	61	66	40
welht			1		23		12	92	86	98	88	98	86	91	99	87	93	97	11	86	79	77	70	81	80	61	7	63
welin		90	97	78	63	99	85	35	97	100	85	51	82	75	63	90	85	68	97	72	79	99	97	96	80	89	99	93
wqbcb									61	50				56		16	78	37			44	52		62	65			60
wqbmp						2	2						100	100					11	89	50				48	71	94	71
mean							**45**							**75**							**76**							**67**
cbmjb						43	43		71		8		69	49	88	76	53	66	48	83	69	52		16		79		49
cbmpr						13	13		73		8		38	40	93	83	65	54		53	69	52		38				45
cbvgi				97	99	82	93				90	64	97	84				100	100	100	100			74	100	85	93	88
cbvtc		67	100	99	96	99	92		78	69	100	100	100	89	16	60	91	95	93	83	73	56	82	77	100	100	100	86
delbl		63	79	74	81	91	77		89	87	88	91	75	86	81	87	88	93	98	81	88	48	98	92	93	96	83	85
delpb			56	82	8	91	59		23	59	77	22	69	50		40	46	57	47	44	47		90	85	64	81	72	78
delsl		62	59	76	98	79	75		81	97	88	66	97	86	94	85	97	97	98	67	89	70	71	98	93	98	80	85
mulb6			95	69	78	77	80			96	80	84	100	90		60	65	88	92	100	81		89	70	73	90	100	84
mulba			78	61	89	77	76			100	91	88	100	95			100	88	100	100	97		88	89	99	100	94	94
mulcn			86	73	89	69	79		6	100	92	74	95	73		100	100	95	57	81	87		77	99	95	95	84	90
mean							**69**							**74**							**80**							**78**
acebb	30	41	88	80	74	88	67	58	15	93	56	89	63	62	60	43	86	79	88	90	74	77	84	88	86	91	69	82
acesp	27	60	91	80	98	89	74	64	62	93	35	93	59	68	67	58	52	68	89	86	70	76	57	93	77	93	71	78
niwdc				29	90	83	67				86	77	73	79				97	69	92	86				75	62	94	77
niwol		89	79	84	91	84	85		72	92	97	89	82	86		76	80	87	88	77	82		79	85	92	93	89	88
niwta	96	88	66	92	84	84	85	83	83	74	99	89	81	85	95	91	84	87	87	92	89	67	75	90	93	73	94	82
nocms	61	74	71	90	94	100	82	95	97	77	79	91	100	90	65	63	66	97	82	97	78	81	96	81	95	99	100	92
noczi	40	91	62	83	97	96	78	63	97	64	89	83	50	74	97	93	79	90	75	96	88	99	94	79	95	80	100	91
sapfd		37	0	0			12	0	54	0	0			14	0	46	0	0			11	0	31	0	0			8
saphd						88	88						77	77					91	82	86					88	68	78
sapld					100	89	95					100	100	100					98	100	99				16	95	100	70
sapml		6	0	0			2	0	81	0	0			20	0	42	0	0			10	0	46	0	0			11
mean							**67**							**69**							**70**							**69**
apaeb		55	100	100	100	79	87	51	76	100	86	100	100	86	80	100	100	93	100	100	95	81	100	99	98	100	99	96
apaes		100	100	67	95	100	92	68	100	100	78	99	100	91	85	84	100	89	100	100	93	100	100	89	80	99	100	95
job09		99	64		44	38	61		94	46	26	50	58	55		59		11	69	46	46	12	88	28	58	44	70	50
job10		65		32	45	67	52		95	48		35	84	65		82		18	38	42	45		65	13	28		93	50
rkbbr				38	100	5	48				100	100		100				100	84		92				100	100		100
rkbmb						100	100						84	84						100	100					26	66	46
rkbuh			77	100	100	85	90			100	100	100	100	100			100	100	100	100	100		59	100	80	100	72	82
wkbfr		99	98	93	99	95	97		99	99	99	86	96	96		99	99	98	84	99	96	69	88	80	84	67	98	81
wkbwb		99	88	83	87	82	88		99	98	83	82	85	89		100	77	98	96	100	94	70	100	83	78	99	99	88
mean							**79**							**85**							**85**							**77**

Appendix 8. Seasonal and inter-annual variability in percent of pH data collected, NERR SWMP 1995-2000.

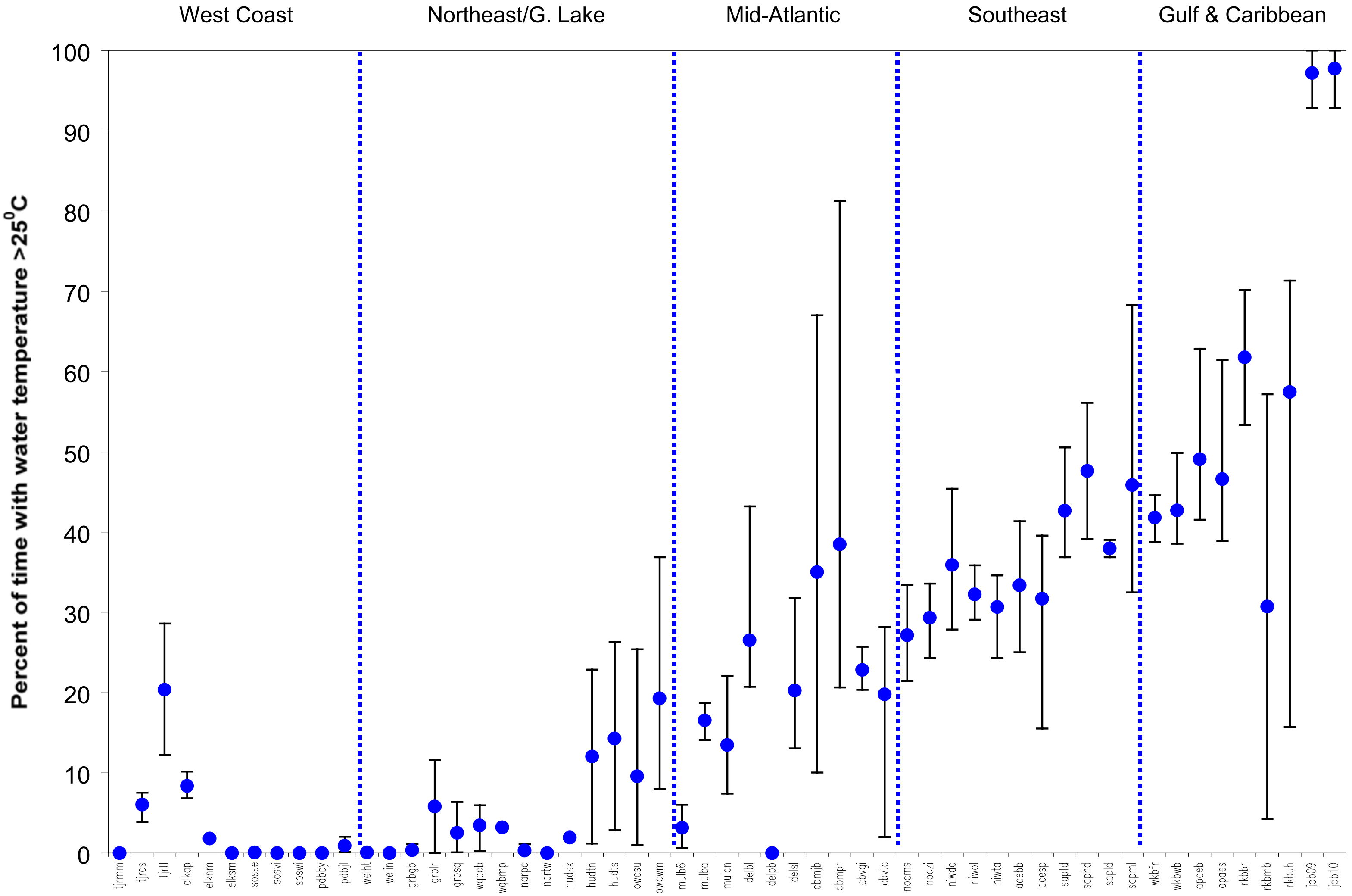
	Winter							Spring							Summer							Fall						
Site	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**
elkap		91	68	92	63	98	82	4	91	89	99	99	77	77	68	92	99	100	83	60	84	61	87	99	100	81	2	72
elknm						86	86					72	100	86					86	95	90					88	68	78
elksm		98	99	99	97	99	99	0	94	89	98	55	100	73	32	96	73	81	82	75	73	49	79	83	85	97	57	75
pdbby		59	40	92	98	63	70		84	100	100	89	100	95	25	98	99	77	67	100	78	70	98	60	97	91	100	86
pdbjl		48	83	100	100	94	85	12	61	88	99	99	100	77	57	100	98	100	100	100	92	0	68	99	96	66	24	59
sosse		28	27	0	67	94	43	15	8	22		92	97	47	16	44			47	95	51	38		0	0	97	96	46
sosvi						69	69					28	96	62					64	95	79					96	97	97
soswi		43	12	0	67	94	43	78	44	22	0	85	97	54	9	38		0	83	95	45	25		0	0	97	97	44
tjrmm																											41	41
tjros		47	68	59	76	16	53		53	50	73	55	85	63		47	63	90	75	66	68		63	0	75	21	46	41
tjrtl				87	10	0	32			27	28		59	38			30	11		12	17			70	74	0		48
mean							**66**							**67**							**68**							**62**
grbgb									71	53	79	43	56	60	45	66	78	87	100	44	70	37	36	61	65	89	48	56
grblr												59	49	54					100	99	99				48	80	63	64
grbsq											66	70	35	57			73	76	92	37	69			60	48	71	46	56
hudsk								46	55	75	100	83	48	68	59	12	97	100	82	99	75	56		89	91	79	80	79
hudtn													45	45					71	91	81					71	70	70
hudts								30	61	58	99	76	41	61	79	84	87	90	94	98	89	58	42	71	90	85	69	69
narpc		77	73	93	100	76	84		73	100	93	87	75	85		83	77	87	100	82	86	15	100	100	85	99	78	79
nartw			100		14	89	67			96		78	75	83		12	55		98	86	63		85	100		61	100	86
owcsu						34	34	41	52	88	100	100	100	80	99	83	100	100	100	100	97	12	33	33	34	64	66	40
owcwm						34	34	41	72	100	94	80	88	79	99	66	89	100	100	95	92	21	33	30	34	61	66	41
welht			1		23		12	92	86	98	88	98	86	91	36	87	93	97	11	86	68	77	70	81	80	61	7	63
welin		90	90	69	45	99	79	35	97	100	85	51	82	75	32	90	85	68	97	72	74	99	97	96	80	89	99	93
wqbcb									61	50				56		16	78	37			44	52		62	65			59
wqbmp						2	2						100	100					11	89	50				48	71	94	71
mean							**44**							**71**							**75**							**66**
cbmjb						43	43		44		8		69	40	88	61	53	66	0	83	59	52		16		27		32
cbmpr						0	0		67		8		0	25	80	64	65	48		0	51	52		38				45
cbvgi				97	99	82	93				90	72	97	86				100	100	100	100			74	100	85	93	88
cbvtc		67	100	99	96	99	92		78	69	100	100	100	89	16	85	91	95	93	83	77	42	89	95	85	100	100	85
delbl		63	79	74	81	91	77		89	81	75	91	75	82	81	87	64	93	98	81	84	48	98	92	93	96	83	85
delpb			60	87	8	94	62		27	74	96	37	91	65		42	81	85	86	55	70		90	98	98	97	48	86
delsl		62	59	76	98	79	75		81	97	72	66	97	83	94	85	97	97	98	67	89	70	71	98	93	97	80	85
mulb6			95	69	78	77	80			96	80	84	84	86		60	65	88	92	100	81		89	70	73	90	100	84
mulba			78	61	89	77	76			100	91	88	100	95			100	88	100	100	97		88	89	99	100	94	94
mulcn			86	73	89	69	79		6	100	92	67	95	72		100	100	95	50	81	85		77	99	95	95	84	90
mean							**68**							**72**							**79**							**77**
acebb	30	28	88	0	52	88	48	24	57	30	1	79	63	42	31	43	54	79	88	86	63	50	84	28	31	91	51	56
acesp	27	60	91	80	55	89	67	10	62	93	8	90	59	54	0	25	52	68	71	86	50	50	57	93	51	76	71	66
niwdc				29	90	83	67				86	77	73	79				97	69	83	83				75	62	94	77
niwol		85	79	84	76	84	82		72	92	97	89	82	86		88	80	87	88	63	81		79	85	82	93	70	82
niwta	0	88	66	92	84	84	69	15	83	74	99	75	81	71	77	50	57	87	69	92	72	38	75	90	93	73	94	77
nocms	61	60	92	90	94	100	83	95	97	77	79	91	99	90	35	63	64	97	82	97	73	81	97	74	95	73	100	87
noczi	60	91	35	83	97	96	77	80	97	51	89	83	50	75	97	93	55	90	75	96	84	99	94	79	95	80	100	91
sapfd	50	83	100	93			81	68	85	100	80			83	98	100	96	73			92	84	93	94	79			88
saphd						88	88						77	77					91	65	78					88	12	50
sapld					100	89	95					86	100	93					98	61	79				16	95	72	61
sapml		82	100	83			88	40	99	100	100			85	82	91	98	70			85	56	100	92	100			87
mean							**65**							**70**							**72**							**75**
apaeb		69	100	100	100	48	84	51	80	100	100	100	81	85	80	100	100	100	78	100	93	81	100	99	98	100	99	96
apaes		97	99	48	96	65	81	52	97	99	80	99	100	88	84	84	96	93	100	100	93	99	99	66	81	99	99	91
job09		99	64		44	38	61		94	46	26	50	58	55		59		11	69	46	46	12	88	28	58	44	80	52
job10		65		32	45	67	52		95	19		14	84	53		82		18	38	42	45		65	13	28		69	44
rkbbr				38	100	5	48				100	100		100				100	84		92				100	100		100
rkbmb						85	85						84	84						100	100					26	100	63
rkbuh			77	100	100	85	90			100	100	100	55	89			100	100	100	91	98		59	100	80	100	55	79
wkbfr		99	82	93	99	95	94		99	99	99	86	97	96		99	84	92	84	99	91	69	88	36	76	99	98	78
wkbwb		99	88	31	87	82	78		99	98	83	82	85	89		100	77	55	96	100	86	70	100	83	78	99	99	88
mean							**75**							**82**							**83**							**77**

Appendix 9. Seasonal and inter-annual variability in percent of turbidity data collected, NERR SWMP 1995-2000.

