

**Bays Eutrophication Model (BEM)
Model Verification for the Period
1998-1999**

Massachusetts Water Resources Authority

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SECTION 1

INTRODUCTION

In 1991, the Massachusetts Water Resources Authority (MWRA) funded HydroQual, Inc. and the U.S. Geological Survey (USGS) to develop a coupled hydrodynamic/water quality model of the Massachusetts Bay/Cape Cod Bay system. The Bays Eutrophication Model (BEM) was to be used to assess the potential impact of relocation the effluent discharges from Boston's Nut and Deer Island wastewater treatment plants (WWTP) to a location 15 km east of Deer Island in Massachusetts Bay. During the process of permitting the new outfall, a permit was written that required MWRA to collect data to monitor the water quality impact of the new outfall and to run the model once the outfall went online.

The model (BEM) was originally calibrated to a period from October 1989 to May 1991 and later verified by data collected in 1992 (HydroQual and Normandeau, 1995). During the process of model calibration and verification, a model evaluation group (MEG) was assembled to peer-review and guide the modeling process. Since the model was to be used as part of MWRA's permit requirements the MEG suggested modeling additional years to improve the model's ability to reproduce existing conditions in the bays. These years included 1993, which had evidence of a large fall bloom, and 1994 during which low dissolved oxygen was measured. The results of this study were presented in HydroQual (2000).

After reviewing the results of the 1993 and 1994 analysis, the MEG suggested modeling 1998 and 1999 to further test the model. 1998 was a year that did not have a spring bloom, and 1999 had low dissolved oxygen levels. In addition, in July 1998 the discharge of effluent from the Nut Island WWTP was routed to Deer Island and discharged from that location. Also, in the period between 1994 and 1998, the Boston WWTP's began secondary treatment, thereby reducing the carbon load to the system and increasing the dissolved inorganic nitrogen (DIN) loading from Boston.

This report provides a summary of the modeling analysis conducted for the years 1998 and 1999. The analysis was conducted in a similar manner as the earlier analyses with a few exceptions. In previous analyses, the water quality model was run on an aggregated grid in order to reduce the computational burden of running the model on the finer hydrodynamic model grid. Based on a recent analysis (HydroQual, 2001a) and MEG comments, the water quality model was run on a grid that had the spatial resolution as the hydrodynamic grid, but did not include the portion of the grid that extended into the Gulf of Maine. The model loads and boundary conditions were modified to

reflect the conditions that were observed in 1998 and 1999. The remaining inputs to the model, including the parameters and constants, remained unchanged from those used in the 1992-1994 analysis.

The report also includes two sensitivities which include the addition of a third algal group as described in HydroQual (2001c) and the modification of the nutrient recycle rates.

SECTION 2

POLLUTANT LOADINGS

2.1 INTRODUCTION

The pollutant loadings used for this modeling analysis were developed in the same manner as previous analyses with some minor exceptions that will be discussed below. The reader is referred to HydroQual and Normandeau (1995) for details on the procedures and assumptions used to develop pollutant loadings. This section presents information concerning year to year variability in the loadings of carbon (C), nitrogen (N), and phosphorus (P). The years 1998 and 1999 will be compared to the last year previously analyzed, 1994.

2.2 LOADING COMPARISON

Loadings were developed in a similar fashion as was used in previous analyses. MWRA loads were estimated using flows and concentrations from plant records and input into the model on a monthly basis. One exception to this was the transitional period of April to July 1998 when flow was diverted from the Nut Island WWTP to the Deer Island WWTP. During this period, loadings were specified every 10 days to better approximate the actual loading from the Nut Island WWTP. The annual daily average total flow from the two WWTPs was 383 MGD, 412 MGD and 343 MGD for 1994, 1998, and 1999, respectively. The non-point source loads in Boston Harbor were also calculated in a different manner for this analysis. In the past, estimated CSO flows were determined by a runoff model and available on a time-variable basis. For this analysis, an annual overflow CSO volume was provided by MWRA. The same annual volume was used for both 1998 and 1999. The timing of the CSO flows were modified to vary on a monthly basis based on the flow record of the Charles River for 1998 and 1999. Each month was assigned a fraction of the annual overflow volume based on the fraction of total annual Charles River flow that occurred during each month. The non-MWRA WWTP, riverine, and atmospheric loads were all determined with the same method used for the previous years' analyses.

Figure 2-1 presents a comparison between total carbon, total nitrogen and total phosphorus daily average loadings from various sources for the years 1994, 1998, and 1999 that were used in the water quality model. The loading sources include MWRA WWTPs, non-MWRA WWTPs, non-point sources (including CSOs, storm sewers, overland runoff, and groundwater), riverine sources and atmospheric deposition. In the period from 1994 to 1998 there was a dramatic decrease in the

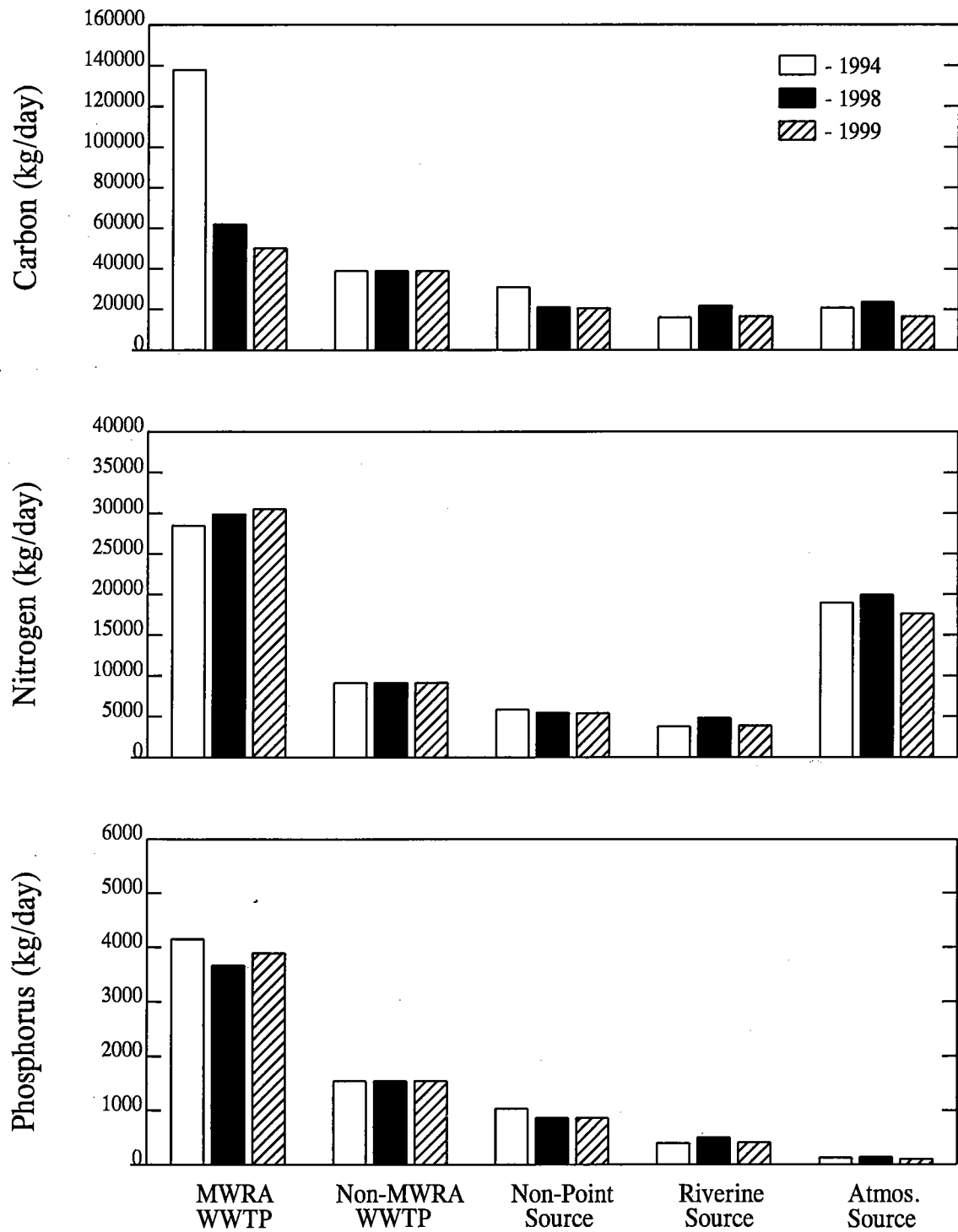


Figure 2-1. Loading Comparison of Sources for 1994, 1998, and 1999

total carbon load from MWRA WWTPs due to increased levels of secondary treatment at the plants. The 1999 MWRA total carbon loads (approx. 50,000 kg/day) are approaching the estimated total carbon loads from all non-MWRA WWTPs (approx. 39,000 kg/day). Non-point sources of carbon have also decreased from 1994 levels. The riverine and atmospheric loads reflect the fact that 1998 was a relatively "wet" year as compared to 1994 and 1999. The total annual rainfall amounts for 1994, 1998, and 1999, respectively were 47.6 in., 53.5 in., and 37.8 in. In 1998 and 1999, non-point-sources, riverine sources and atmospheric sources all contributed a similar quantity of carbon to Massachusetts and Cape Cod Bays (16-22 MT/day).

The nitrogen loads continue to be dominated by MWRA sources. A small increase in nitrogen loading is observed from 1994 to 1999. Atmospheric loads are the second largest nitrogen source, and 1998 had the largest atmospheric loading of these three years. The non-MWRA WWTPs, non-point sources, and the riverine sources are all smaller contributors of nitrogen to the system. The majority of the phosphorus loading emanates from MWRA WWTPs. The remaining contributors, in descending order, are non-MWRA sources, non-point sources, riverine sources and atmospheric deposition.

Figure 2-1 shows that while MWRA WWTPs remain the largest sources of carbon to the system, the total percentage of the load has decreased dramatically from 1994 levels due to the implementation of secondary treatment. The figure also shows that, besides the carbon loading from the MWRA WWTPs, there is not much variability in the loadings to the bays. However, this figure does not take into account the influence of the Gulf of Maine as a source of nutrients to the bays. A previous analysis (HydroQual, 2000) showed that in 1992 the Gulf of Maine was by far the largest source of nitrogen to the bays.

SECTION 3

WATER QUALITY DATA

3.1 INTRODUCTION

The credibility of model calculations is judged, to a large degree, on the basis of the agreement of the model with observed data. Beyond the constraint that the model must behave reasonably well and conform with general scientific principles, observed data offer perhaps the only external criteria available to assess the validity and, hence the utility of a complex hydrodynamic/water quality model. A properly validated deterministic model is a powerful tool because it represents, as closely as possible, the mechanisms that affect the system.

The data used herein were collected as part of MWRA's Harbor and Outfall Monitoring program (HOM). The monitoring program was not designed specifically for use in a water quality model. Rather, it was developed to assess the natural variation of water quality within the bays before the new outfall went on-line, and to detect possible changes in water quality after the new outfall began operation. The data collected provide adequate information to assess the model's ability to reproduce water quality conditions in the bays. This section will summarize some of the observed differences between the water quality conditions that occurred in 1994, 1998 and 1999. During these years, the data were collected by Battelle Ocean Sciences. These years are being analyzed because both 1994 and 1999 were observed to have low dissolved oxygen in the fall, 1998 did not have a spring bloom, and 1999 had a fall bloom. In addition, 1994 was included to this data analysis as a point of reference to work that was previously conducted (HydroQual, 2000).

3.2 HOM WATER QUALITY DATA

In 1999, the HOM water quality monitoring program consisted of 48 stations, 21 near field stations (in the vicinity of the outfall) and 27 far field stations. These stations cover the majority of Massachusetts and Cape Cod Bays. Figures 3-1 and 3-2 present the locations of the sampling stations. The near field stations are sampled 17 times per year and the far field stations are sampled six times per year. The data from these sampling events will be presented as a series of probability figures in an effort to display the differences and/or similarities between data collected in the years 1994, 1998 and 1999. Data from the near field stations are presented on a seasonal basis and on an annual basis. The far field station data are presented on an annual basis. The winter data include February and December, but no data were collected in January.

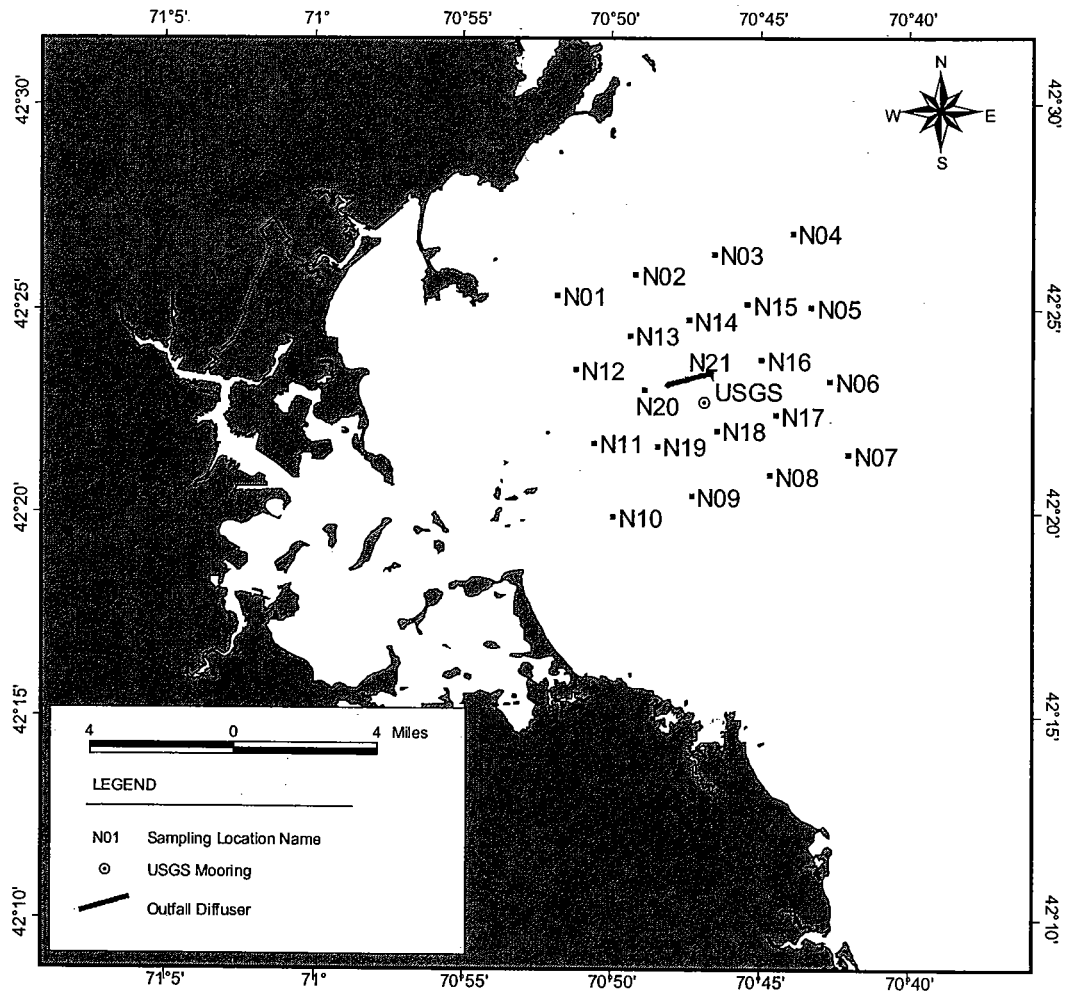


Figure 3-1. Near Field Sampling Stations (from Libby et al., 2000)

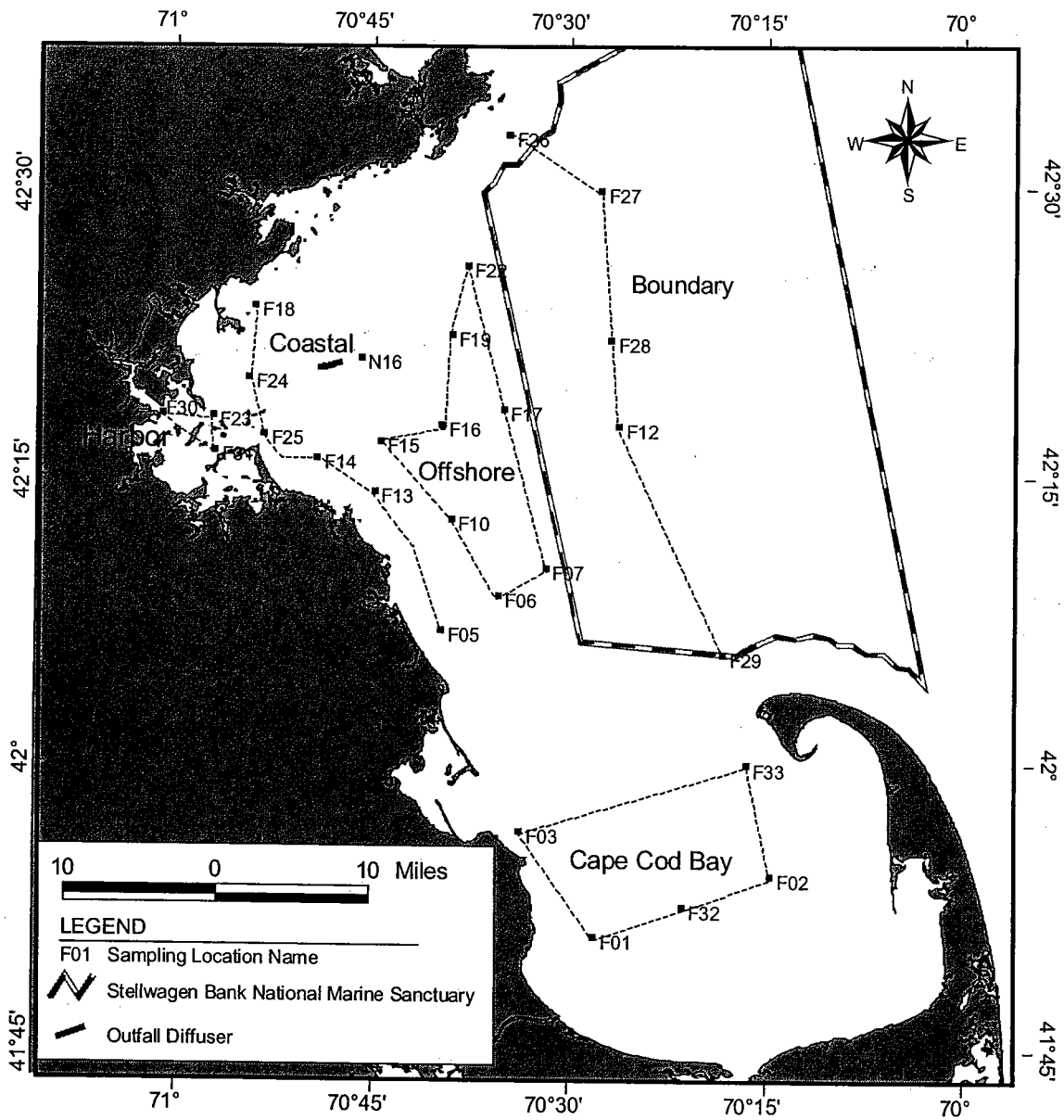


Figure 3-2. Far Field Sampling Stations (from Libby et al., 2000)

3.2.1 Temperature

Surface temperature data are presented in Figure 3-3. There are noticeable differences between the years. These temperature differences can be important because they affect hydrodynamic and biological processes that occur in the bays. In the near field area, the winter surface temperatures in 1998 and 1999 are quite similar. Compared to 1994, however, the February data are approximately two degrees cooler and the December data are approximately two degrees warmer. During the spring, the 1998 and 1999 near field surface temperature data sets remain similar to each other while the 1994 data remain cooler. For the summer period, it is the 1994 and 1998 data sets that are similar while data in 1999 are a few degrees warmer with maximum surface temperatures approaching 22°C. In the fall, the surface temperatures in 1998 and 1999 began higher than the temperature in 1994, but by the end of fall the temperature in 1994 was approximately three degrees higher than the temperatures measured in the other years. On an annual basis, the surface temperature distributions for the near field indicate that the lowest temperatures were observed in 1994 and the highest temperatures were observed in 1999. The median of the surface temperature data is approximately the same for each year at approximately 12.5°C. Differences in the far field temperature distributions are smaller. The warmest temperatures were also observed in 1999 and the coldest in 1994.

Figure 3-4 presents the bottom temperature data probability distributions. The bottom water temperature is important because it affects the biological processes in the water column and the sediment. The patterns described for the surface data are the same in the winter and spring for the bottom data. In the summer, the pattern changes from that seen at the surface. The 1998 and 1999 data sets are very similar, and it is the 1994 data set, not the 1999 data set, that has the highest temperatures. In the fall, the bottom water temperatures are highest in 1994 and the lowest in 1998. There is an approximately 4°C difference between the fall bottom water temperature in 1994 and 1998. The annual bottom temperature probability plots show more variability between the years than the surface data plots in the near field. 1994 had the largest temperature change from 0 to 15°C. The variability in the far field data is smaller. The 1998 and 1999 annual bottom water temperature distributions for the far field are similar.

These surface and bottom temperature data show that there can be a great deal of variability from season to season and year to year in the near field. It is more difficult to draw the same conclusion from the far field data because the data are collected less often.

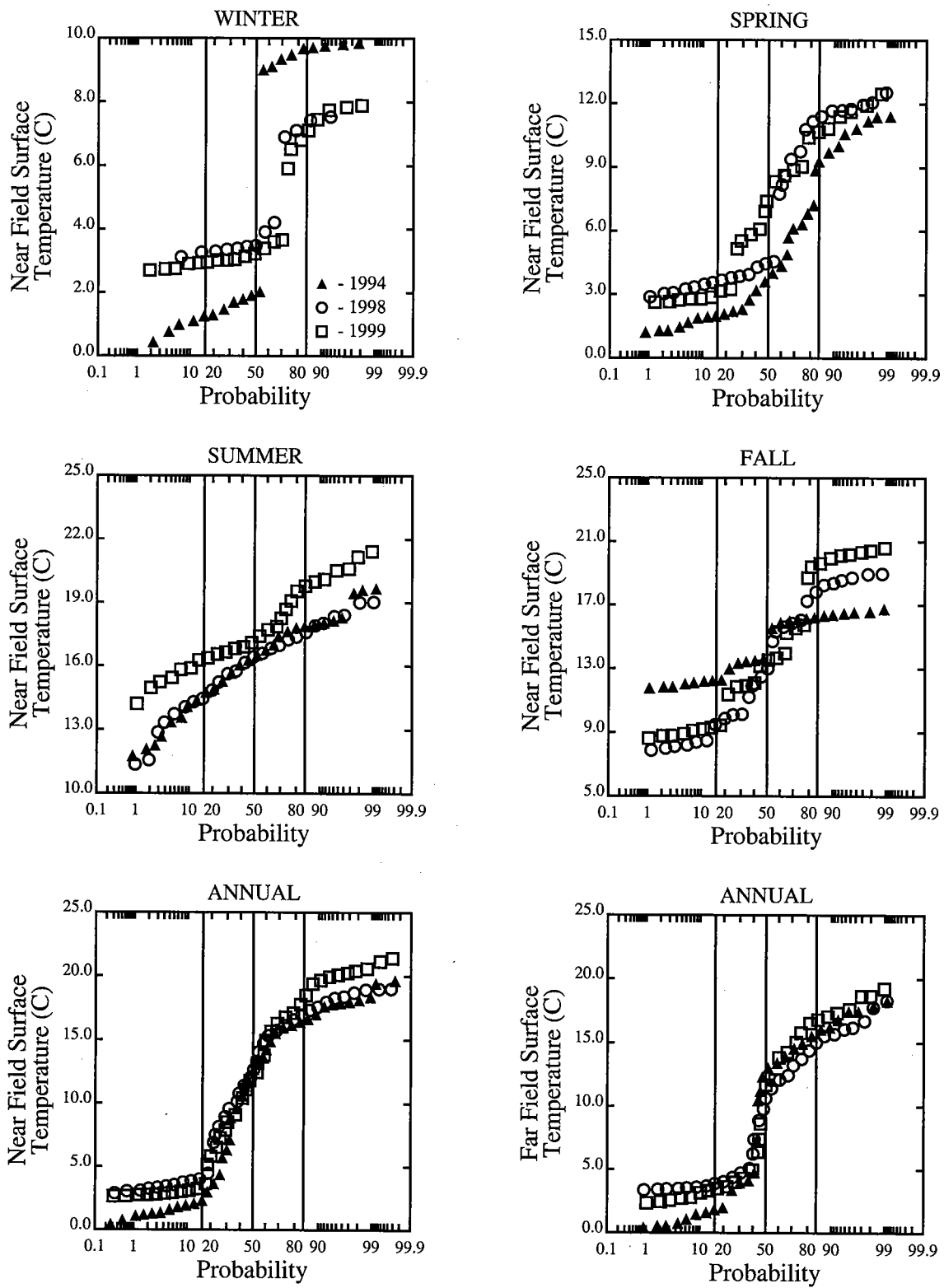


Figure 3-3. Surface Temperature Data Probability Distributions for 1994, 1998 and 1999

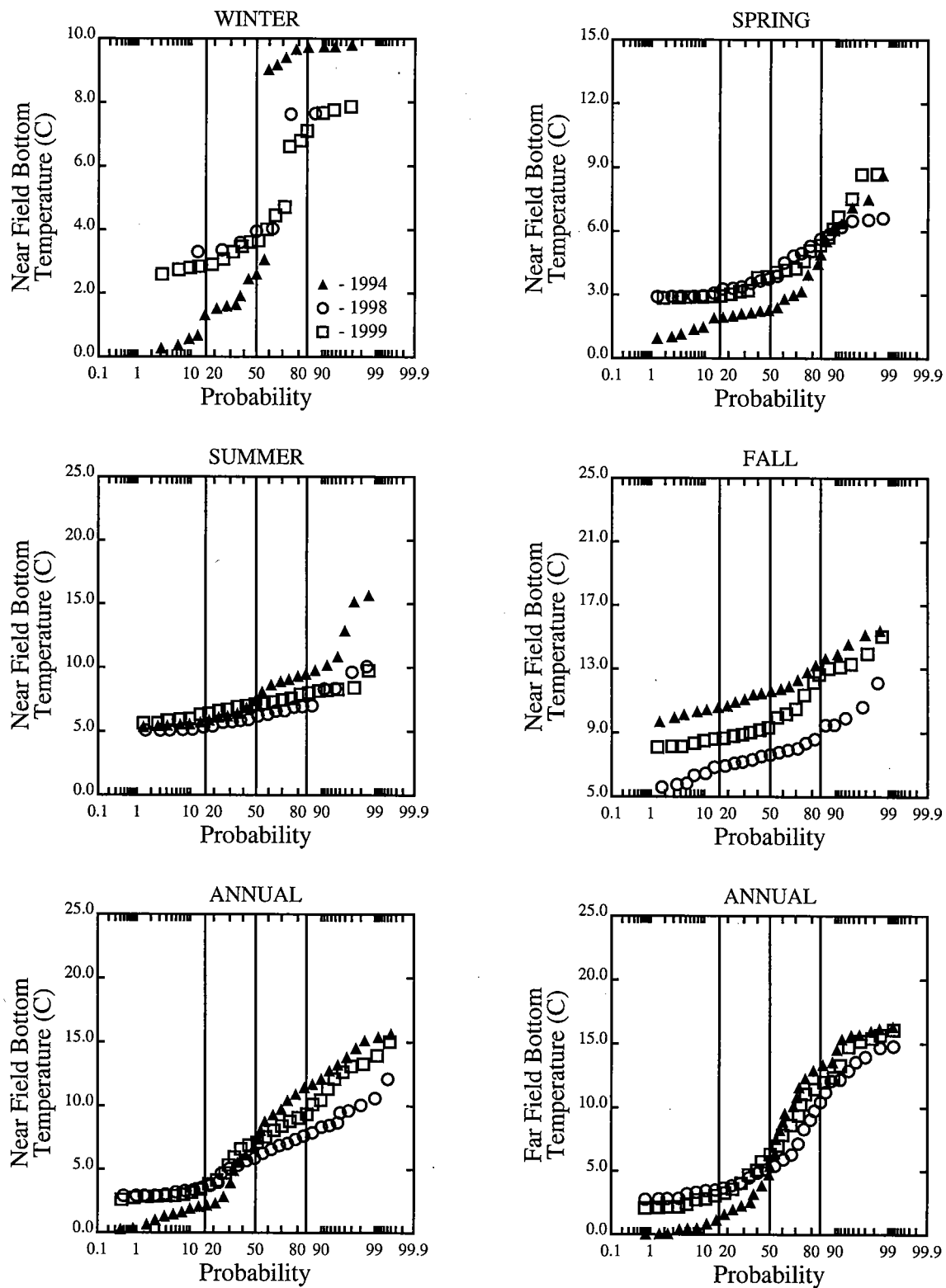


Figure 3-4. Bottom Temperature Data Probability Distributions for 1994, 1998 and 1999

3.2.2 Salinity

The surface salinity and the bottom salinity are presented in Figures 3-5 and 3-6, respectively. Note the scale difference between the two figures. Salinity is important because it contributes to the density stratification in the water column and it affects the dissolved oxygen saturation concentration in the water column. During the winter there is very little variation in both the surface and bottom salinity. The 1994 data are the most saline, but only by a few tenths of a ppt. During the spring, with its snow melt and rain events, there is more variability in the salinity data. Both the surface and bottom spring data indicate that 1994 was the most saline year of the three, while 1998 was the freshest. In the summer, 1994 and 1999 had very similar salinity levels. In June 1998, there was a major rainfall event and this drove the salinity to the lowest levels measured since the beginning of the HOM program. In the fall, 1994 and 1999 continued to have similar salinity concentrations in the surface and bottom. The 1998 salinity data are approximately 0.5 ppt lower than the other two years. The annual probability distributions indicate that 1994 and 1999 were similar with regard to salinity and that 1998 was substantially lower. These data show that there is a fair amount of variability in salinity in the bays from season to season and year to year.

3.2.3 Density

The density difference between the surface water and the bottom water is due a combination of the temperature and salinity differences. Larger differences in the gradient between the surface and bottom waters inhibit mixing and can prevent dissolved oxygen from the surface waters mixing downward and nutrients from the bottom waters mixing into the surface waters. 1998 had more annual rainfall than either 1994 or 1999, and had a large rainfall event during June. The larger amount of fresh water that entered the system during this period in 1998 resulted in greater density differences between the surface and bottom (Figure 3-7). In general, the density differences between the surface and bottom are smallest in the winter and the largest in the summer. All three years follow this pattern. During the fall 1994 had much less density stratification than the other two years. It is also apparent from the annual data that density differences during 1994 were slightly smaller than both 1998 and 1999. It is interesting that despite the differences in density between 1994 and 1999 during the fall, both of these years had some of the lowest DO concentrations measured in the bays.

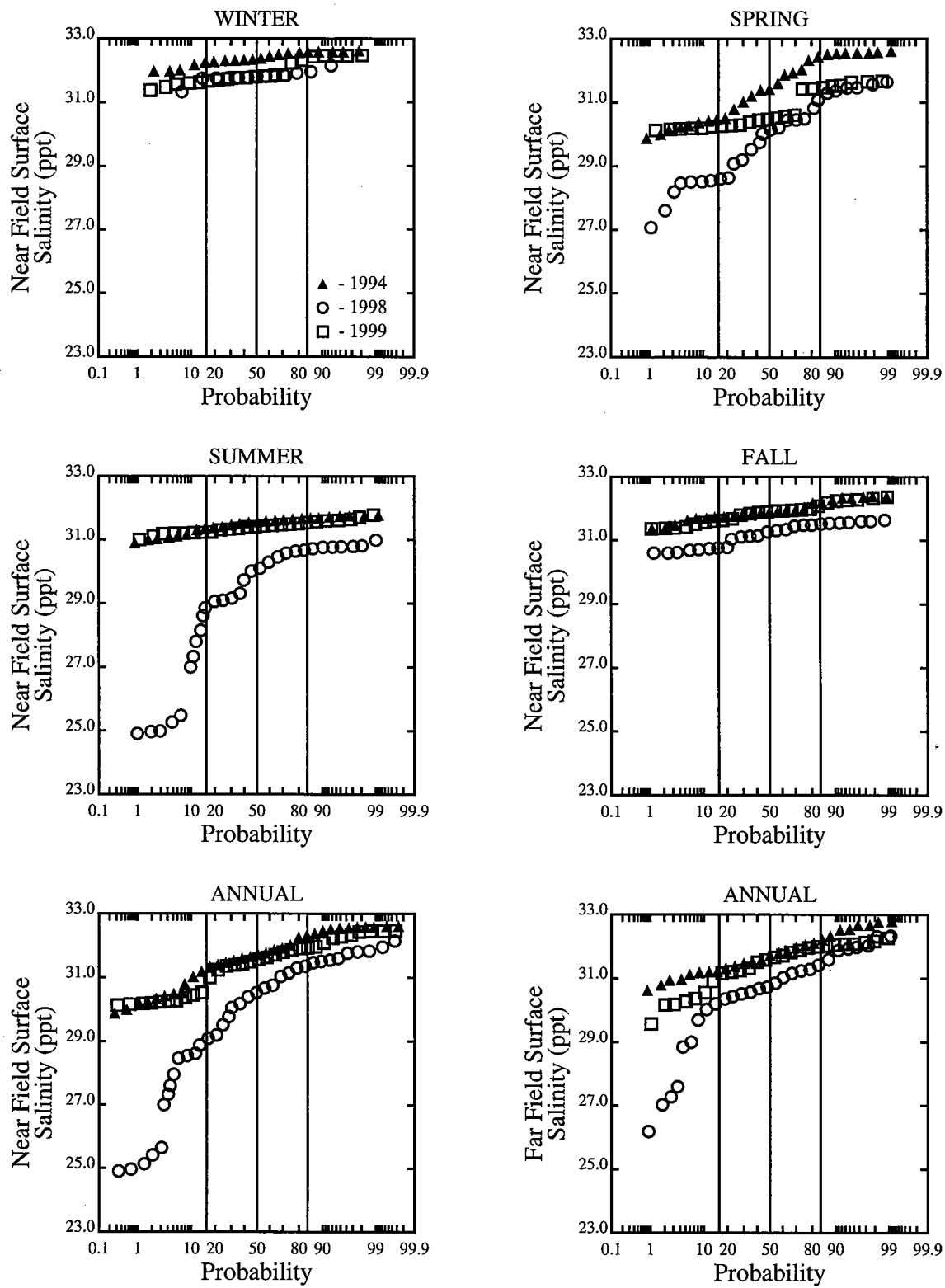


Figure 3-5. Surface Salinity Data Probability Distributions for 1994, 1998 and 1999

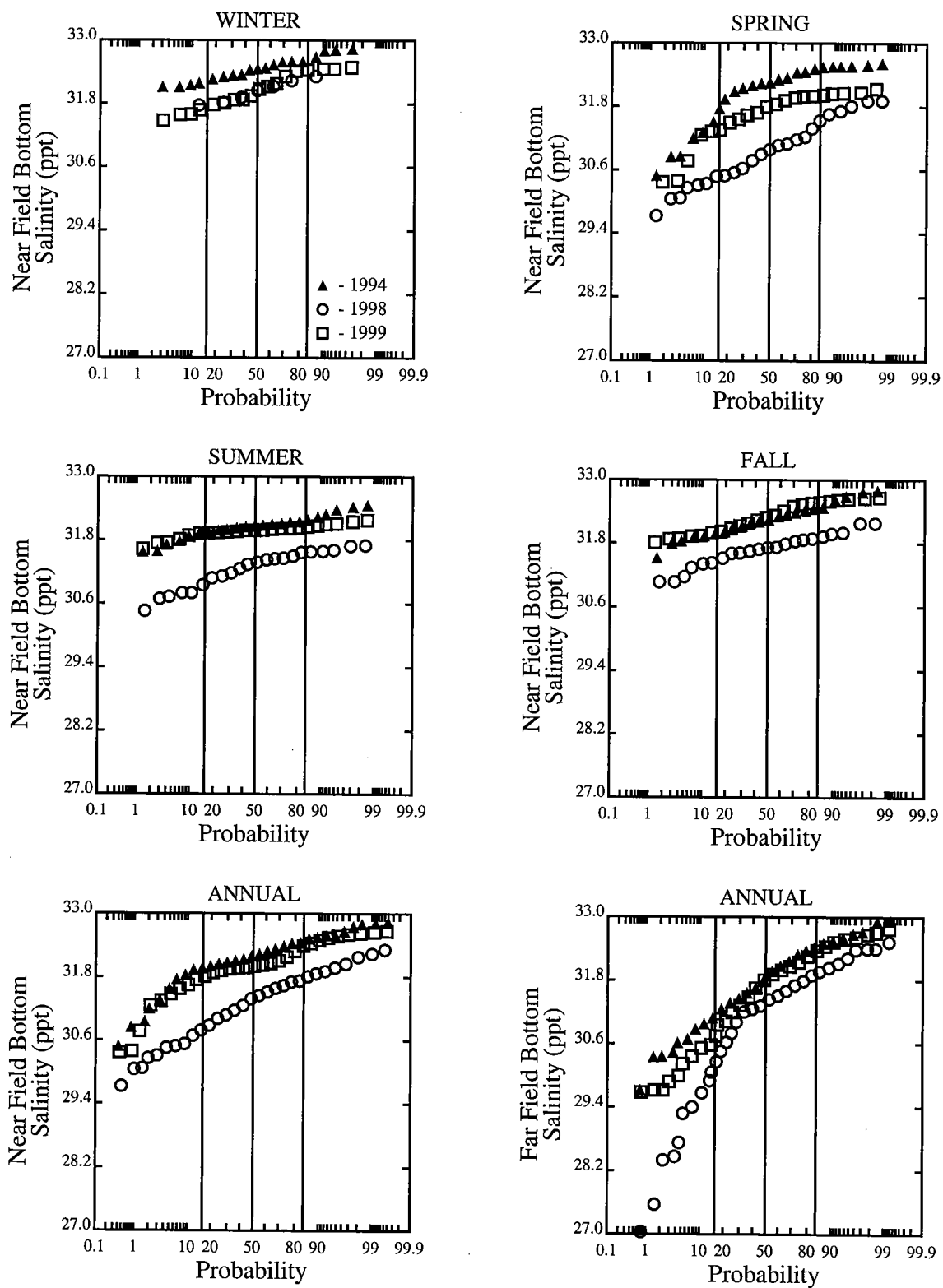


Figure 3-6. Bottom Salinity Data Probability Distributions for 1994, 1998 and 1999

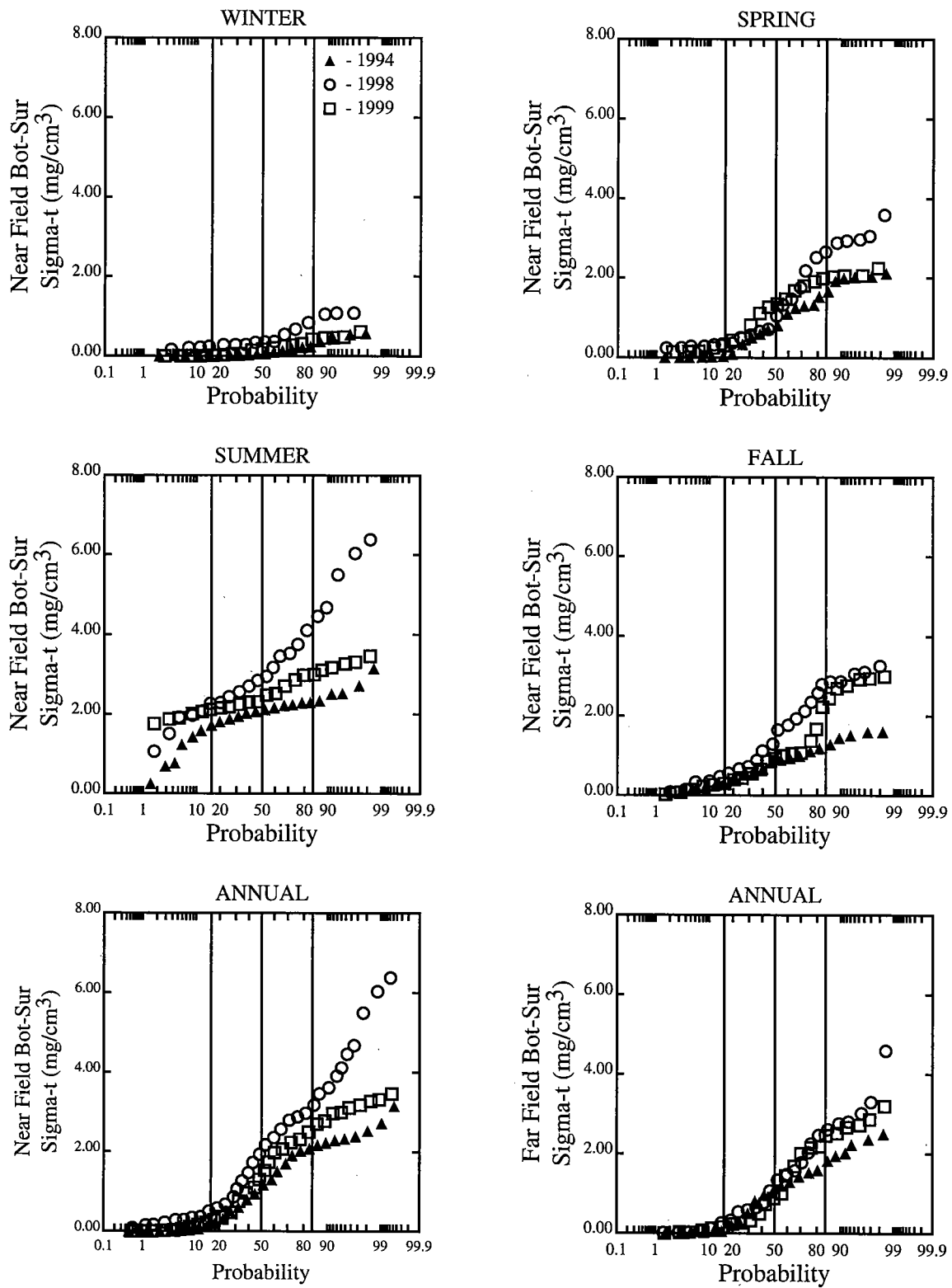


Figure 3-7. Probability Distributions for Surface to Bottom Density Differences in 1994, 1998 and 1999.