	Winter							Spring							Summer							Fall						
Site	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**mean**
elkap		0	0	92	63	97	50	0	0	0	99	99	77	46	0	0	67	100	53	53	45	0	0	99	100	95	97	65
elknm						100	100					47	99	73					59	46	52					87	1	44
elksm		0	0	17	97	99	42	0	0	0	71	55	89	36	0	0	0	78	81	89	41	0	0	66	85	97	94	57
pdbby		0	40	91	97	99	66		20	63	100	89	99	74	0	79	66	77	67	99	65	0	98	60	97	53	100	68
pdbjl		20	42	88	98	92	68	0	61	77	78	49	91	59	0	100	97	100	99	99	83	0	53	97	90	94	24	60
sosse		0	27	0	67	94	38	0	0	10		92	97	40	0	22			47	95	41	0		0	0	97	96	39
sosvi						69	69					28	87	57					40	95	68					26	97	62
soswi		0	0	0	0	94	19	0	0	12	0	78	97	31	0	15		0	83	95	39	0		0	0	97	97	39
tjrmm																											0	0
tjros		16	78	44	96	61	59		42	72	56	76	85	66		30	66	84	84	22	57		65	35	94	99	16	62
tjrtl				28	0	20	16			40	18		59	39			2	13		12	9			70	24	31		42
mean							**53**							**52**							**50**							**49**
grbgb									0	0	0	60	54	23	0	0	0	0	100	99	33	0	0	0	30	87	66	30
grblr												59	49	54					89	96	92				22	80	66	56
grbsq											45	70	10	42			0	15	100	7	30			0	0	71	12	21
hudsk								0	22	75	100	84	48	55	0	12	97	100	74	99	64	0		89	91	90	80	70
hudtn						71	71						45	45					49	91	70						70	70
hudts								0	61	58	93	59	41	52	0	63	87	86	94	97	71	0	29	70	90	85	68	57
narpc		13	34	23	100	73	49		19	51	27	87	58	48		2	25	87	86	80	56	0	45	63	85	99	67	60
nartw			40		14	98	51			44		15	60	40		0	33		60	53	37		24	23		71	48	42
owcsu						34	34	0	51	88	77	100	100	69	0	71	100	94	100	100	78	0	26	33	34	64	66	37
owcwm						34	34	0	59	100	94	80	73	68	0	66	74	100	100	95	73	0	33	30	34	61	66	37
welht			1		23		12	0	60	98	88	96	86	71	0	87	93	97	11	86	62	0	70	81	80	61	7	50
welin		49	97	78	63	99	77	0	83	100	55	24	56	53	0	90	85	68	97	41	64	0	66	96	80	89	99	72
wqbcb									61	50				56		16	78	33			42	0		47	65			37
wqbmp						2	2						100	100					11	89	50				48	71	94	71
mean							**41**							**55**							**59**							**51**
cbmjb						0	0		0		0		0	0	0	0	0	0	0	0	0	0		0		0		0
cbmpr						0	0		0		0		0	0	0	0	0	0		0	0	0		0				0
cbvgi				97	99	82	93				84	72	97	85				97	100	100	99			74	100	85	93	88
cbvtc		38	0	92	96	99	65		58	61	100	100	100	84	0	35	91	95	92	83	66	0	7	95	100	100	100	67
delbl		0	79	45	81	91	59		46	58	86	91	73	71	0	87	88	93	67	75	69	0	98	92	93	96	83	77
delpb			60	87	8	94	62		14	74	96	37	91	62		42	96	85	86	55	73		90	98	98	98	78	92
delsl		0	59	76	98	79	62		57	97	88	66	97	81	0	85	97	84	98	67	72	0	71	98	93	98	80	73
mulb6			69	54	78	60	65			96	69	84	100	87		60	65	85	59	97	73		89	70	73	90	98	84
mulba			53	22	89	77	60			100	91	88	82	90			100	59	68	100	82		88	89	99	100	72	90
mulcn			86	57	70	69	71		6	100	72	74	95	69		100	100	66	57	81	81		54	77	71	95	84	76
mean							**54**							**63**							**61**							**65**
acebb	0	0	88	48	39	37	35	0	46	93	56	60	5	43	0	43	86	79	39	86	56	0	84	12	74	91	0	44
acesp	0	0	91	74	49	38	42	0	52	93	62	90	29	54	0	58	52	68	44	86	51	0	57	43	77	46	53	46
niwdc				29	90	58	59				86	77	34	66				88	69	92	83				75	62	67	68
niwol		72	79	84	91	33	72		67	92	97	89	69	83		67	80	87	88	75	79		79	85	92	93	89	88
niwta	0	69	66	92	84	84	66	11	42	74	99	37	71	56	0	91	57	87	69	92	66	0	75	90	93	73	94	71
nocms	0	18	83	90	60	100	59	0	72	77	65	91	99	67	0	56	25	97	74	97	58	0	97	81	95	99	100	79
noczi	0	37	62	82	97	96	62	0	20	62	89	79	50	50	0	68	25	90	75	96	59	0	83	79	95	80	100	73
sapfd	0	21	0	28			12	0	20	16	22			15	0	15	0	27			10	0	0	44	0			11
saphd						69	69						35	35					20	47	34					63	52	57
sapld					19	49	34					0	37	19					8	53	31				0	18	6	8
sapml		12	33	5			17	0	28	0	0			7	0	0	0	11			3	0	0	17	0			4
mean							**48**							**45**							**48**							**50**
apaeb		0	0	0	0	25	5	0	0	0	0	0	59	10	0	0	0	0	0	29	5	0	0	36	0	0	61	16
apaes		0	99	65	96	97	71	0	0	99	80	99	100	63	0	0	96	93	69	99	60	0	16	86	81	99	77	60
job09		0	64		44	38	36		0	46	26	49	57	36		0		11	62	26	25	12	0	28	58	43	73	36
job10		0		32	32	34	25		0	48		28	49	31		0		18	21	4	11		0	13	28		63	26
rkbbr				38	100	5	48				100	100		100				100	84		92				100	85		92
rkbmb						100	100						68	68						69	69					26	100	63
rkbuh			77	100	86	41	76			100	100	100	100	100			100	100	100	86	96		59	100	80	100	55	79
wkbfr		0	0	0	83	95	35		0	0	11	69	97	36		0	0	37	45	68	30	0	0	0	83	32	67	30
wkbwb		0	0	0	61	0	12		0	0	0	39	0	8		0	0	0	0	55	11	0	0	0	30	0	59	15
mean							**45**							**50**							**44**							**46**



Appendix 10. Mean (and inter-annual range) percent of time that NERR sites experienced water temperatures <10°C, 1995-2000.



Appendix 11. Mean (and inter-annual range) percent of time that NERR sites experienced water temperatures >25°C, 1995-2000.
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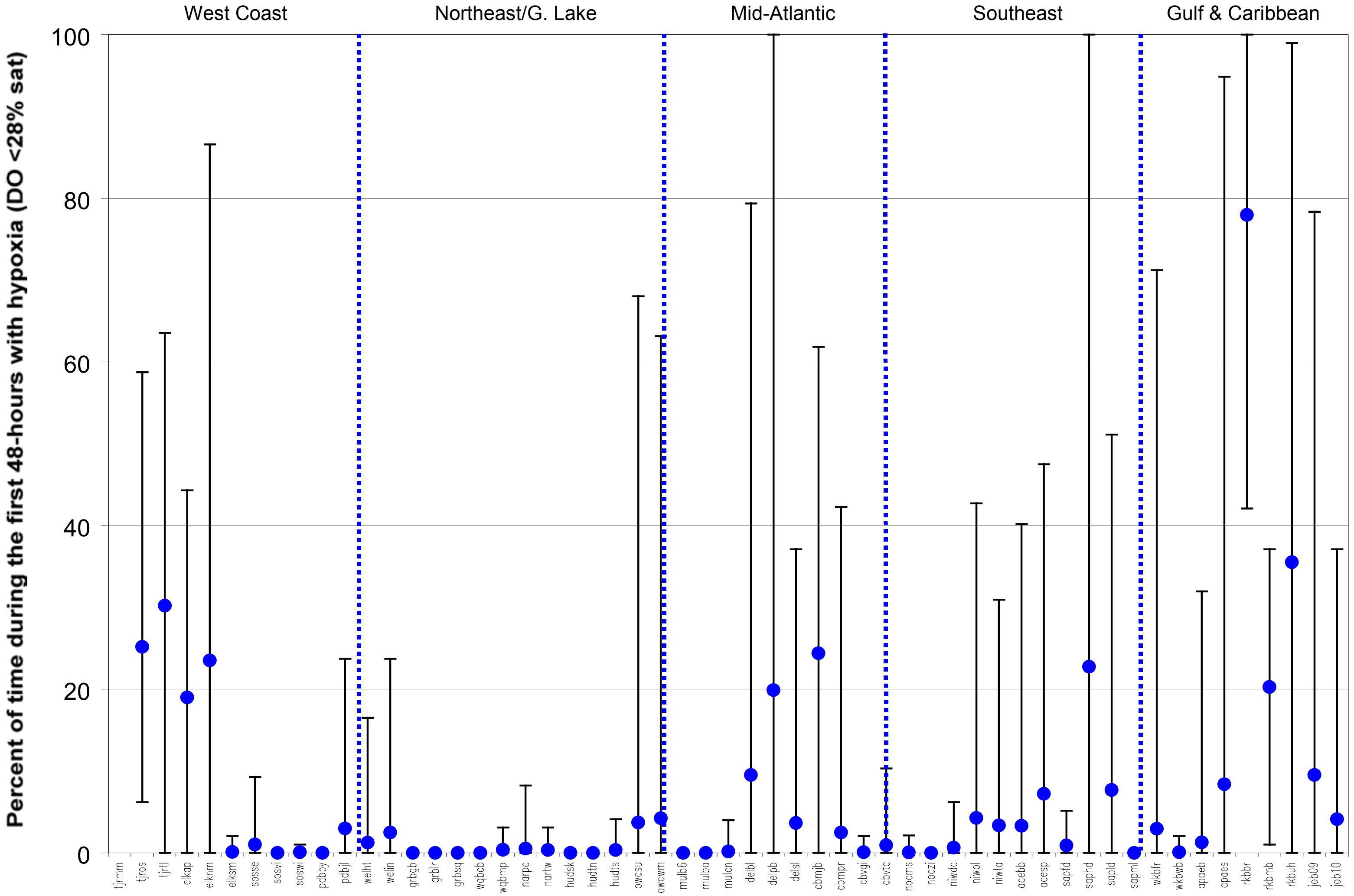
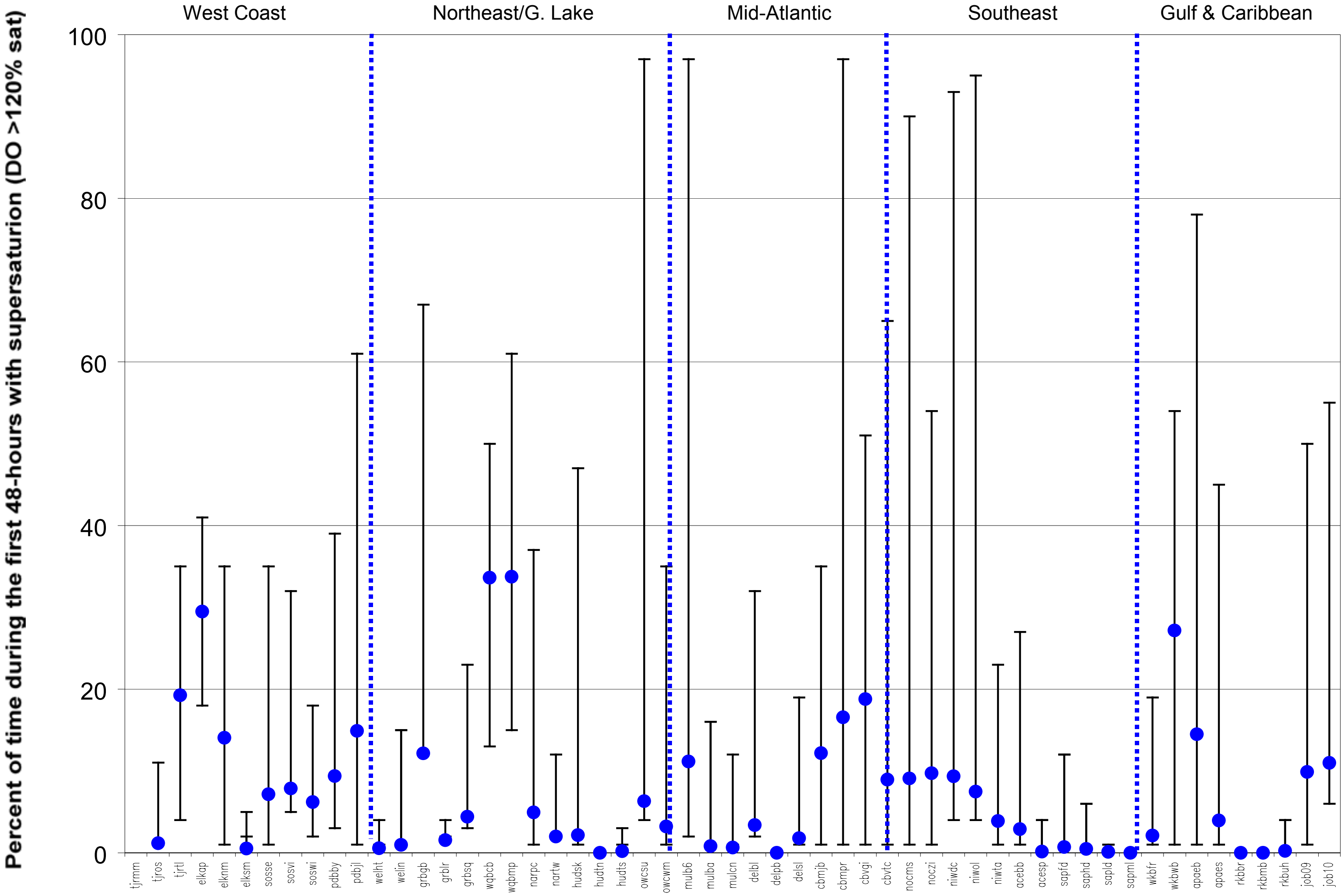
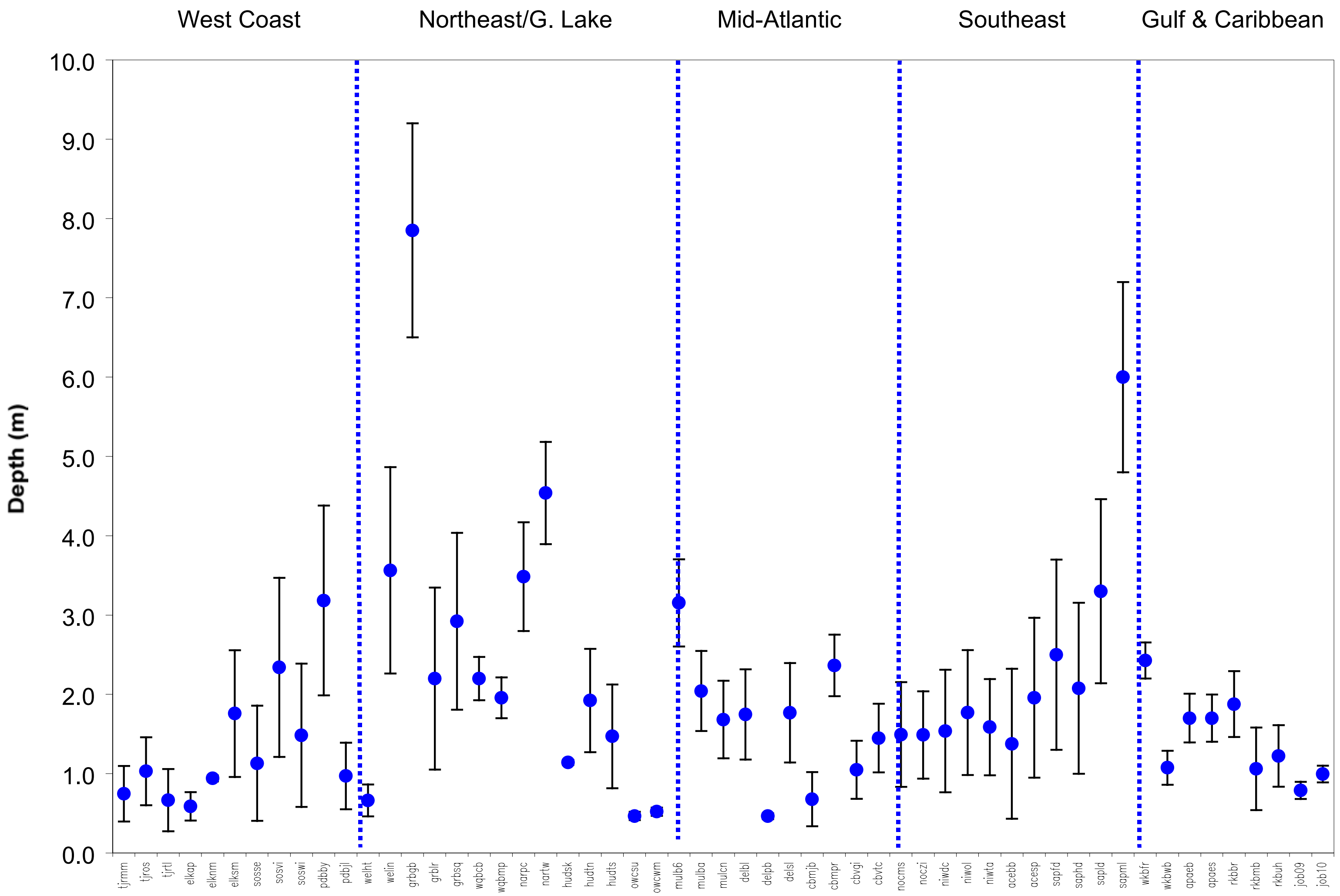


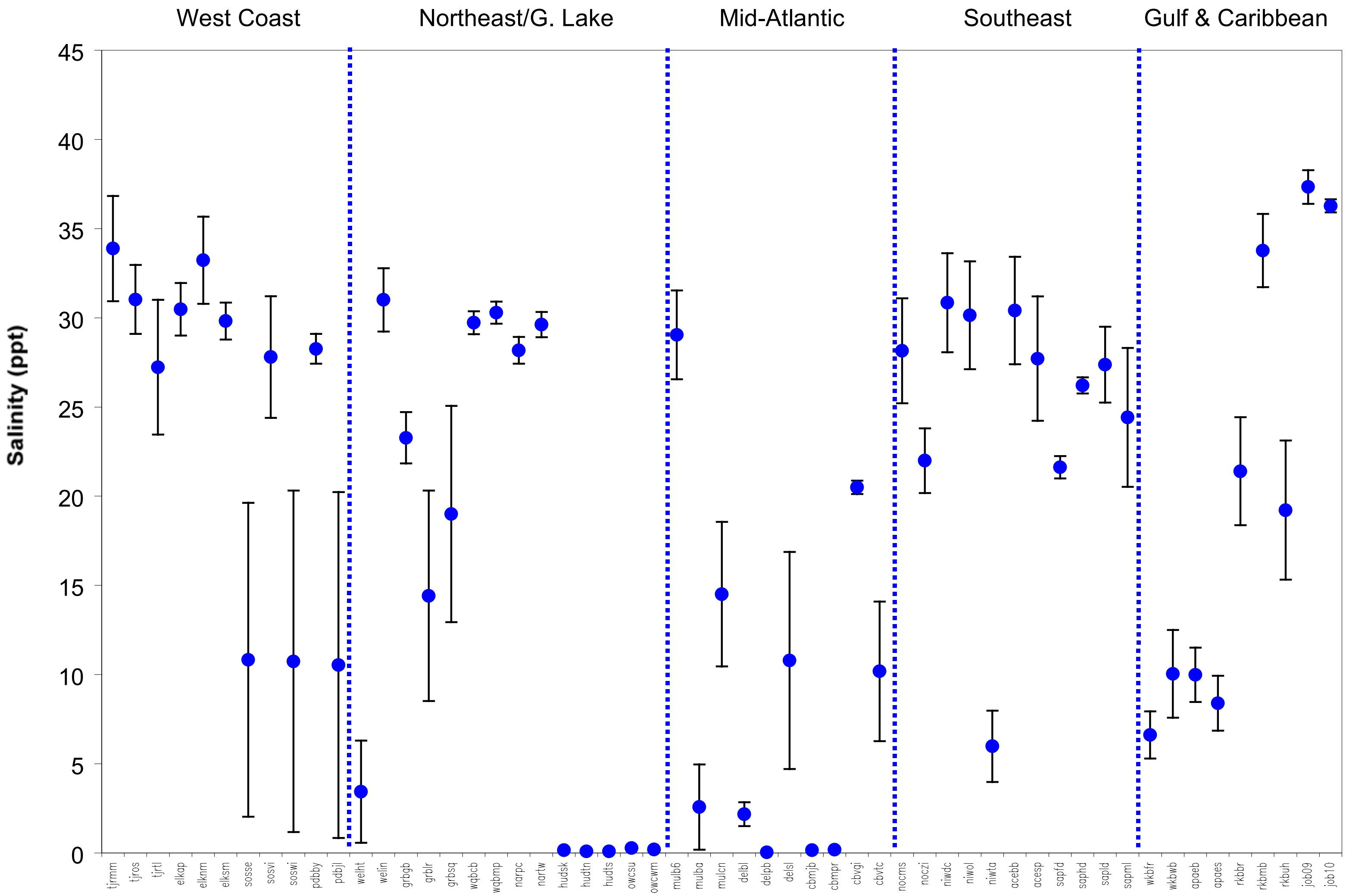
Appendix 12. Summertime hypoxia (mean and range) during the first 48-hours post-deployment, NERR SWMP sites (1995-2000).



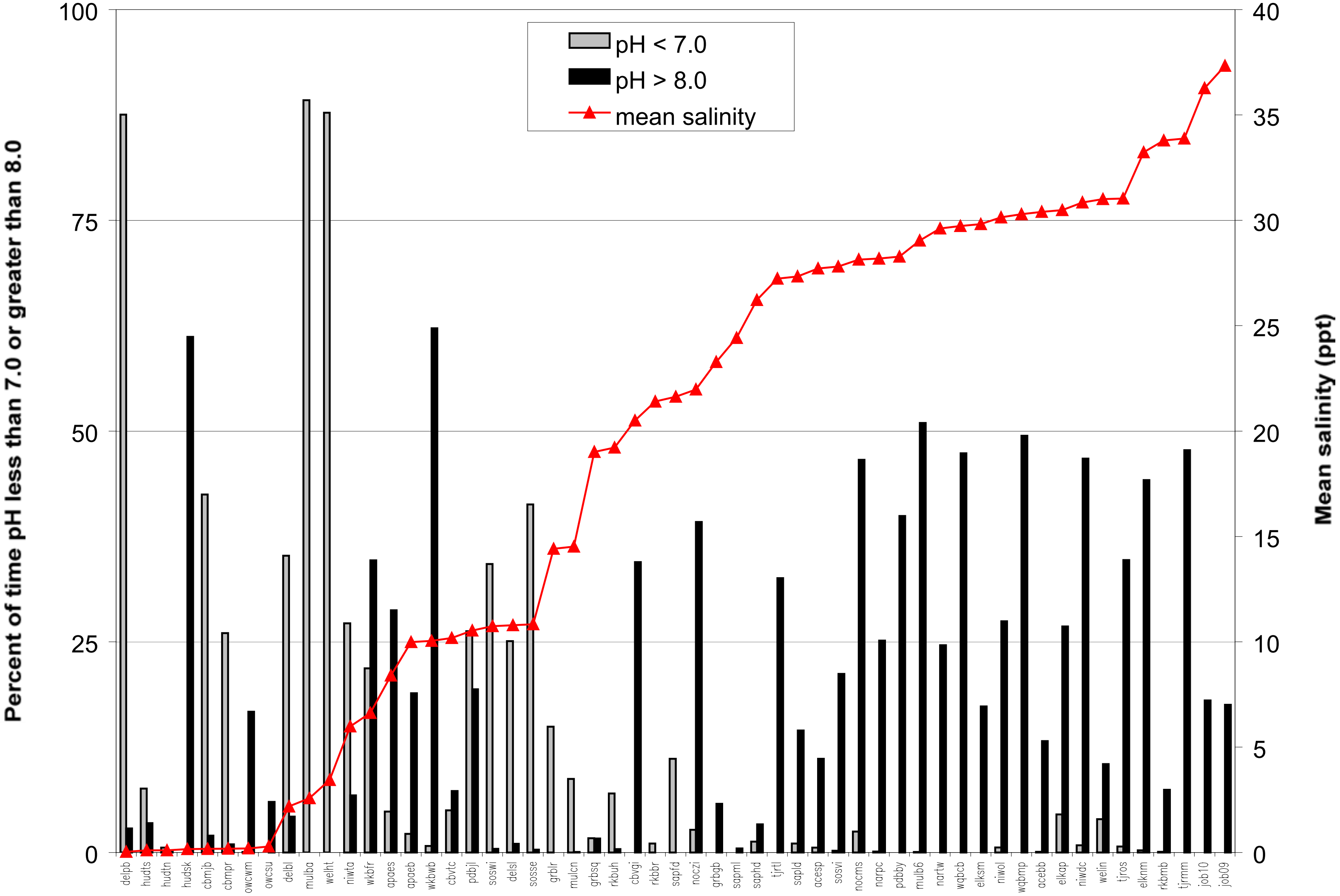
Appendix 13. Summertime supersaturation (mean and range) during the first 48-hours post-deployment, 1995-2000.



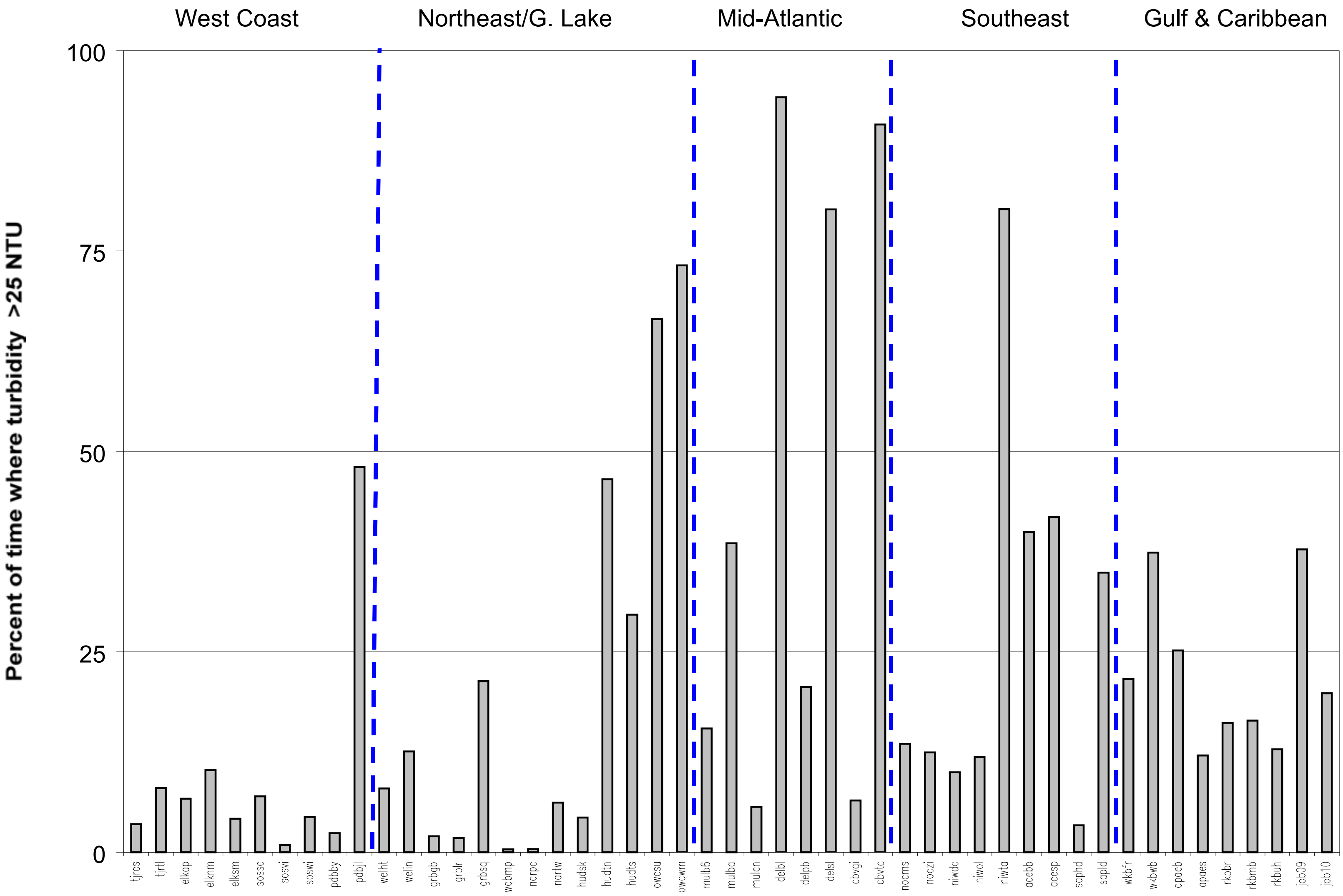
Appendix 14. Mean depth (circle) and mean daily depth range (line) at NERR SWMP sites, 1995-2000.



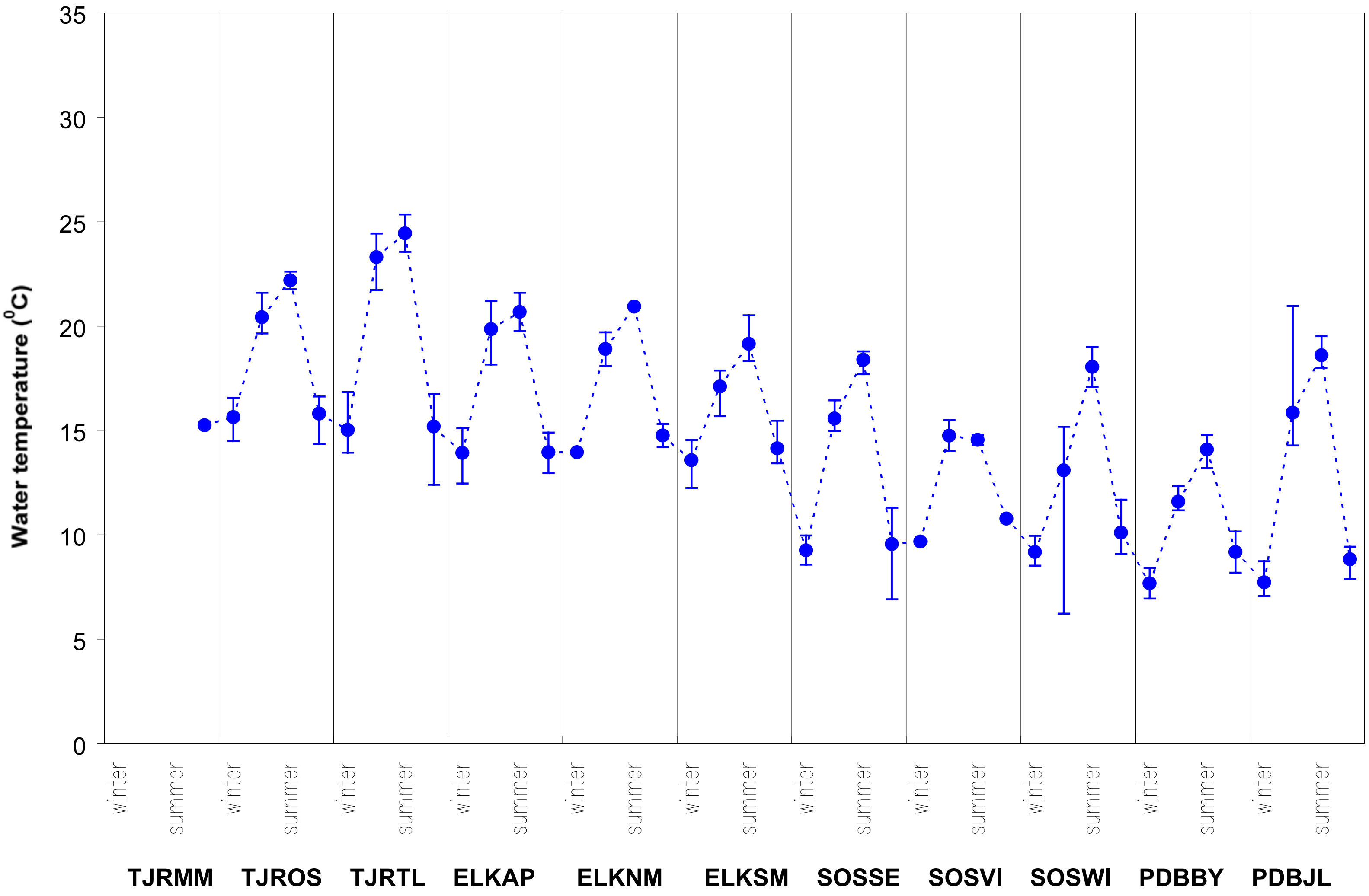
Appendix 15. Overall mean salinity (circle) and mean daily salinity range (line) at NERR SWMP sites, 1995-2000.