3.2.4 Chlorophyll-a

Chlorophyll-a is a commonly used indicator of algal biomass. Surface chlorophyll-a probability distributions are presented in Figure 3-8 (Note the log scale on the y-axis). During the winter, the data indicate that the chlorophyll-a concentrations were substantially higher in 1999 than in 1994 and 1998, which had similar chlorophyll-a levels. In the spring there is more variation between the years. 1994 and 1999 show evidence of a spring bloom while the 1998 spring chlorophyll concentrations were lower and similar to the winter 1998 chlorophyll concentrations. By the summer, all three years had similar chlorophyll-a concentrations. In the fall, the variation returns. In 1999, there is strong evidence of a fall bloom with chlorophyll-a concentrations greater than 30 ug/L. Lower chlorophyll-a levels are observed in 1994 and the lowest are observed in 1998. On an annual basis, the near field data clearly indicate that 1999 had the highest surface chlorophyll-a concentrations with a median chlorophyll-a concentration of approximately 3 ug/L. 1994 had the next highest median concentration of approximately 1.3 ug/L, followed by 1998 with a median concentration of slightly over 1.0 ug/L. The far field data also show 1999 as having higher surface chlorophyll-a concentrations than the other two years. Chlorophyll-a levels in 1994 and 1998 are much more similar.

In some cases, the highest chlorophyll-a concentrations are not observed at the surface; possibly due to photo-inhibition and algae's ability to increase chlorophyll-a production under lower light conditions. Mid-depth chlorophyll-a concentrations are presented in Figure 3-9. In general, the relative concentration patterns observed at the surface are observed at mid-depth with 1999 having the highest chlorophyll-a concentrations. The maximum concentrations were in most cases observed at the surface. Median concentrations were higher at the mid-depth during the summer and on an annual basis at the far field stations during 1999.

3.2.5 Fluorescence

Fluorescence can be used to estimate chlorophyll-a concentrations. Fluorescence can be easily measured with a probe; so more fluorescence measurements were taken than discrete chlorophyll-a concentration measurements. The surface fluorescence in Figure 3-10 shows essentially the same relative patterns as the chlorophyll-a data; however, the magnitude of the median fluorescence data sometimes differs from the median chlorophyll-a data. Examples of this are the winter of 1994 (1.43 vs. 0.78) and the winter and spring of 1999 (5.06 vs. 2.96 and 2.39 vs. 1.16, respectively). The same conclusion can be made with regard to the mid-depth fluorescence

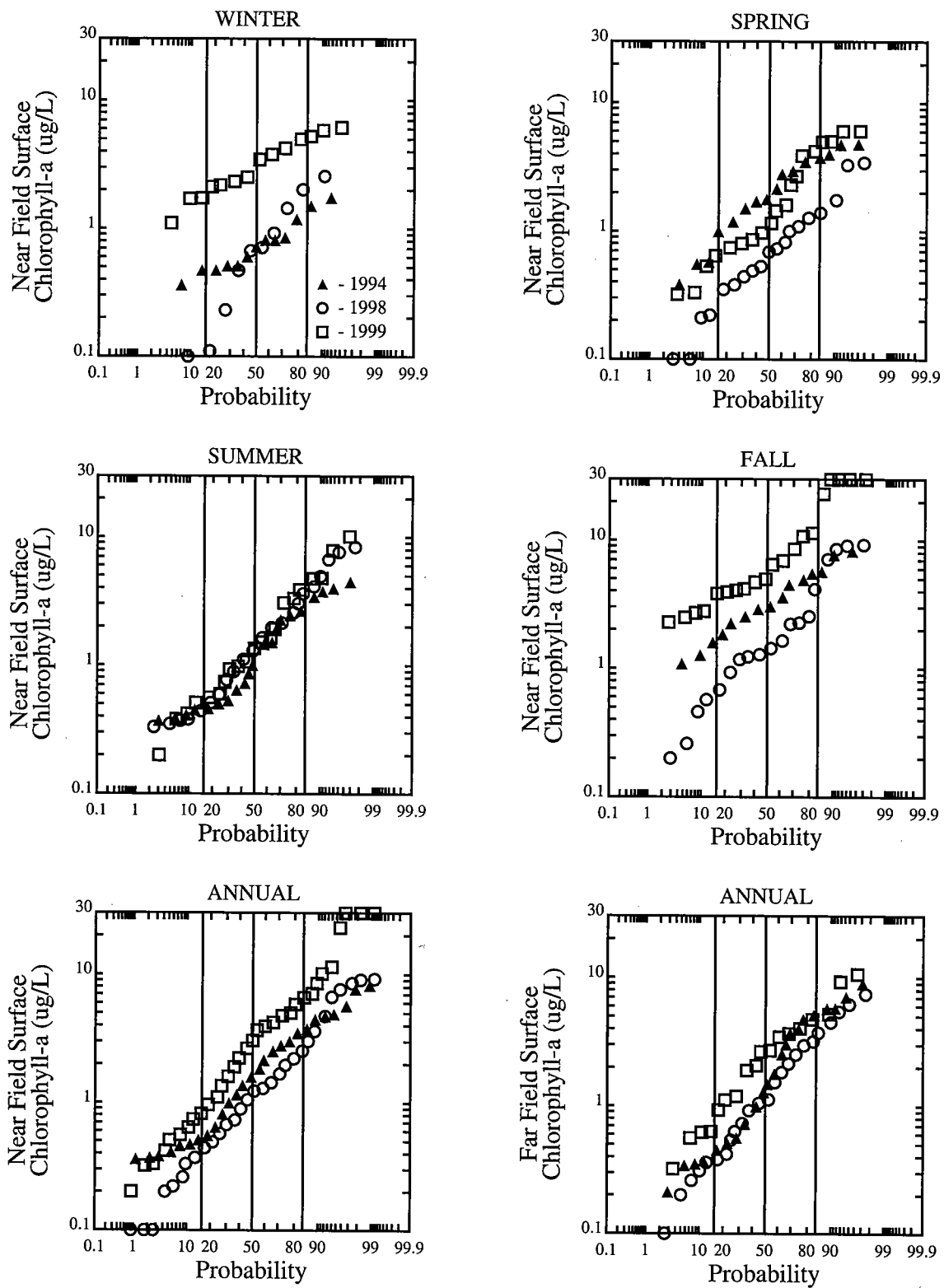


Figure 3-8. Surface Chlorophyll Data Probability Distributions for 1994, 1998 and 1999

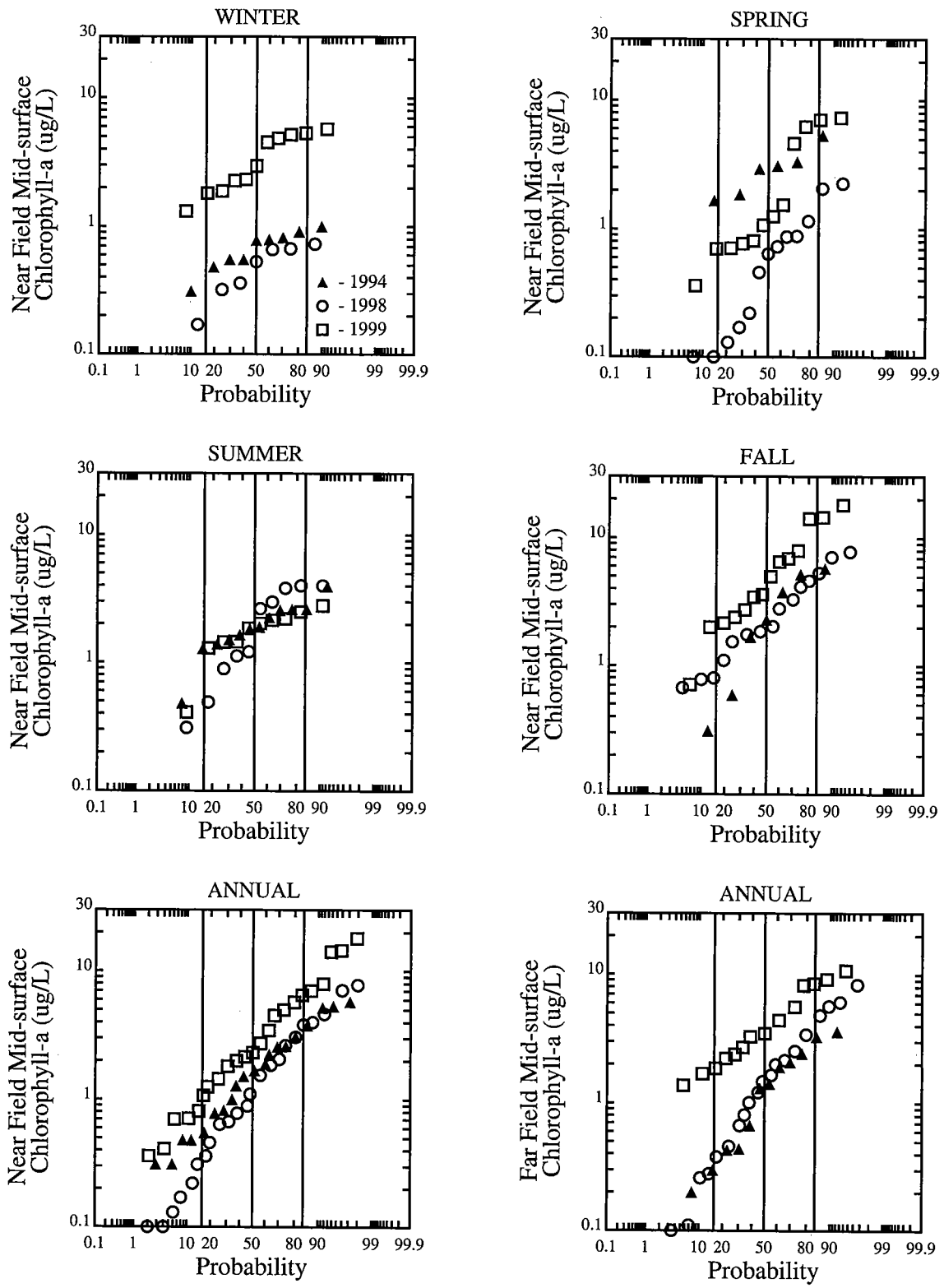


Figure 3-9. Mid-surface Chlorophyll Data Probability Distributions for 1994, 1998 and 1999

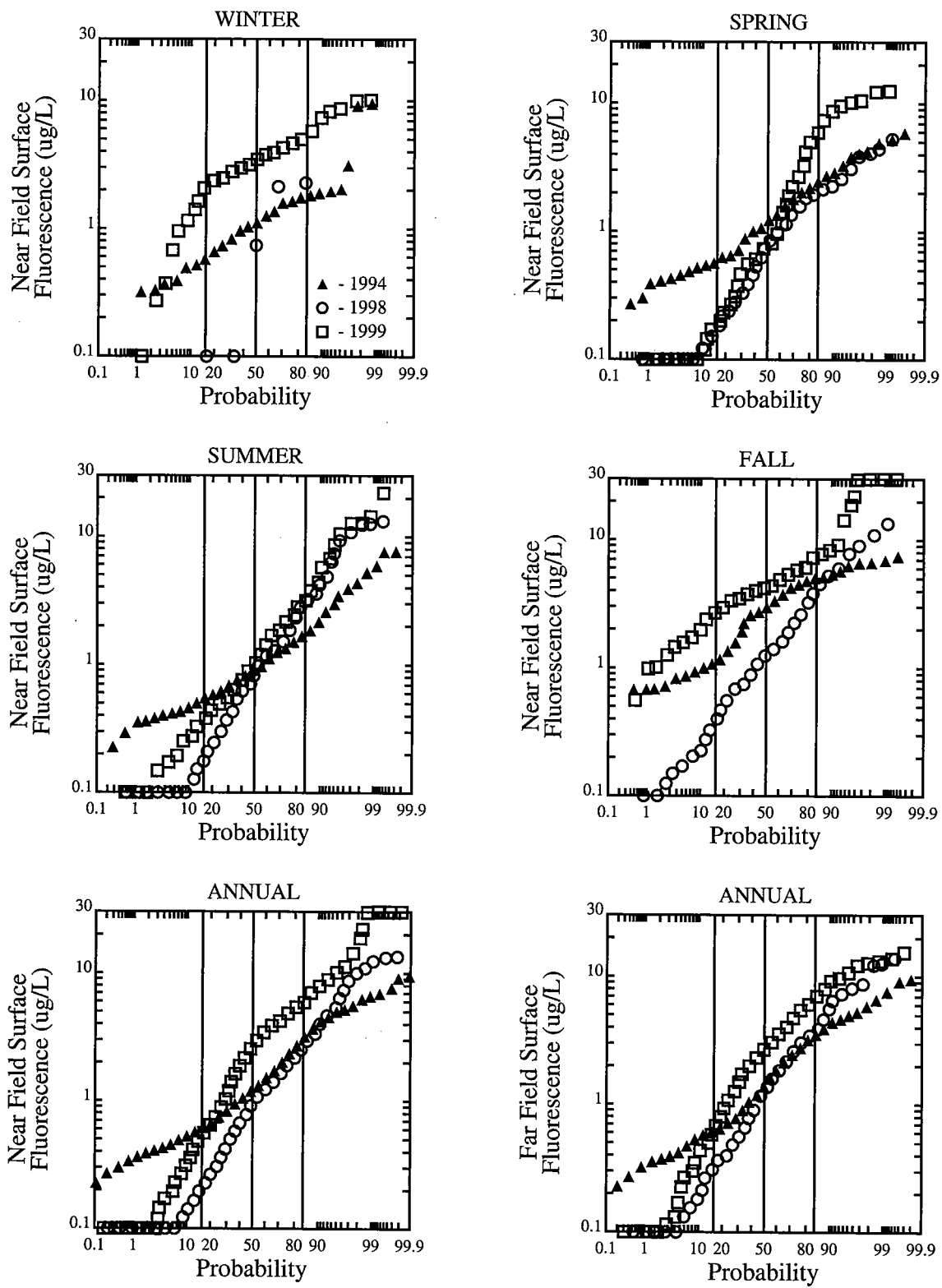


Figure 3-10. Surface Fluorescence Data Probability Distributions for 1994, 1998 and 1999

data (Figure 3-11). The 1994 winter fluorescence and chlorophyll-a near field data are quite a bit different and the annual far field chlorophyll-a data from 1999 is higher than the fluorescence data.

3.2.6 Particulate Organic Carbon

Particulate organic carbon (POC) can also be used as an indicator of algal biomass in regions removed from other sources of POC such as wastewater treatment plants. In Figure 3-12, the winter POC shows a similar pattern to the surface chlorophyll-a. The 1999 winter surface POC data are 2-3 times greater than the POC data from the other years. Trends in the spring POC data are quite a bit different from the chlorophyll-a data. The median 1994 spring chlorophyll-a data are the highest of the three years while the POC concentrations in the spring of 1994 are the lowest of the three years and 1999 is the highest. During the summer, the surface chlorophyll-a concentrations were very similar for the three years, but the 1998 and 1999 POC data are 3-4 times higher than the 1994 POC data with 1998 being the highest. This is interesting because the 1994 POC data were very similar to the 1992 and 1993 summer POC data (HydroQual, 2000). During the fall, the 1999 POC data are the highest followed by 1998 and 1994, respectively. On an annual basis, the near field median POC concentrations are 0.3, 0.19, and 0.11 mg/L, for 1999, 1998, and 1994 respectively. This differs from the chlorophyll-a data because the median near field chlorophyll-a in 1994 is higher than the 1998 median.

3.2.7 Phosphate

Figure 3-13 presents the probability distributions for the surface phosphate (PO_4) data. During the winter, the PO_4 data are quite similar from year to year. Moving forward into the spring, the 1998 and 1999 data remain similar, but there is an indication of uptake by algae in 1994 due to the decline in the PO_4 concentrations on the lower end of the distribution. 1994 has much lower PO_4 data on the order of 20 percent of the time. These lower PO_4 concentrations appear to be short lived because they are not apparent in the summer of 1994. In 1999 and especially 1998 lower summer PO_4 concentrations are observed. By the fall the majority of data are the same between the years, although approximately 10 percent of the data in 1998 are lower than in the other years. In general, PO_4 is not the limiting nutrient in Massachusetts and Cape Cod Bays for algal growth, but in a few cases in the spring of 1994 and the summer of 1998 the concentrations appear to be low enough to have been limiting (< 0.004 mg P/L).

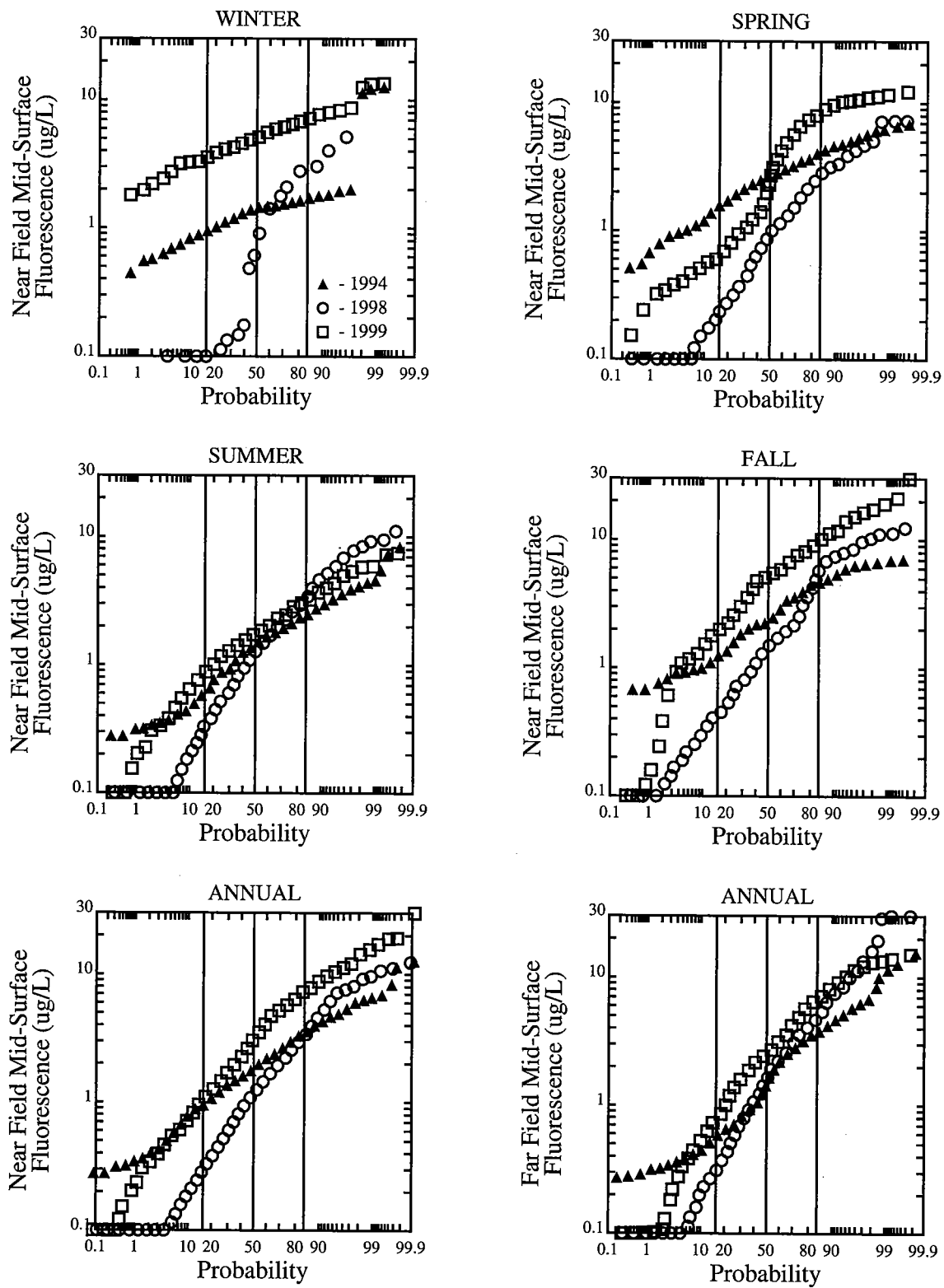


Figure 3-11. Mid-surface Fluorescence Data Probability Distributions for 1994, 1998 and 1999

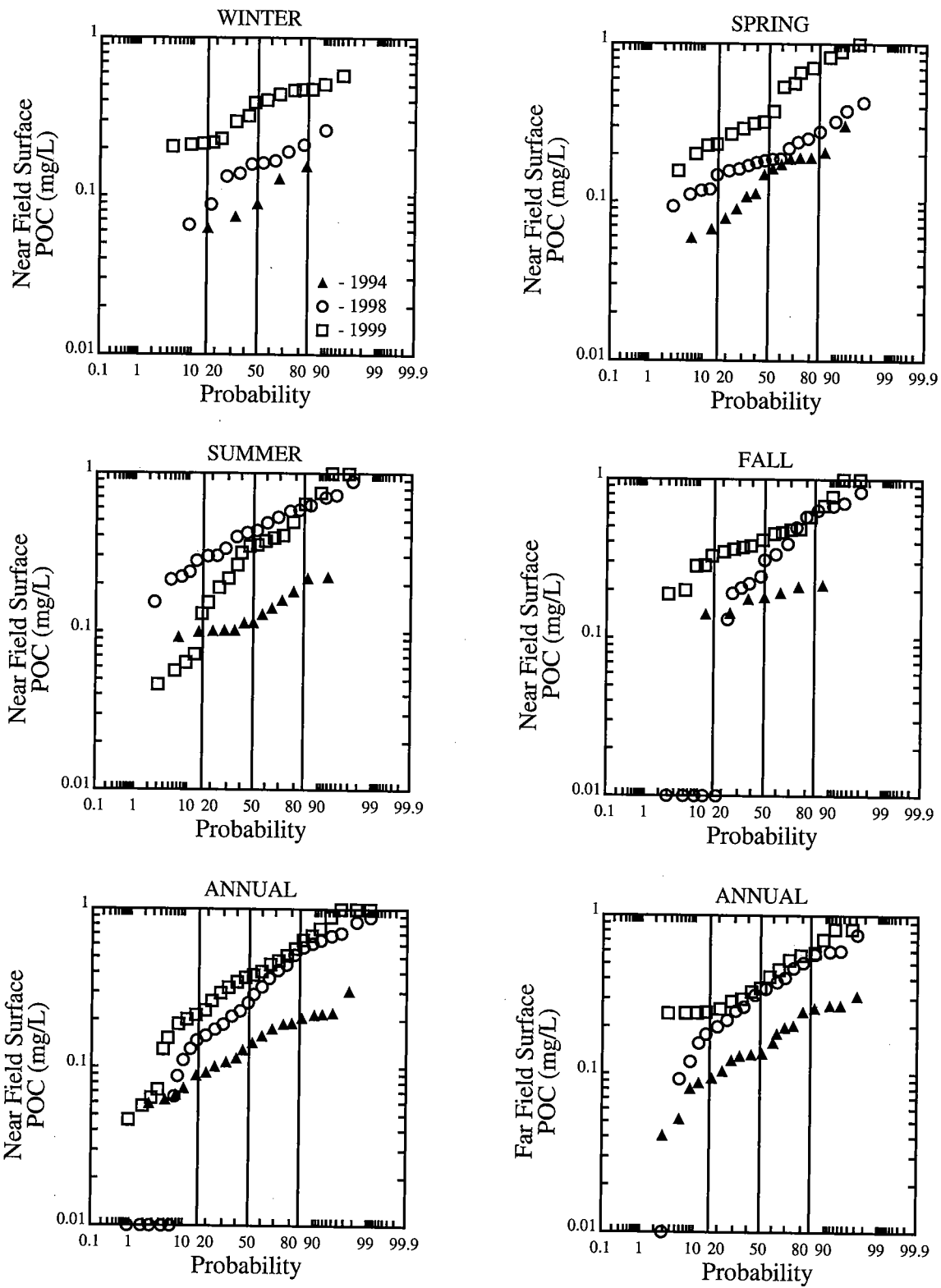


Figure 3-12. Surface POC Data Probability Distributions for 1994, 1998 and 1999

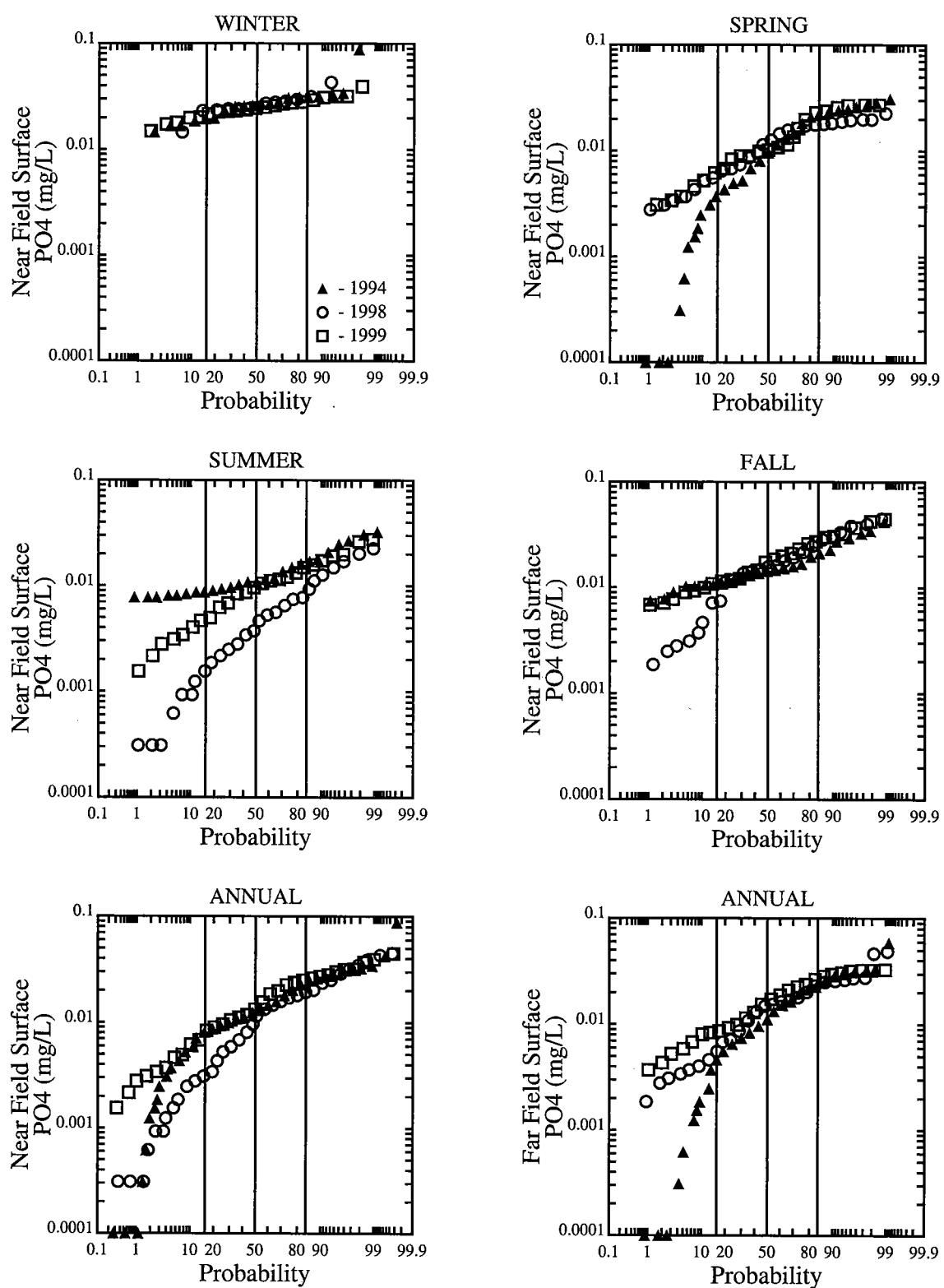


Figure 3-13. Surface PO₄ Data Probability Distributions for 1994, 1998 and 1999

3.2.8 Dissolved Inorganic Nitrogen

Dissolved inorganic nitrogen (DIN) is the sum of ammonium (NH_4), nitrite (NO_2) and nitrate (NO_3) nitrogen. In general, when the waters of Massachusetts and Cape Cod Bays are found to be nutrient limiting to algal growth, it is usually due to either nitrogen or silica. When DIN concentrations fall below 0.04 mg N/L, nitrogen is thought to be the limiting nutrient. Figure 3-14 presents the surface DIN probability distributions. On initial inspection, DIN appears to be very similar from year to year. This is in part due to the use of a log scale on the y-axis. Upon closer inspection, however, it is apparent that the 1994 data in the summer and fall are on the order of two times lower than the data in 1998 and 1999. The far field data show a larger difference between 1994 and the other years. The median DIN in 1994 is nearly a factor of ten less than the median of the data in 1998 and 1999. This is also an interesting observation. The 1998 and 1999 POC data tend to be higher than the 1994 POC, yet it is the 1994 DIN data that are lower than the other two years.

3.2.9 Dissolved Silica

Figure 3-15 presents the surface dissolved silica (DSi) probability distributions. During the winter, the lowest DSi concentrations were measured in 1999. In the spring, the lowest values were measured in 1994. In 1999, there is also evidence of uptake of silica by diatoms for part of the spring. The 1998 DSi spring concentrations show only a minor decline from the winter DSi concentrations. In the summer period, the relative magnitude of the silica concentrations has changed; 1999 has the highest minimum concentrations and 1998 has the lowest DSi concentrations except for approximately 10 percent of the summer. In the fall, the 1999 DSi concentrations are a factor of two higher than the 1994 and 1998 data, which have similar concentration distributions. What is noteworthy about this observation is that a fall bloom was observed in 1999, yet the highest DSi concentrations were also observed in 1999. This may indicate that the 1999 bloom was not a diatom bloom as was the case in 1993. On an annual basis, the 1999 DSi data are higher than the other years approximately 50 percent of the time and all of the years are similar during the other 50 percent of the time.