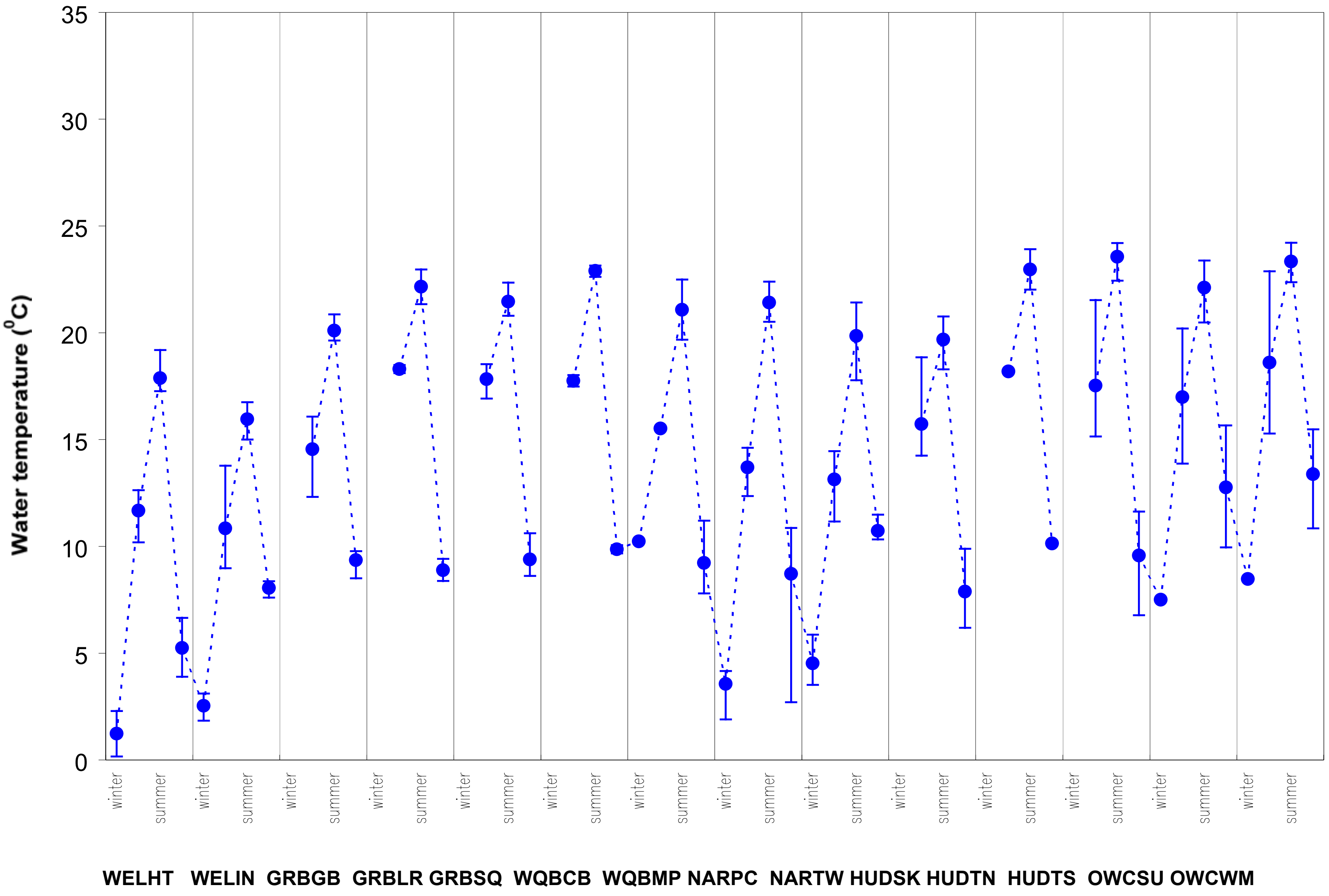
Appendix 16. Frequency of pH <7.0 and >8.0 (1999-2000) vs. mean salinity (1995-2000) at NERR SWMP sites.



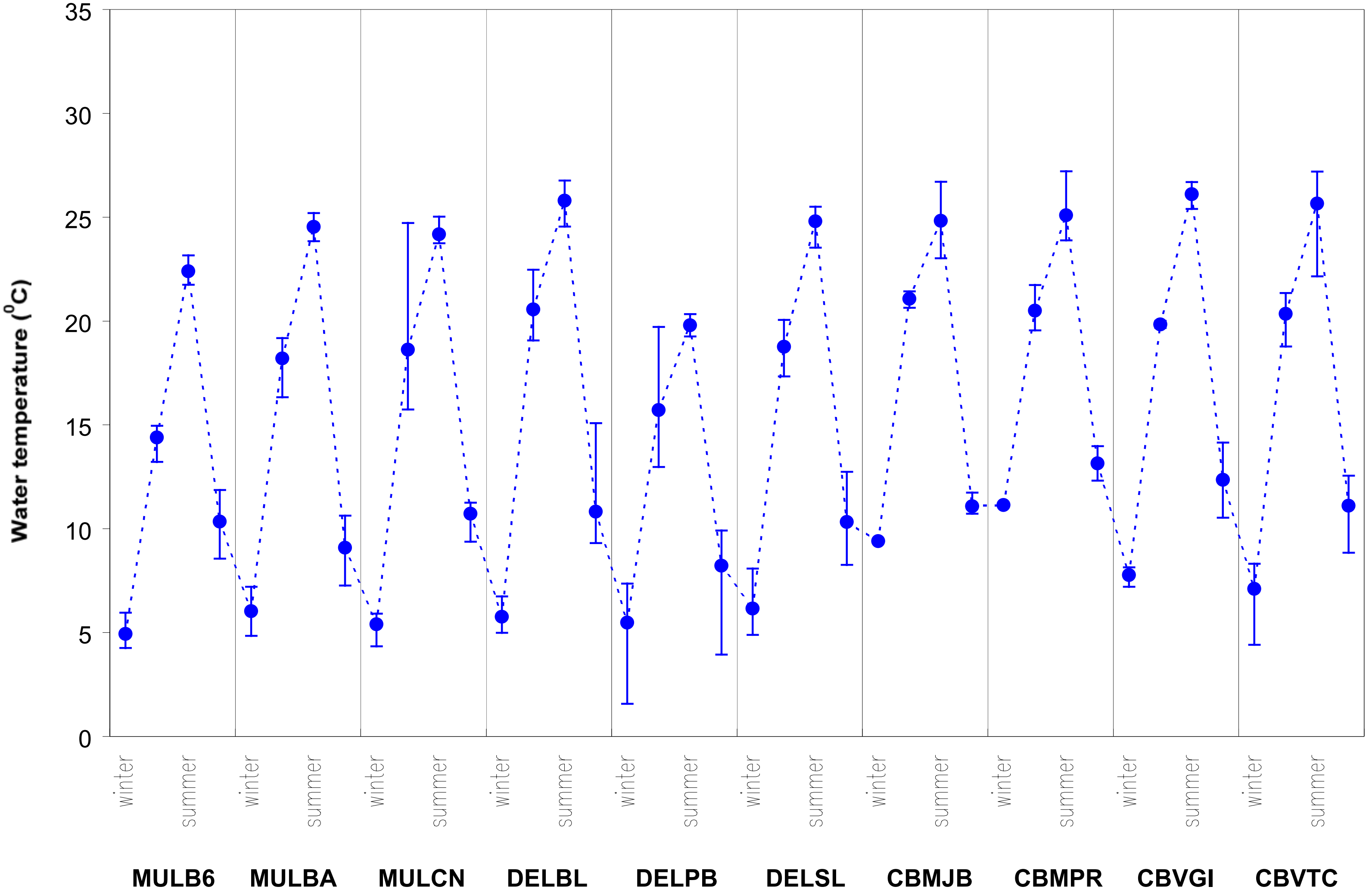
Appendix 17. Frequency of turbidity >25 NTU among NERR SWMP sites, 1999-2000.



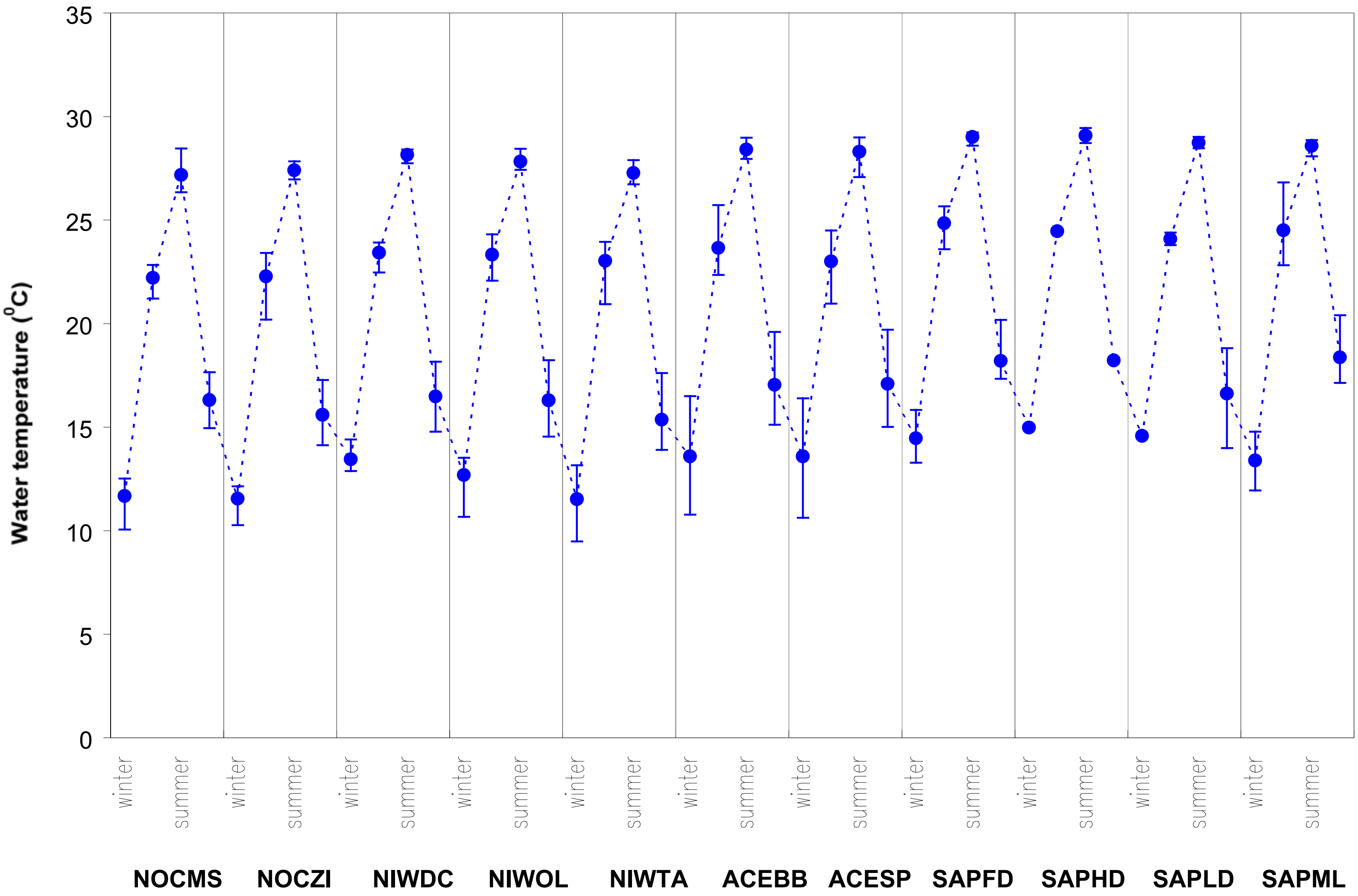
Appendix 18. Seasonal water temperature mean and range (+/- 1 std. dev.), West Coast NERRs (1995-2000).



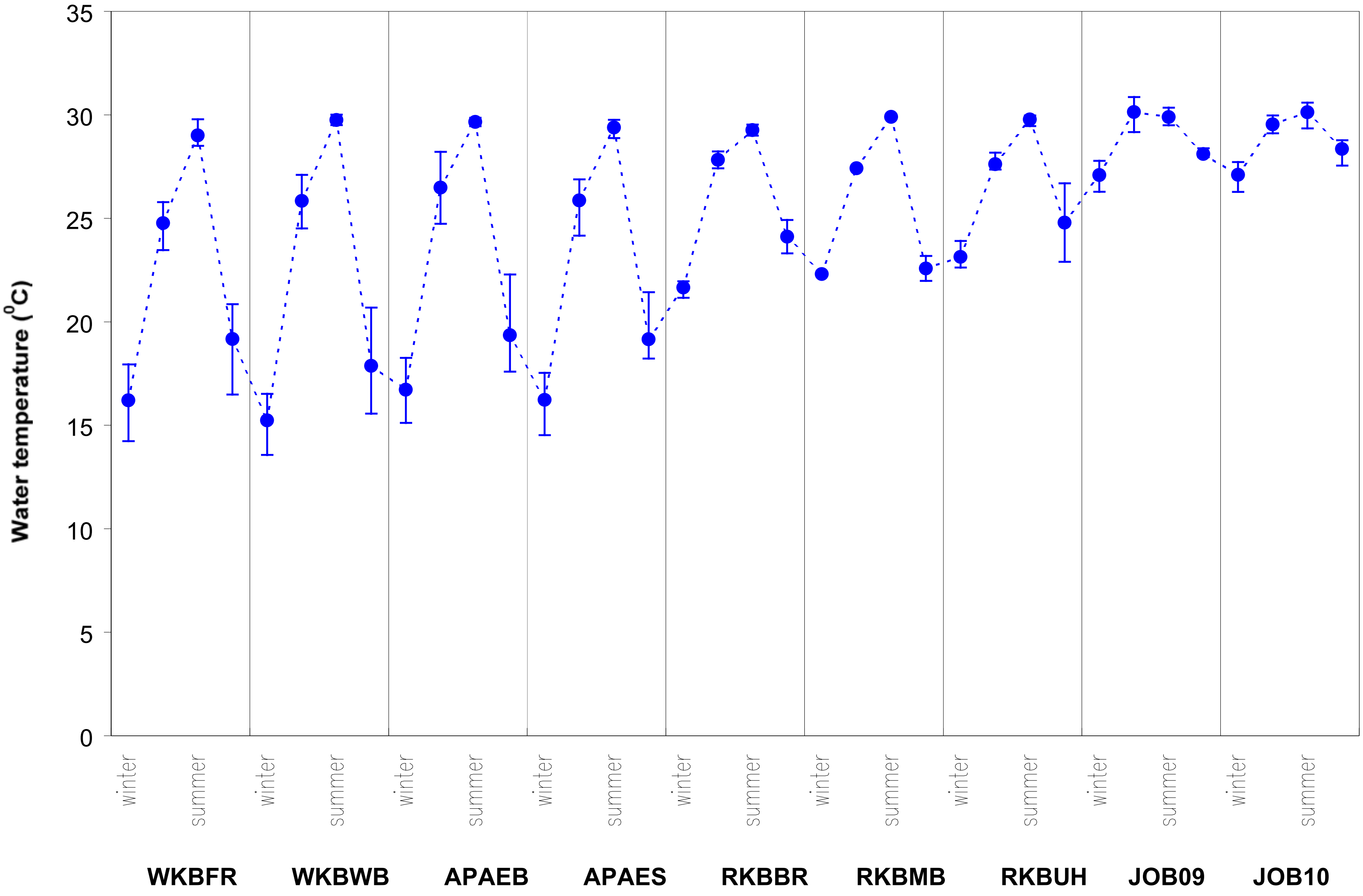
Appendix 19. Seasonal water temperature mean and range (+/- 1 std. dev.), Northeast NERRs (1995-2000).



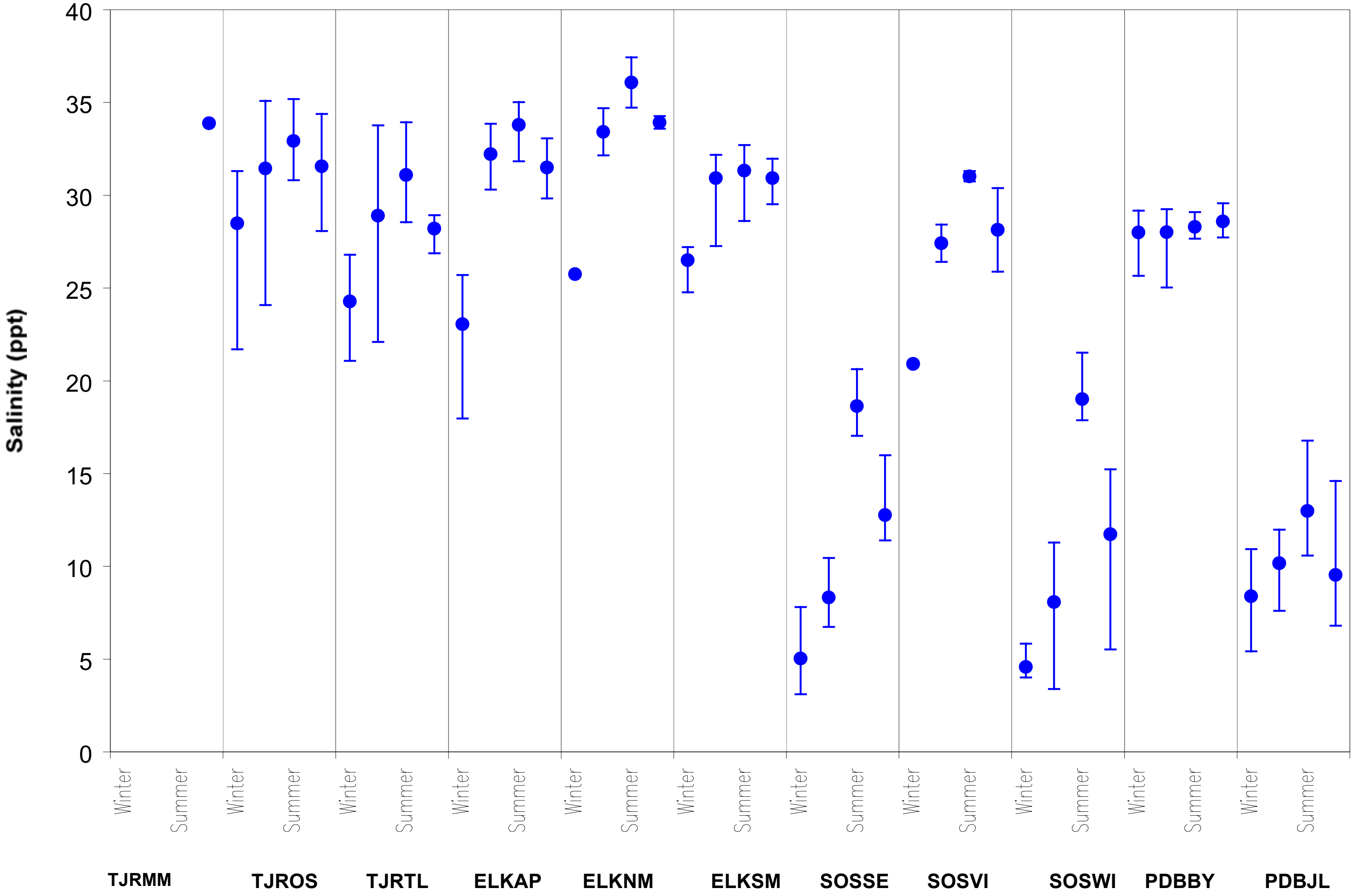
Appendix 20. Seasonal water temperature mean and range (+/- 1 std. dev.), Mid-Atlantic NERRs (1995-2000).



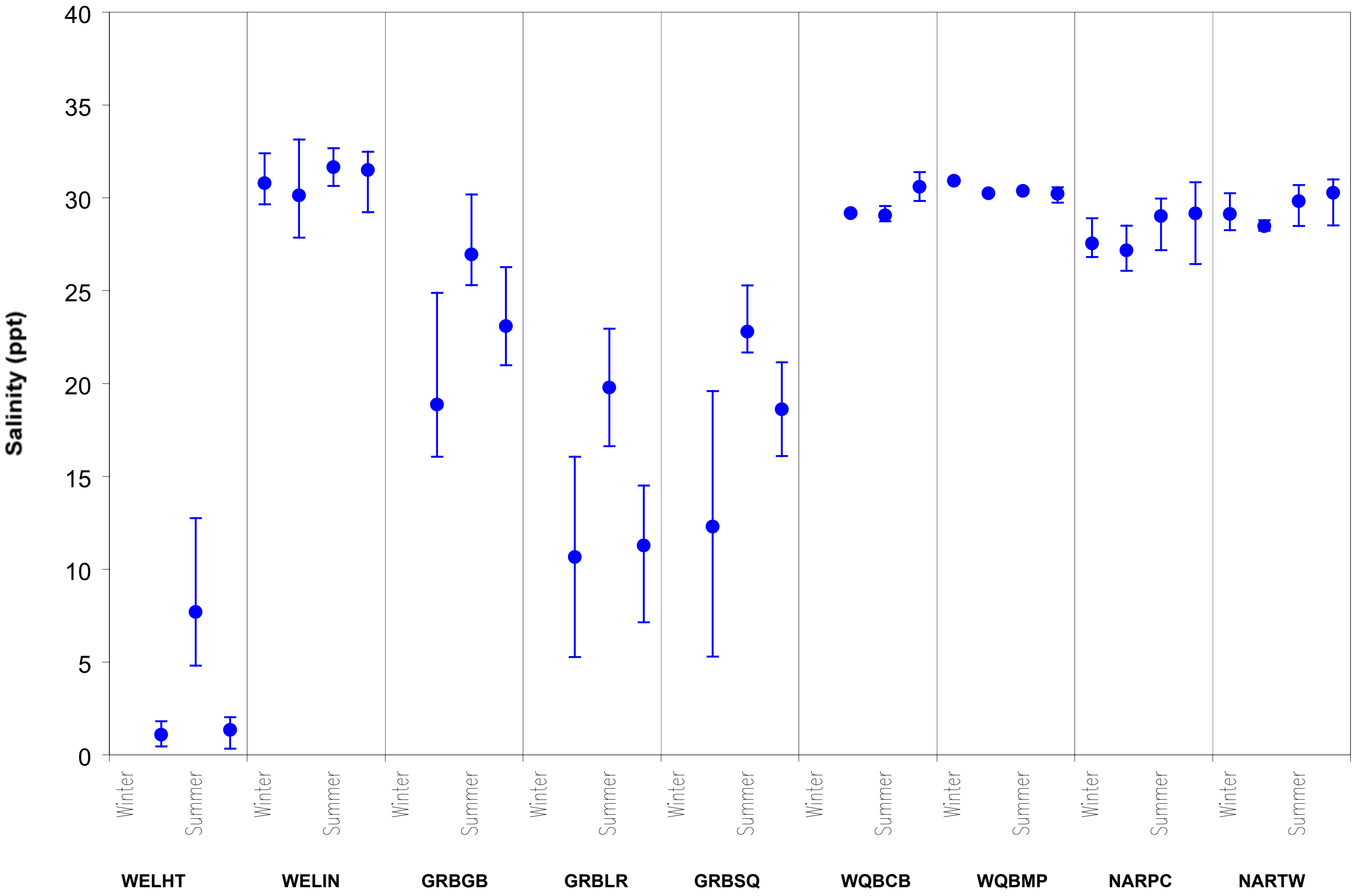
Appendix 21. Seasonal water temperature mean and range (+/- 1 std. dev.), Southeast NERRs (1995-2000).



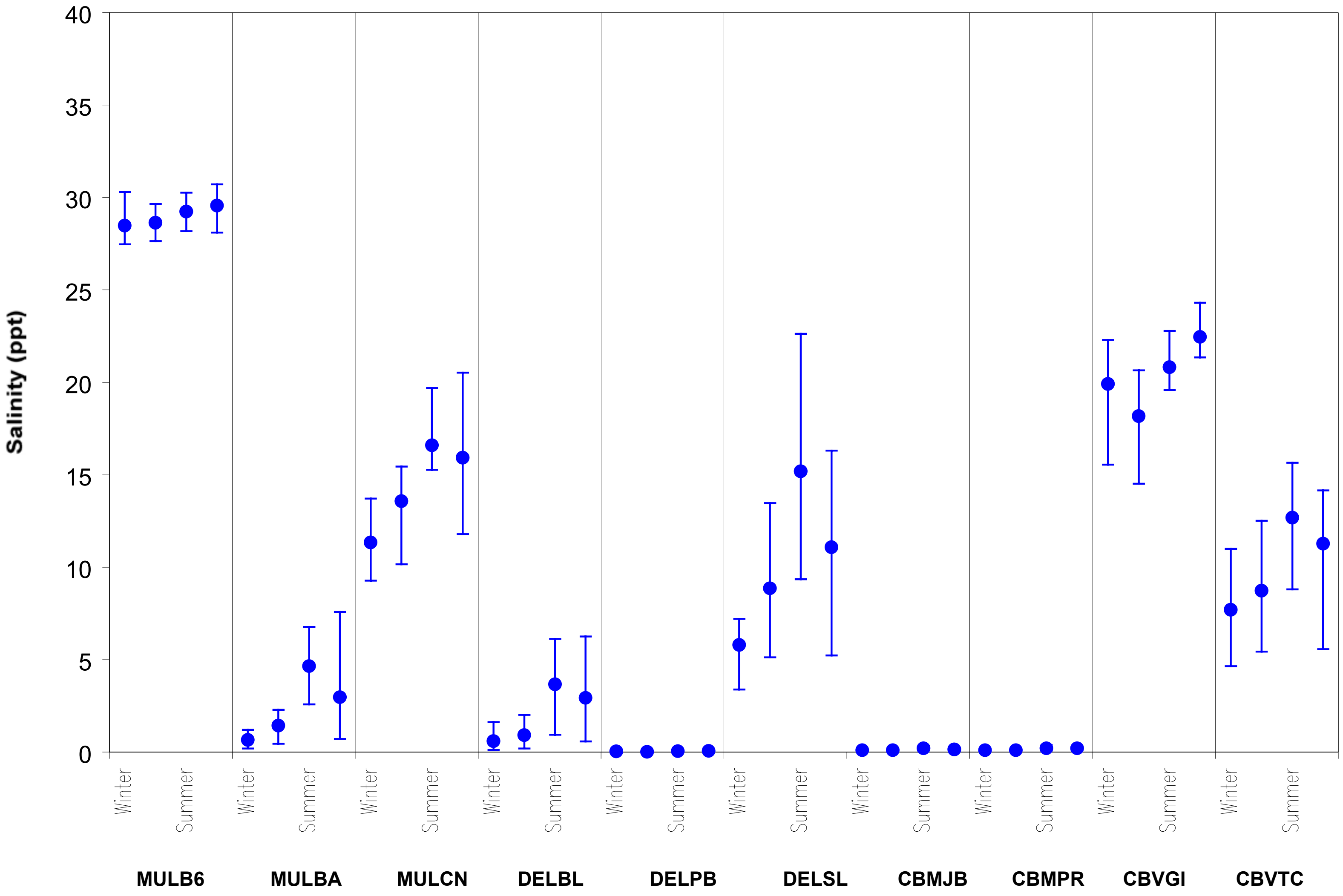
Appendix 22. Seasonal water temperature mean and range (+/- 1 std. dev.), Gulf of Mexico and Puerto Rico NERRs (1995-2000).



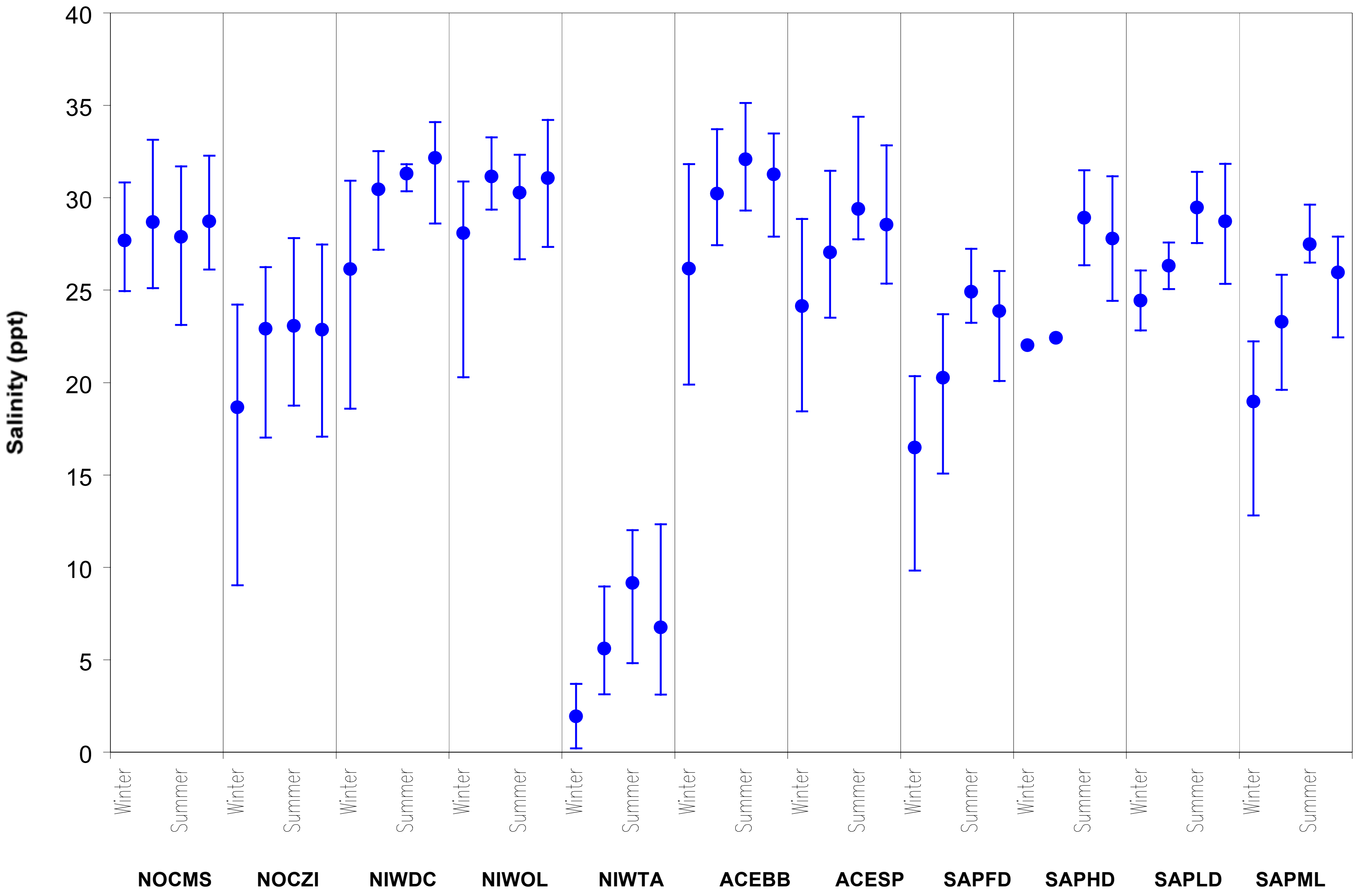
Appendix 23. Seasonal mean salinity and intra-seasonal variability (of mean salinity), West Coast NERRs (1995-2000).