3.2.10 Nutrient Ratios

Analyzing nutrients ratios of over the course of the year can indicate which nutrient may be potentially limiting during portions of the year. Assuming a Redfield ratio for the phytoplankton, the ratio of DIN to DIP (dissolved inorganic phosphorus or PO_4) that determines whether nitrogen

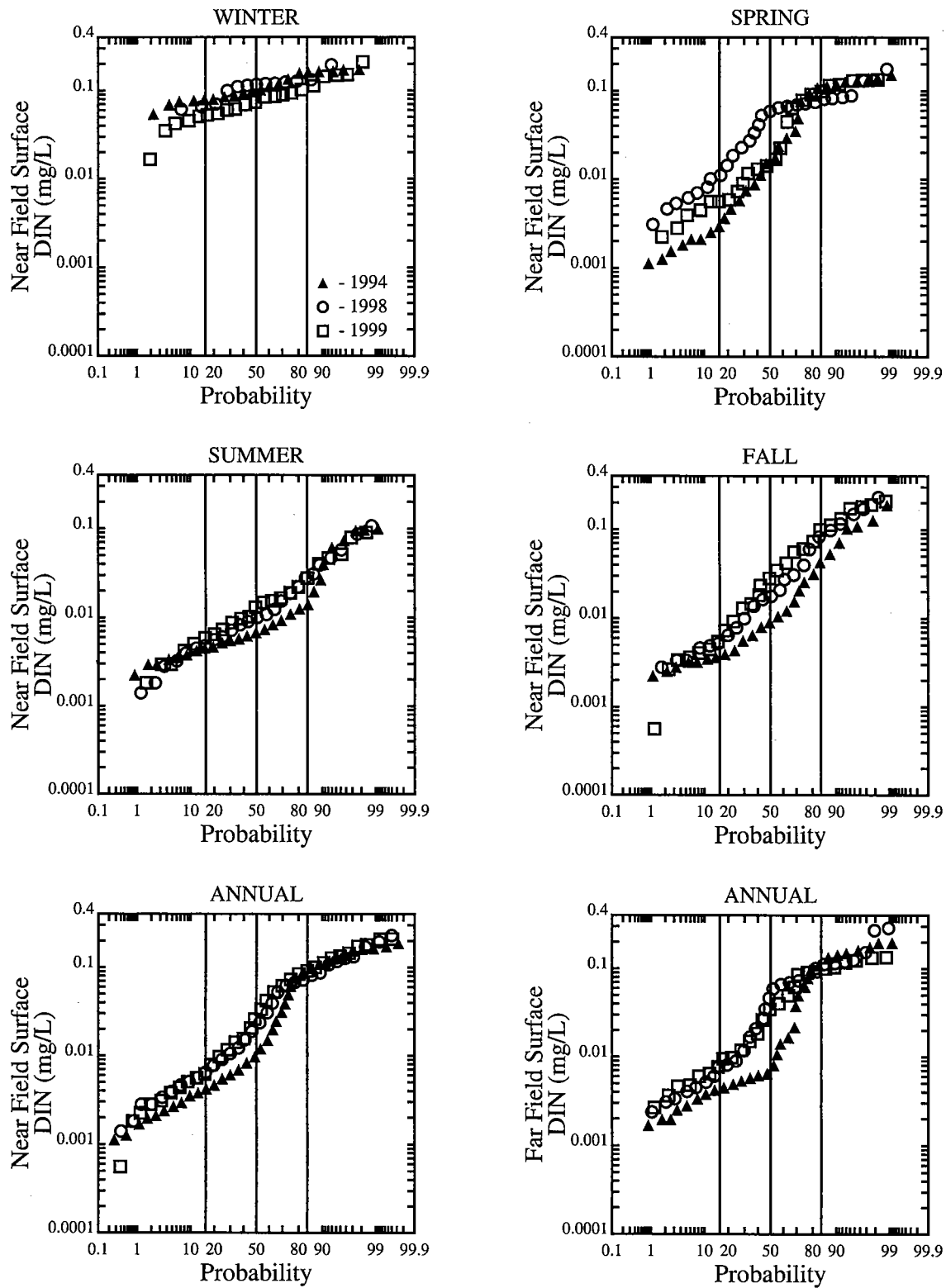


Figure 3-14. Surface DIN Data Probability Distributions for 1994, 1998 and 1999

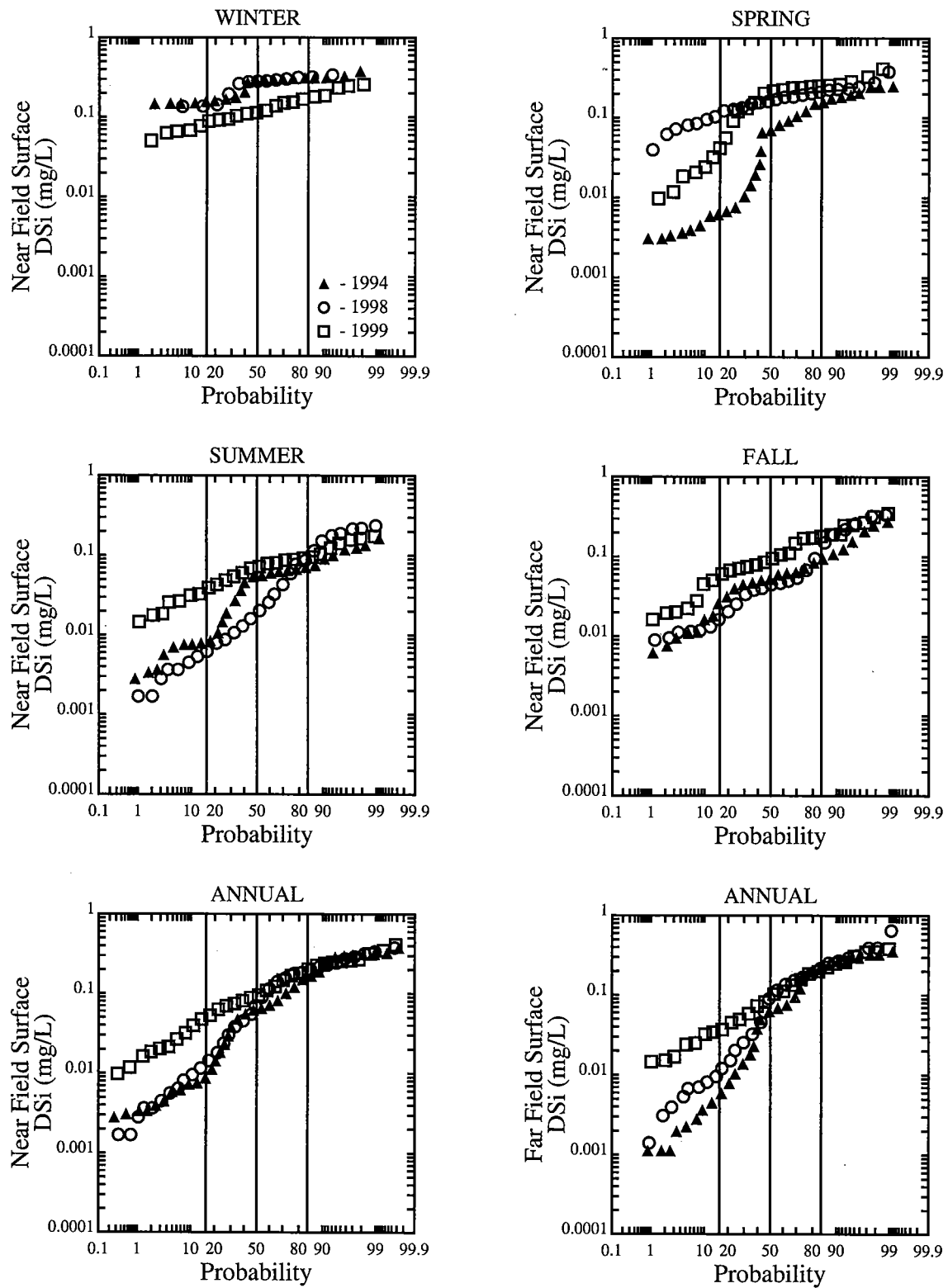


Figure 3-15. Surface DSi Data Probability Distributions for 1994, 1998 and 1999

or phosphorus is the limiting nutrient is 7.0. If the ratio is below 7.0, nitrogen is the potentially limiting nutrient. Conversely, if the ratio is above 7.0, phosphorus is the potentially limiting nutrient. However, while one nutrient may be more potentially limiting, it is not until one evaluates the actual concentrations of the nutrient that one can determine if nutrient limitation is occurring. Figure 3-16 presents the probability distributions of the DIN/DIP ratio. It is apparent that both the near field and far field are more potentially nitrogen limited. The year and season that is the most potentially phosphorus limited is the summer of 1998 when potential phosphorus limitation occurred 10 percent of the time.

Determining a ratio at which nitrogen or silica is the potentially limiting is not as straightforward as it is for nitrogen and phosphorus. Diatoms are the only algal group that requires silica, so that when a mixed assemblage of algae are present the silica concentration levels may only be limiting to diatom growth. Assuming, however, that only diatoms are present, and using the C:N and C:Si ratios assumed in the model, a DIN to DSi ratio of less than 0.5 suggests that DIN may potentially limit diatom growth, while a ratio greater than 0.5 suggests the silica may potentially limit diatom growth. Figure 3-17 presents the probability distributions for the surface DIN to DSi ratio at the near field and far field stations. During the winter the DIN/DSi ratio is close to 0.5 during all three years. Of these three years, 1999 is the most potentially silica limiting for diatoms. In the spring, 1994 is almost equally divided between being potentially silica limiting and potentially DIN limiting. 1998 and 1999 are shifted more toward being potentially DIN limited. During the summer it is 1998 that is almost equally divided between potential DIN or DSi limitation with 1994 and 1999 being more potentially DIN limited. During the fall, all three years are slightly more potentially DIN limiting.

3.2.11 Dissolved Oxygen

The dissolved oxygen (DO) of a water body is one of the more important water quality parameters. Since DO is necessary to maintain aquatic life, it reflects the general health of a water body and indicates the ability of an aquatic ecosystem to support a balanced habitat. When periods of hypoxia ($\text{DO} < 3.0 \text{ mg O}_2/\text{L}$) occur, the ability of fish and other aquatic life to reproduce and grow may be impaired. A review of the available data indicates that Massachusetts and Cape Cod Bays do not experience hypoxic conditions. The current Massachusetts state DO standard is never less than $6.0 \text{ mg O}_2/\text{L}$ (unless background conditions are lower).

Figure 3-18 presents seasonal and annual bottom DO probability distributions for 1994, 1998 and 1999. The DO concentrations that occurred during these three years are very similar during the winter and spring with variations from year to year generally less than 0.5 mg/L . During the summer, 1994 and 1999 remain similar while 1998 DO concentrations are $1\text{-}2 \text{ mg/L}$ higher than

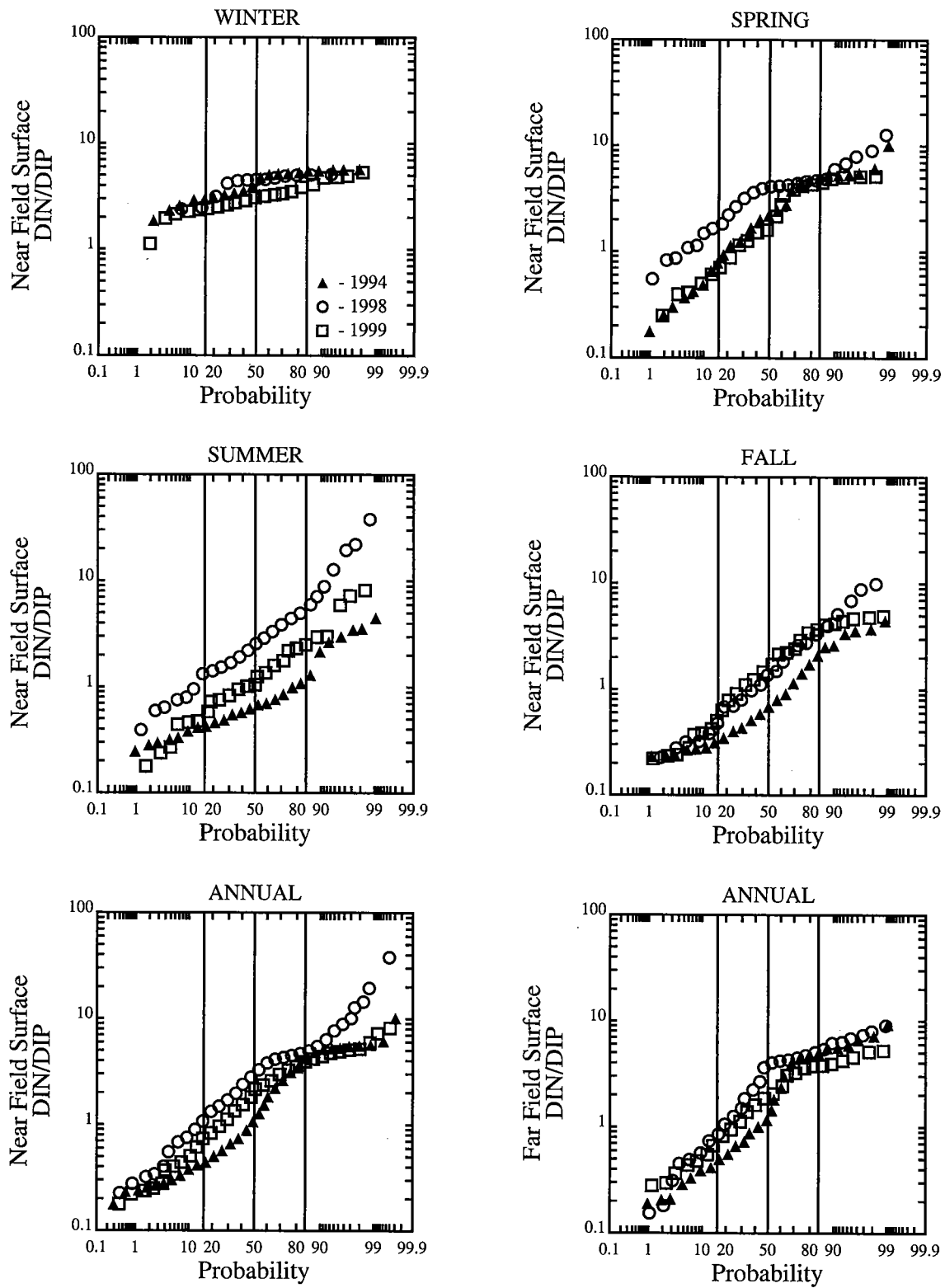


Figure 3-16. Surface DIN/DIP Data Probability Distributions for 1994, 1998 and 1999

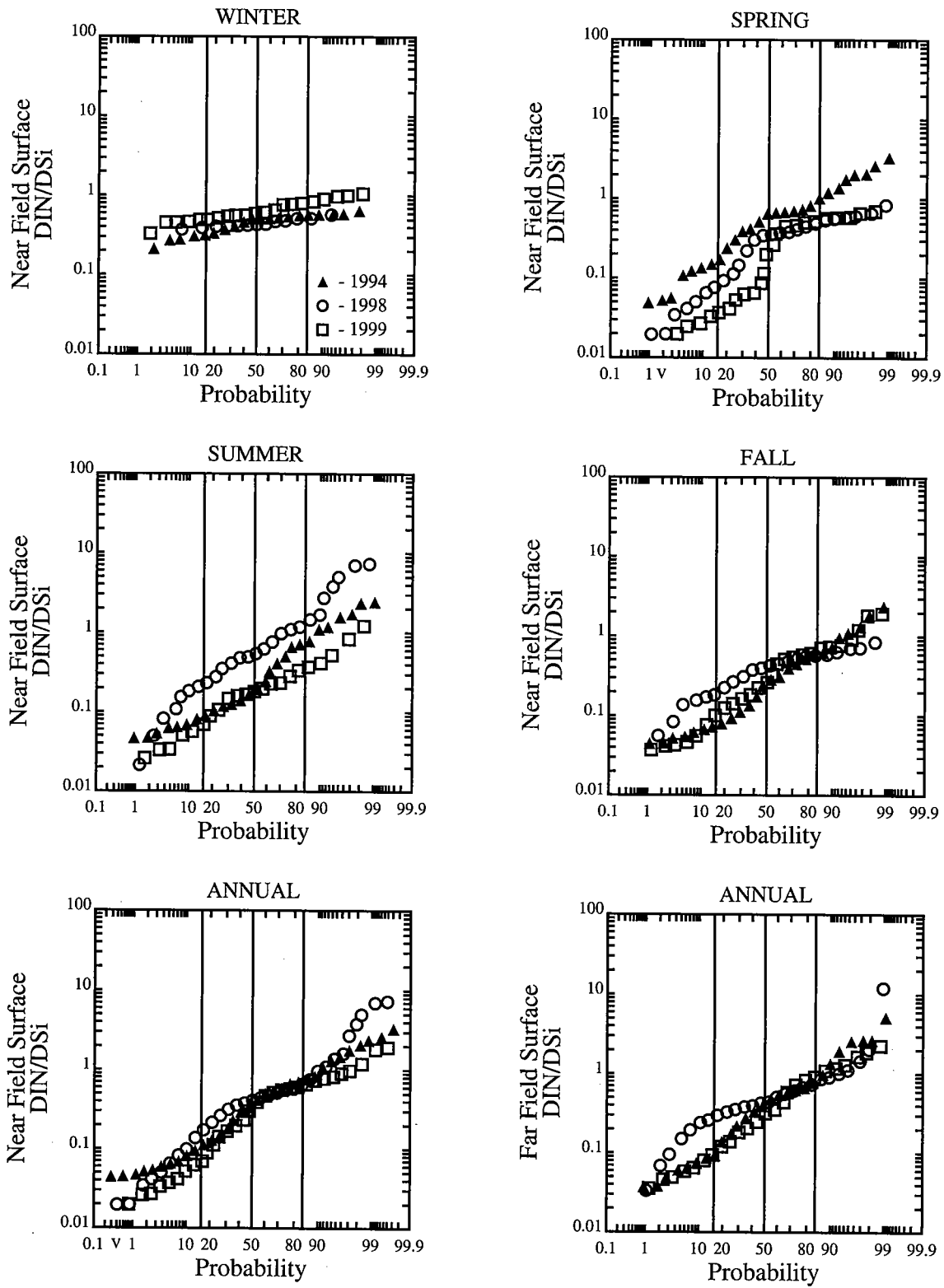


Figure 3-17. Surface DIN/DSi Data Probability Distributions for 1994, 1998 and 1999

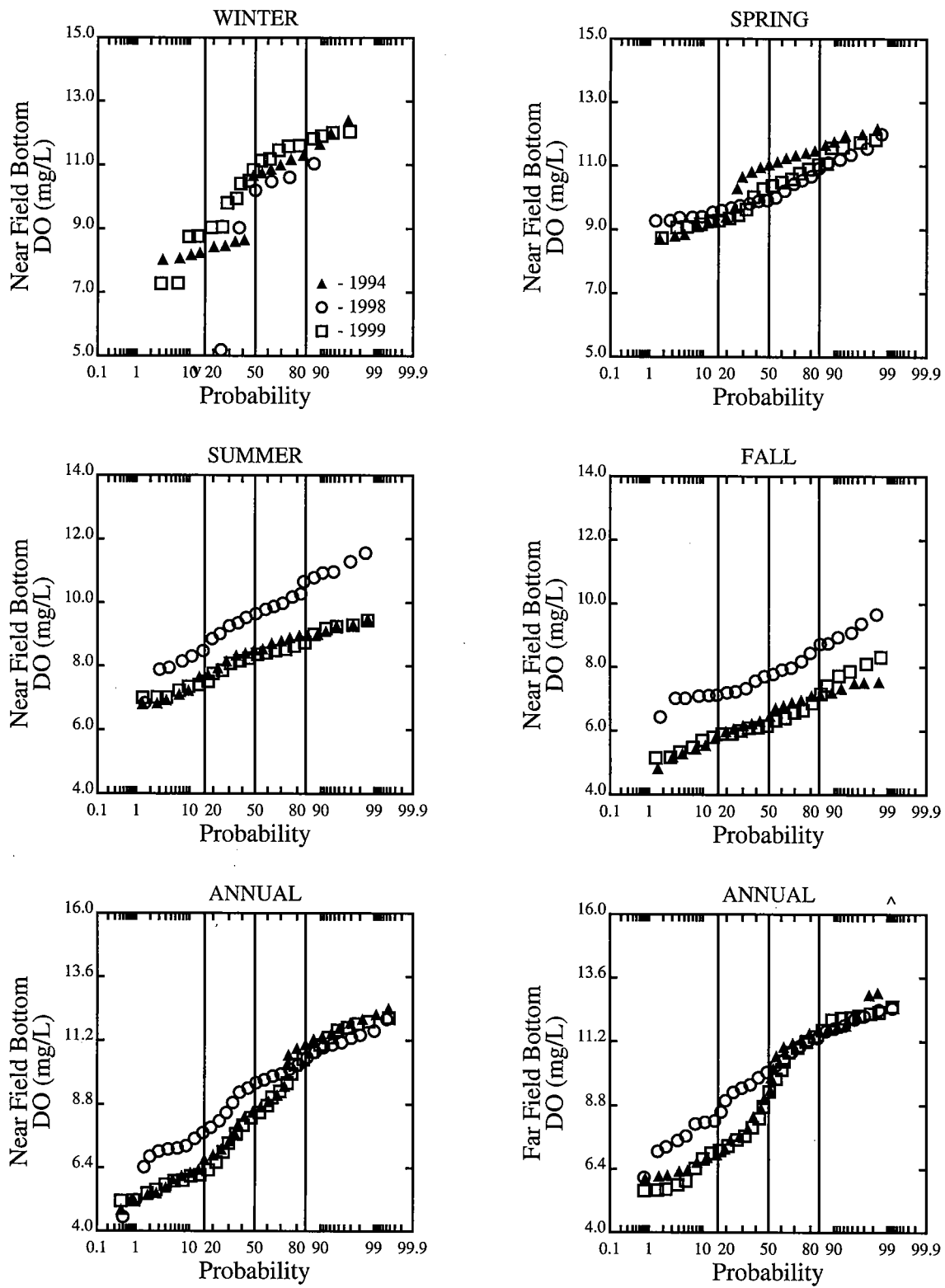


Figure 3-18. Bottom DO Data Probability Distributions for 1994, 1998 and 1999

the other years. While 1994 was shown to have lower DO in the summer than 1992 and 1993 (HydroQual, 2000), the higher summer DO concentrations in 1998 are approximately 1.0 mg/L higher than those observed in 1992 and 1993. The fall DO concentrations in 1994 and 1999 are also quite similar and are among the lowest DO measurements taken during the HOM program. The data show that during the fall of 1994 and 1999 approximately 20 percent of the DO measurements were less than the state standard 6.0 mg/L. The fall DO concentrations in 1998 are approximately 1.5 mg/L higher than those observed in 1994 and 1999. On an annual basis, the years 1994 and 1999 were quite similar from a DO perspective, while 1998 had higher DO concentrations in the summer and fall. (Note: the low DO concentrations measured during the winter of 1998 are under review and may be adjusted slightly higher.)

3.2.12 Water Quality Data Summary

The data collected as part of the HOM program, and presented above, indicate that there can be a high degree of year to year variability in the water quality conditions within Massachusetts and Cape Cod Bays. These large variations occur during a period of time when the anthropogenic sources to the bays are relatively constant, as shown in Section 2, or have been reduced as in the case of carbon loadings. The largest variations are observed in the chlorophyll-a, POC and DO. The reasons for these differences cannot be gleaned from only the water quality data. Some potential causes for these differences are meteorological forcings that affect temperature, salinity and circulation and also changes that occur out in the Gulf of Maine that effect the bays near the "boundary" of the bays.

3.3 BOUNDARY DATA

The data collected near the boundary of the water quality model are very important due to the significant impact the Gulf of Maine has on water quality conditions in Massachusetts and Cape Cod Bays. The majority of the flow that enters Massachusetts Bay from the Gulf of Maine enters from the north around Cape Ann. The circulation in the bays is generally counterclockwise so the water that enters Massachusetts Bay from the Gulf of Maine exits Cape Cod Bay near Race Point. For this reason, stations F26 and F27 are the key stations for assigning boundary conditions for the model. Since these are far field stations, they are sampled six times per year, generally in February, March, April, June, August and October. Station F26 is classified by Battelle as station type E. At type E stations, NH_4 , NO_2 , NO_3 , PO_4 , SiO_4 , and DO are measured. Station F27 is classified as station type D. At type D stations, the inorganic nutrients for type E stations are measured, as well as dissolved organic carbon (DOC), total dissolved nitrogen (TDN), total dissolved phosphorus (TDP),

particulate carbon (PC), particulate nitrogen (PN), particulate phosphorus (PP), biogenic Si, chlorophyll, total suspended solids (TSS), DO, phytoplankton and zooplankton.

The following section will present data from stations F26 and F27 as they are used to guide the specification of boundary conditions. In the model, boundary conditions are specified at four specific depths or "standard levels." The model then interpolates these standard level concentrations to the 10 sigma layers in the model at the boundary. These standard levels are specified at depths of 0, 20, 60 and 110 meters. The data used to aid in the specification of these concentrations were extracted from depths of 0-5 m, 10-30 m, 50-70 m and greater than 80 m. The figures that follow will present the data at each standard level.

Figure 3-19 presents phytoplankton carbon data. These data are somewhat different from the other data that will be presented. These data are estimates of the phytoplankton carbon biomass from abundance data, rather than actual biomass measurements. Estimates were available for the top two levels. In 1998, the phytoplankton biomass is low, no spring bloom was observed. There is a small increase in June followed by a large peak in August that is followed by phytoplankton levels in October similar to June levels. In 1999, there is a small peak in late February that was not observed in 1998. Also, the 1999 phytoplankton levels in August and October are higher than those observed in 1998.

The TDP data collected in 1994, 1998 and 1999 at station F27 is presented in Figure 3-20. The data in the top five meters show a decline from winter concentrations into the spring or summer followed by an increase during the fall. In 1994, the TDP reaches lower levels than in 1998 or 1999. At the mid-depths it is more difficult to discern a pattern. At the deepest level, lower concentrations are observed in the spring, but during the rest of the year the concentrations are relatively constant.

The phosphate (PO_4) data in Figure 3-21 show a similar pattern to the TDP data. During the winter the majority of TDP concentration is composed of PO_4 . During the summer, the surface TDP is comprised mostly of dissolved organic phosphorus (DOP). 1994 differs from the other two years in that there is a precipitous decline in the surface and mid-depth PO_4 . In 1998 and 1999, the decline in the PO_4 is much more gradual. This suggests that there was a stronger spring bloom in 1994 than in the other years.

TDN data are presented in Figure 3-22. The surface TDN data are quite similar in all three years with concentrations of approximately 0.20 mg/L throughout the year. Two exceptions are large spikes in March and August of 1998. Based on the inorganic nitrogen data that follows, the increases are due to spikes in the dissolved organic nitrogen (DON). Again, the TDN data at the

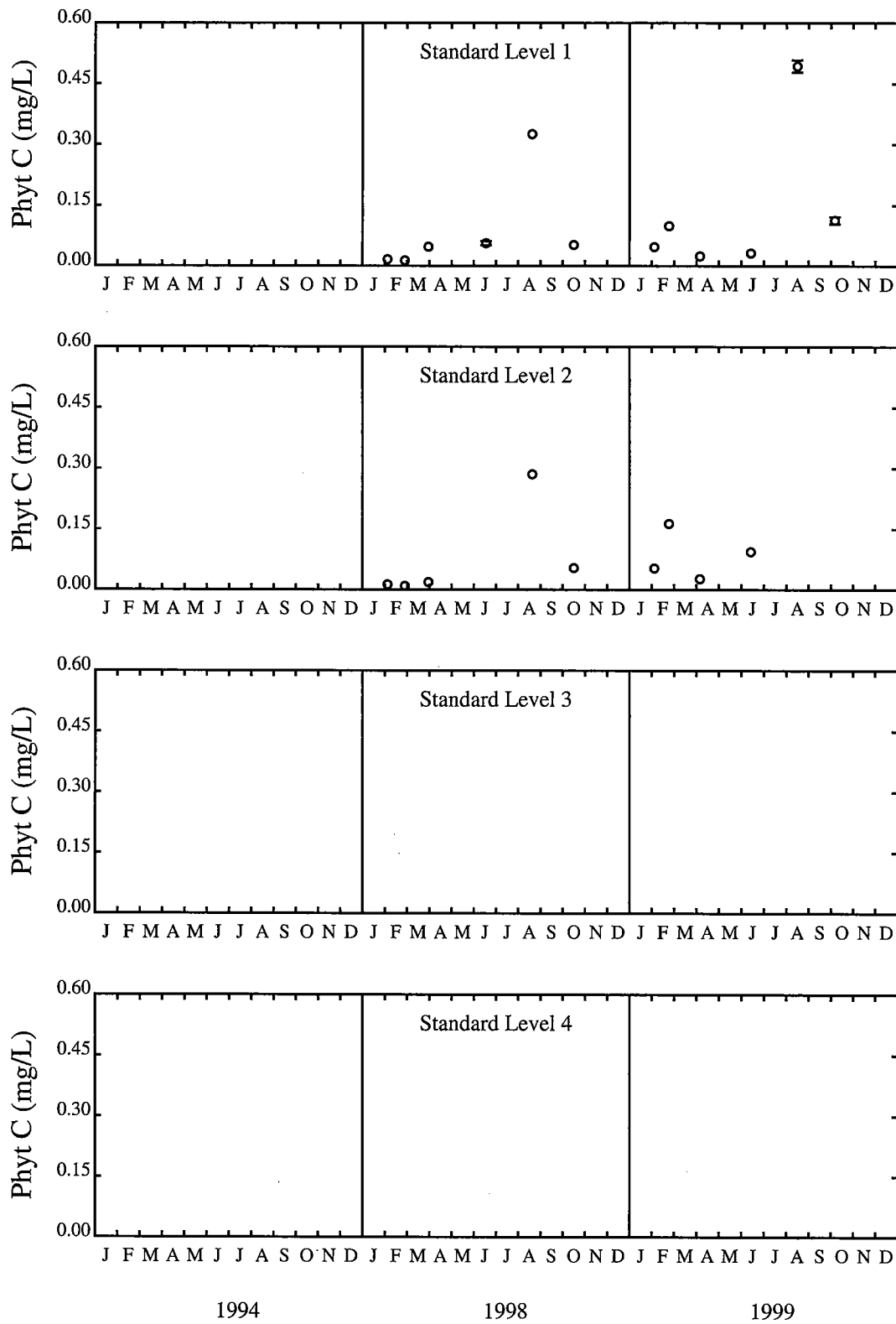


Figure 3-19. Estimated Phytoplankton Carbon Biomass Near Water Quality Model Boundary

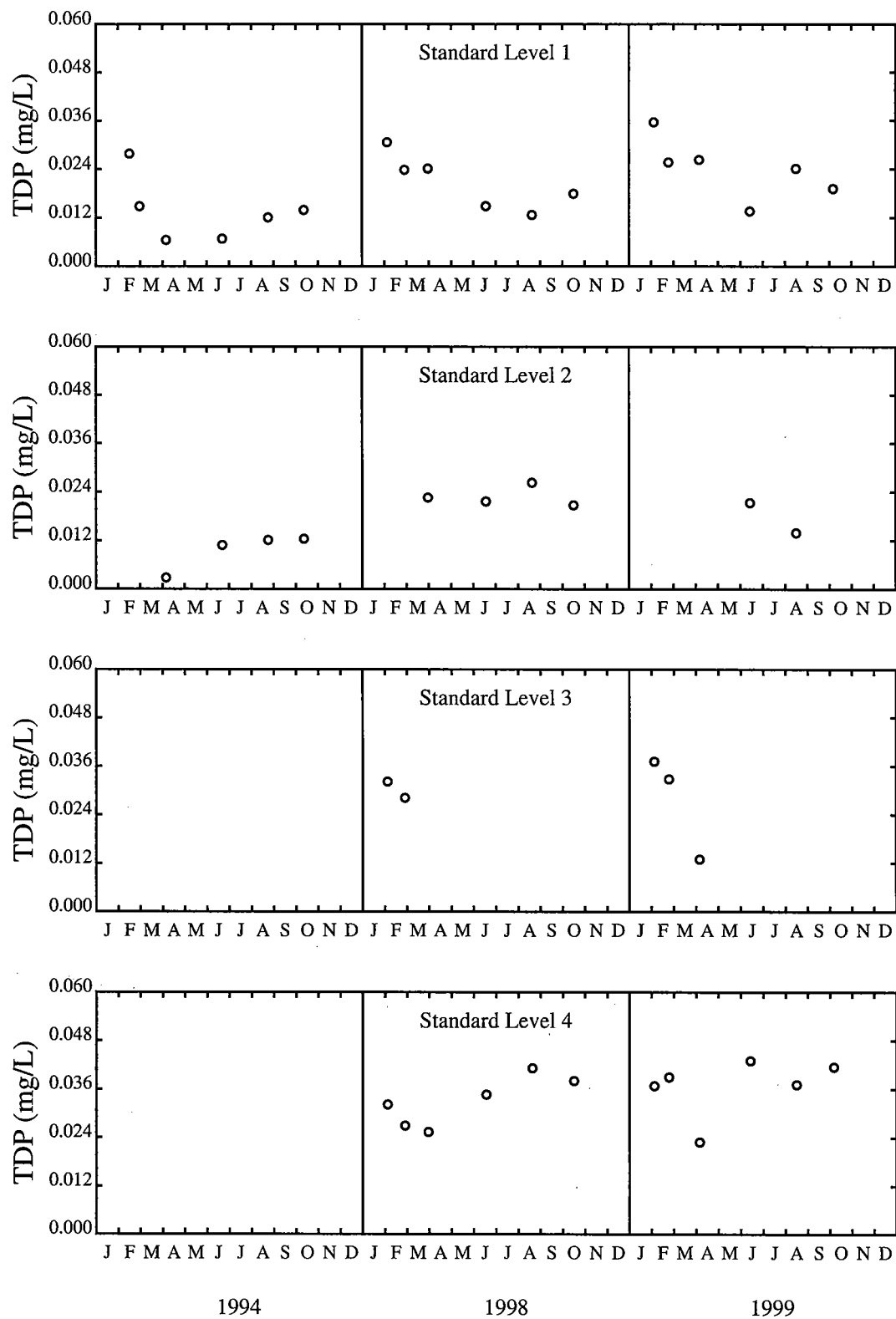


Figure 3-20. TDP Concentrations at Station F27 During 1994, 1998 and 1999

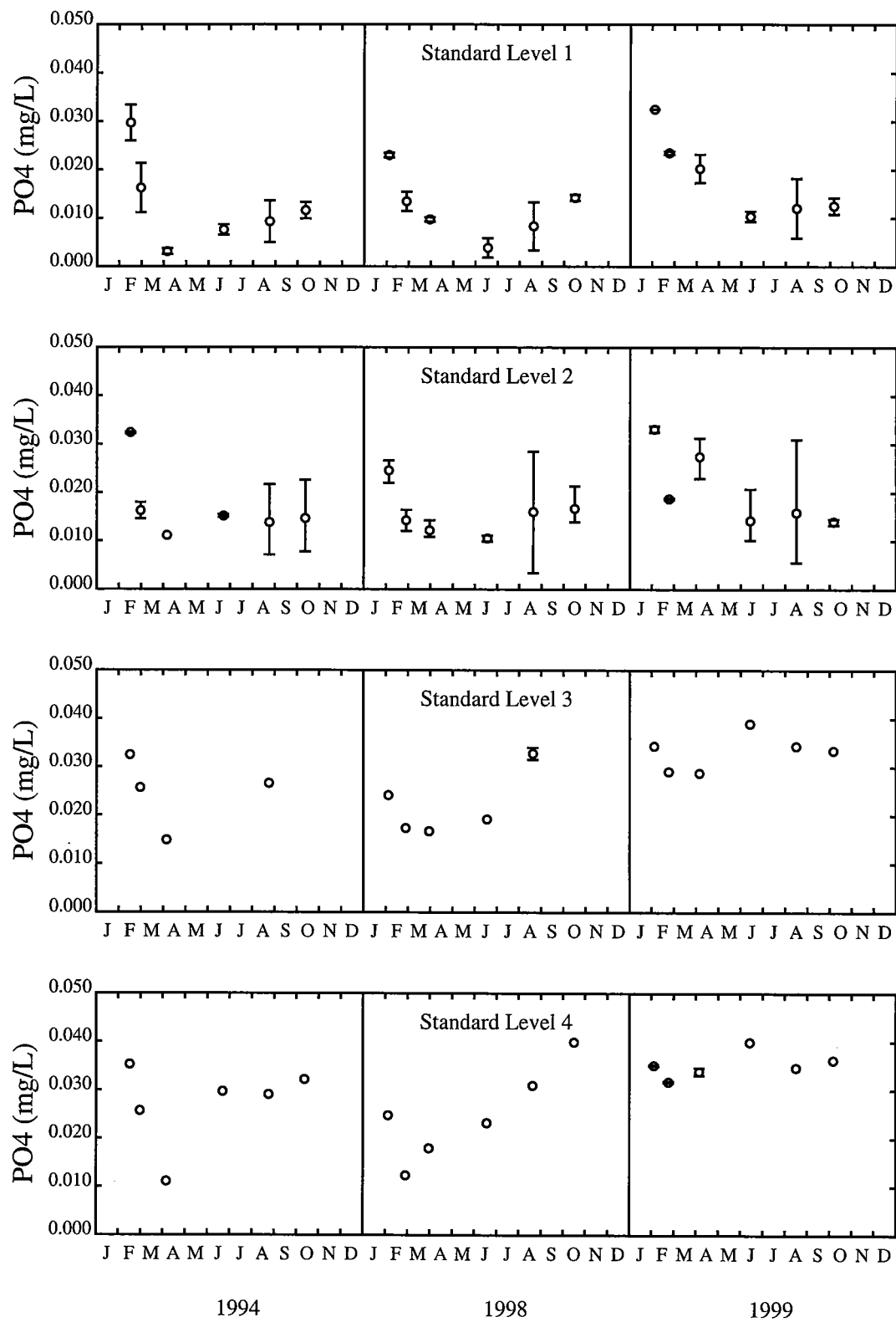


Figure 3-21. PO₄ Concentrations at Stations F26 and F27 during 1994, 1998 and 1999

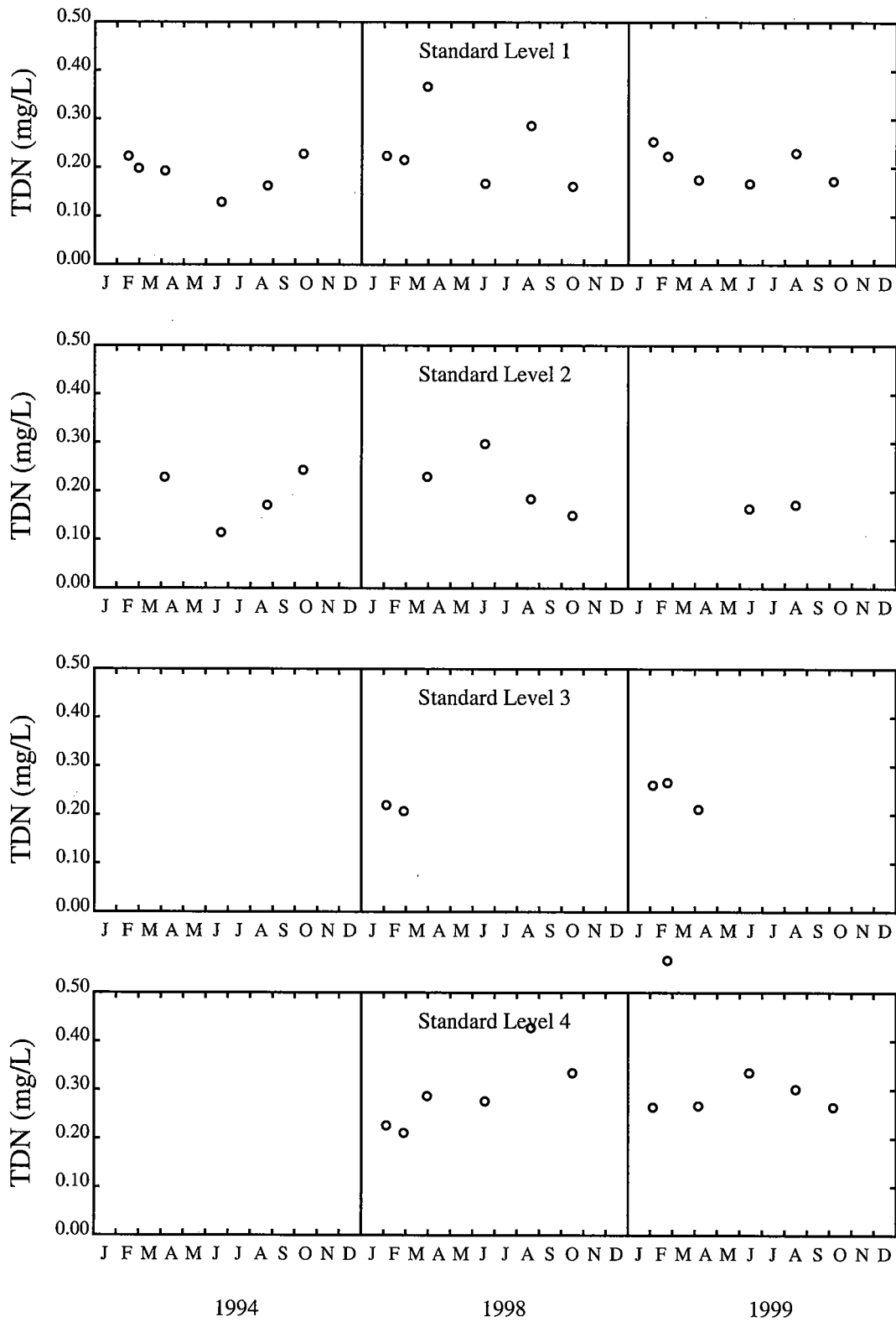


Figure 3-22. TDN Concentrations at Station F27 during 1994, 1998 and 1999

mid-depths do not show an easily recognizable pattern. In 1998, there is a general increasing trend in the bottom data, while the 1999 data is relatively constant except for the large spike in February.