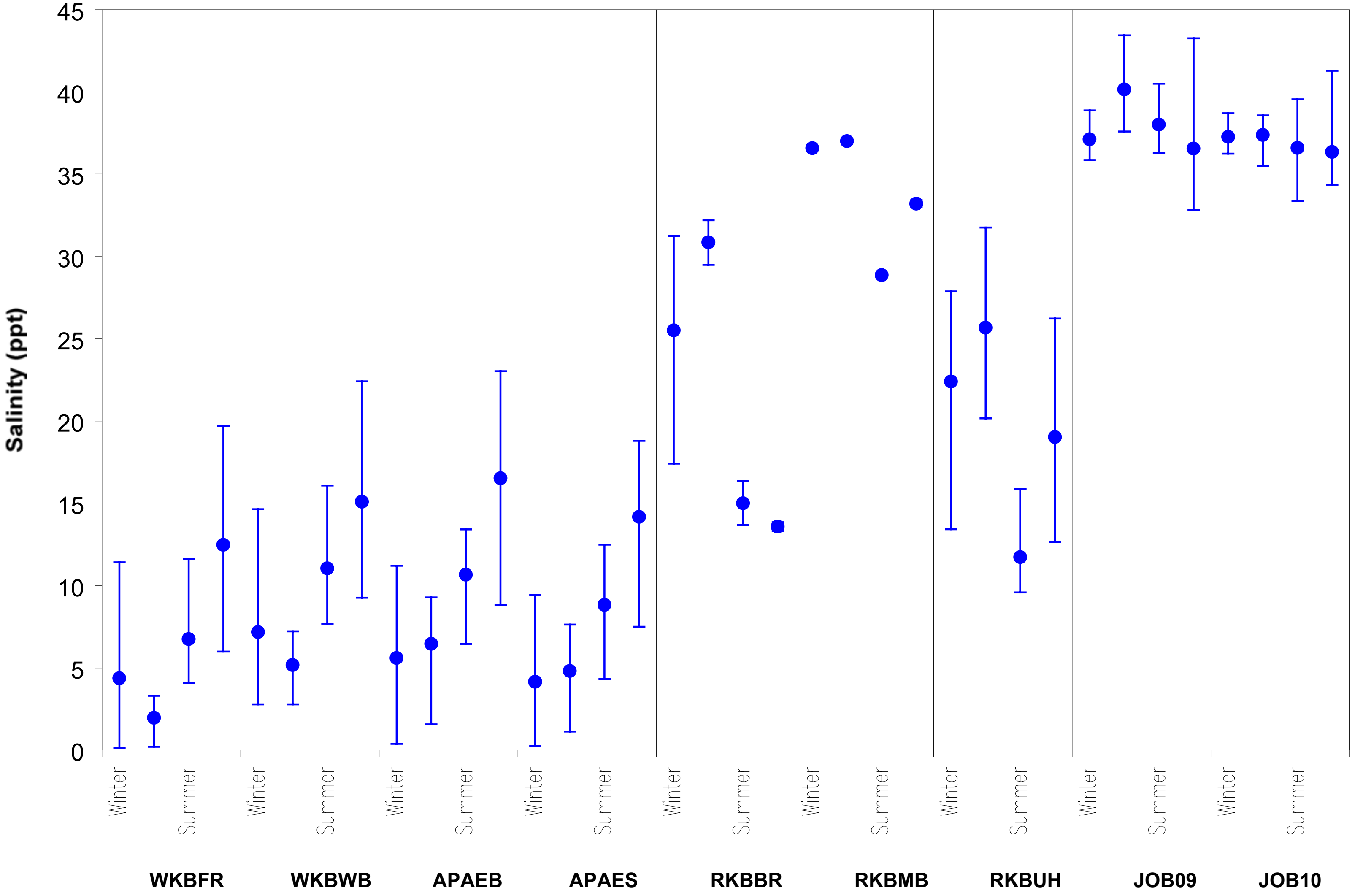
Appendix 24. Seasonal mean salinity and intra-seasonal variability (of mean salinity), Northeast NERRs (1995-2000). Five freshwater sites (OWCSU, OWCWM, HUDTS, HUDTN, HUDSK) not shown.



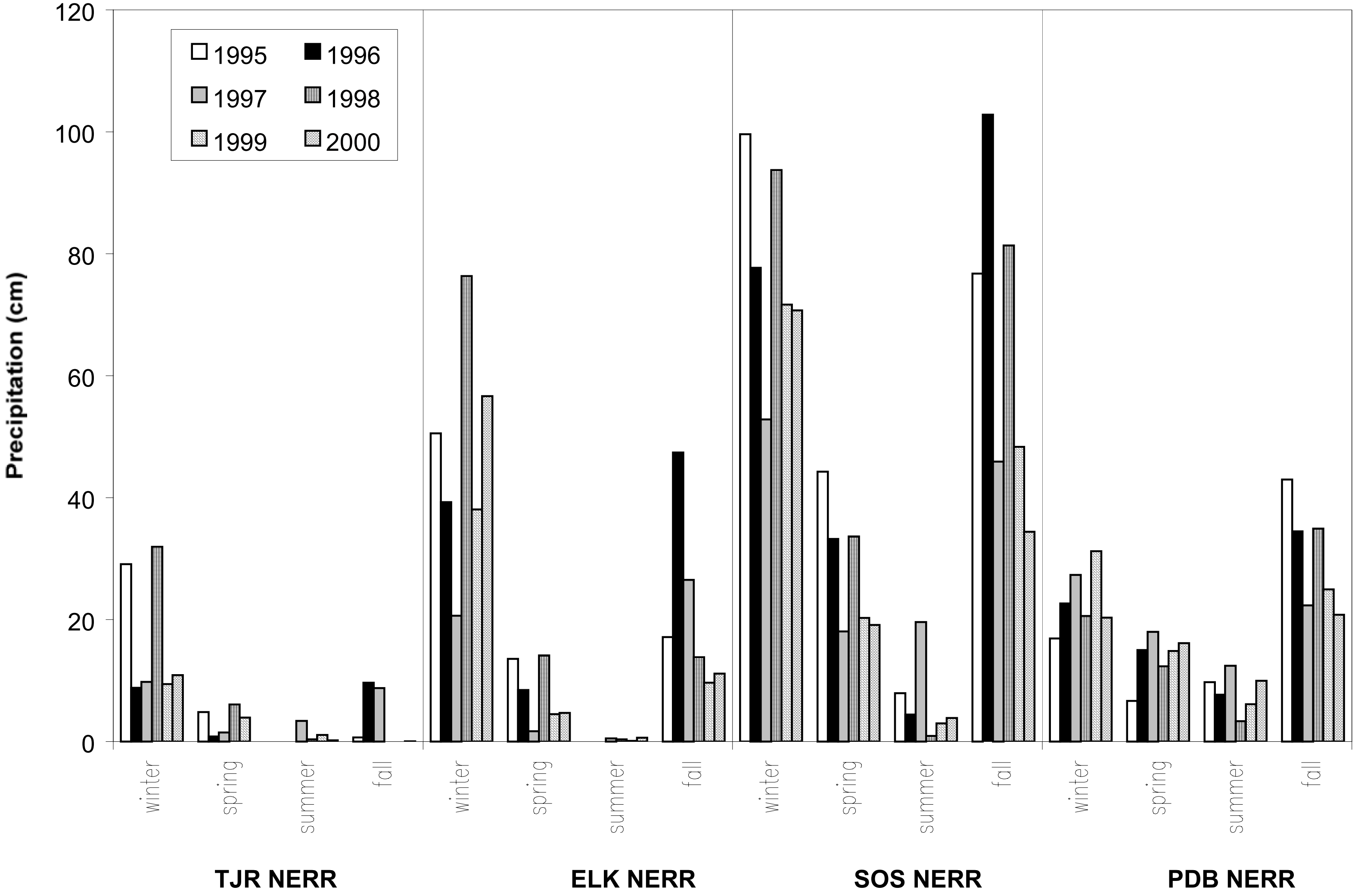
Appendix 25. Seasonal mean salinity and intra-seasonal variability (of mean salinity), Mid-Atlantic NERRs (1995-2000).



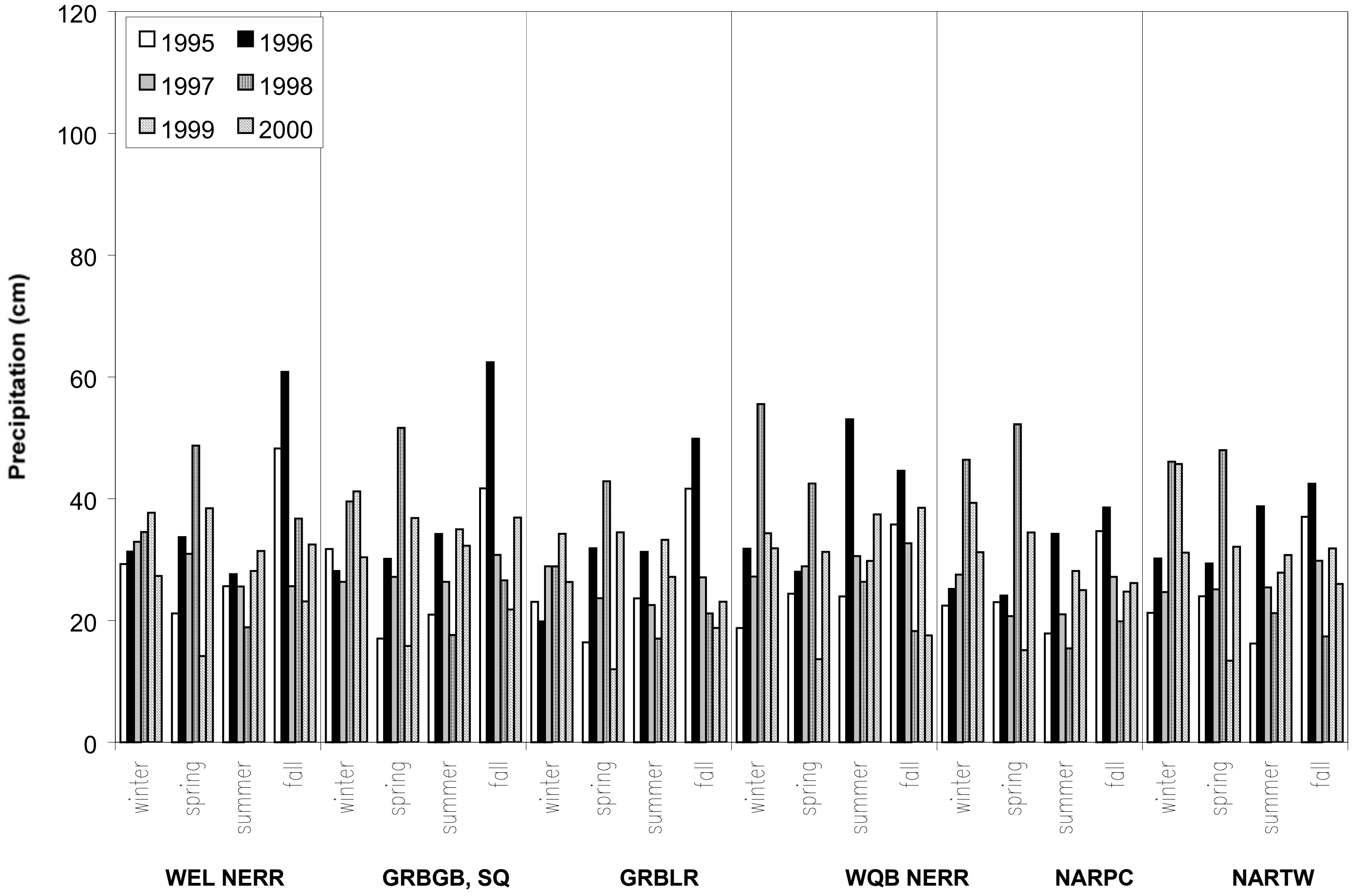
Appendix 26. Seasonal mean salinity and intra-seasonal variability (of mean salinity), Southeast NERRs, 1995-2000.



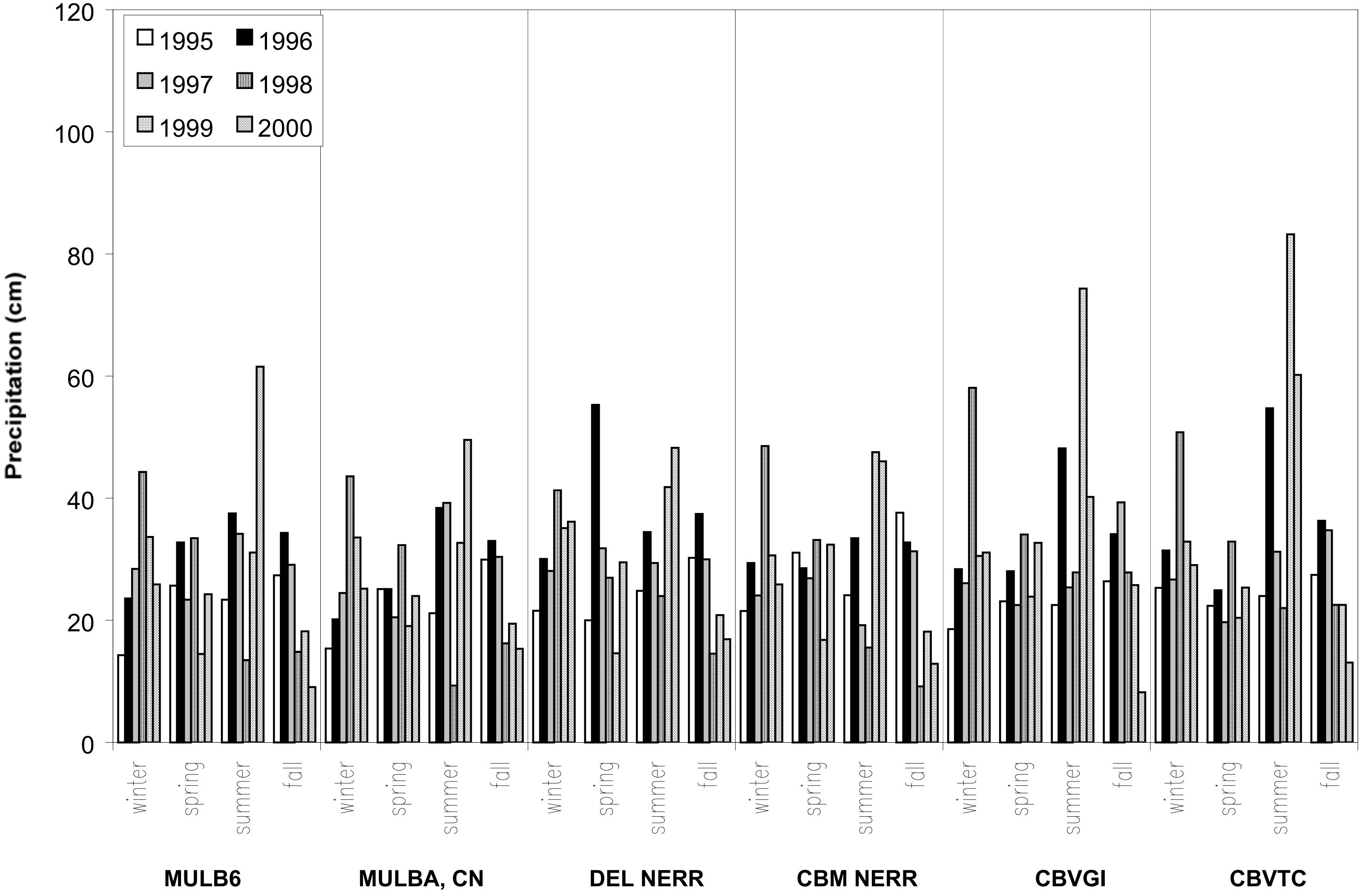
Appendix 27. Seasonal mean salinity and intra-seasonal variability (of mean salinity), Gulf & Puerto Rico NERRs (1995-2000).