The ammonium (NH_4) data are shown in Figure 3-23. The NH_4 concentrations in Massachusetts Bay tend to be lower than the nitrite + nitrate ($\text{NO}_2 + \text{NO}_3$) data. The data show different patterns in each year. In 1994, there is a clear decline in NH_4 from the winter to the spring in all of the levels. The NH_4 concentrations in the deeper levels of the water column recovered more rapidly than did the surface concentrations. In 1998, the NH_4 concentrations are relatively constant throughout the year and throughout the water column with concentrations of approximately 0.01 mg/L. In 1999, there is a small decline in the NH_4 concentration in February, but the major feature is a large spike in the concentration in June.

The $\text{NO}_2 + \text{NO}_3$ data shown in Figure 3-24 have a different pattern than the NH_4 . In all three years there is a large decline in the $\text{NO}_2 + \text{NO}_3$ surface data; however, the decline is more rapid in 1994. In 1999, a peak is evident in August in the upper portions of the water column. Differences in the deeper levels are also apparent. The decline in the 1994 $\text{NO}_2 + \text{NO}_3$ concentration is the largest and most rapid. A smaller decline is evident in 1998. In 1999, the $\text{NO}_2 + \text{NO}_3$ concentrations in the deeper levels of the water column are relatively constant at approximately 0.15 mg/L.

Figure 3-25 presents the biogenic silica (BSi) data from station F27. Biogenic silica is a more recent addition to the HOM program. In 1998, BSi concentrations do not vary too much during the year nor with depth. Most measured values for BSi in 1998 range from 0.01 to 0.05 mg/L. In 1999, there are elevated (>0.1 mg/L) BSi concentrations during February and March. During the remainder of 1999, the BSi concentrations are generally less than 0.05 mg/L.

The dissolved silica (Si) data presented in Figure 3-26 are similar to the other nutrients examined, so far, in terms of temporal and vertical patterns. In 1994, there is a rapid decline in silica during the spring that occurs throughout the water column. In 1998, the decline is not as rapid, and surface level concentrations are not as low as in 1994. In the deeper levels, the 1998 decline and recovery of the Si concentrations are similar to 1994 except that the beginning of year concentrations are not as high. In 1999, the surface Si concentration actually increases during the spring before it declines in the summer. The bottom water does not show as great a decline in Si in 1999 as was evident in the other years.

DOC data are presented in Figure 3-27. The 1994 data are relatively constant throughout the year ranging from 1.0 to 2.0 mg/L with the majority of the data being closer to 1.0 mg/L. By 1998, there is a definite increase in the average DOC with most of the concentrations closer to 2.0

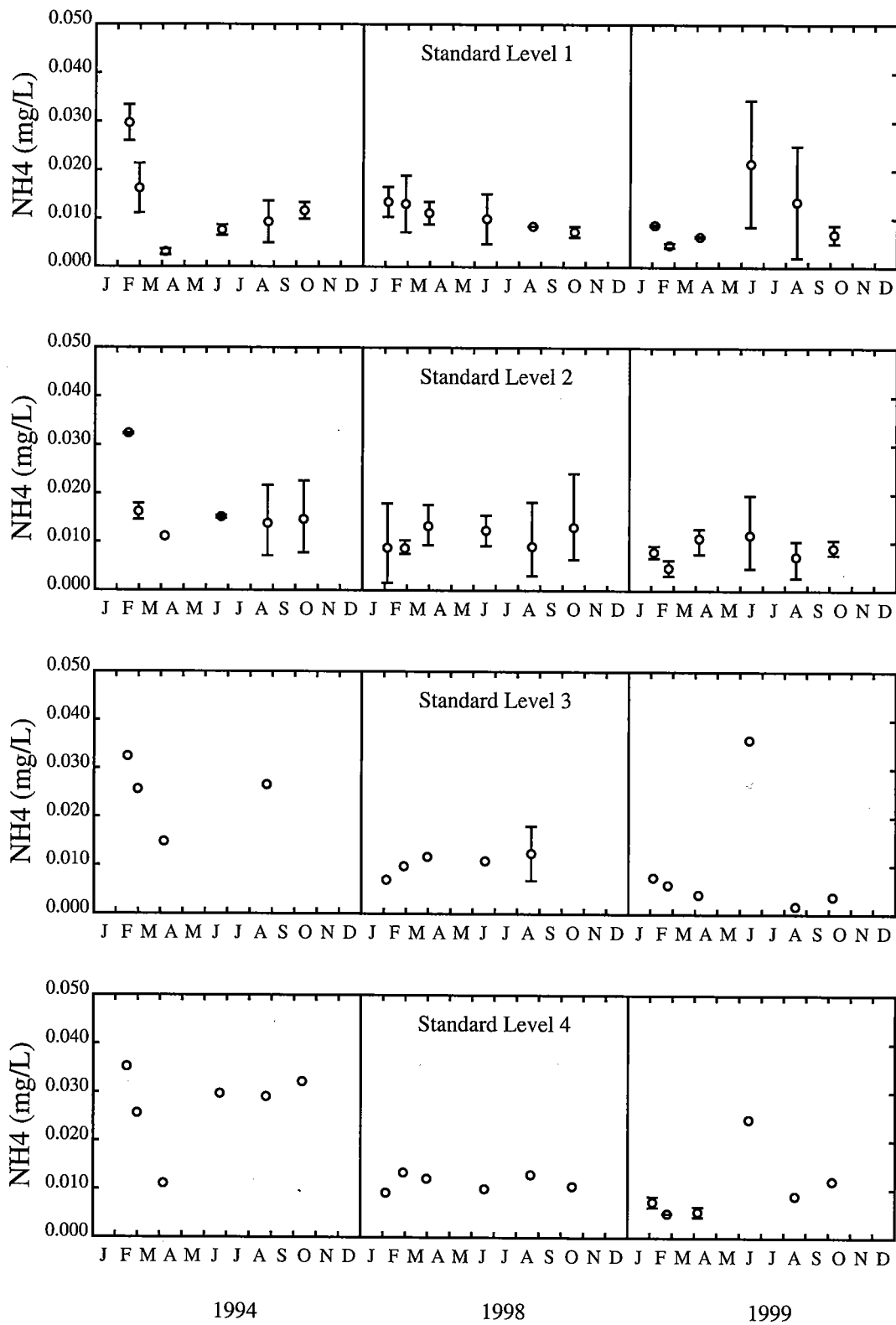


Figure 3-23. NH₄ Concentrations at Stations F26 and F27 during 1994, 1998 and 1999

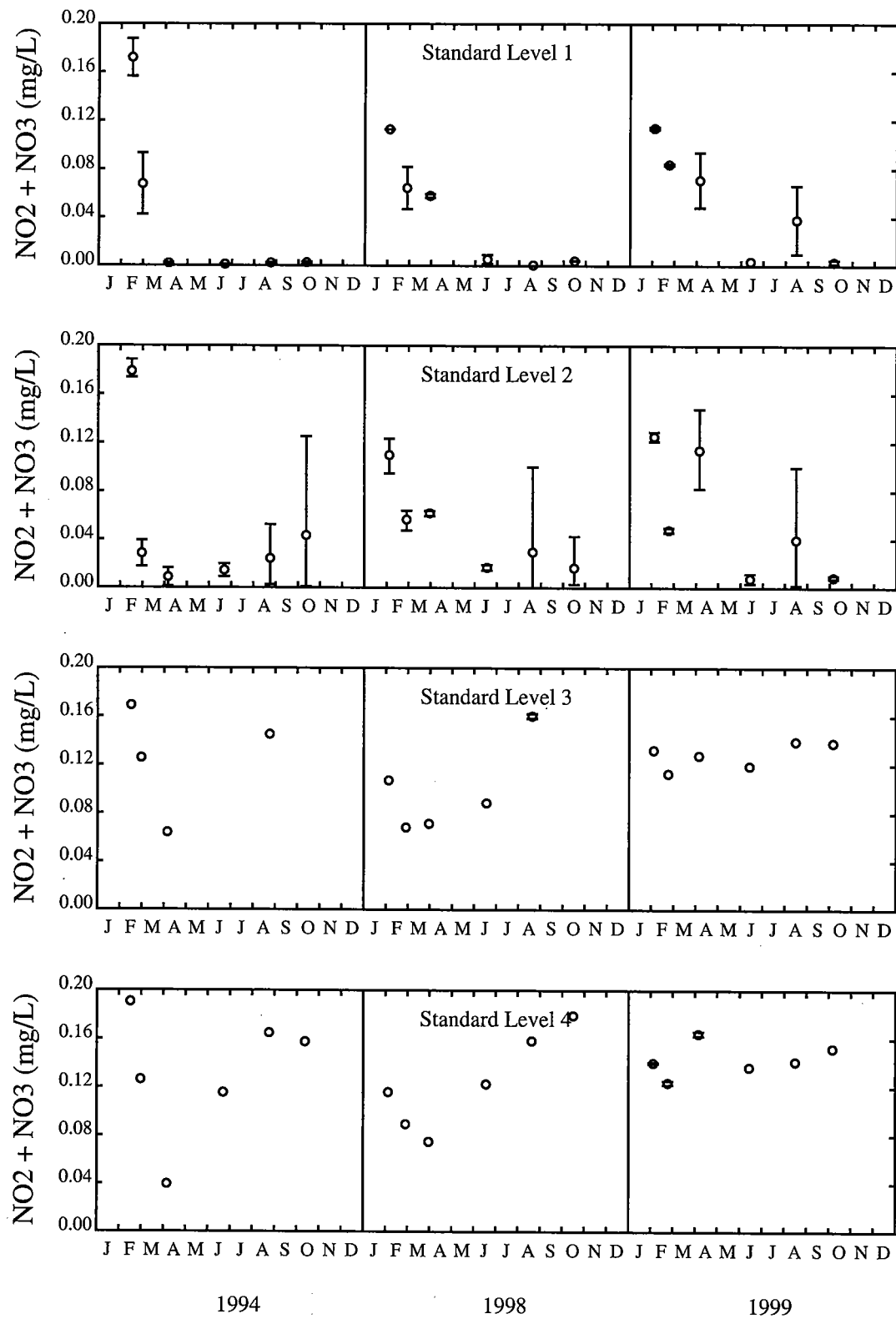


Figure 3-24. NO₂+NO₃ Concentrations at Stations F26 and F27 during 1994, 1998 and 1999

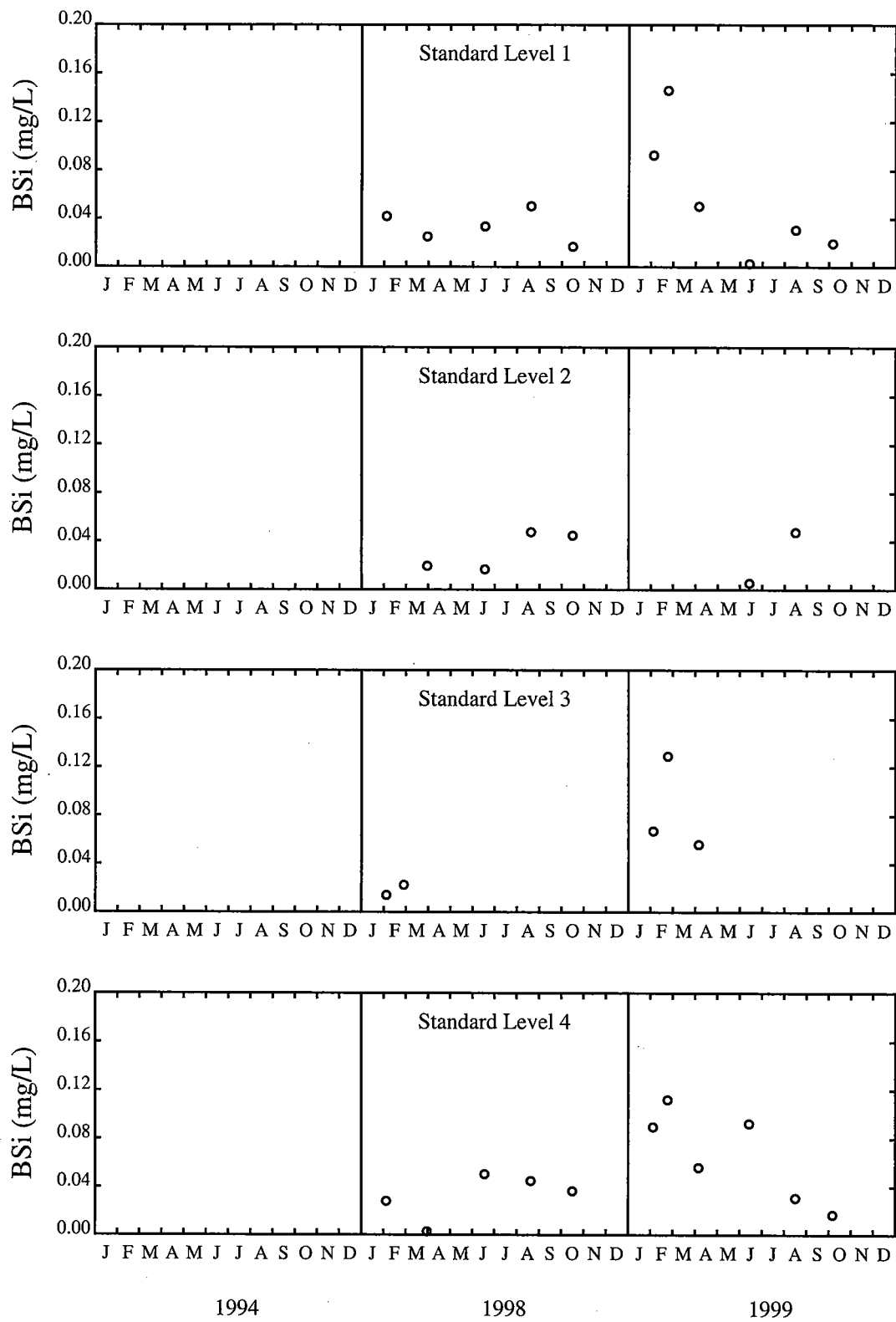


Figure 3-25. BSi Concentrations at Station F27 during 1994, 1998 and 1999

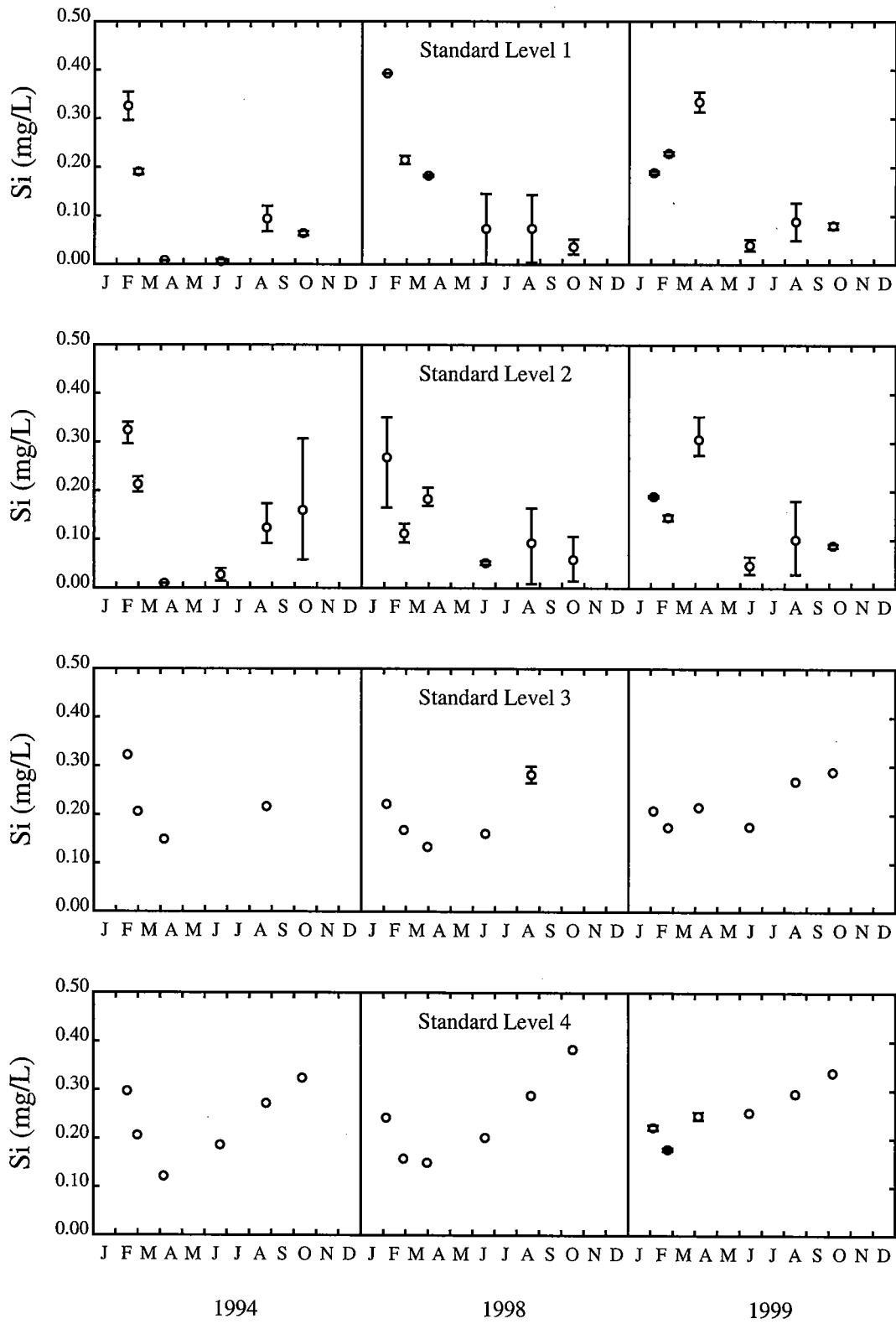


Figure 3-26. Si Concentrations at Stations F26 and F27 during 1994, 1998 and 1999

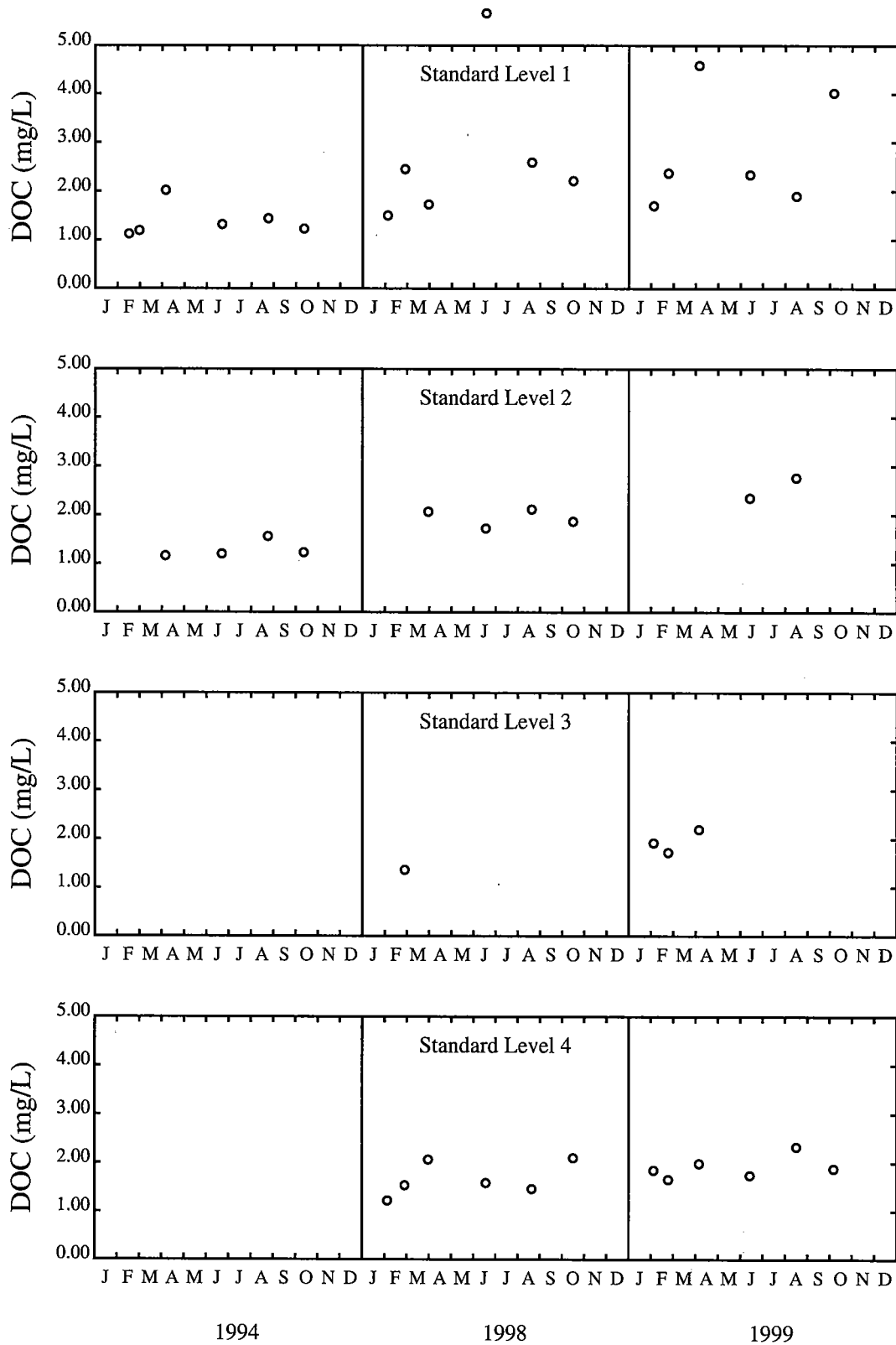


Figure 3-27. DOC Concentrations at Station F27 during 1994, 1998 and 1999

mg/L and one value greater than 5.0 mg/L in June. DOC concentrations remain elevated in 1999. Peaks in the surface data are seen in April and October.

The POC data, shown in Figure 3-28, tend to be much lower than the DOC data. However, like the DOC data the POC data are generally higher in 1998 and 1999 than 1994. In 1998, higher POC values are observed in the spring and in August. The higher POC values in the spring do not match the phytoplankton carbon concentrations presented in Figure 3-19. This may indicate that the POC was detrital material rather than phytoplankton biomass. In 1999, a springtime peak is not evident; however, high POC concentrations were measured in the late summer and fall.

The DO concentration data, presented in Figure 3-29, show that 1994 and 1999 have similar patterns. Both of these years were chosen for model verification purposes because the DO concentrations were lower than observed in other years. In these two years, the DO concentration increases into March and then steadily declines into the fall. The trend in DO concentrations in 1998 is quite different in that the increase in DO levels in the spring is relatively small and the DO concentrations in June are quite high. Only after June do the DO concentrations decline and the October DO level is not as low as was observed in 1994 and 1999.

The data collected during the period of 1992 through 1999 are beginning to show a pattern that was somewhat unexpected. The initial concept of the Gulf of Maine being a water body that has relatively constant water quality has to be abandoned based on the data that has been collected. The effects from the large rivers that discharge into the gulf, and meteorological factors create a more dynamic water body than was anticipated. Even constituents such as DOC, most of which would be expected to be refractory, can vary by a factor of five over the year. These data indicate that some of the assumptions made for developing the model boundary conditions have to be changed to reflect the greater year to year variability in the data. This will be discussed further when the model boundary conditions are presented.

3.4 SEDIMENT DATA

3.4.1 Fluxes

As part of the HOM Program sediment nutrient fluxes were measured in Boston Harbor and Massachusetts Bay in the vicinity of Boston Harbor. These fluxes include ammonium (J_{NH_4}), nitrite + nitrate (J_{NO_3}), denitrification (J_{N_2}), phosphate (J_{PO_4}), silicate (J_{Si}), and sediment oxygen demand (SOD). A complete writeup of the data and the data collection is provided in Tucker et al. (2000). This section will present data from three stations (BH03, MB01, and MB05) for the years

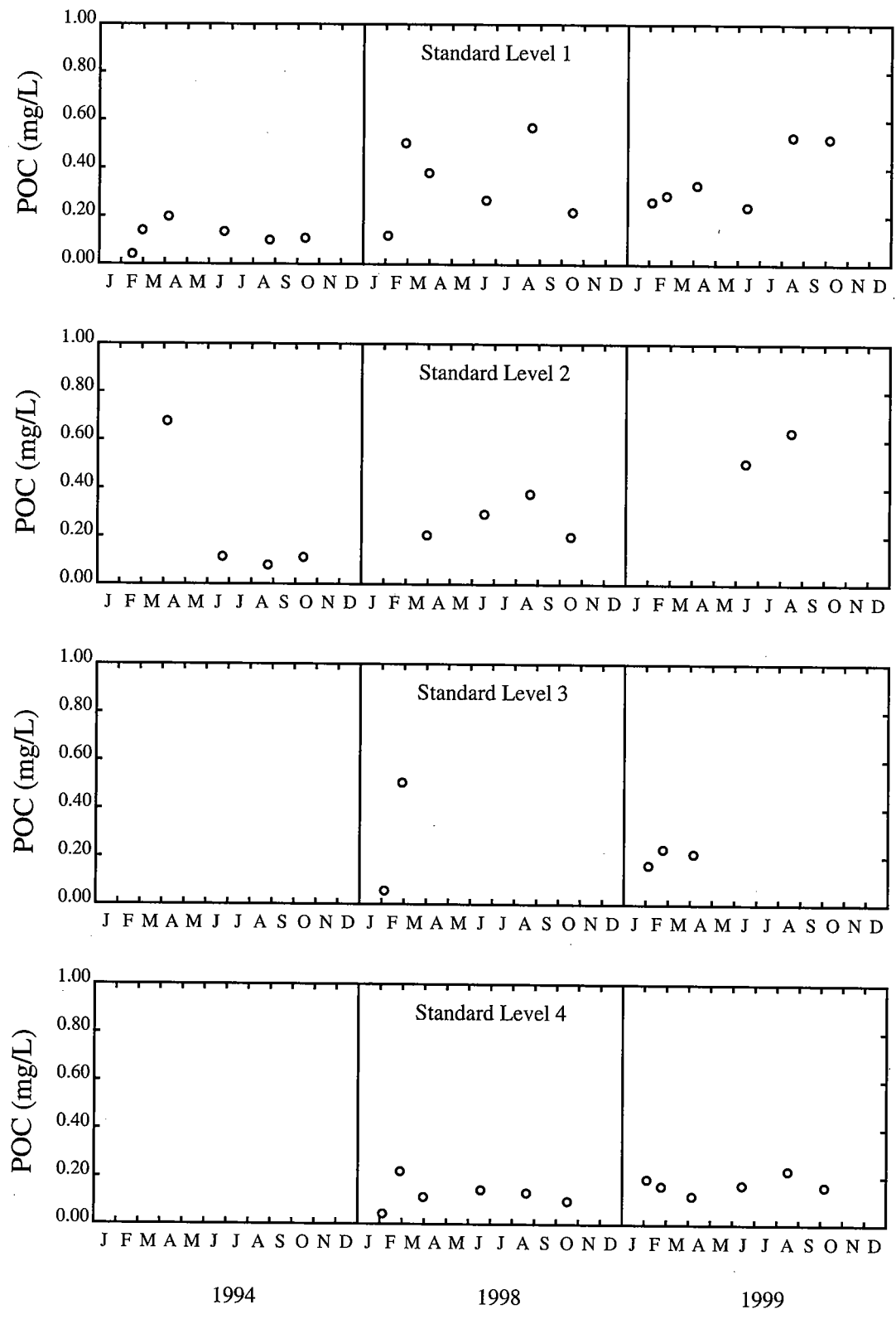


Figure 3-28. POC Concentrations at Station F27 during 1994, 1998 and 1999

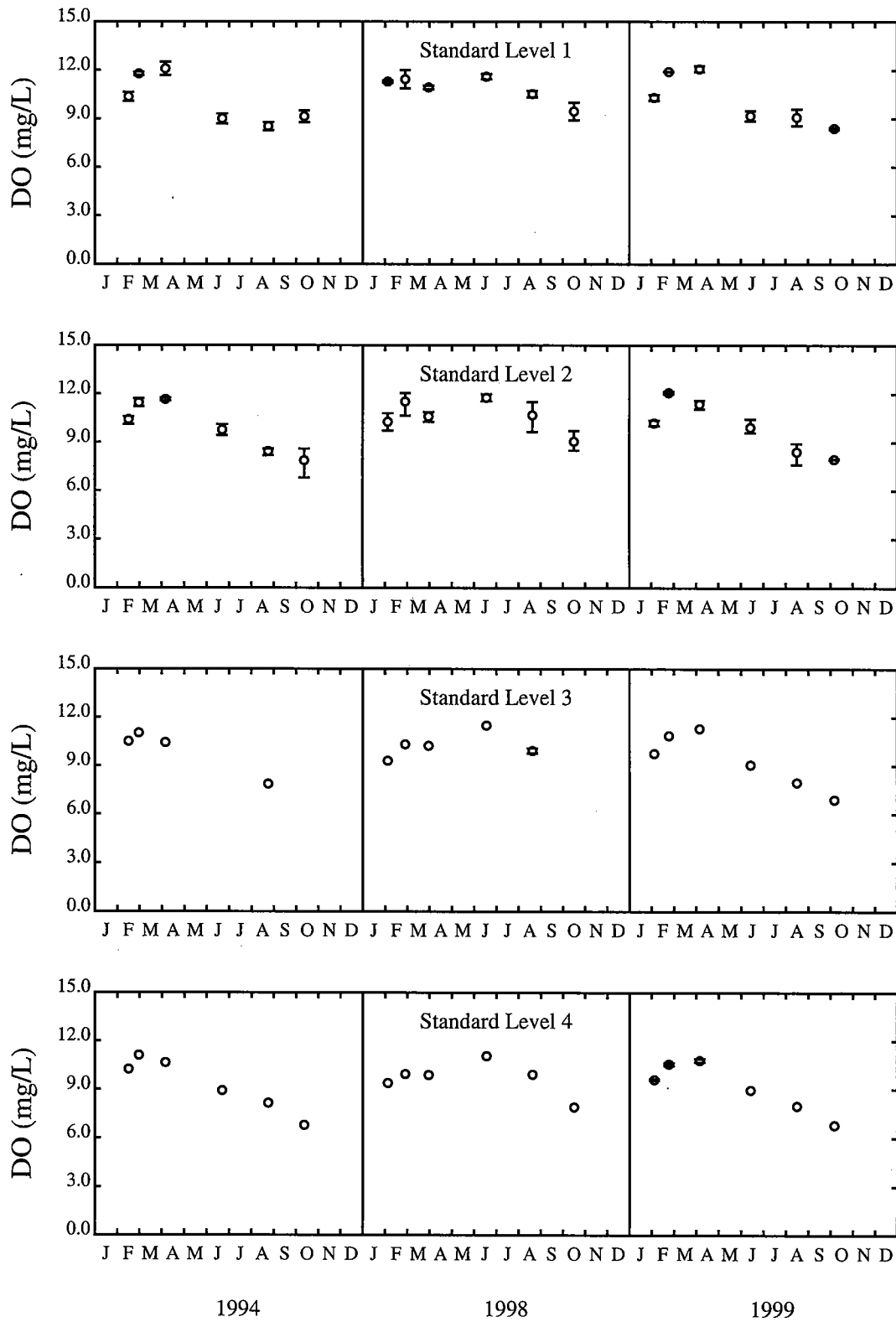


Figure 3-29. DO Concentrations at Stations F26 and F27 during 1994, 1998 and 1999

1994, 1998, and 1999. The purpose of presenting the data is to identify year to year variability occurring within the data set.

Figure 3-30 presents the fluxes measured at station BH03. The sparseness and variability in the data make it difficult to discern year to year trends. Overall, the sediment data appear relatively similar from year to year. In general, the smaller fluxes occur during the cooler months and the larger fluxes occur during the warmer months. However, there are occasions when the highest fluxes were measured in October. The large flux of ammonium into the sediment and the large flux of nitrite + nitrate out of the sediment in 1999 stand out as differences from the other years, but it is difficult to draw the conclusion that 1999 is different based on one data point. The phosphate flux in 1999 does appear to be higher than in the other years. As will be shown, the highest measured fluxes occur in Boston Harbor and then diminish with distance from Boston Harbor.

The fluxes measured at station MB01 are presented in Figure 3-31. Lacking data for 1998 makes concluding that there is year to year variability more difficult. However, the data that do exist make the case that the sediment conditions did not vary very much from 1994 conditions to 1999. (It should be noted that temperature and DO conditions in 1994 and 1999 were very similar.) The largest difference appears in the silica flux, but when the June 1994 flux is factored out the two data sets are similar. This figure shows that the fluxes outside of Boston Harbor are smaller than those measured within the harbor.

Station MB05 is the data station that is furthest from Boston Harbor. The flux data collected at station MB05 is presented in Figure 3-32. These data also show little variation between 1994 and 1999. One can argue, though, that the 1994 JSi data are higher than the 1999 data. The fluxes measured at this station were the lowest measured at any station.

The flux data indicate that while there is variability in the data, there are no clear year to year trends in the data over the three years presented in this section.

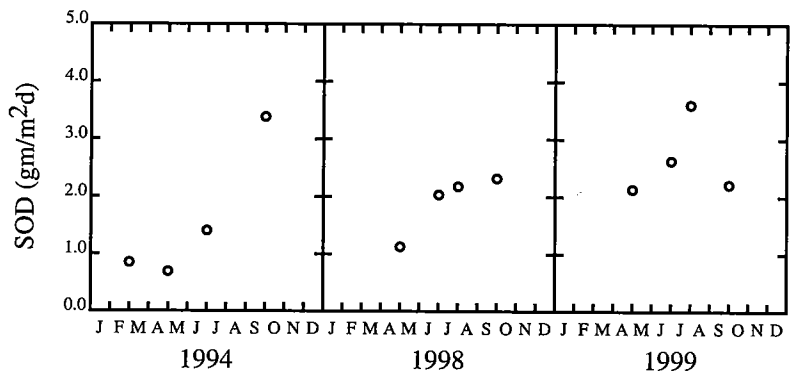
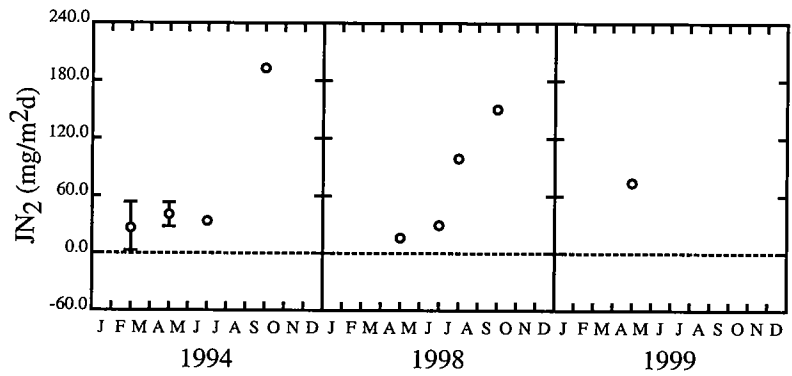
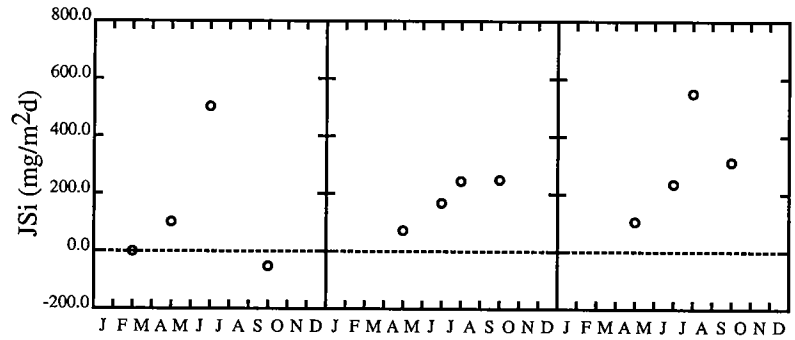
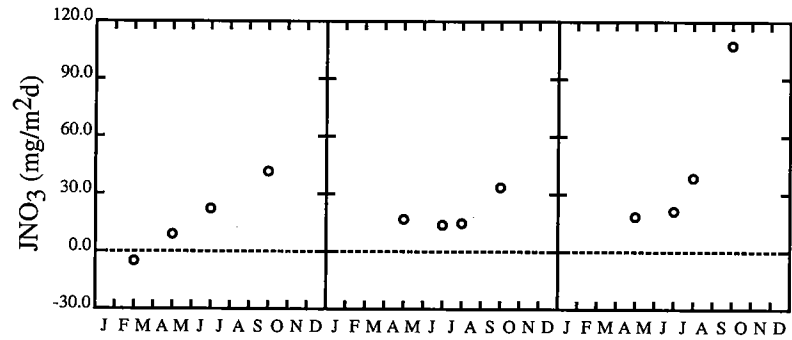
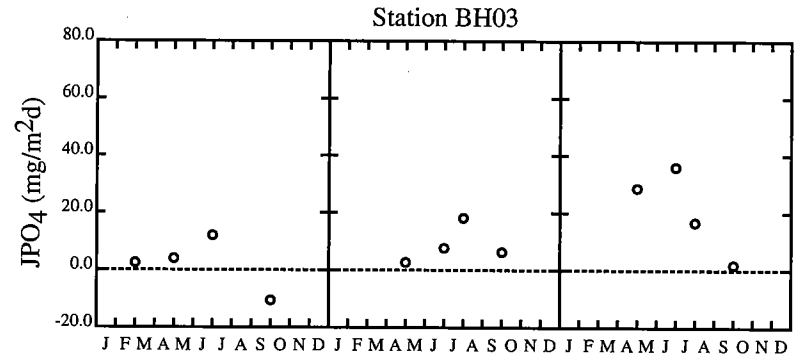
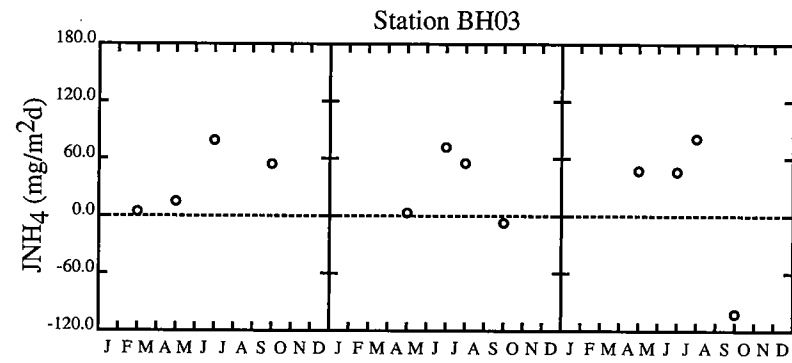


Figure 3-30. Sediment Fluxes Measured at Station BH03 during 1994, 1998 and 1999

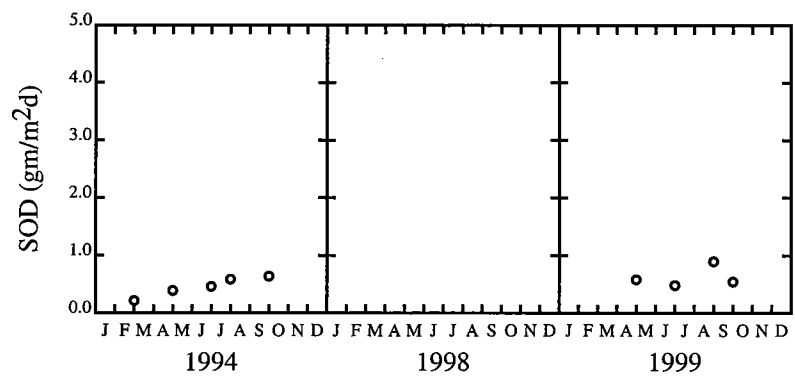
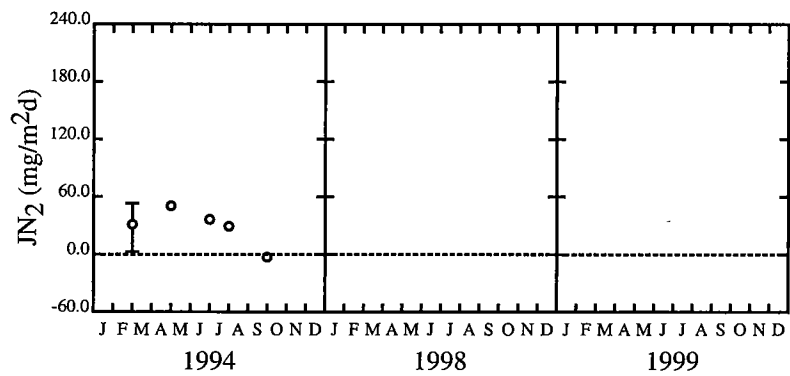
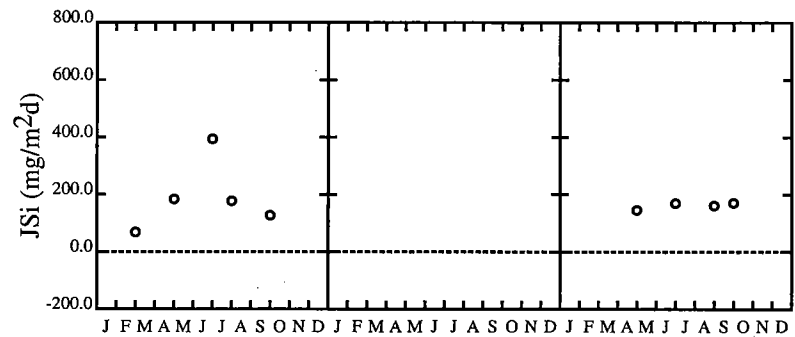
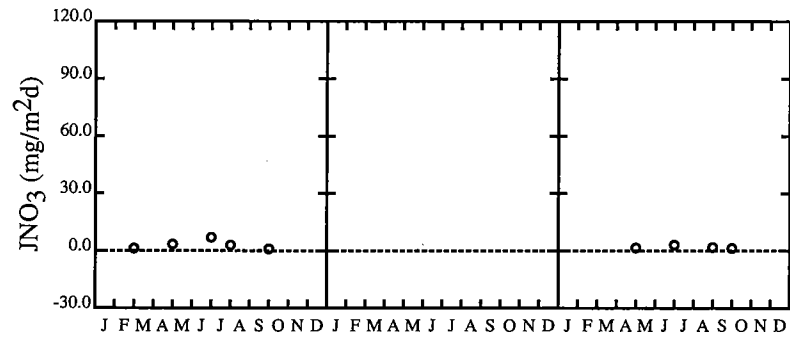
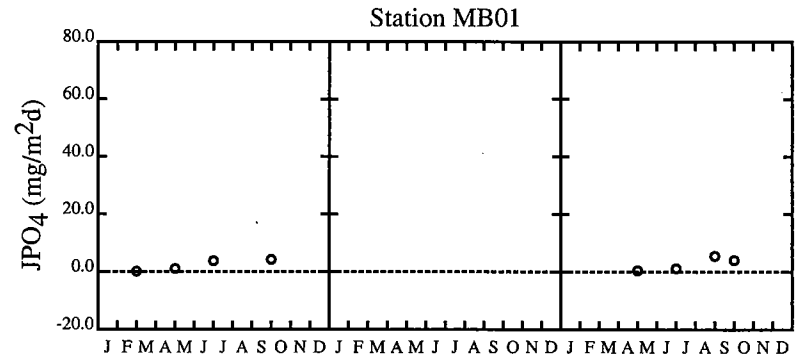
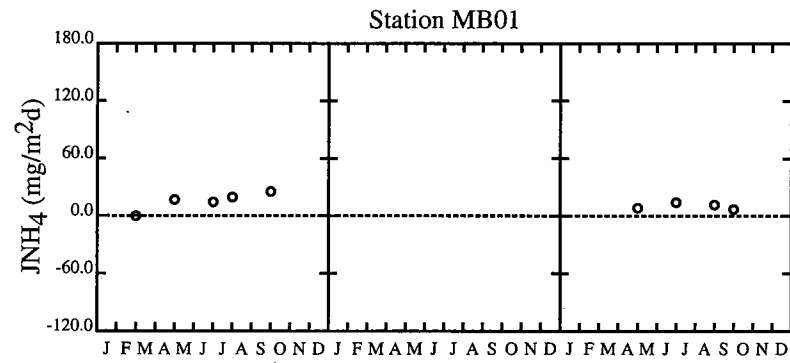


Figure 3-31. Sediment Fluxes Measured at Station MB01 during 1994, 1998 and 1999

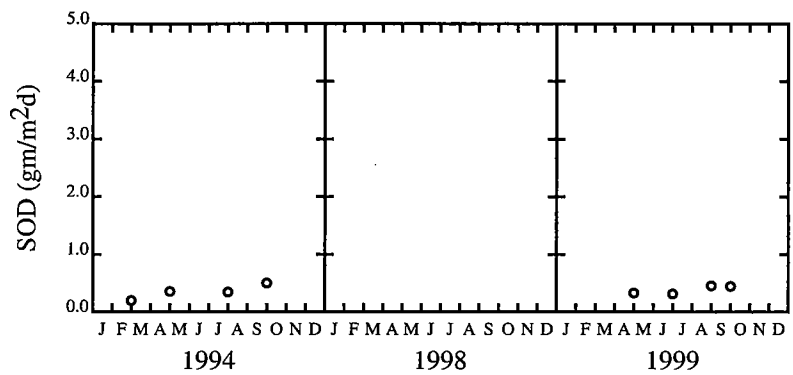
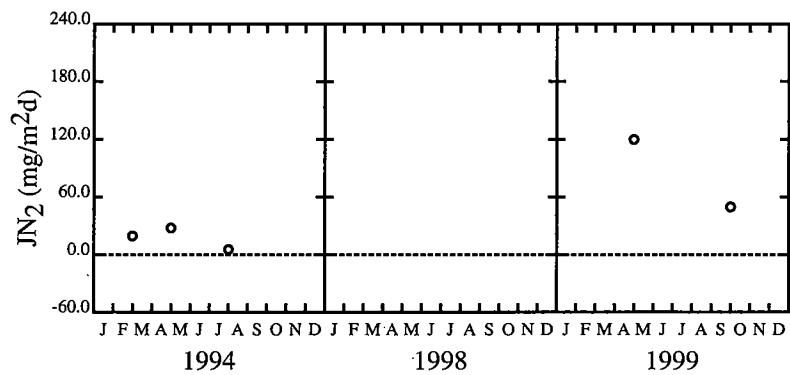
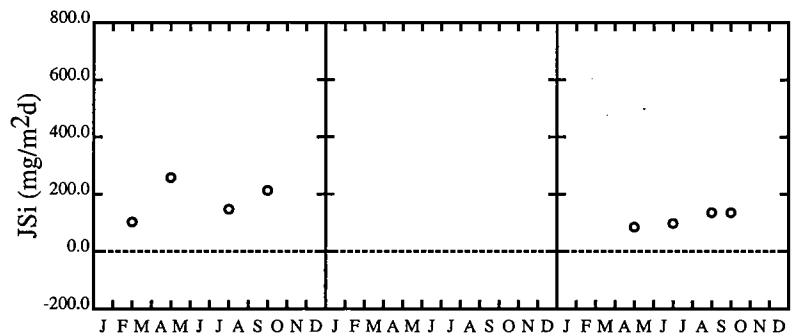
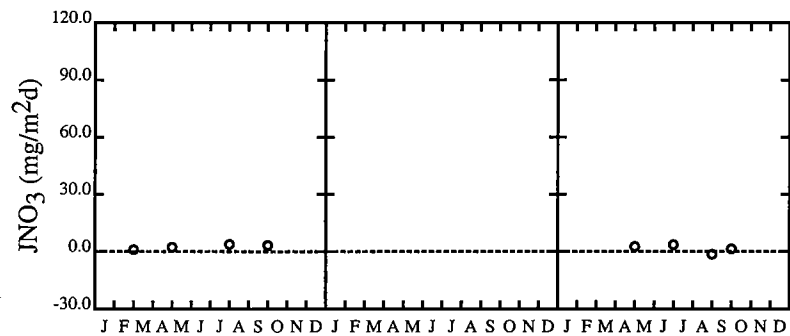
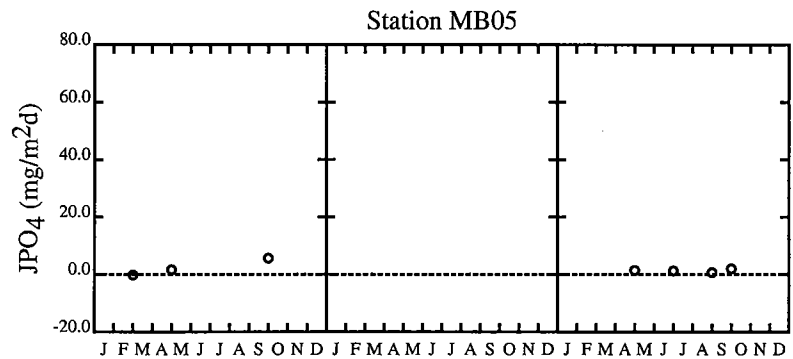
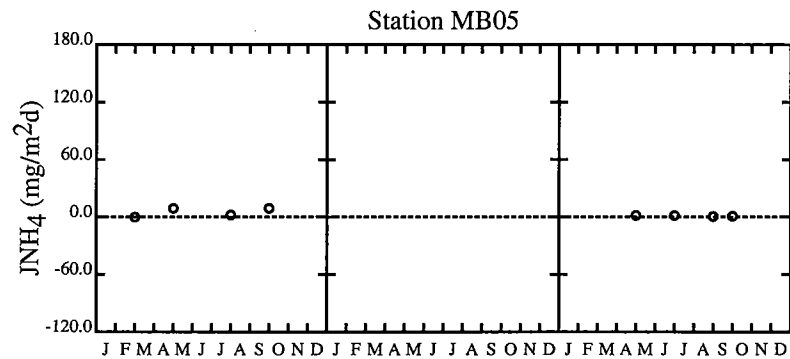


Figure 3-32 Sediment Fluxes Measured at Station MB05 during 1994, 1998 and 1999

SECTION 4

MODEL VERIFICATION

4.1 MODEL INPUTS

4.1.1 Hydrodynamics

A key factor affecting water quality conditions in Massachusetts and Cape Cod Bays is the time-variable circulation and vertical density of the bays. These transport processes determine the movement of particulate and dissolved constituents in the bays. In order to simulate these transport processes, a variant of the Blumberg-Mellor (1987) hydrodynamic model previously developed by the USGS was calibrated for the years 1998 and 1999 (HydroQual and Signell, 2001). This time-variable three-dimensional hydrodynamic model is coupled with the water quality model in order to perform mass balance calculations and water quality simulations in the bays. The hydrodynamic model provides all of the transport information to the water quality model as well as temperature and salinity information. The success of the water quality model results relies heavily on the success of the hydrodynamic model calibration. The hydrodynamic model grid is presented in Figure 4-1.

Reports on the hydrodynamic modeling can be found in HydroQual and Signell (2001) and HydroQual (2002); however, a brief review of the hydrodynamic modeling results will be presented below to provide a background for the water quality modeling results. Figures 4-2 through 4-9 present time-series plots of model versus temperature and salinity data at four near field and eight far filed stations in Massachusetts and Cape Cod Bays for 1998 and 1999. These figures are essentially the same figures that were presented in HydroQual and Signell (2001). The exception is that data from the Boston Harbor monitoring program have been added to the plots for station F31. In general, these figures show that the hydrodynamic model is able to reproduce many of the temperature and salinity conditions that occurred within the bays in 1998 and 1999. While the model remains fresher in the surface water than the data would indicate in the later half of 1998, and underpredicts the salinity in mid-1998 in Cape Cod Bay, the model is able to reproduce most of the data that were collected. Also, the model appears to be able to reproduce the magnitude and duration of the temperature and salinity stratification that occurs in each year. Further, the model is able to reproduce the wetter (lower salinities) and cooler conditions that occurred in 1998 along with the drier (relatively constant salinities) and warmer conditions of 1999.

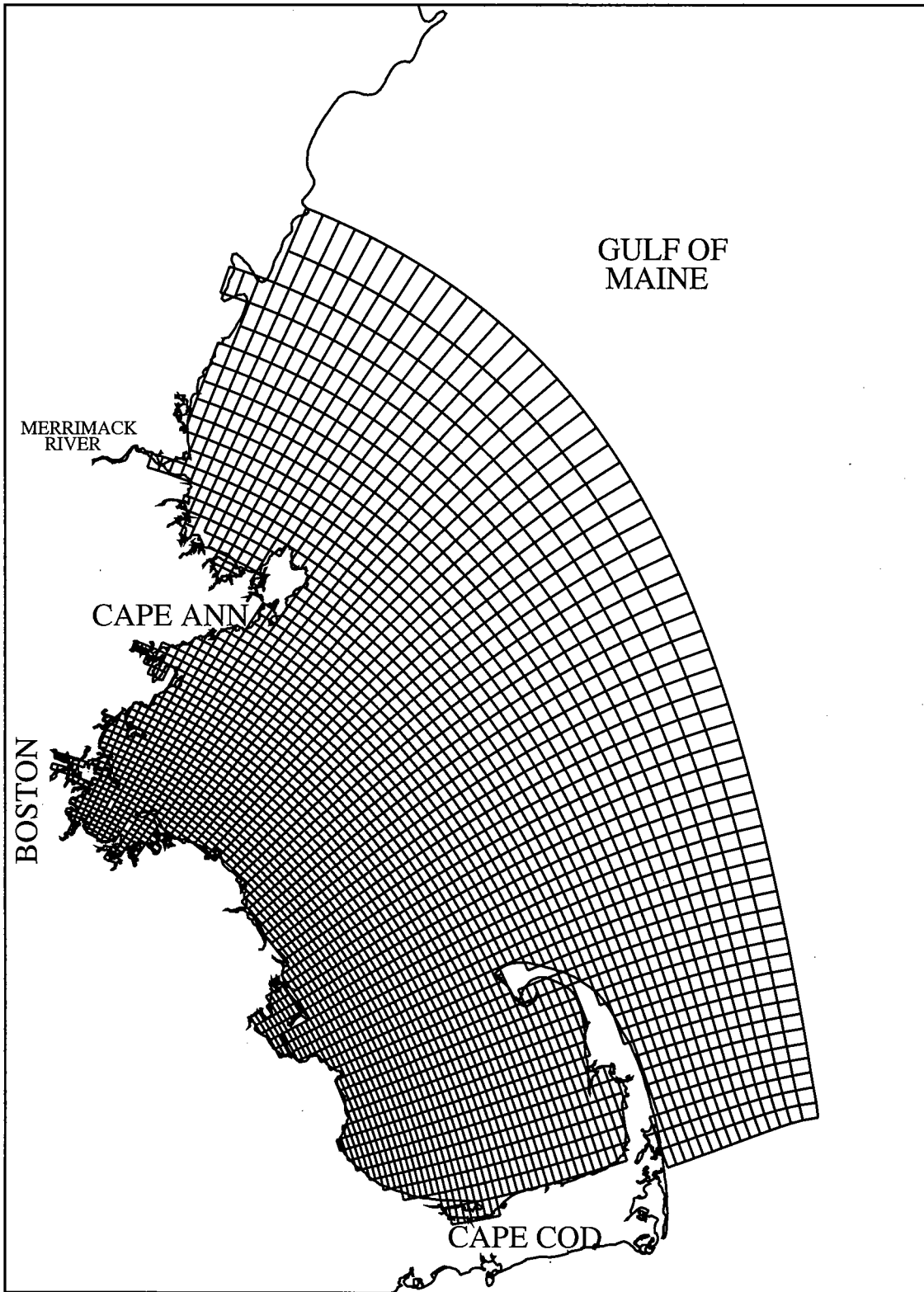


Figure 4-1. Hydrodynamic Model Grid

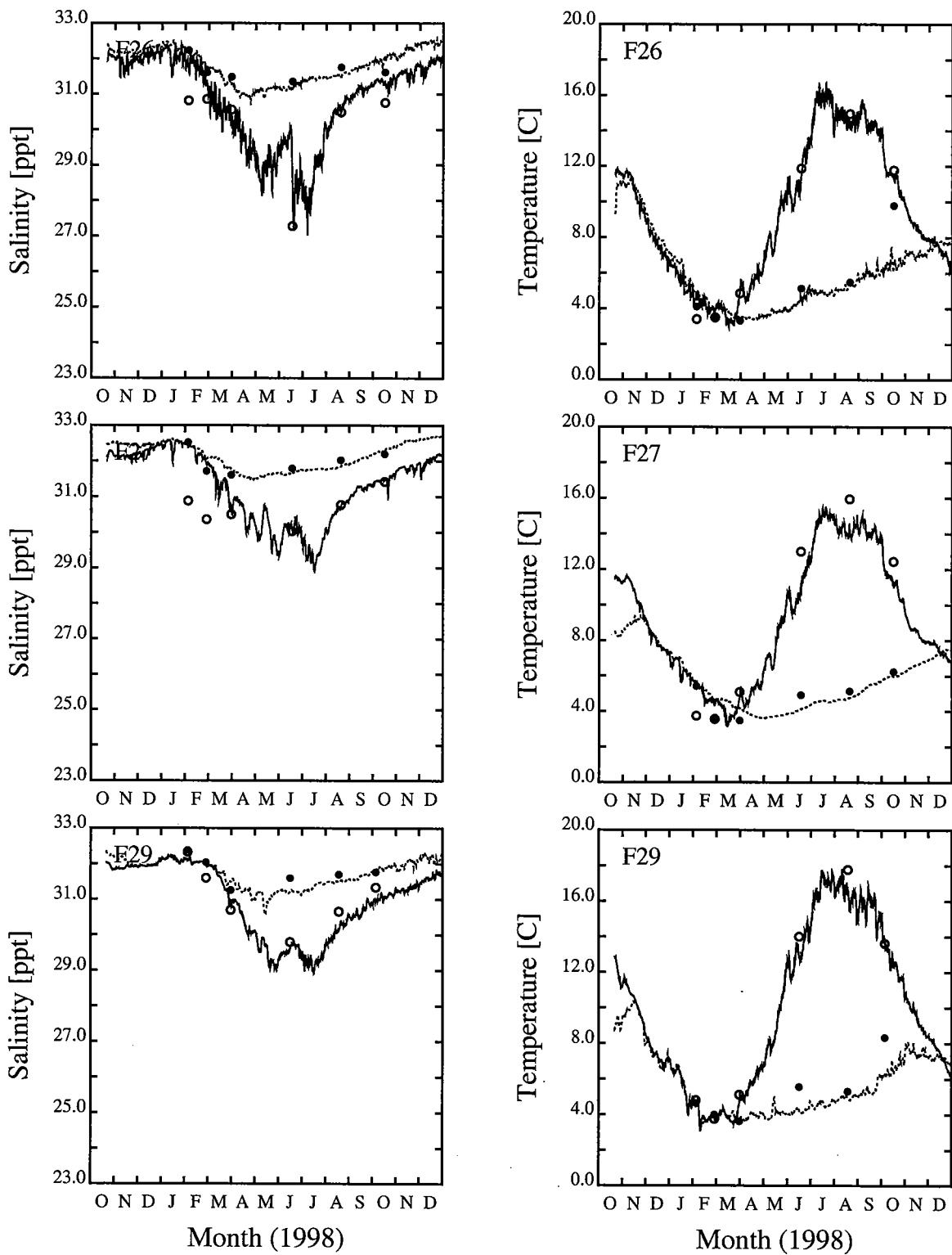


Figure 4-2. 1998 Salinity and Temperature Calibration at Stations F26, F27 and F29

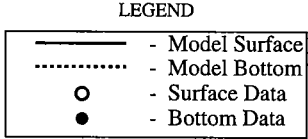
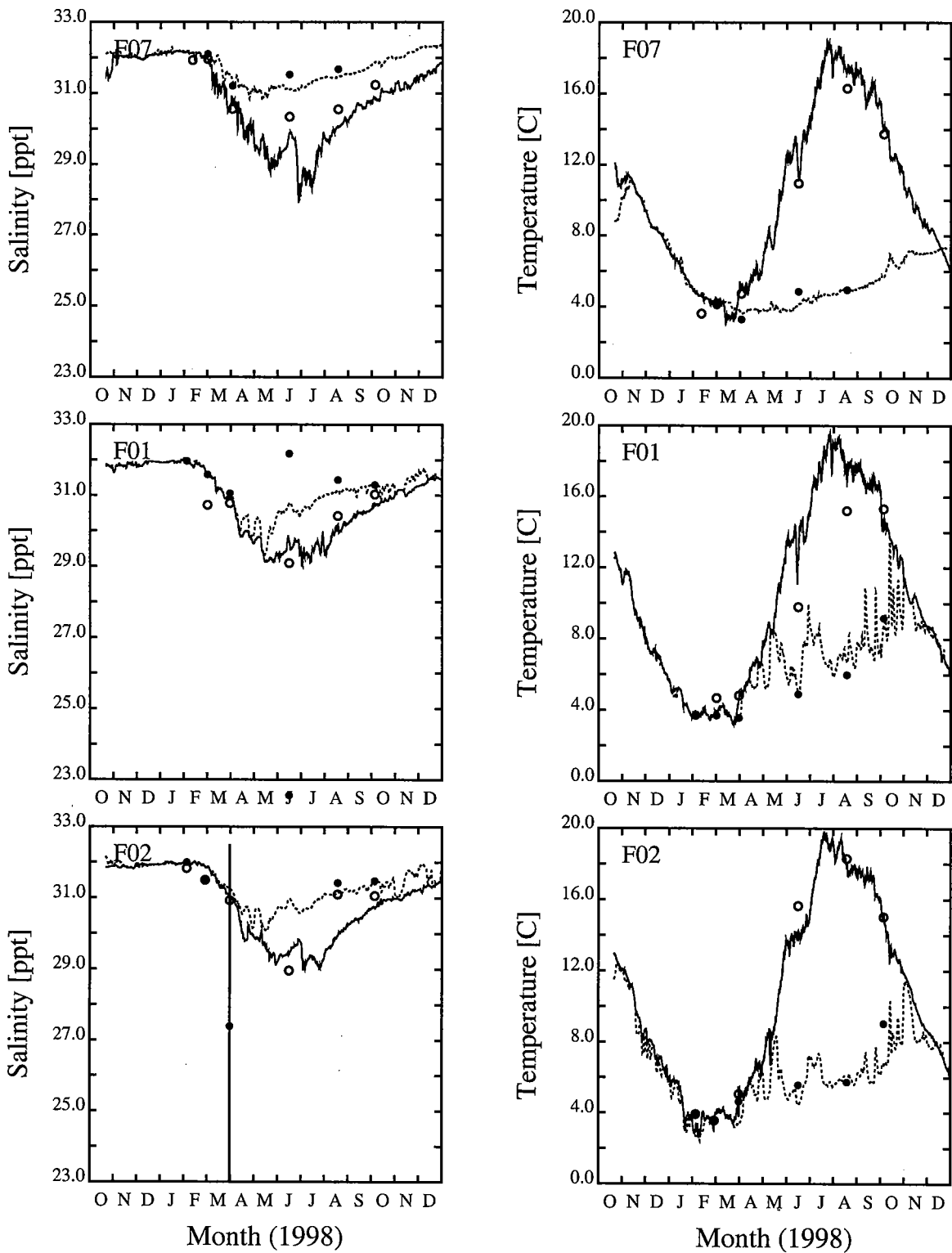


Figure 4-3. 1998 Salinity and Temperature Calibration at Stations F07, F01 and F02

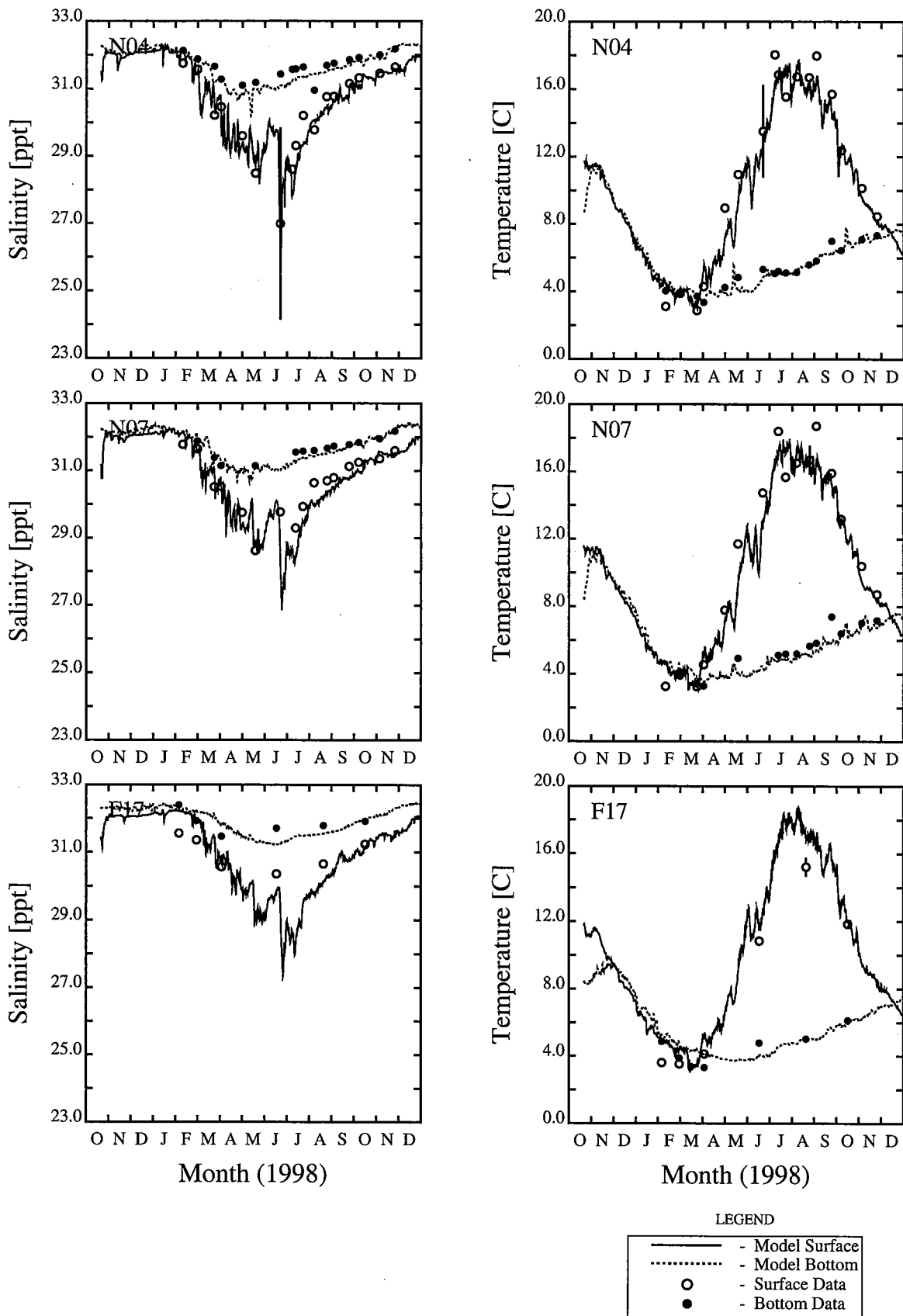


Figure 4-4. 1998 Salinity and Temperature Calibration at Stations N04, N07 and F17

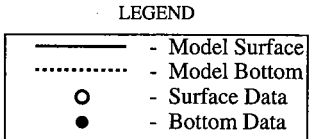
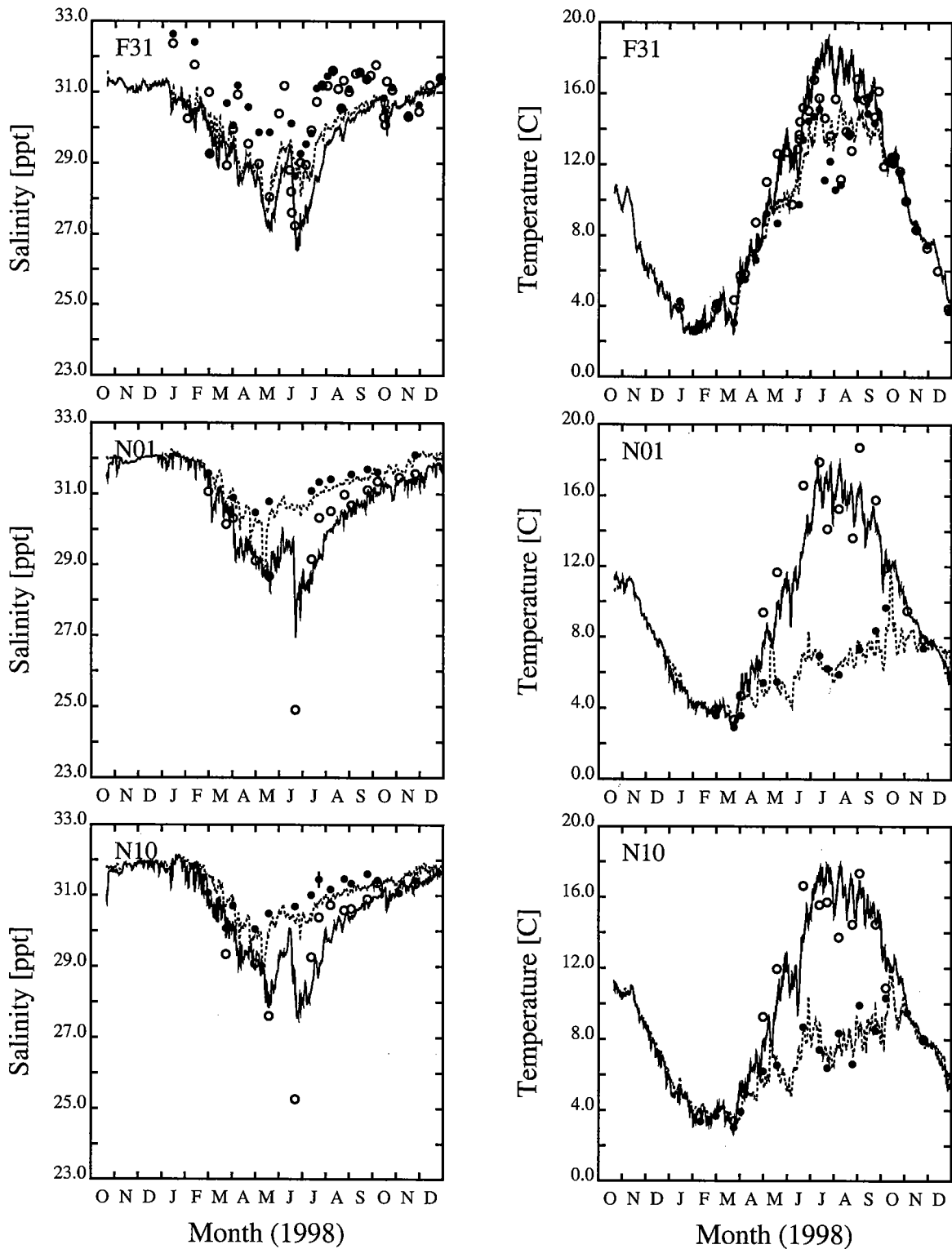


Figure 4-5. 1998 Salinity and Temperature Calibration at Stations F31, N01 and N10