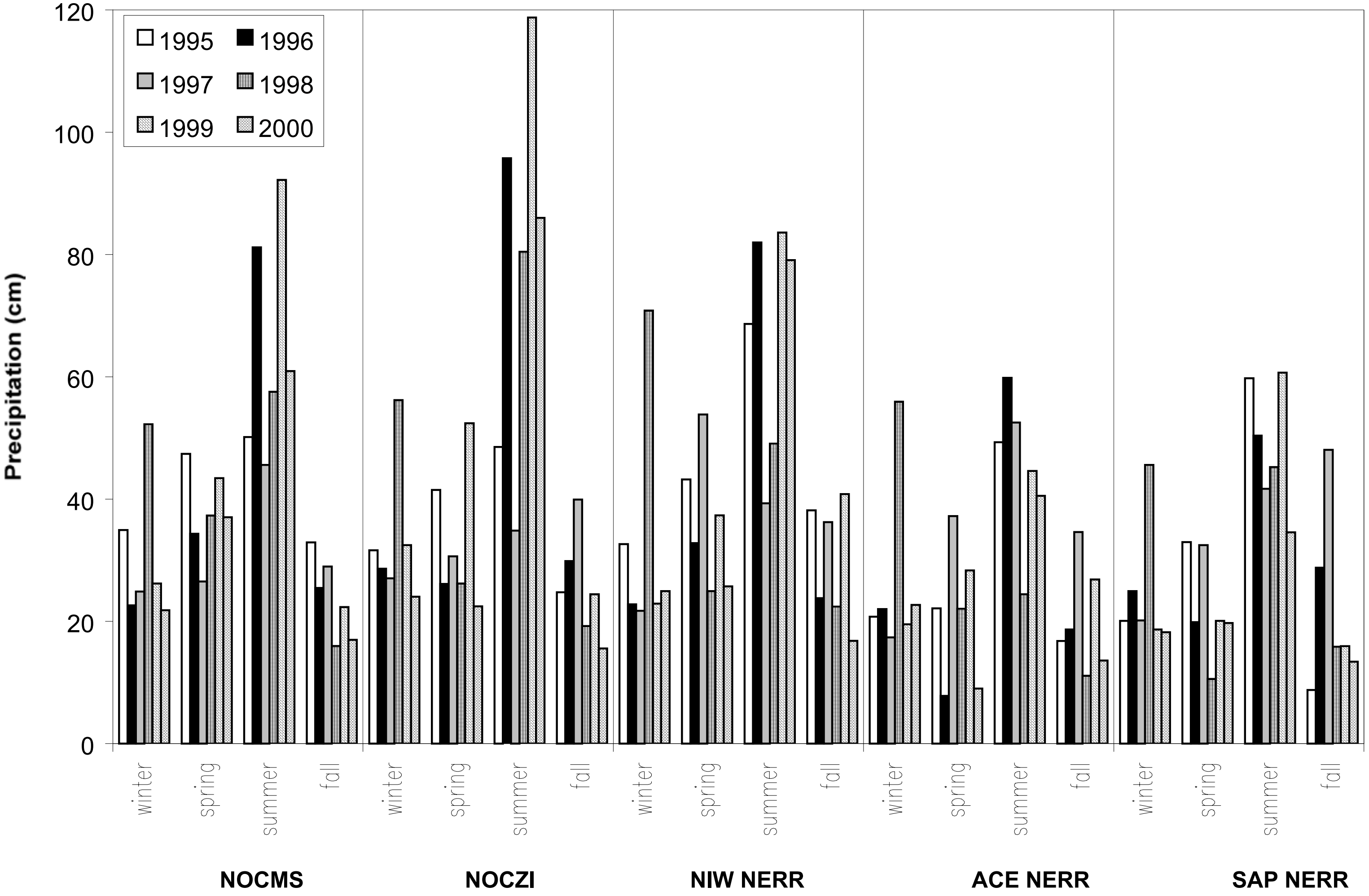
Appendix 28. Seasonal precipitation among West Coast NERRs, 1995-2000.



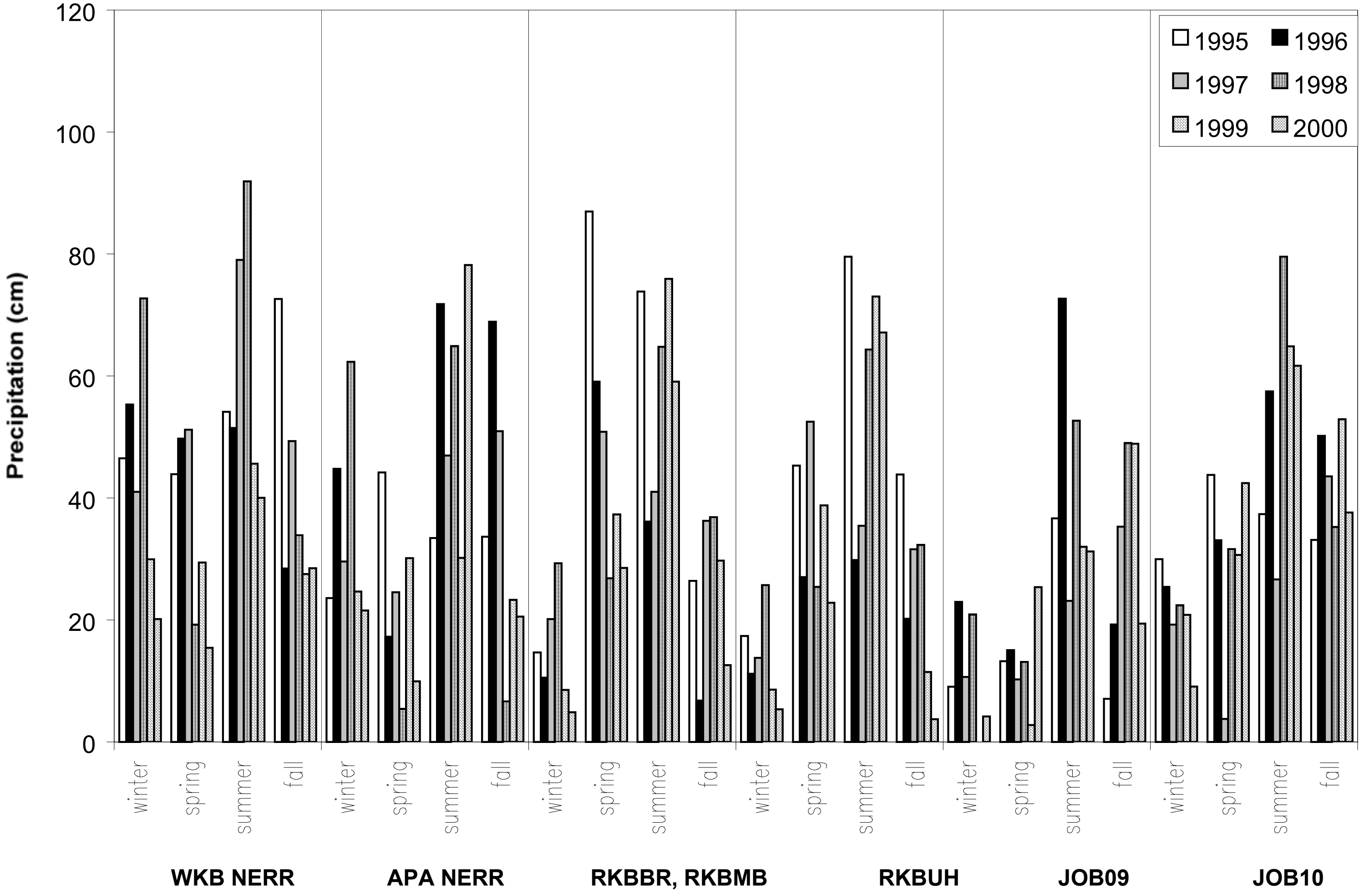
Appendix 29. Seasonal precipitation among Northeast NERRs, 1995-2000. Precipitation at freshwater Reserves (Hudson River and Old Woman Creek) not shown.



Appendix 30. Seasonal precipitation among Mid-Atlantic NERRs, 1995-2000.



Appendix 31. Seasonal precipitation among Southeast NERRs, 1995-2000.



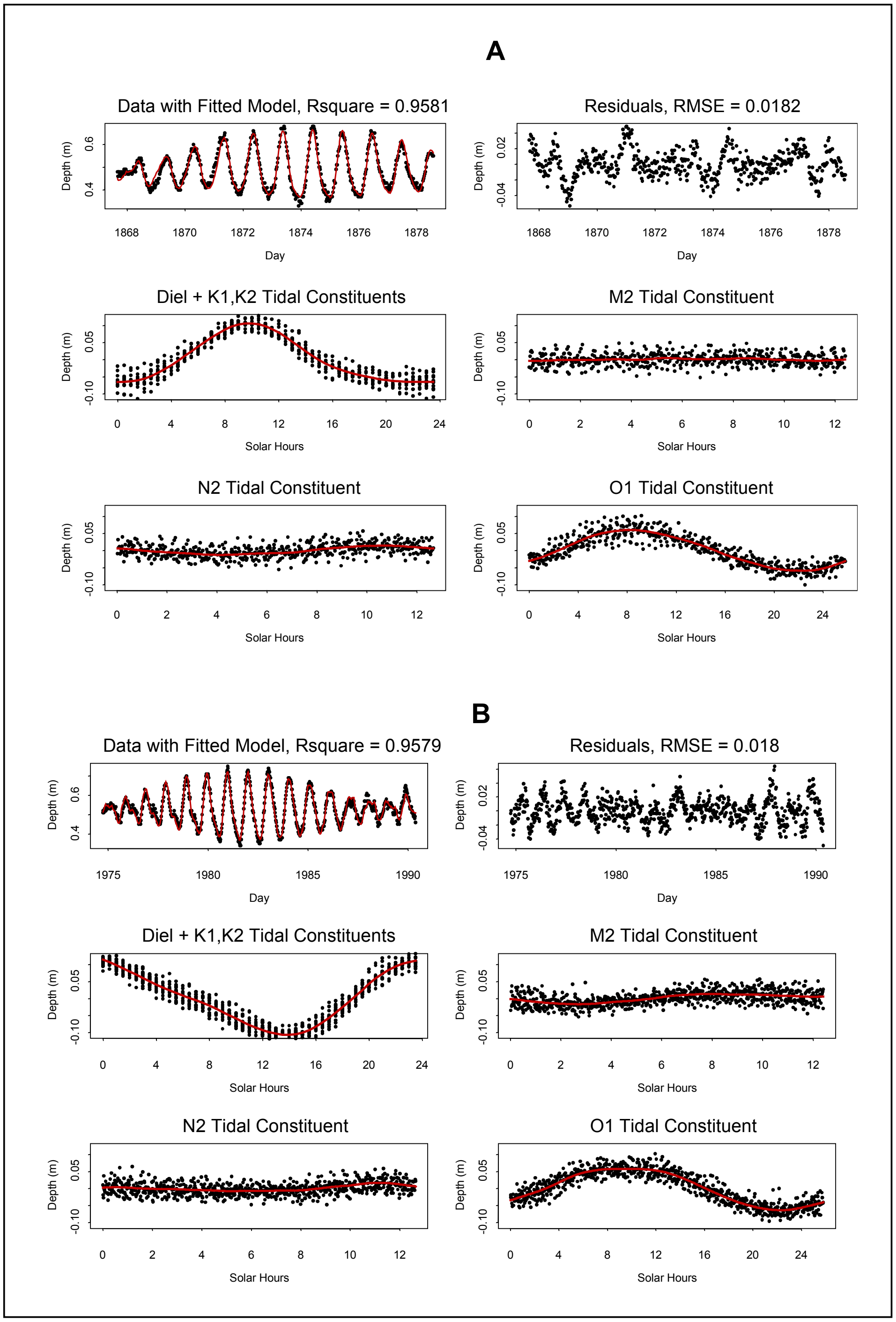
Appendix 32. Seasonal precipitation among Gulf & Puerto Rico NERRs, 1995-2000.

Appendix 33. The first four Eigenvectors of principal components analysis.

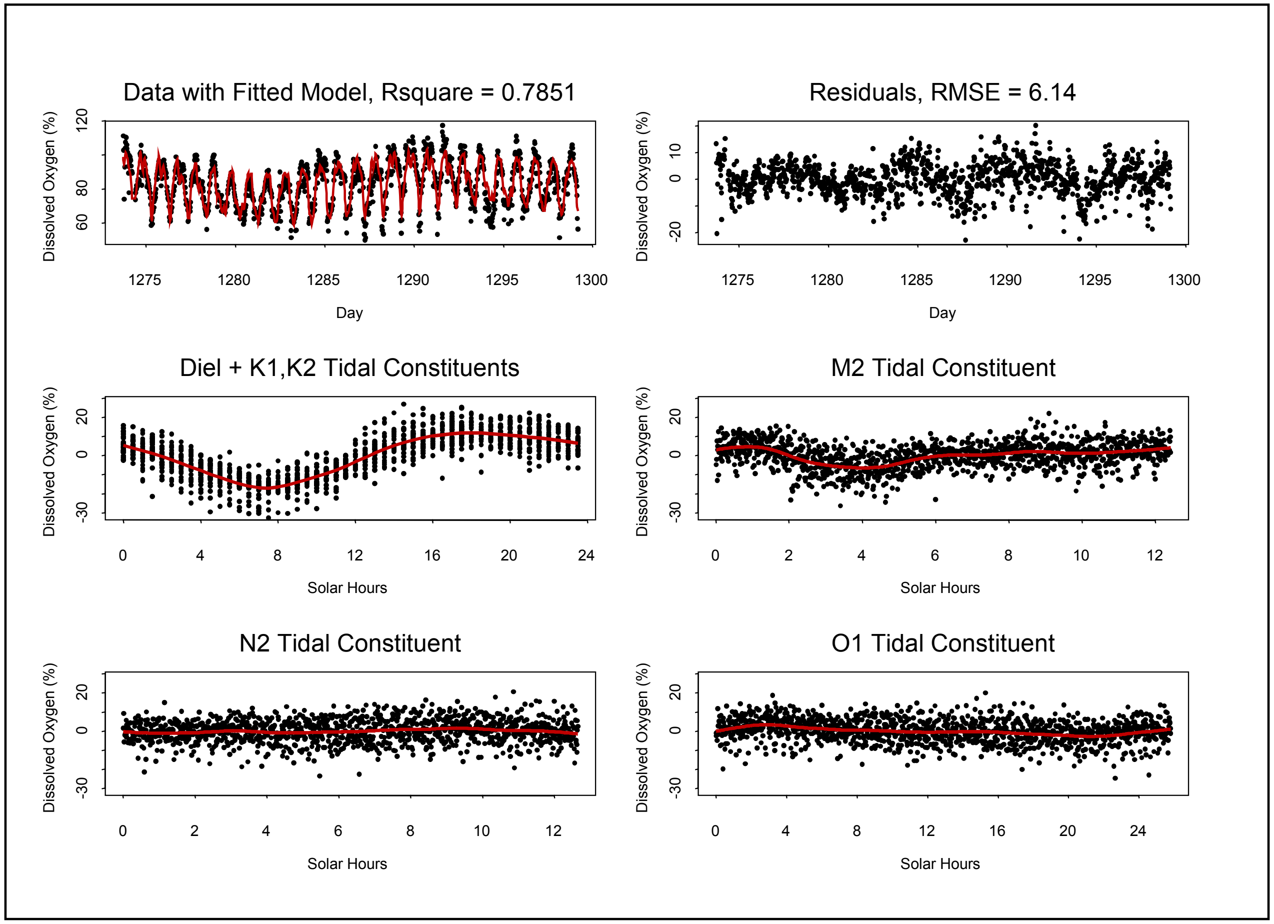
Eigenvector	1	2	3	4
Permeability	-0.14093	-0.11092	0.260428	-0.52845
Watershed area (Ha)	-0.15553	0.017239	-0.08211	0.053673
Clay (%)	0.328198	0.003068	-0.086	0.518855
Agricultural Land (%)	0.044817	0.349906	-0.30988	-0.01959
Forested Land (%)	-0.40957	-0.02353	0.241641	0.059304
Urban / Developed (%)	-0.02782	-0.15143	-0.30863	-0.2228
Wetland (%)	0.391912	-0.09189	0.285323	0.006699
Shellfish (%)	0.06696	-0.29789	0.125217	-0.06954
Width at site (m)	-0.20982	-0.23014	-0.10227	-0.01907
1995-2000 Precipitation (cm)	-0.13832	0.051921	0.363678	0.054494
% of time water temp <10°C	-0.42045	-0.07843	-0.04289	0.119071
% of time water >25°C	0.3361	0.114946	0.221946	-0.20496
% of time with hypoxia (DO<28% sat)	0.297001	0.050927	0.015896	-0.39867
% of time with supersaturation (DO>120% sat)	-0.02999	-0.22149	-0.2884	0.055362
Depth Range	0.005277	-0.17942	0.35476	0.343738
Mean salinity (ppt)	0.164917	-0.48801	0.04218	0.044823
Salinity range	-0.08628	0.018472	0.265262	0.13157
% of time pH <7.0	-0.19473	0.313943	0.09967	-0.10641
% of time pH >8.0	0.011054	-0.33509	-0.28695	-0.05331
% of time turbidity >25 NTU	0.070056	0.368895	-0.06133	0.130616

Appendix 34. Comparison of results by principal components analysis (PCA) and nonlinear multidimensional scaling.