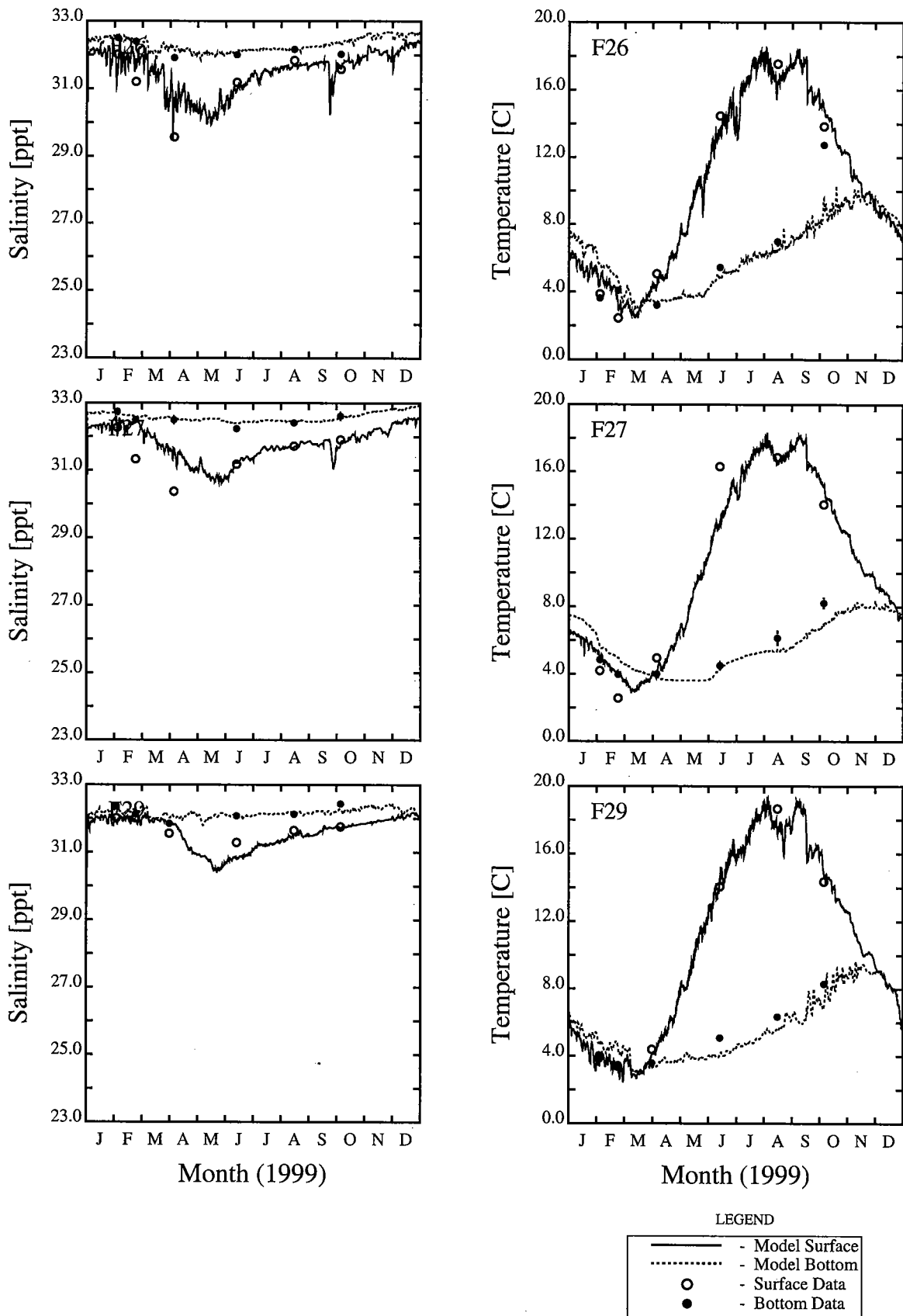


Figure 4-6. 1999 Salinity and Temperature Calibration at Stations F26, F27 and F29

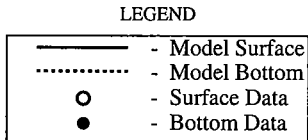
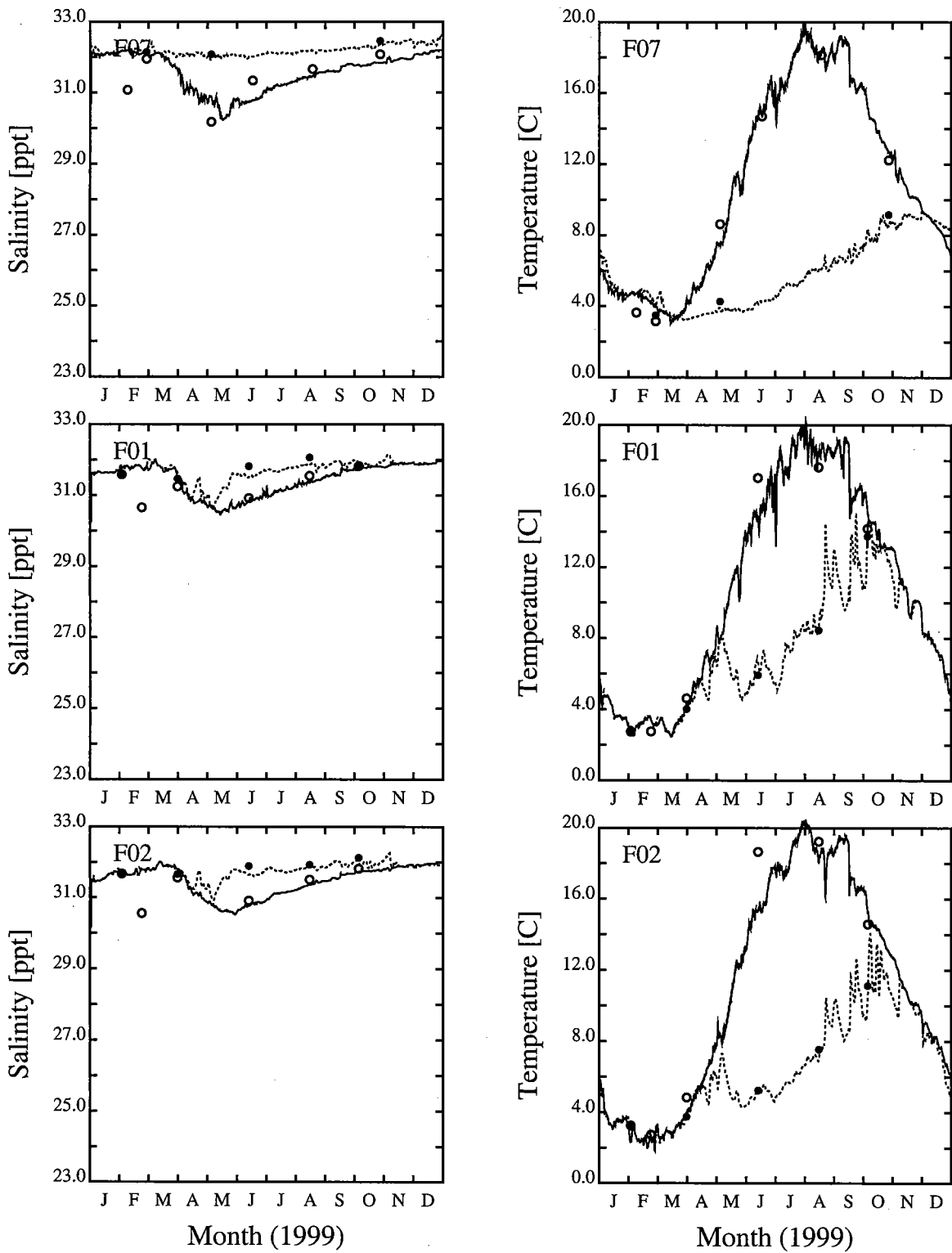


Figure 4-7. 1999 Salinity and Temperature Calibration at Stations F07, F01 and F02

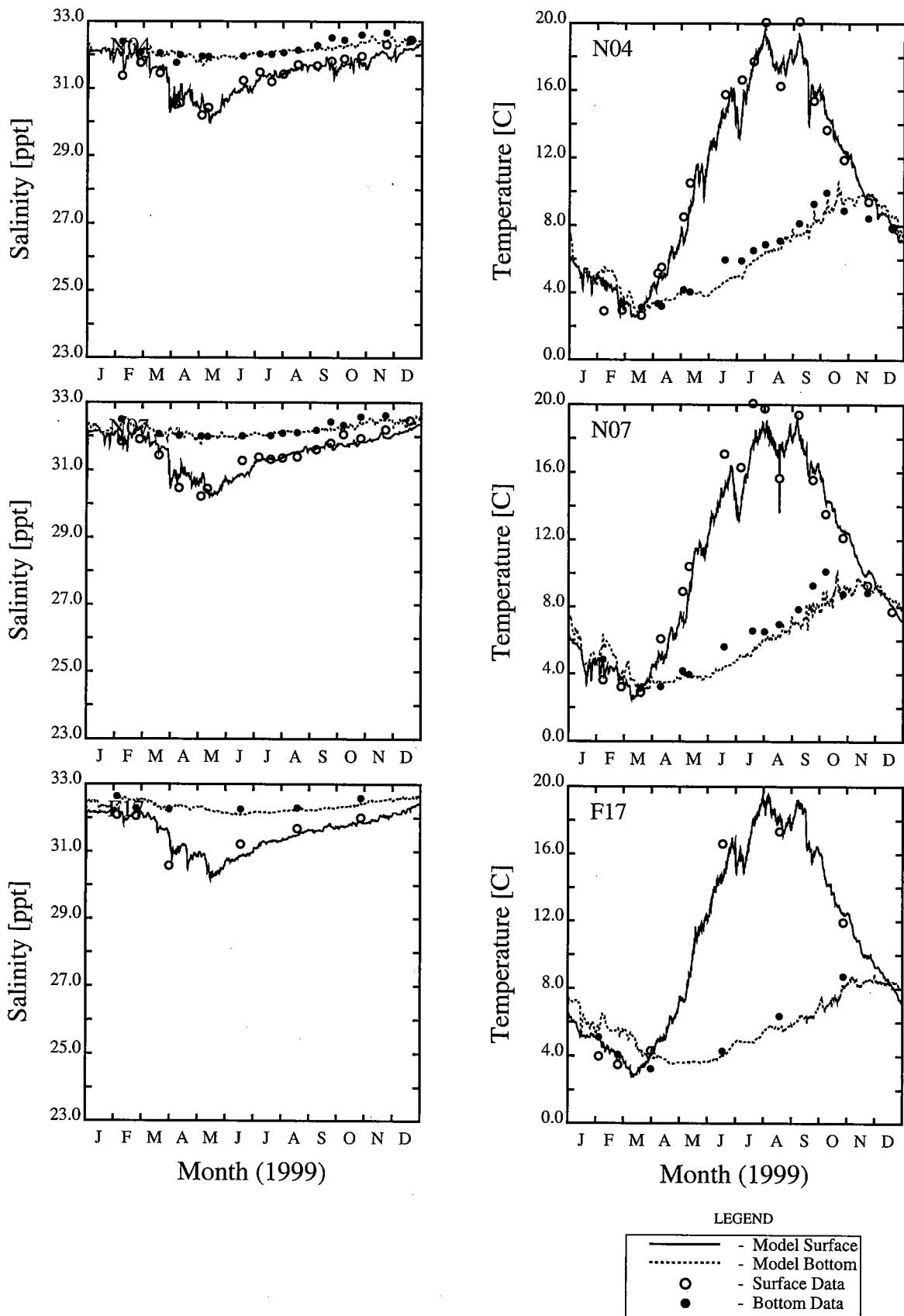


Figure 4-8. 1999 Salinity and Temperature Calibration at Stations N04, N07 and F17

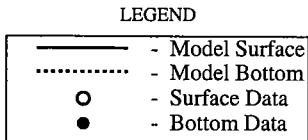
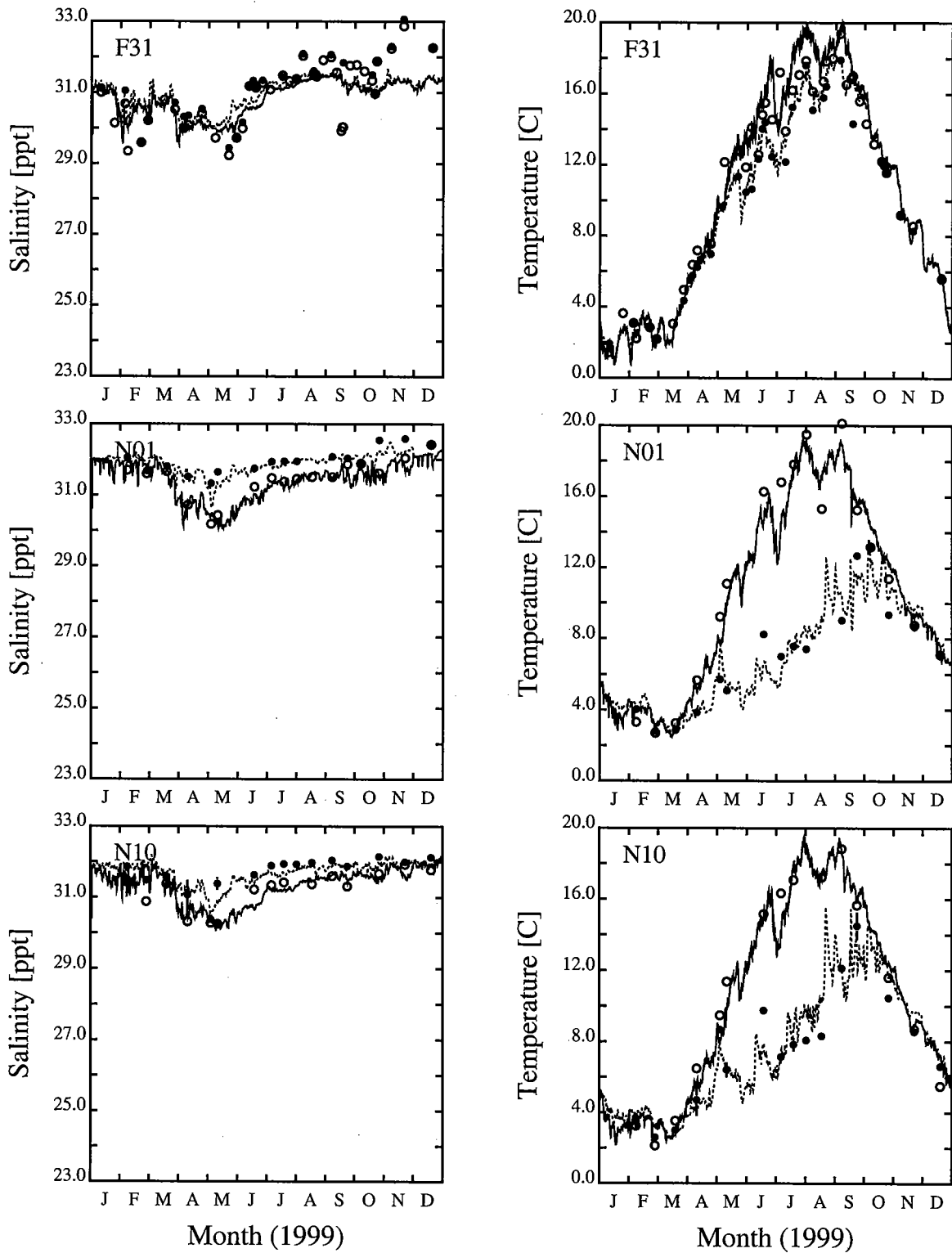


Figure 4-9. 1999 Salinity and Temperature Calibration for Stations F31, N01 and N10

The inclusion of the additional data on Figures 4-5 and 4-9 show that the hydrodynamic model had more difficulty reproducing the wetter conditions in 1998 than the conditions in 1999 in Boston Harbor (station F31). In 1998, the model under predicts the salinity stratification that occurred and over predicts the summer temperatures. For this model to better reproduce the salinity and temperature in Boston Harbor, better storm sewer and CSO flow data may be required. Even with these additional data it may be necessary to develop finer grid resolution within Boston Harbor to more accurately model the harbor. Based on this model versus data comparison, it would be expected that any failure of the water quality model to reproduce conditions in Boston Harbor may be, in part, due to the poor hydrodynamic calibration within the harbor.

Two of the conclusions made in the HydroQual and Signell (2001) report were that: (1) the hydrodynamic model compared favorably to temperature, salinity and current data for both of the years 1998 and 1999 despite the differing conditions between the years in Massachusetts and Cape Cod Bays, and (2) the current hydrodynamic model calibration should be adequate for use as input to the water quality model. Based on these conclusions, HydroQual proceeded with the water quality modeling.

In the previous water quality modeling efforts involving BEM, the hydrodynamic model results were aggregated on to a coarser water quality model grid in order to reduce the computational burden of running the water quality model. Based on the results of a more recent analysis (HydroQual, 2001a) and the fact that computational power of modern computers continues to increase, the hydrodynamic model results to be used for the water quality model were not aggregated in space. The grid used for the water quality modeling analysis is presented in Figure 4-10.

4.1.2 Boundary Conditions

Since this modeling analysis is a model verification, no changes were made to the parameters and constants used for model kinetic calculations. Loads were similar between the calibration and verifications years as well. The only model input that could be adjusted to reproduce the data within Massachusetts Bay and Cape Cod Bay for 1998 and 1999 is the boundary conditions. However, the boundary conditions are known to have a major input on the model results.

MWRA has been collecting water quality data in Massachusetts and Cape Cod Bays since 1992. Surveys are conducted 17 times a year in the near field area, the area surrounding the new outfall diffusers, and six times per year in the far field area. In the far field, there are two stations,

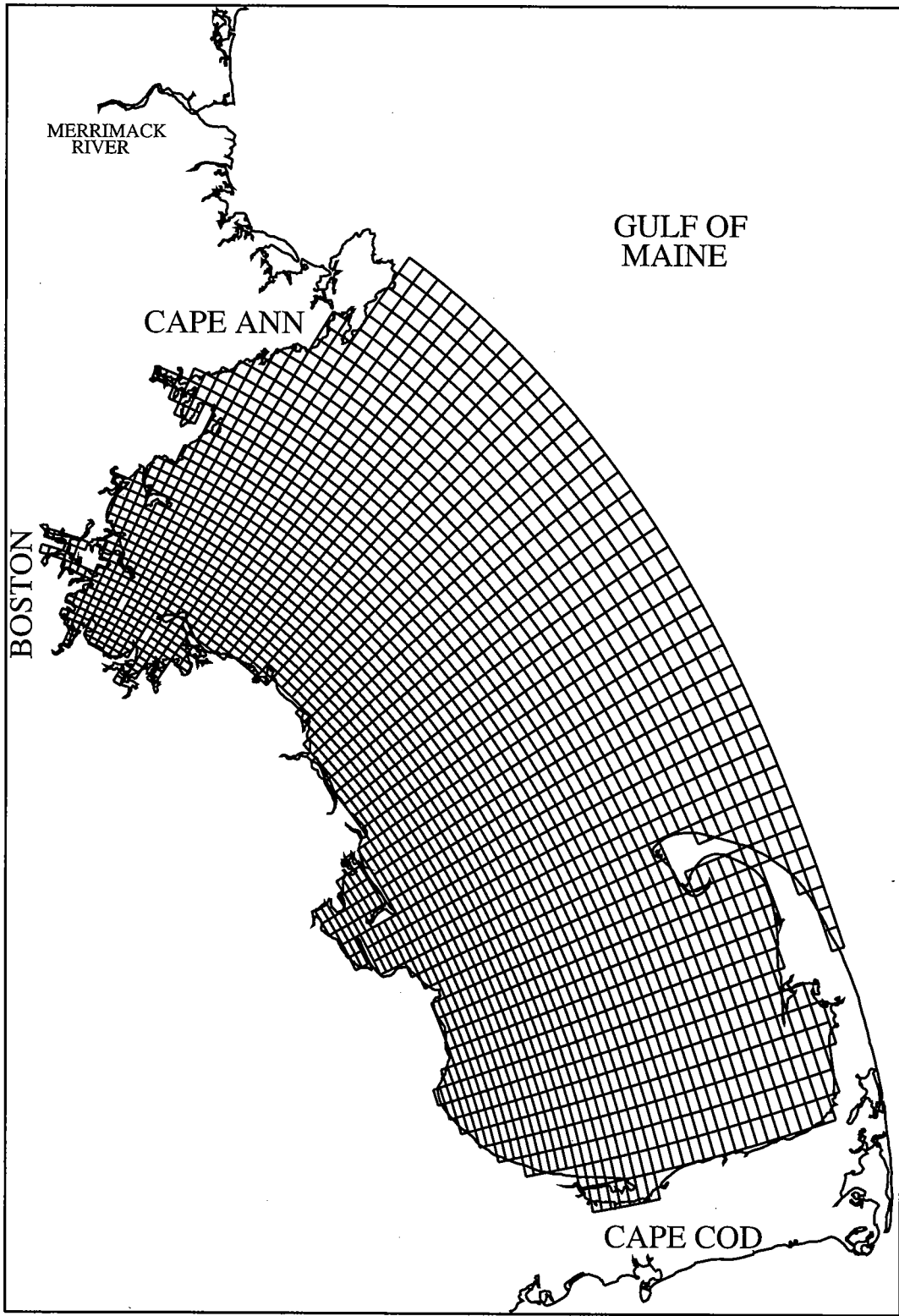


Figure 4-10. Water Quality Model Grid

F26 and F27 (established in 1994), close enough to the water quality boundary to provide insight into the water quality entering the bays for the Gulf of Maine. However, with only six sampling events per year, there are temporal gaps in the data that make it difficult to prescribe the boundary conditions over an annual cycle. These gaps also make it difficult to determine if water quality features observed within the bays are due to internal or external influences. Due to the sparseness of the data, boundary conditions were assigned to be horizontally constant. Using the available data, boundary conditions were assigned in the model at four standard levels (depths). The four standard levels assigned were at 0, 20, 60 and 110 meters. The model then computes concentrations for each of the 10-sigma layers in the model by interpolating the boundary input from the standard levels. Temporally, boundary conditions were assigned every 15 to 31 days based on the available data both near the boundary and within the model domain.

When possible, the boundary conditions assigned were based on data. The parameters for which the most data were available are dissolved oxygen (DO), dissolved inorganic phosphorus (PO_4), ammonia (NH_4), nitrate + nitrite ($\text{NO}_2 + \text{NO}_3$) and silica (Si). While phytoplankton carbon (Phyt1 + Phyt2), particulate organic phosphorus (POP), total dissolved phosphorus (TDP), particulate organic nitrogen (PON), total dissolved nitrogen (TDN) biogenic silica (Bsi), particulate organic carbon (POC), and dissolved organic carbon (DOC) were measured, the organic carbon, nitrogen, silica, and phosphorus state-variables were more difficult to assign. These data were collected at fewer stations and less often than the inorganic nutrients. Since some of the model's state-variables were not measured directly (e.g., DOP and DON), these constituents had to be determined by difference (e.g., $\text{TDP} - \text{PO}_4 = \text{DOP}$). Additionally, labile and refractory fractions are assigned for the organic pools. All of these factors required the specification of boundary conditions to be based on assumptions, approximations, previous experiences and calibration. When data were not available, 1994 boundary conditions were used as a starting point.

Salinity

Salinity, as in previous calibration runs, was determined by the hydrodynamic model output at the boundary.

Phytoplankton

In previous years analyzed, phytoplankton biomass data were not available for model comparison and boundary condition determination. In 1998 and 1999, limited data were available for boundary condition assignment. These data are estimates of biomass calculated from cell abundance and an assumed biomass per cell, which varies by species. In 1998, no spring bloom of phytoplankton could be observed from the data set at the boundary stations. This required a

modification of the boundary conditions used in previous years such as 1994 when the phytoplankton boundary conditions had an assumption of a phytoplankton spring bloom due to nutrient concentrations. Figure 4-11 shows that there is, however, a significant phytoplankton spring bloom in 1999 that has much higher phytoplankton biomass than was estimated in previous years. Fall phytoplankton blooms were also observed, and input into the model at the boundary (Figure 4-12). These fall blooms are significantly higher than previous boundary assumptions with 1999 higher than 1998. It has also been observed from the SeaWiFS satellite imagery that chlorophyll blooms in Massachusetts Bay and Cape Cod Bay appear to be greater in 1998 and 1999 than in previous years.

Particulate Organic Phosphorus

The non-algal POP is divided into refractory and labile fraction in the model as state variables. 1994 boundary conditions were used as a starting point because there are no POP data available. After reviewing organic carbon data, which are higher than in previous years modeled, it was concluded that both labile and refractory POP should be doubled at the top two standard levels while maintaining the original ratio assigned to the labile and refractory fractions. The assigned boundary RPOP and LPOP concentrations are presented on Figures 4-13 and 4-14, respectively.

Dissolved Organic Phosphorus

DOP is also divided into refractory and labile fractions in the model. Since DOP was not measured directly in the MWRA data set, it was calculated by subtracting PO_4 from total dissolved phosphorus, parameters that are measured and reported. Calculated DOP and assigned boundary conditions are presented in Figure 4-15. Often when data are calculated by the difference of two or more measured parameters, the results can be quite variable. This is apparent in the data in Figure 4-15. During calibration, LDOP boundary conditions were increased slightly during period from May through September in an effort to introduce more phosphorus into the bay to increase the PO_4 concentration. No changes were made in RDOP boundary conditions for the verification years from the 1994 calibration. The assigned RDOP and LDOP boundary concentrations are presented on Figures 4-16 and 4-17, respectively.

Dissolved Inorganic Phosphorus

Boundary conditions for PO_4 were based on what was assigned for boundary conditions in 1994. Where there were data at stations F26 and F27 that were different from boundary conditions that were previously assigned, changes were made to the boundary condition so that it would be reflective of the data. Figure 4-18 shows PO_4 data and the assigned boundary conditions. It should

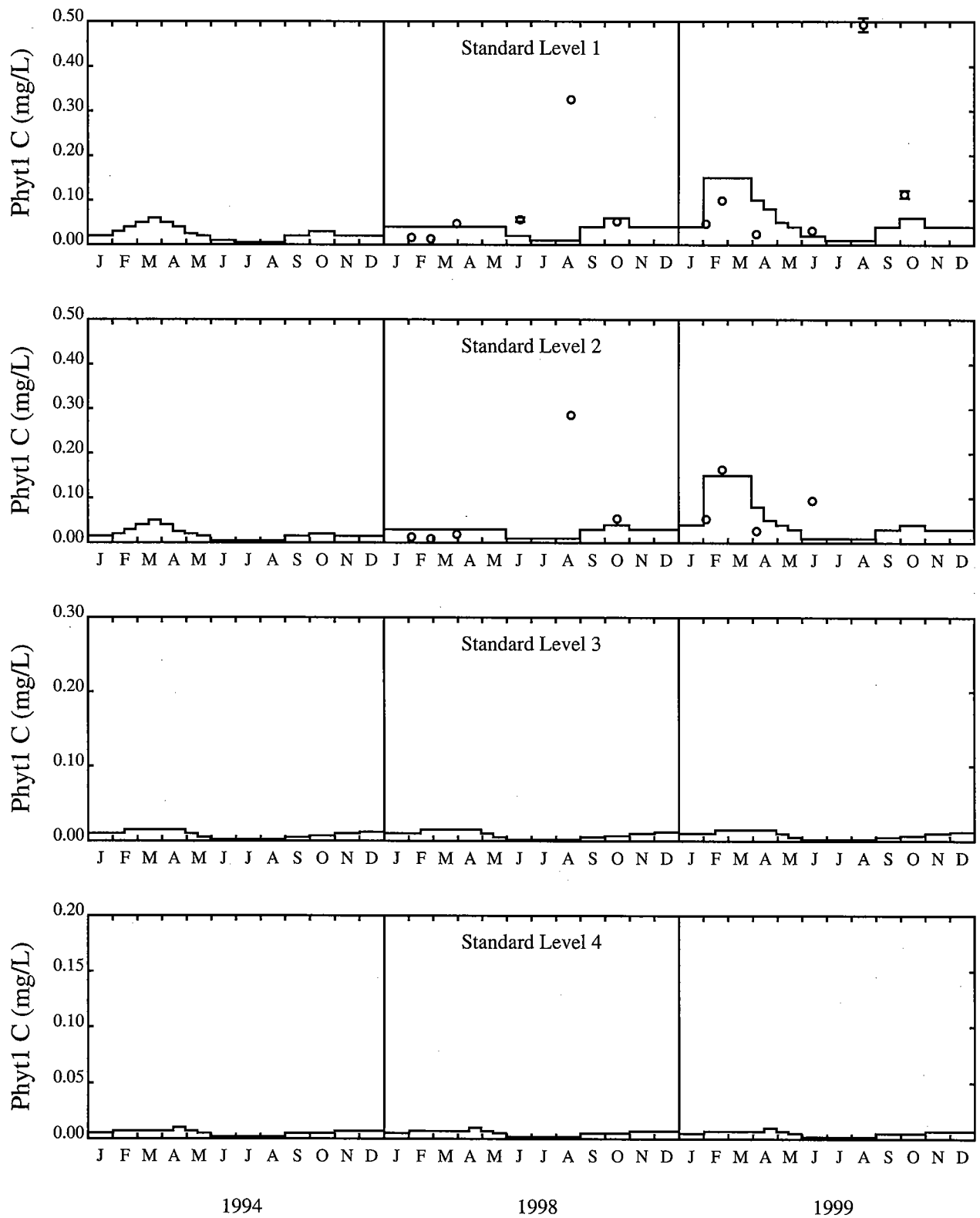


Figure 4-11. Assigned Winter Diatom Phytoplankton Carbon Boundary Conditions for 1994, 1998 and 1999

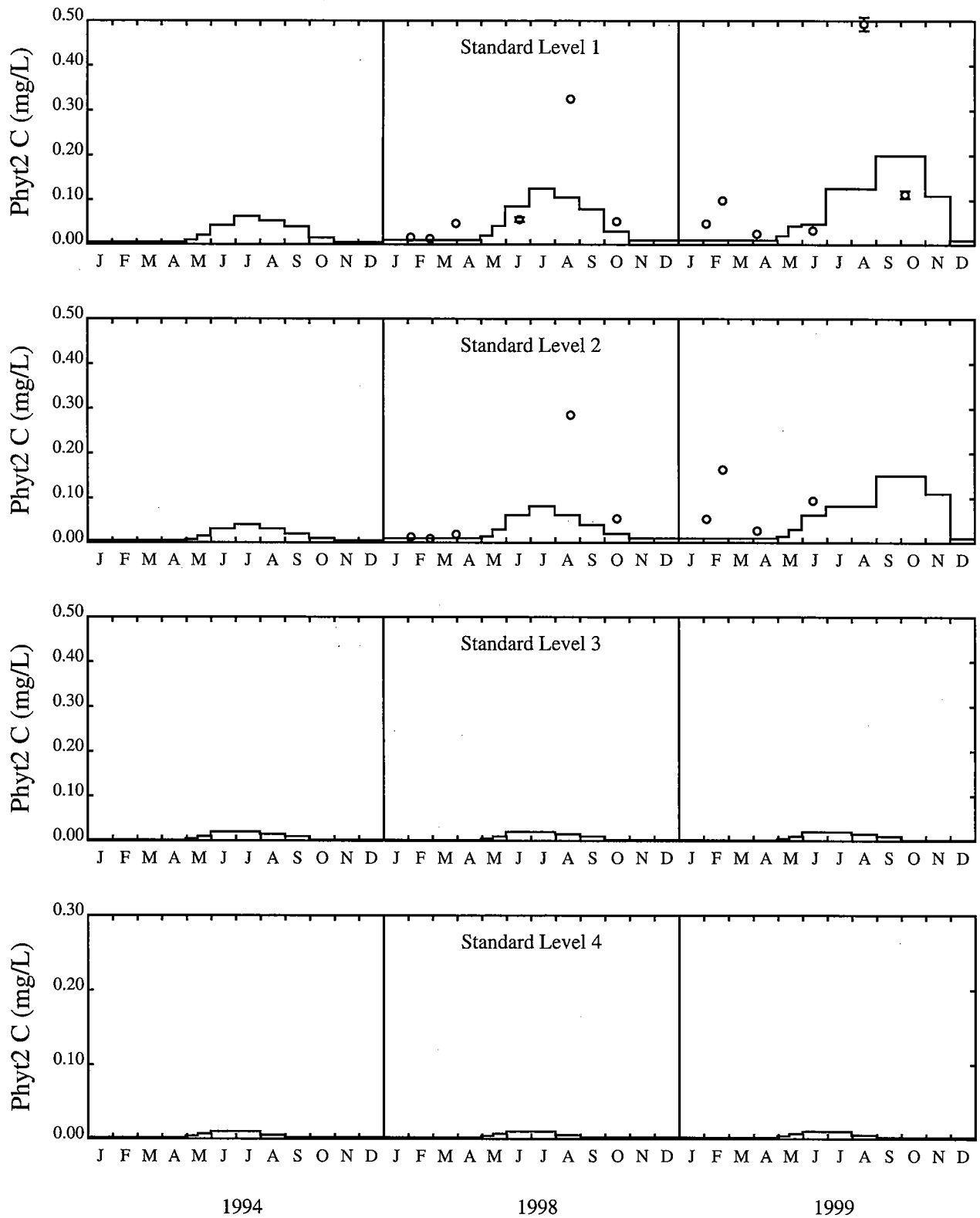


Figure 4-12. Assigned Summer Assemblage Phytoplankton Carbon Boundary Conditions for 1994, 1998 and 1999

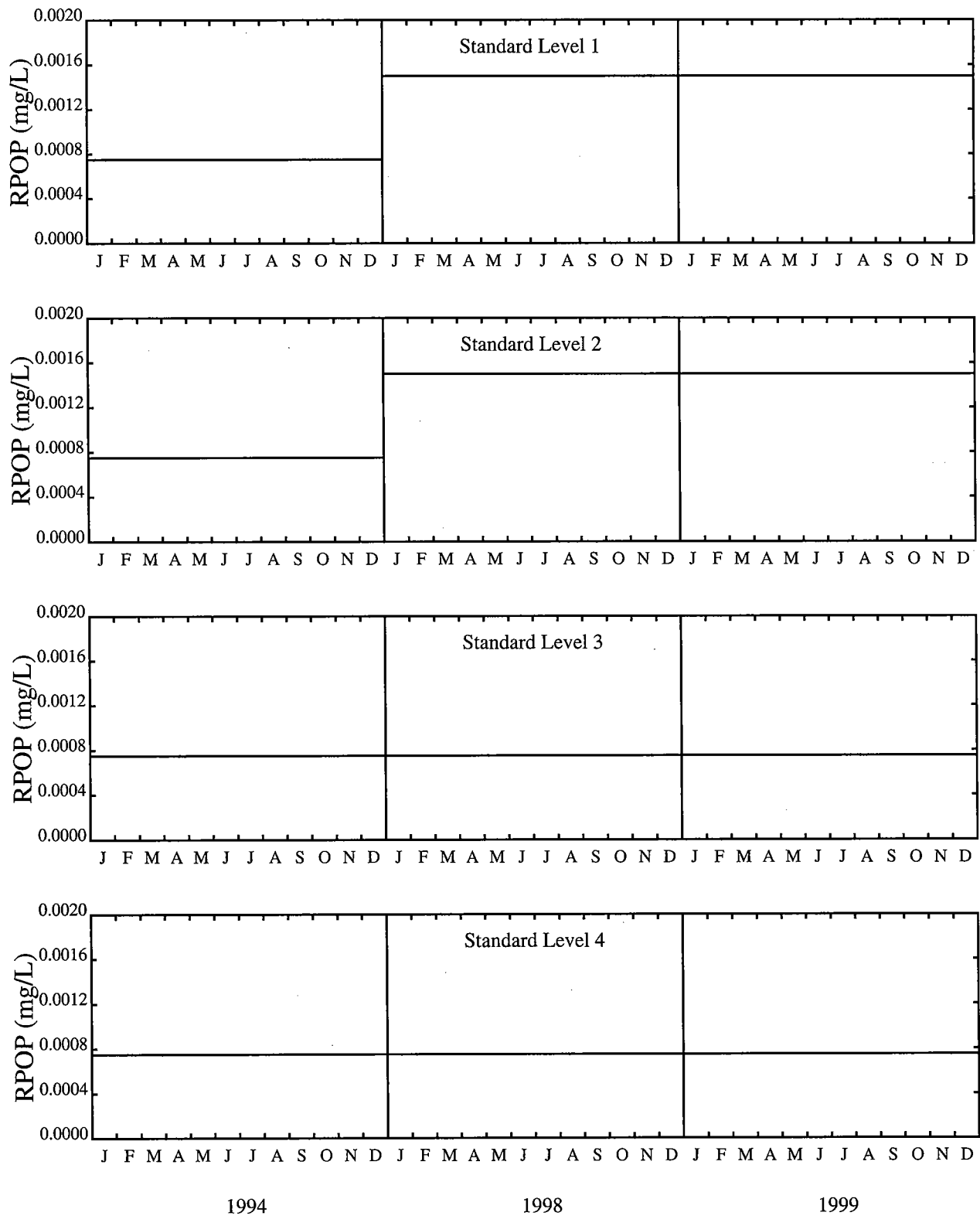


Figure 4-13. Assigned RPOP Boundary Conditions for 1994, 1998 and 1999

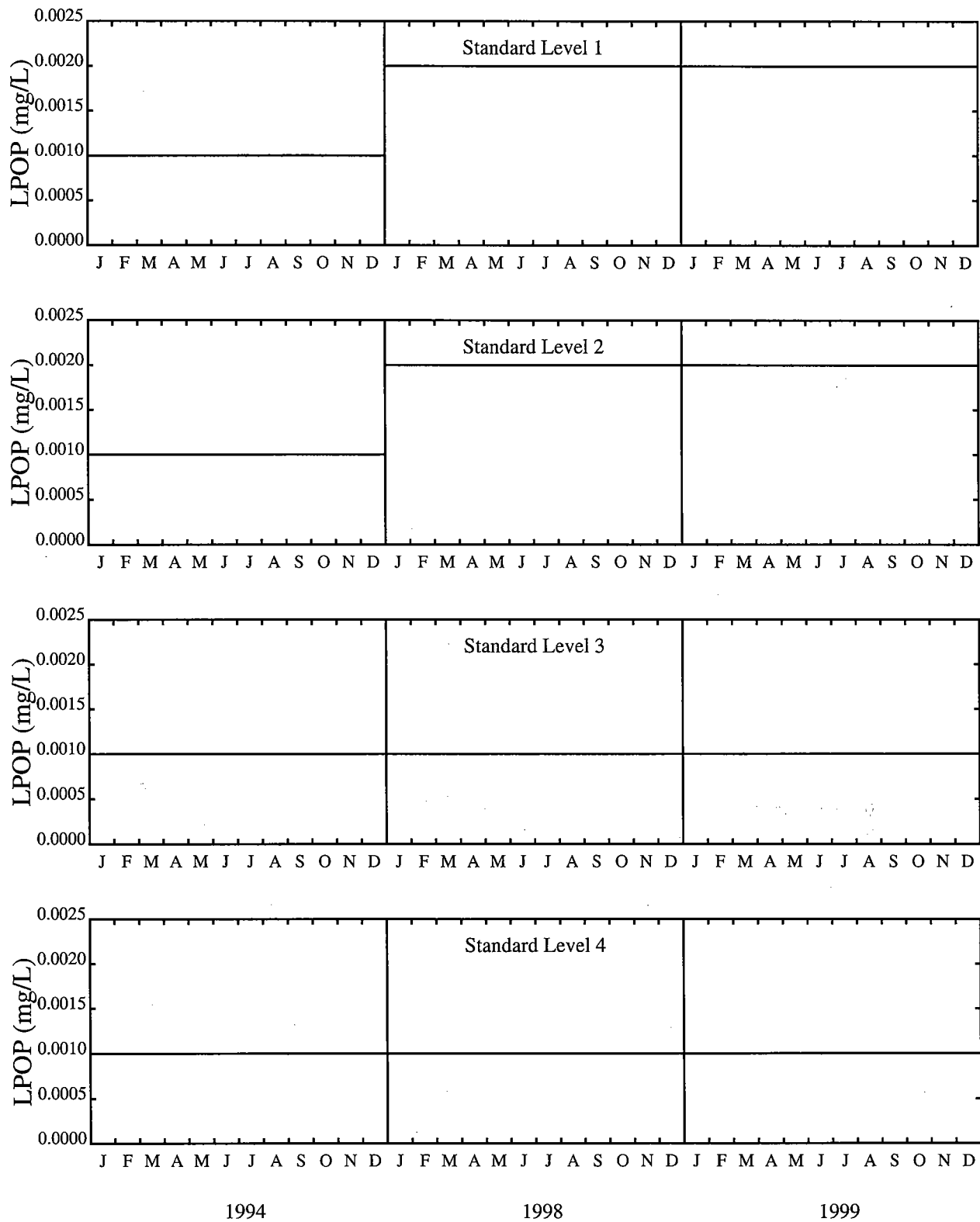


Figure 4-14. Assigned LPOP Boundary Conditions for 1994, 1998 and 1999

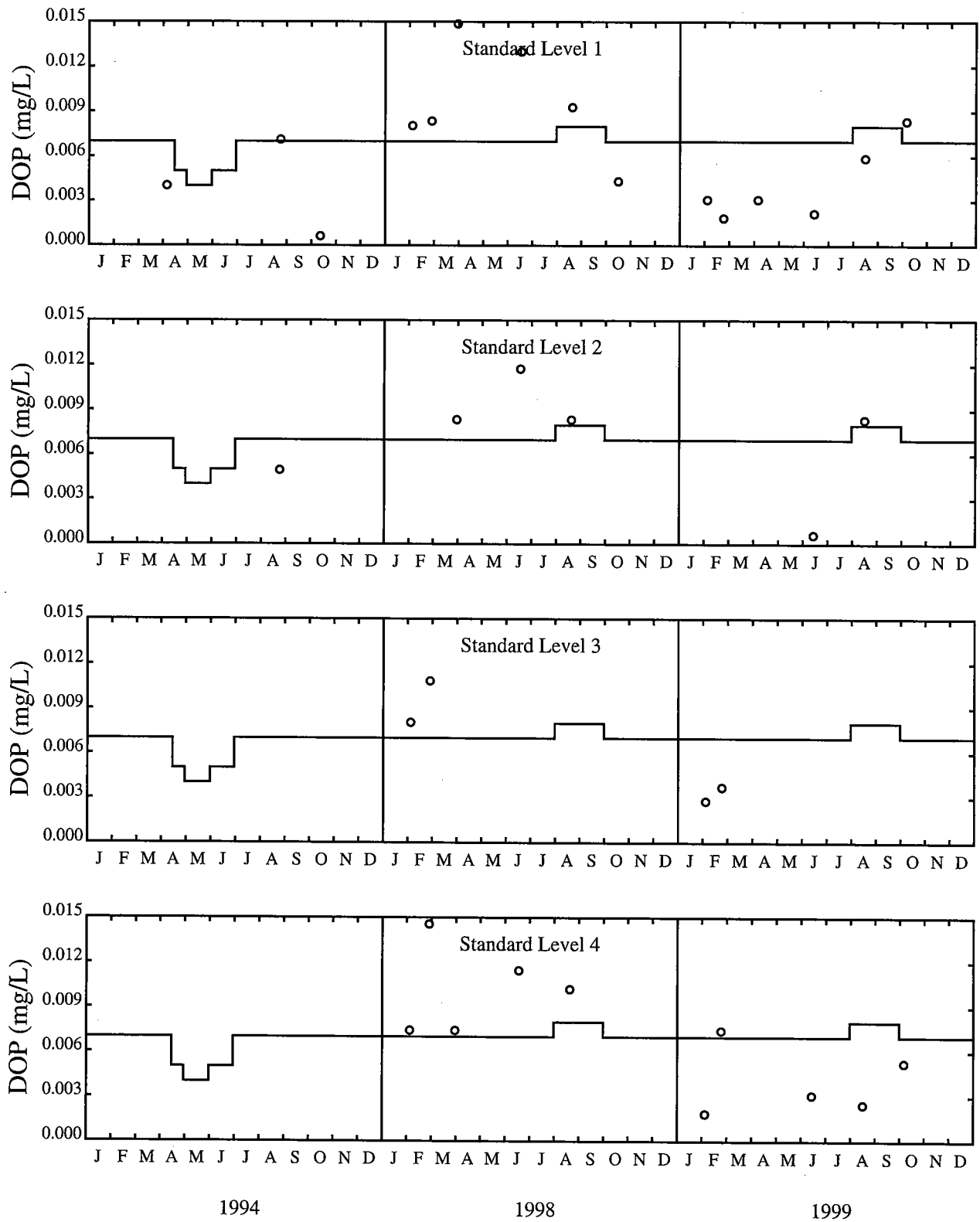


Figure 4-15. Assigned DOP Boundary Conditions for 1994, 1998 and 1999

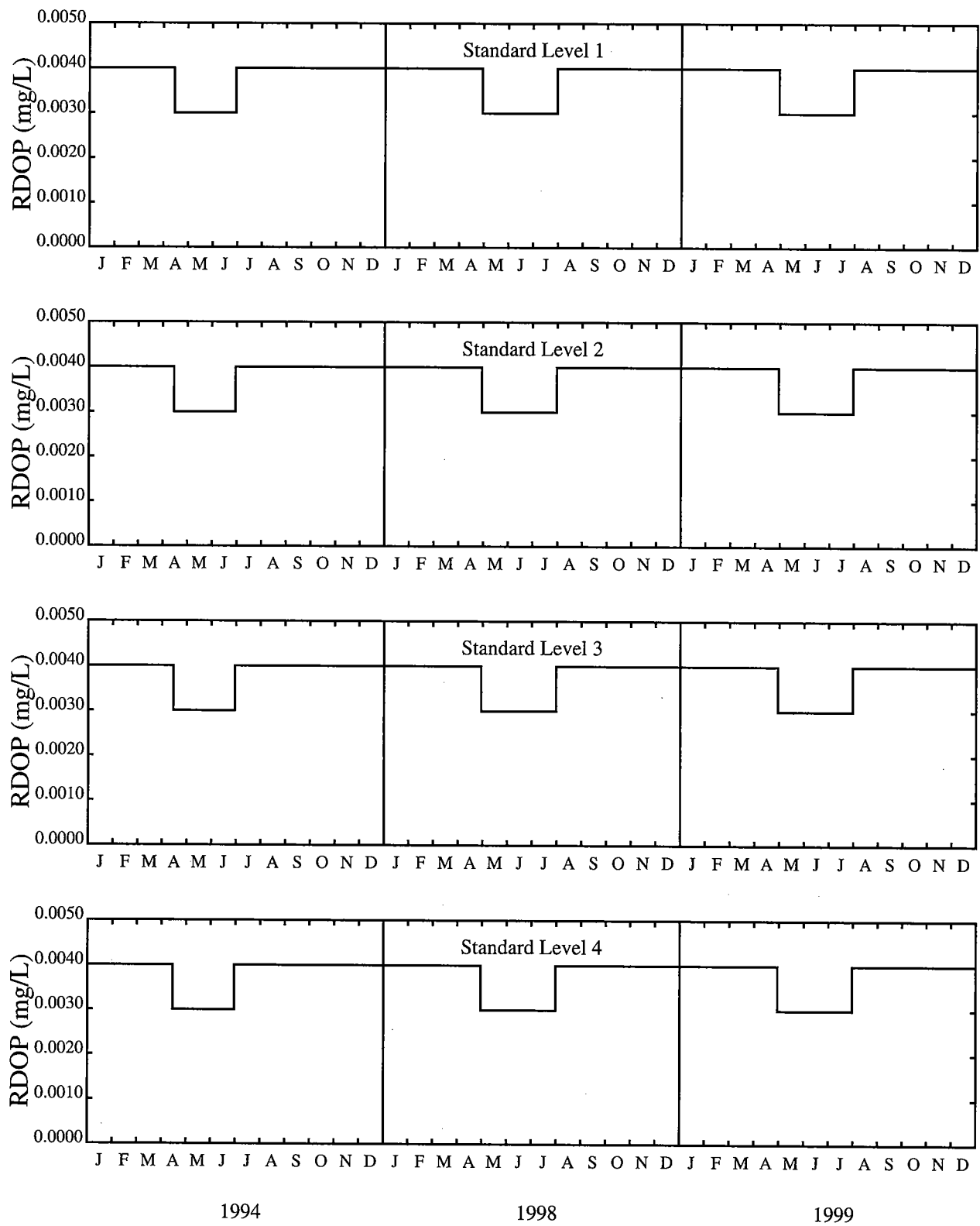


Figure 4-16. Assigned RDOP Boundary Conditions for 1994, 1998 and 1999

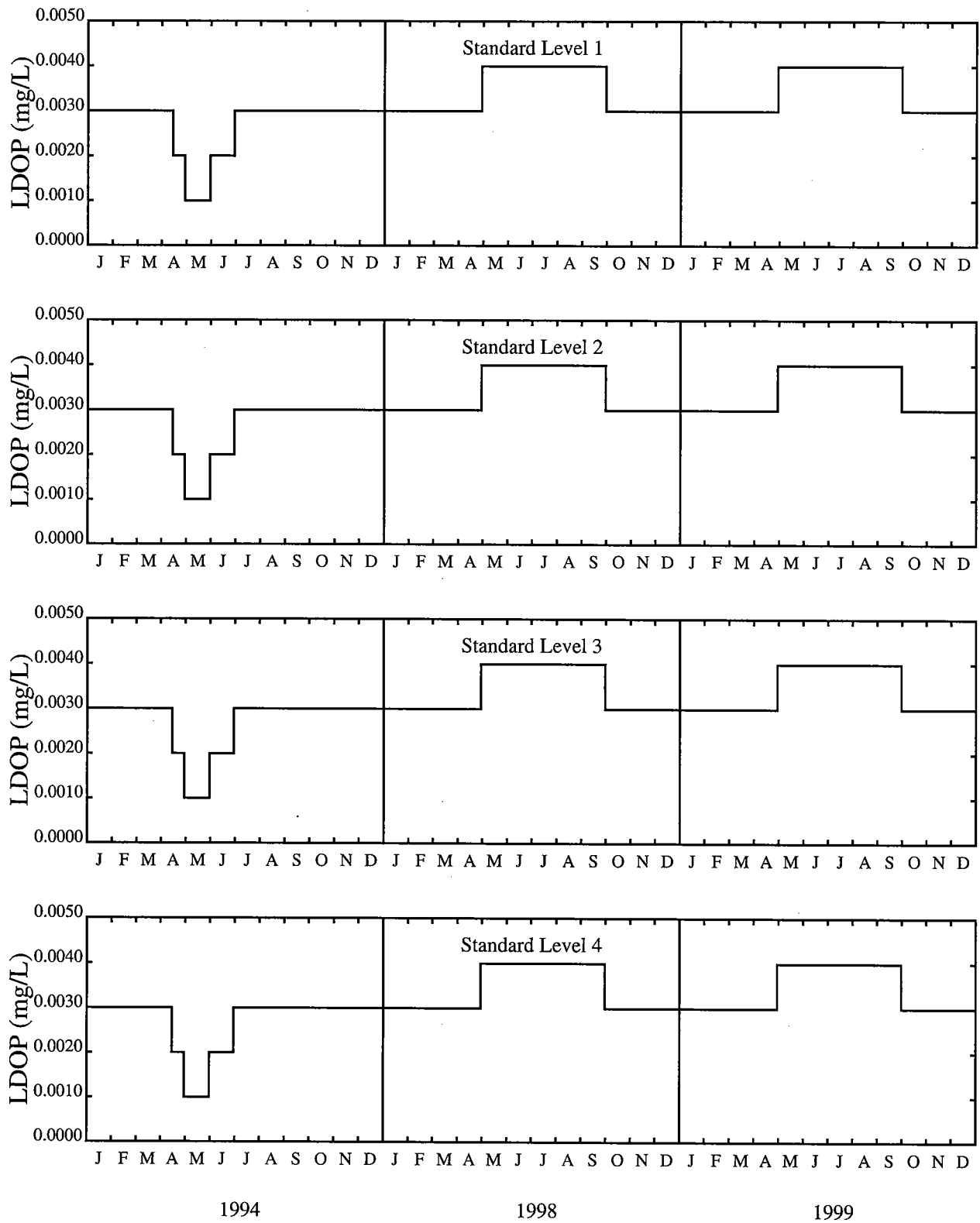


Figure 4-17. Assigned LDOP Boundary Conditions for 1994, 1998 and 1999

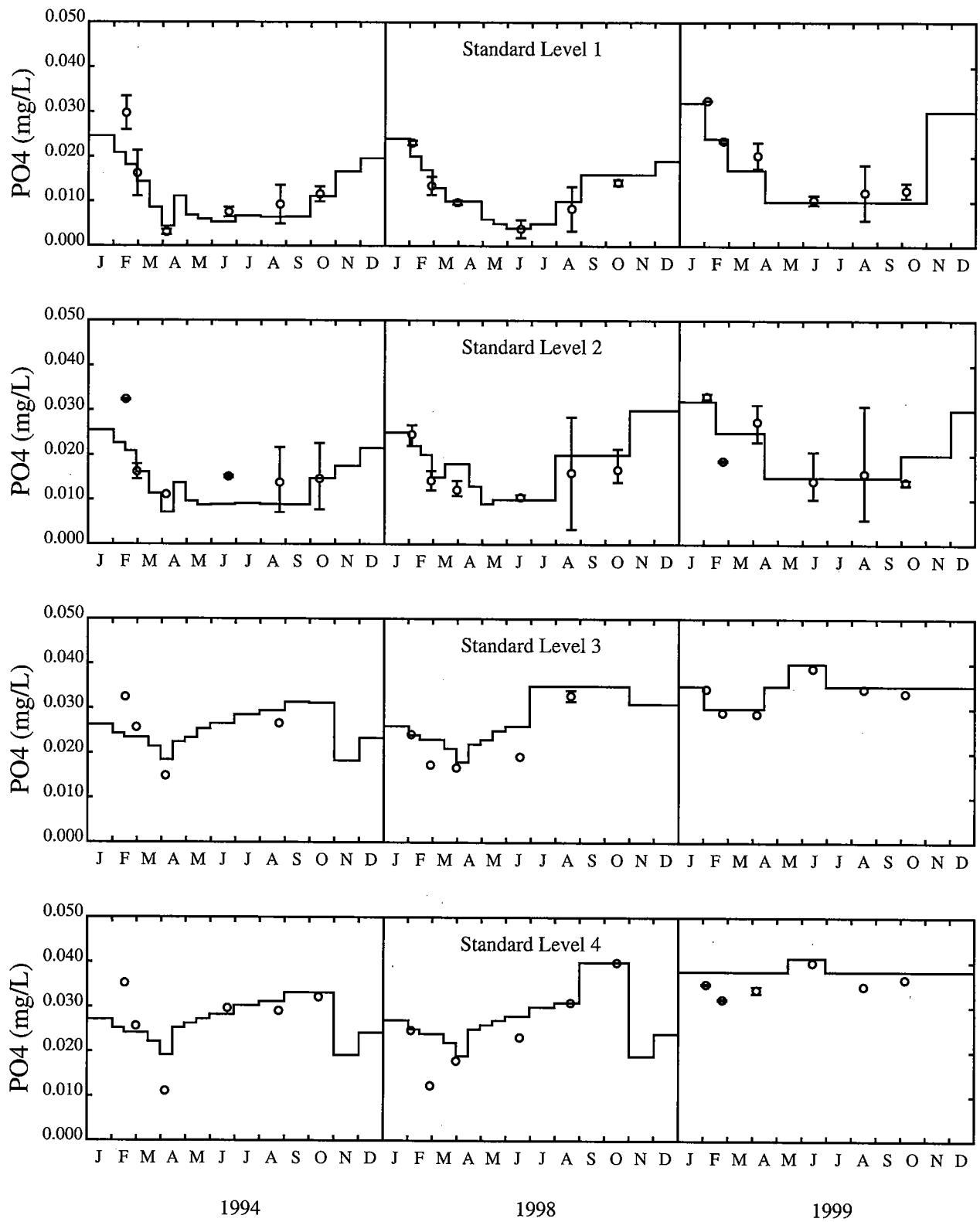


Figure 4-18. Assigned PO₄ Boundary Conditions for 1994, 1998 and 1999

be noted that PO_4 data at the boundary increased towards the later months in 1998 and remained elevated through 1999 compared to those reported in 1994. In the verification analysis, more of an effort was made to reproduce data at the boundary conditions than in the previous calibration runs.

Particulate Organic Nitrogen

The non-algal PON is divided into refractory and labile fractions in the model as state-variables. 1994 boundary conditions were used as a starting point because there are no PON data that can be used to determine what fraction is labile and what fraction is refractory. After reviewing organic carbon data, which are higher than in previous years modeled, it was concluded that both LPON and RPON should be doubled at the top two standard layers, as was done for POP, while maintaining the original fractions assigned for each. The assigned RPON and LPON boundary concentrations are presented on Figures 4-19 and 4-20, respectively.

Dissolved Organic Nitrogen

DON is also divided into refractory and labile fractions in the model. Since DON was not measured directly in the MWRA data set, it was calculated from subtracting dissolved inorganic nitrogen ($\text{NO}_2 + \text{NO}_3 + \text{NH}_4$) from total dissolved nitrogen, parameters that are measured and reported. Calculated DON and assigned boundary conditions are presented in Figure 4-21. The decrease in DON that is seen in the spring through the end of summer 1994 was not seen in the verification years. There is an increasing trend in from mid-April through August that is seen in the data for 1998. It is then reflected in the increase of RDON and LDON in the model boundary conditions for 1998. 1999 DON concentrations remained constant at approximately 0.13 mg/L at the boundary; RDON and LDON concentrations were assigned in 1999 to reflect that. The assigned RDON and LDON boundary concentrations are presented on Figures 4-22 and 4-23, respectively.

Ammonia

Boundary conditions for NH_4 were based on what was assigned for boundary conditions in 1994. Where there were data at stations F26 and F27 that was different from what was previously assigned, changes were made to the boundary condition so that it would be reflective of the data. Figure 4-24 shows NH_4 data and the assigned boundary conditions. It should be noted that 1999 NH_4 data is significantly higher than 1994 and 1998 with the greatest difference seen in the summer and fall months.