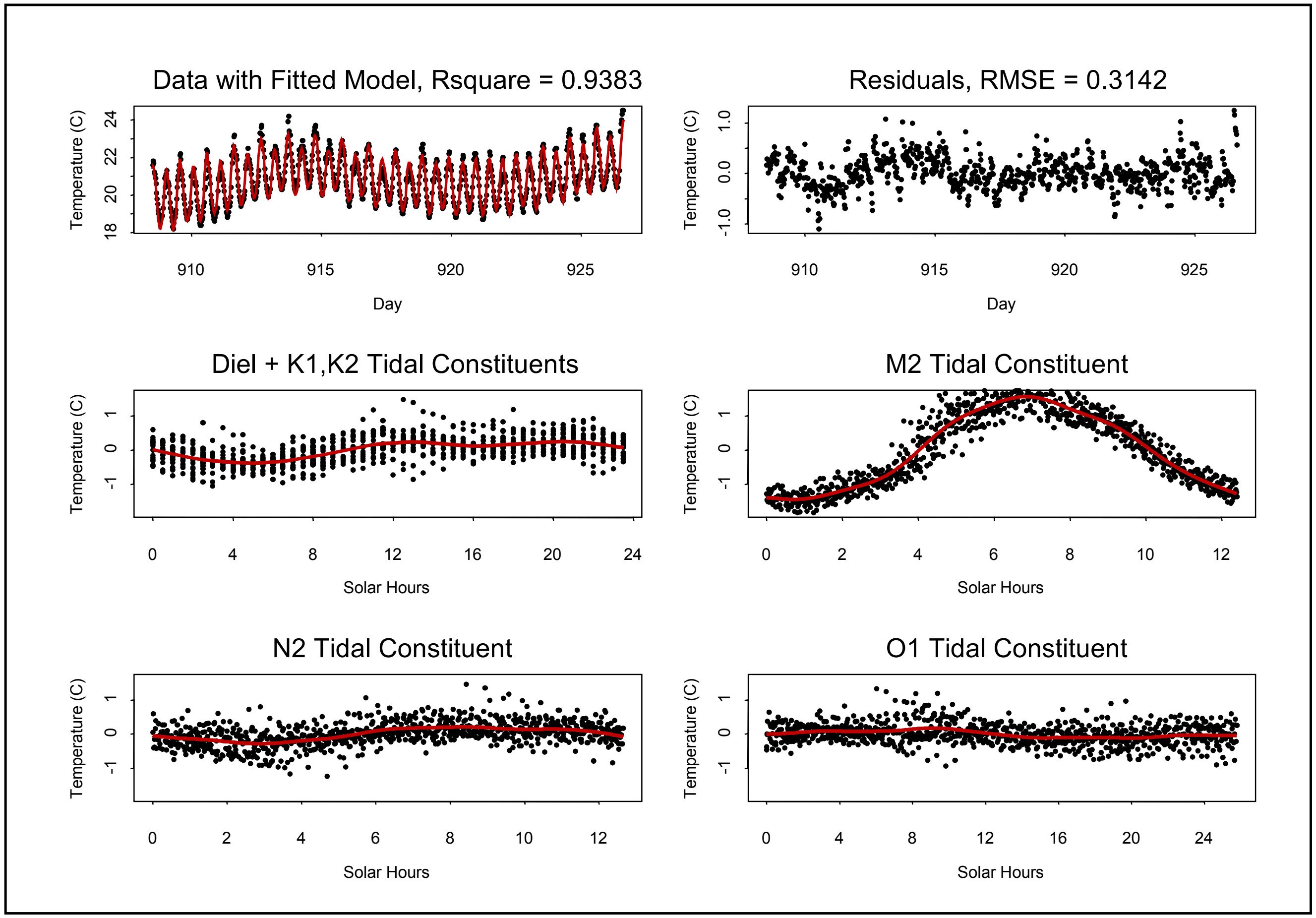
Principal components analysis				Nonlinear multidimensional scaling	
Component/ Dimension	Eigenvalues	% of Variance	Cum. % of Variance	% of Total Variance	Cum. % of Variance
1	3.21881	16.0941	16.0941	20.35	20.35
2	3.00324	15.0162	31.1102	20.95	41.3
3	2.53313	12.6657	43.7759	15.32	56.62
4	1.94596	9.72979	53.5057	12.32	68.94
5	1.86379	9.31897	62.8247	10.1	79.04
6	1.47158	7.35788	70.1826	5.98	85.02
7	1.16674	5.83368	76.0163	4.07	89.09
8	0.886889	4.43444	80.4507	3.33	92.42
9	0.704339	3.52169	83.9724	2.22	94.64
10	0.634832	3.17416	87.1465	1.33	95.97
11	0.598113	2.99056	90.1371	1.09	97.06
12	0.49072	2.4536	92.5907	0.81	97.87
13	0.357926	1.78963	94.3803	0.86	98.73
14	0.343394	1.71697	96.0973	0.4	99.13
15	0.274679	1.3734	97.4707	0.25	99.38
16	0.181294	0.906471	98.3772	0.22	99.6
17	0.141407	0.707033	99.0842	0.11	99.71
18	0.111419	0.557093	99.6413	0.14	99.85
19	0.037846	0.189228	99.8305	0.01	99.86
20	0.033898	0.169489	100	0.07	99.93



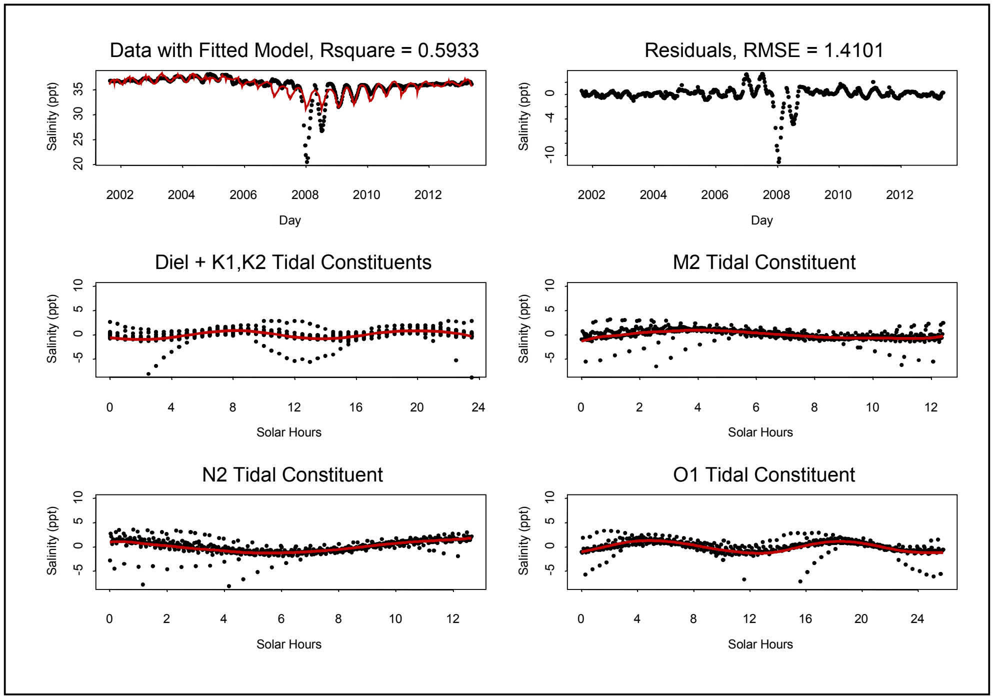
Appendix 35. Solar energy influence on water depth (m) at Station 9, Jobos Bay NERR. Dramatic pattern changes from February (2/10/00 – 2/21/00, panel A) to May (5/27/00 – 6/12/00, panel B) suggest that gravitational forces (e.g. tidal constituents K_1 or P_1) do not drive these changes. Similar patterns were observed at this site in every year evaluated. Note the unusually strong O_1 signature, consistent across these two deployments, and the shallow nature of water depth at this site.



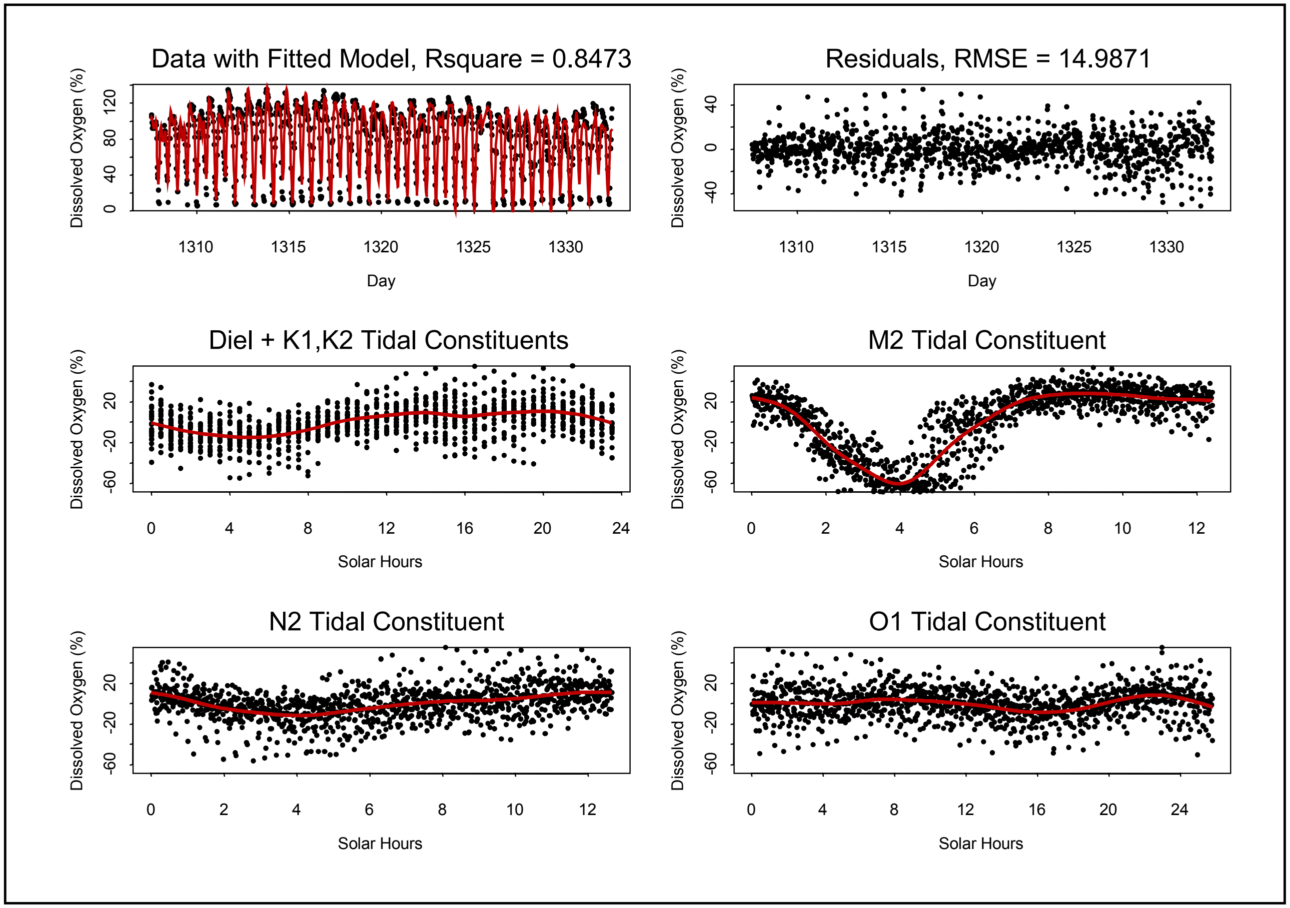
Appendix 36. Dissolved oxygen (% sat) at South Marsh (Elkhorn Slough NERR), 6/26/98 to 7/22/98. Note the weak (if any) M_2 influence, and the strong diel signature. This is a very typical plot for DO, though there are strong tidal effects for DO at some sites. Note also that the diel pattern is non-sinusoidal; the increasing segment of the diel signature is only about 8 hours in duration. This asymmetry is also evident in the raw data (upper left) where most curves are sharper at the base than at the apex.



Appendix 37. Temperature (°C) at Great Bay Buoy (Great Bay NERR), 6/26/97 to 7/14/97. Temperature at most sites was driven by the 24-hour solar energy cycle; however, there were exceptions to this rule as shown in this figure. Inspection of plots for depth at this site revealed that the maximum daily water temperature occurred at low tide. Note the distinct, nonlinear trends in the overall temperature series (top left plot).



Appendix 38. Salinity (ppt) at Oyster Landing (North Inlet NERR), 6/23/00 to 7/5/00. Salinity was the most difficult variable to model well, because of frequent and irregular freshwater (precipitation) intrusion events, which resulted in inconsistent periodicity. In this deployment, actual salinity fluctuations increase in amplitude immediately after the event and take several days to damp out and return to the pre-event level of approximately 36ppt. Note that the model structure assumes a consistency in the periodic component signatures across the entire deployment (as does the classical harmonic regression model); thus, the model is not completely successful in following the salinity levels through this event. Furthermore, in attempting to follow the data through this disruption, some artificially large fluctuations are created in the fitted model both before and after the event. Note that the constituent plots (middle and bottom) are less useful in this example because their axes have been scaled to be uniform across all deployments. It can be inferred that, at some time during this site's five-year salinity record, at least one deployment achieved a fitted signature range of about 20 ppt for at least one of these four constituents.



Appendix 39. Dissolved oxygen (% sat) at the Inlet Site (Wells NERR), 7/30/98 to 8/24/98. In this example of a summer deployment, DO (% sat) shows a recurring state of hypoxia associated with the main tidal cycle. Inspection of any depth variable deployment analysis for this site reveals that this hypoxia occurs at low tide. Similar patterns occur in most years, usually during warm months. Note the non-sinusoidal shape of the M$_2$ profile. The analogous profile for water depth at this site is more similar to a sine wave.

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