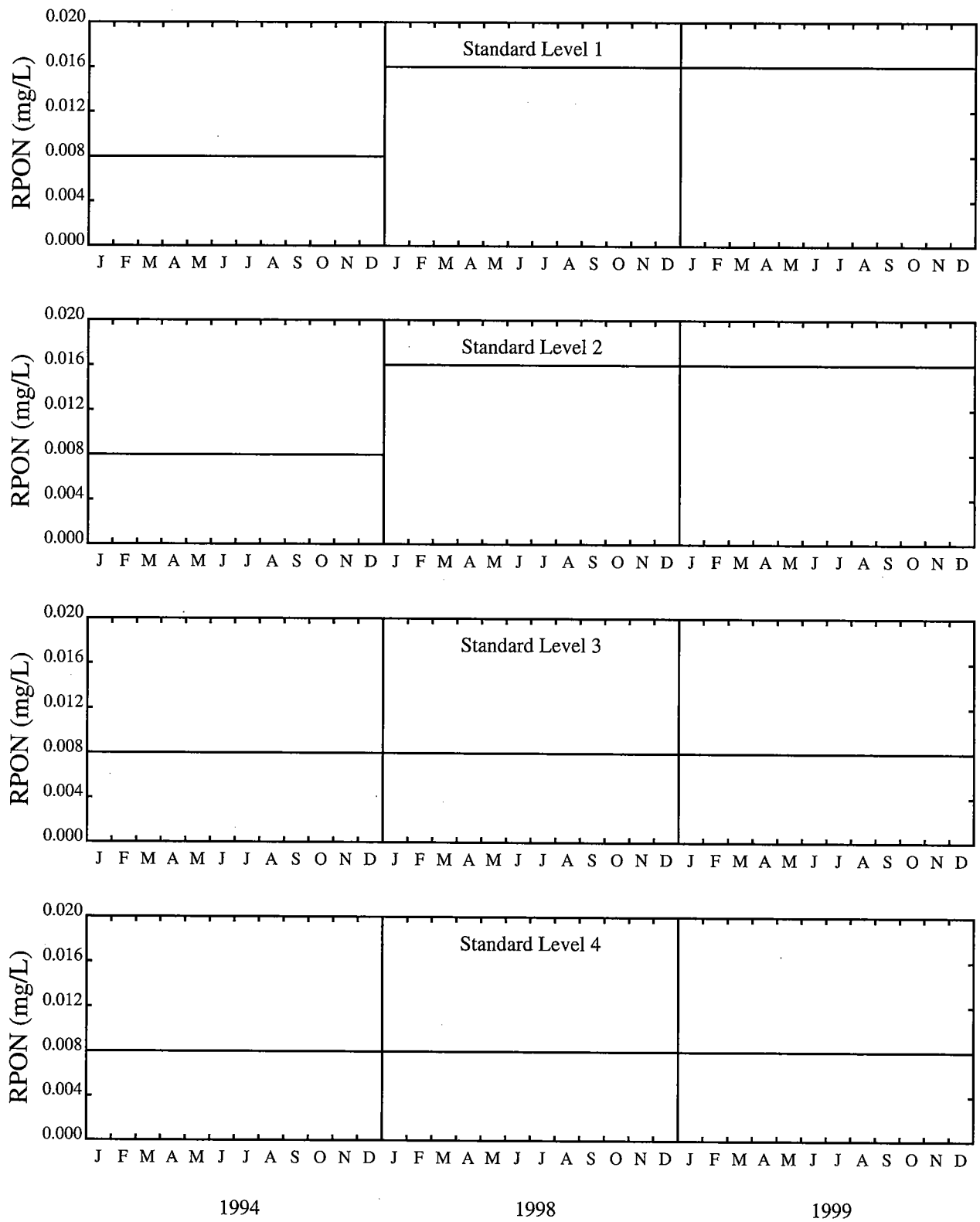


Figure 4-19. Assigned RPON Boundary Conditions for 1994, 1998 and 1999

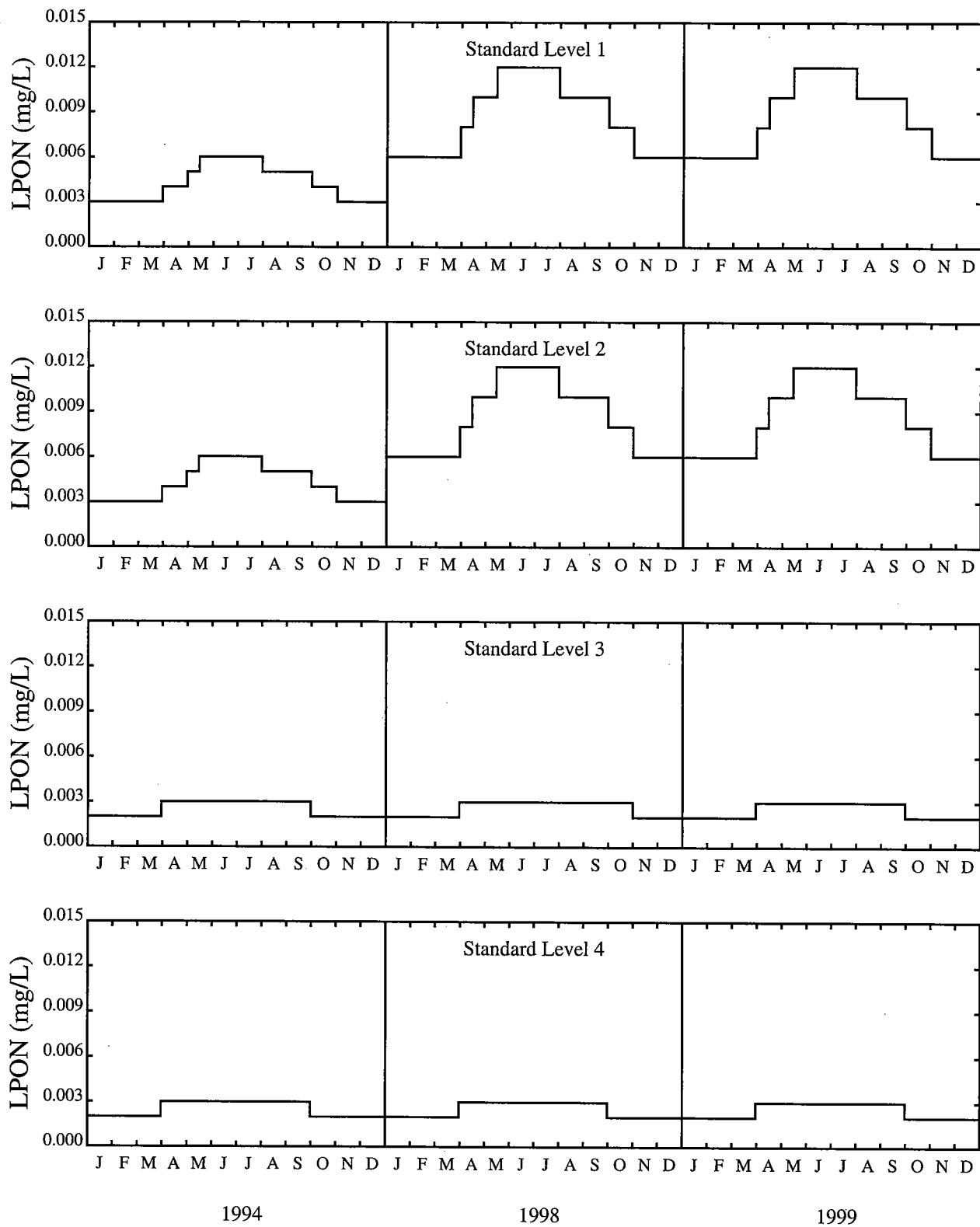


Figure 4-20. Assigned LPON Boundary Conditions for 1994, 1998 and 1999

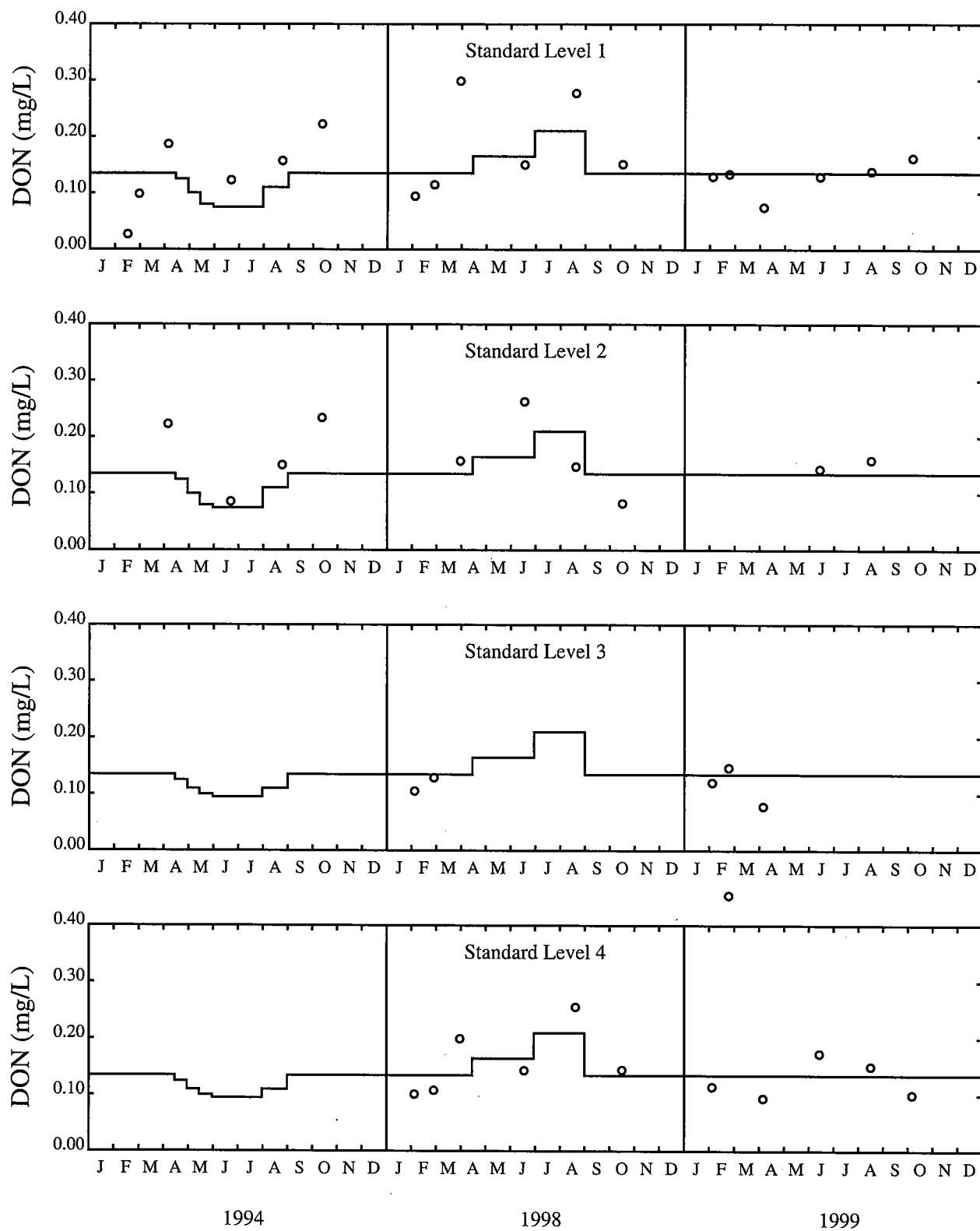


Figure 4-21. Assigned DON Boundary Conditions for 1994, 1998 and 1999

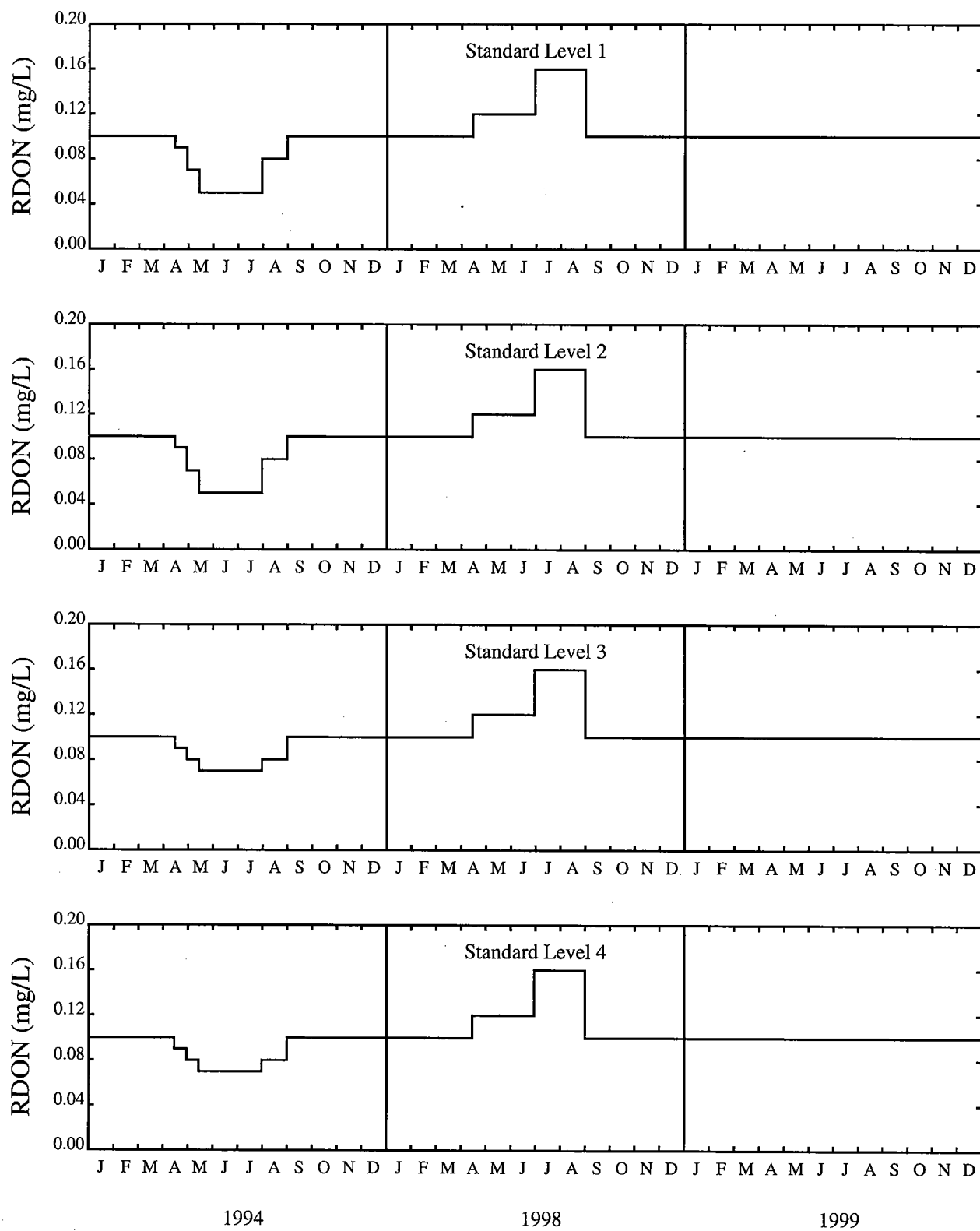


Figure 4-22. Assigned RDON Boundary Conditions for 1994, 1998 and 1999

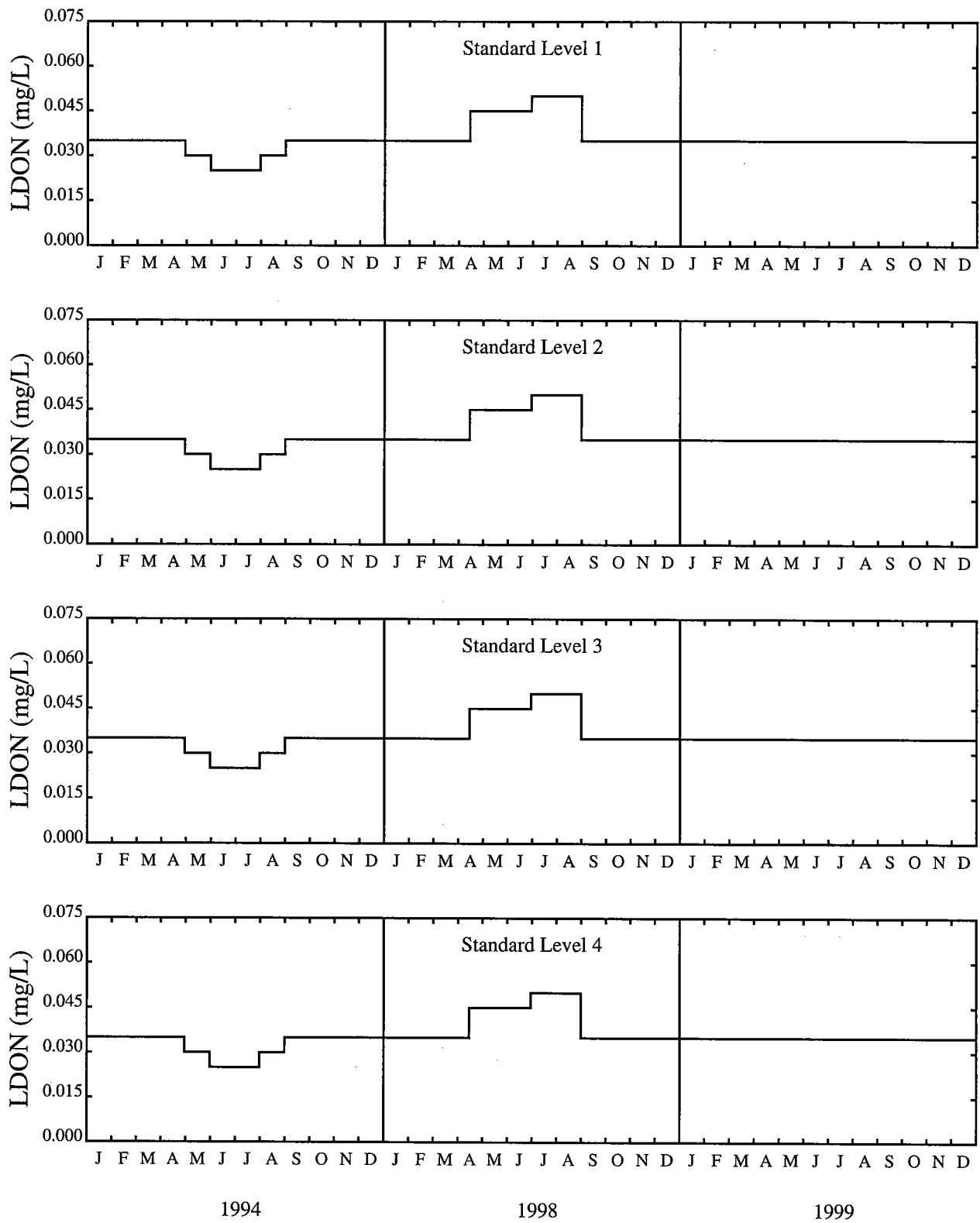


Figure 4-23. Assigned LDON Boundary Conditions for 1994, 1998 and 1999

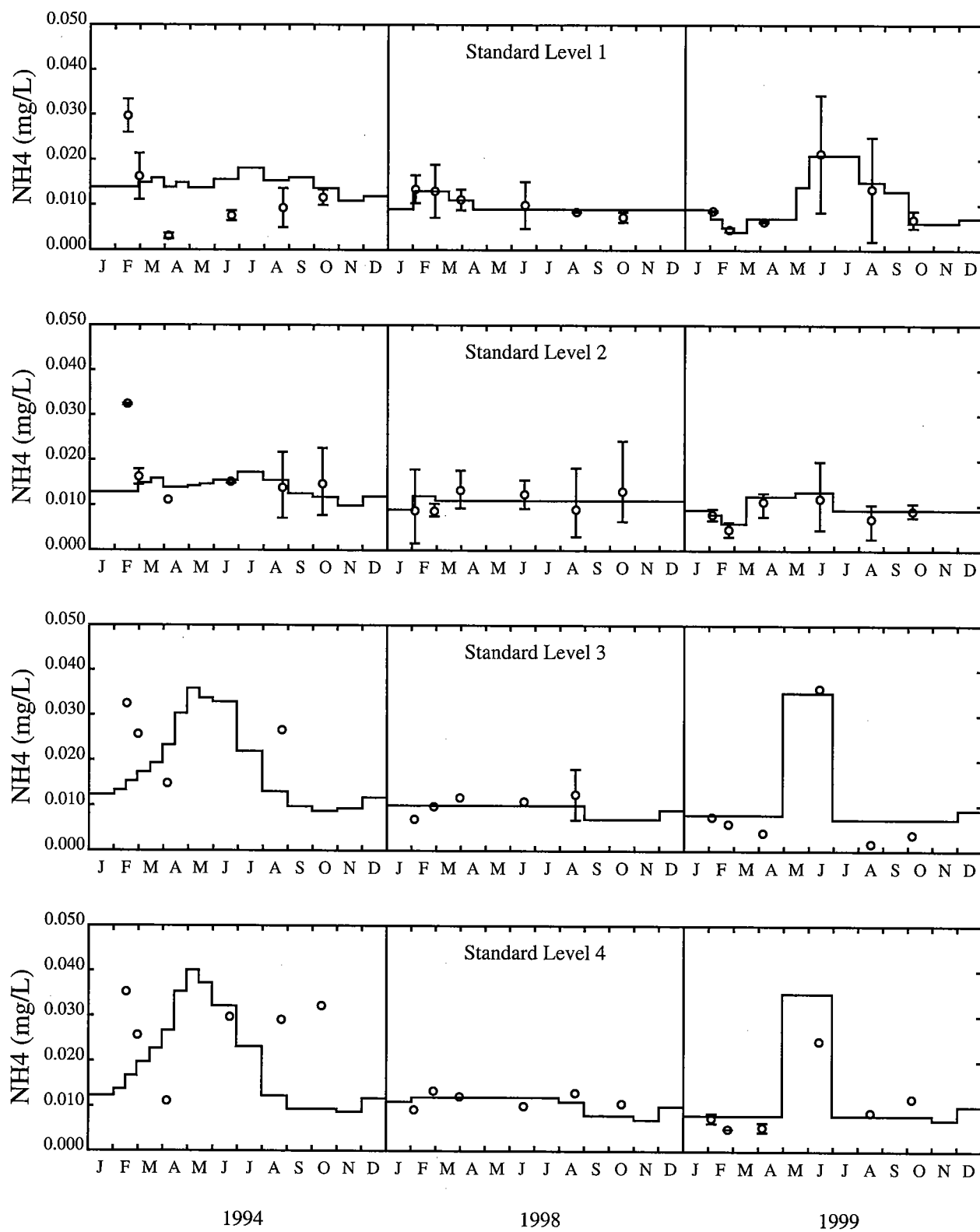


Figure 4-24. Assigned NH₄ Boundary Conditions for 1994, 1998 and 1999

Nitrite + Nitrate

Boundary conditions for $\text{NO}_2 + \text{NO}_3$ were based on what was assigned for boundary conditions in 1994. Where there were data at stations F26 and F27 that were different from what was previously assigned, changes were made to the boundary condition so that it would be reflective of the data. Figure 4-25 shows $\text{NO}_2 + \text{NO}_3$ data and the assigned boundary conditions. It should be noted that 1998 and 1999 $\text{NO}_2 + \text{NO}_3$ data are significantly higher than 1994 with the greatest difference seen from spring through the fall.

Biogenic Silica

MWRA reported BSi data for 1998 and 1999 for both the near field stations and far the stations. These data were not reported in previous years that were modeled so an educated guess was made in assigning BSi boundary conditions to 0.1 mg BSi/L from previous modeling experience and calibration. BSi data in 1998 and 1999 at stations F26 and F27 showed that the actual BSi concentrations at stations F26 and F27 tended to be lower than 0.03 mg/L at all four standard levels. For most of 1998 and 1999, a BSi concentration of 0.03 mg/L was assigned at the boundary. One period when the concentration was adjusted from 0.03 mg/L was during January, February and March of 1999 when an apparent diatom bloom occurred. Figure 4-26 shows BSi data and the assigned boundary conditions.

Silica

Boundary conditions for Si were based on what was assigned for boundary conditions in 1994. Where there were data at stations F26 and F27 that was different from what was previously assigned, changes were made to the boundary condition so that it would be reflective of the data. Figure 4-27 shows Si data and the assigned boundary conditions.

Particulate Organic Carbon

The non-algal POC is divided into refractory and labile fraction in the model as state variables. 1994 boundary conditions were used as a starting point. After reviewing POC data at the boundary, which are as much as two times higher than in previous years modeled, it was concluded that both LPOC and RPOC should be doubled at the top two standard layers, while maintaining the original splits assigned for each. The assigned RPOC and LPOC are presented on Figures 4-28 and 4-29, respectively.

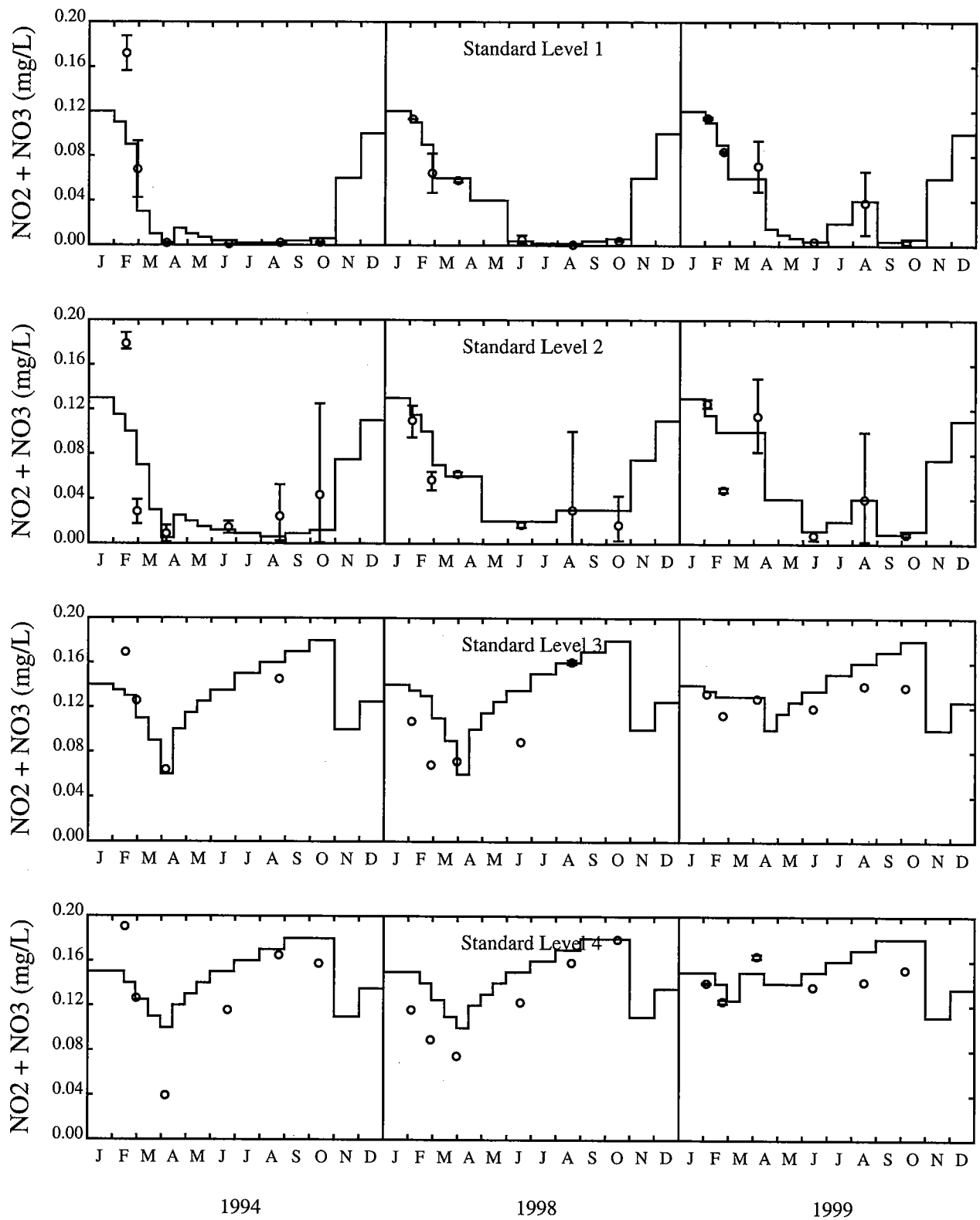


Figure 4-25. Assigned $\text{NO}_2 + \text{NO}_3$ Boundary Conditions for 1994, 1998 and 1999

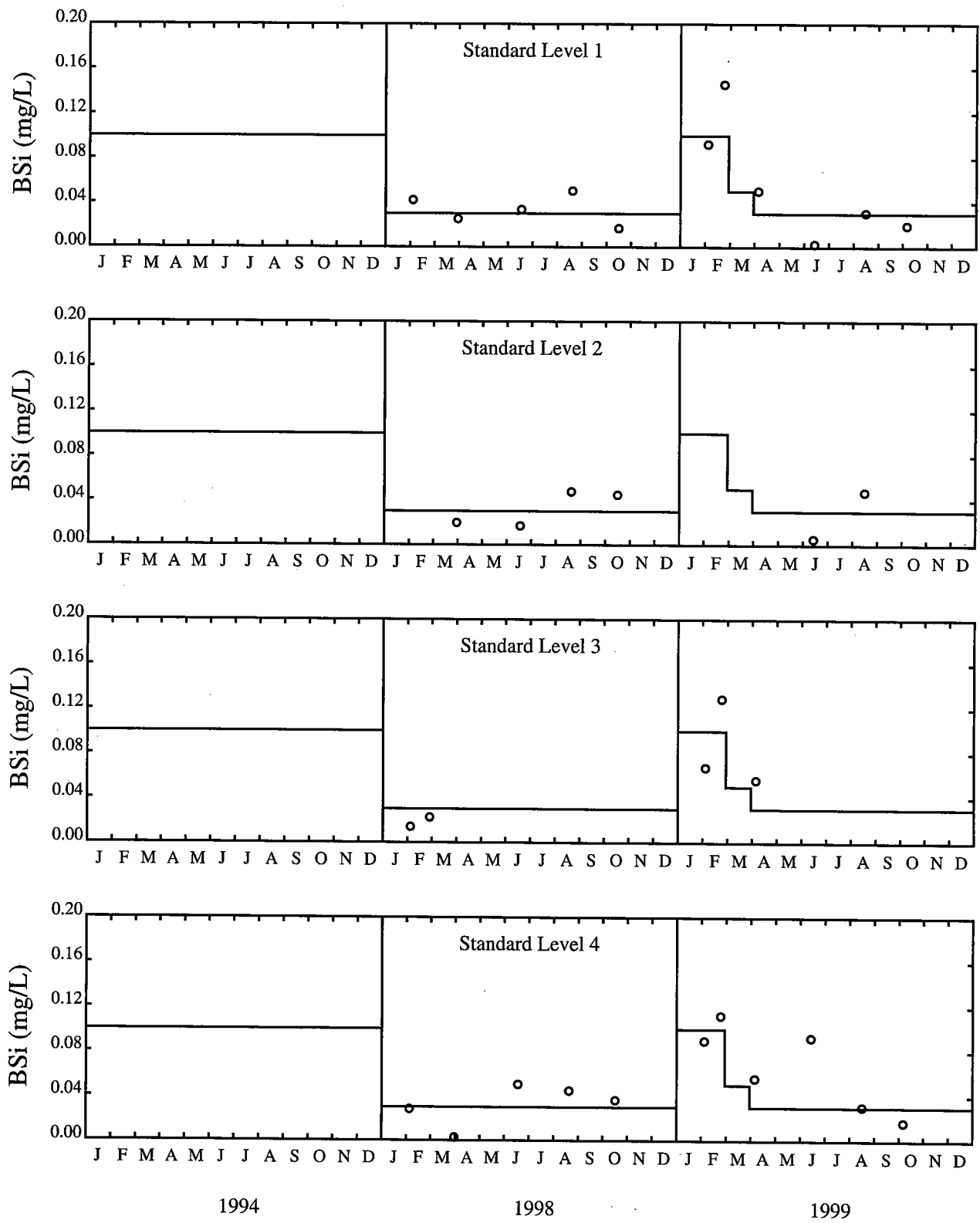


Figure 4-26. Assigned BSi Concentrations for 1994, 1998 and 1999

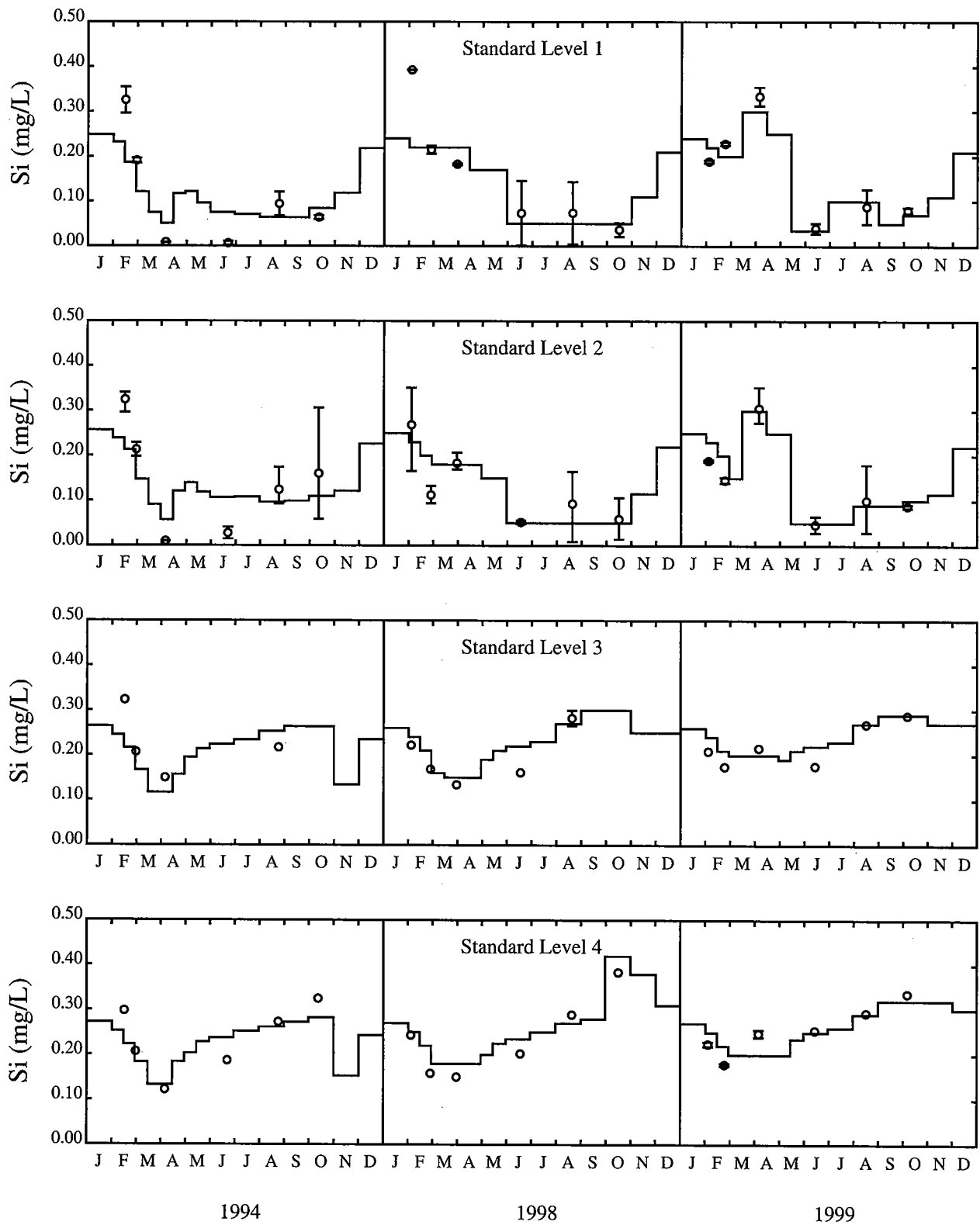


Figure 4-27. Assigned Si Boundary Conditions for 1994, 1998 and 1999

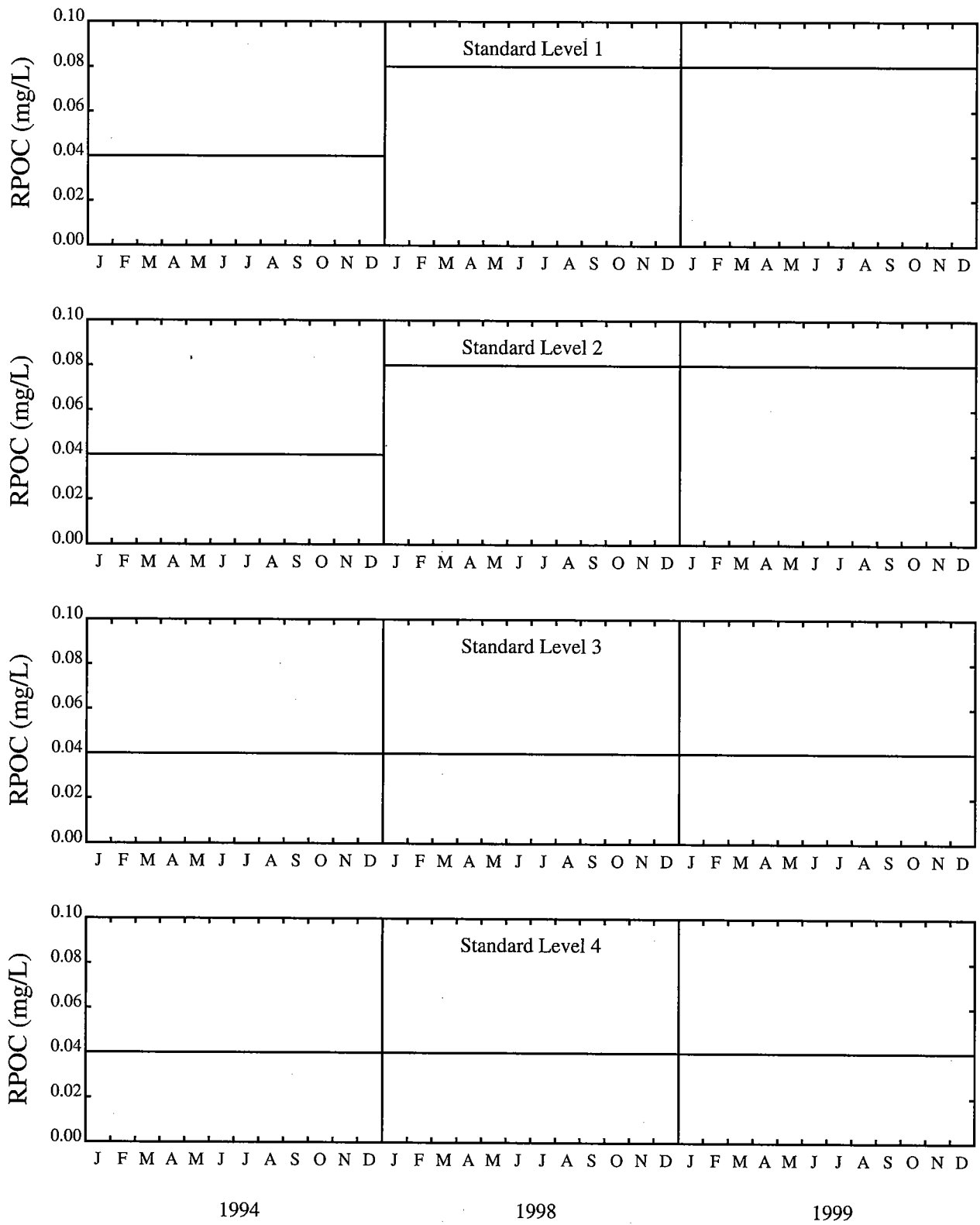


Figure 4-28. Assigned RPOC Boundary Conditions for 1994, 1998 and 1999

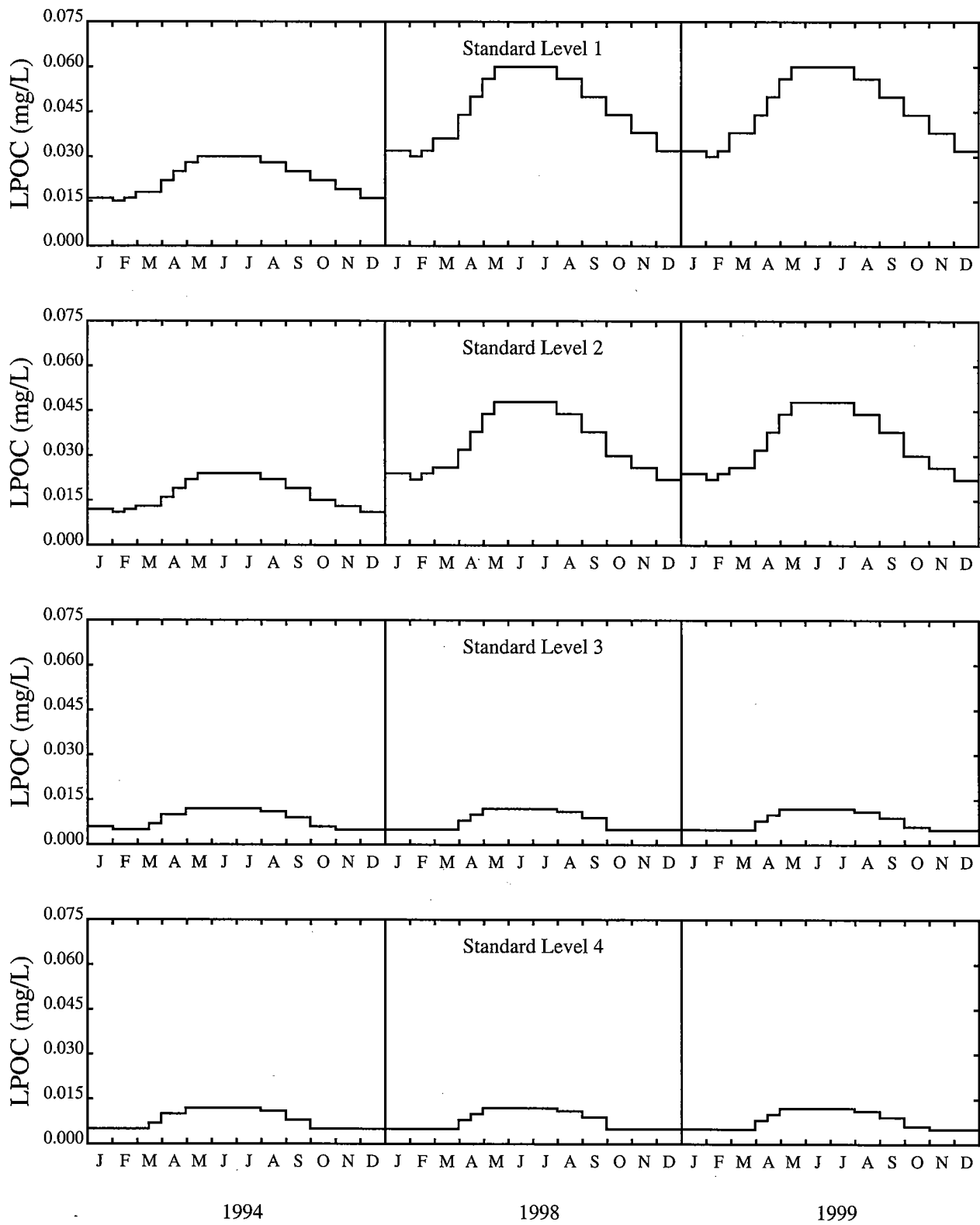


Figure 4-29. Assigned LPOC Boundary Conditions for 1994, 1998 and 1999

Dissolved Organic Carbon

DOC is also divided into refractory and labile fractions in the model. Measured DOC and assigned boundary conditions are presented in Figure 4-30. There is an increasing trend in the verification years in comparison to the 1994 data. Total DOC assigned in 1994 at the boundary condition was approximately 1.4 mg/L. In 1998 and 1999, the assigned value is 2.0 mg/L, which is reflective of the increase in the data observed. As a result, RDOC and LDOC boundary concentrations were increased. The ratio of the labile to refractory remained the same. The assigned RDOC and LDOC boundary concentrations are presented on Figures 4-31 and 4-32, respectively.

Dissolved Oxygen Boundary Conditions

An attempt at developing a relationship between the average DO concentration of the near field stations and the DO concentration boundary conditions, since the near field area is sampled more often than the far field, was conducted in "Boundary Sensitivity Analysis for the Bays Eutrophication Model (BEM)" by HydroQual (2001b.). A far field to near field ratio was calculated for the DO data measured during each month. A median of the ratio (far field to near field) was then determined for each of the standard layers. It was concluded that surface, standard level 1, the ratios hover around 1.0 with the suggestion of an increase in the first part of the year and a decline into August. At the standard level 2 a wide range of ratios are observed. There was a general increase into June and then a decline in August and October. At level 3, a wider range of ratios were found and instead of a continued decline from August into October there was an increase in October. At the deepest level, the ratio between level 4 and level 3 was fairly constant, near 0.975. Table 4-1 presents the far field to near field ratio for each of the standard levels for DO saturation, % DO saturation and DO concentration.

The boundary conditions for DO were developed by multiplying the far field to near field DO concentrations ratio in Table 4-1 for each month and each standard level by the average monthly near field DO concentrations for each month and each standard level. The level 4 boundary conditions for DO were calculated using a constant fraction of 0.97 of the level 3 DO boundary condition concentrations. The developed boundary conditions were then temporally plotted against actual far field data at stations F26 and F27 for the six sampling events in Figure 4-33. Where far field data differed from calculated boundary conditions, adjustments were made to fit the boundary condition to data present.

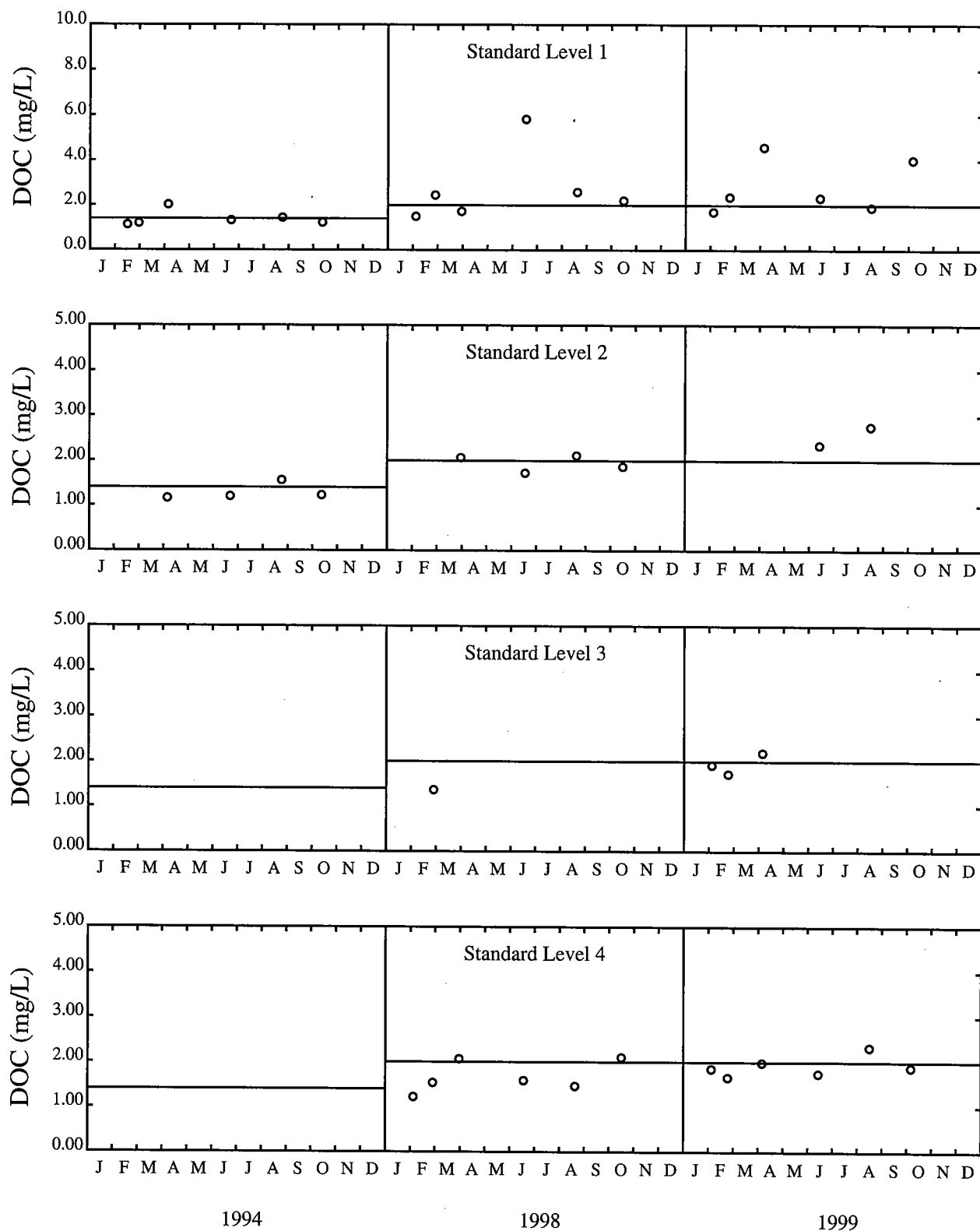


Figure 4-30. Assigned DOC Boundary Conditions for 1994, 1998 and 1999

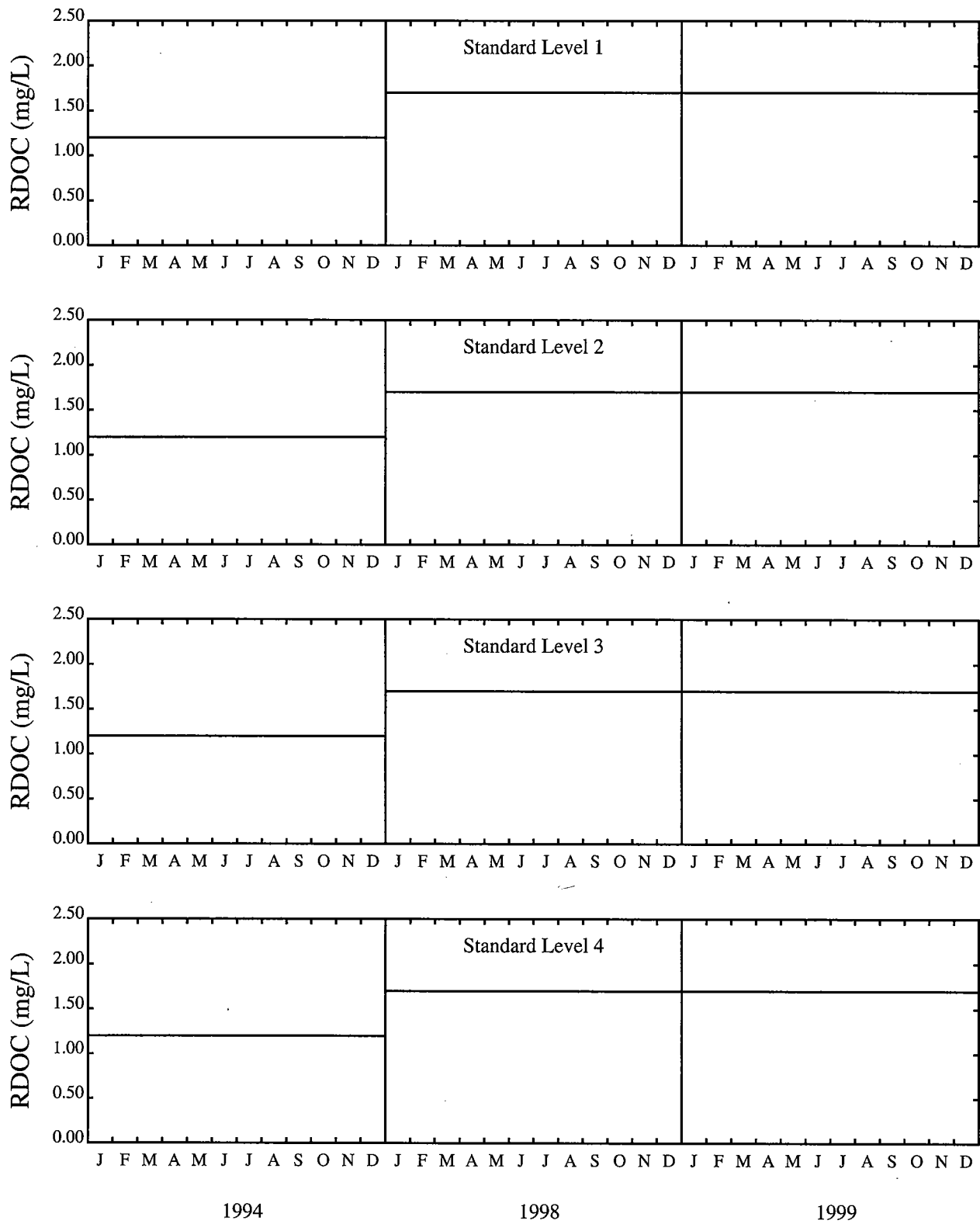


Figure 4-31. Assigned RDOC Boundary Conditions for 1994, 1998 and 1999

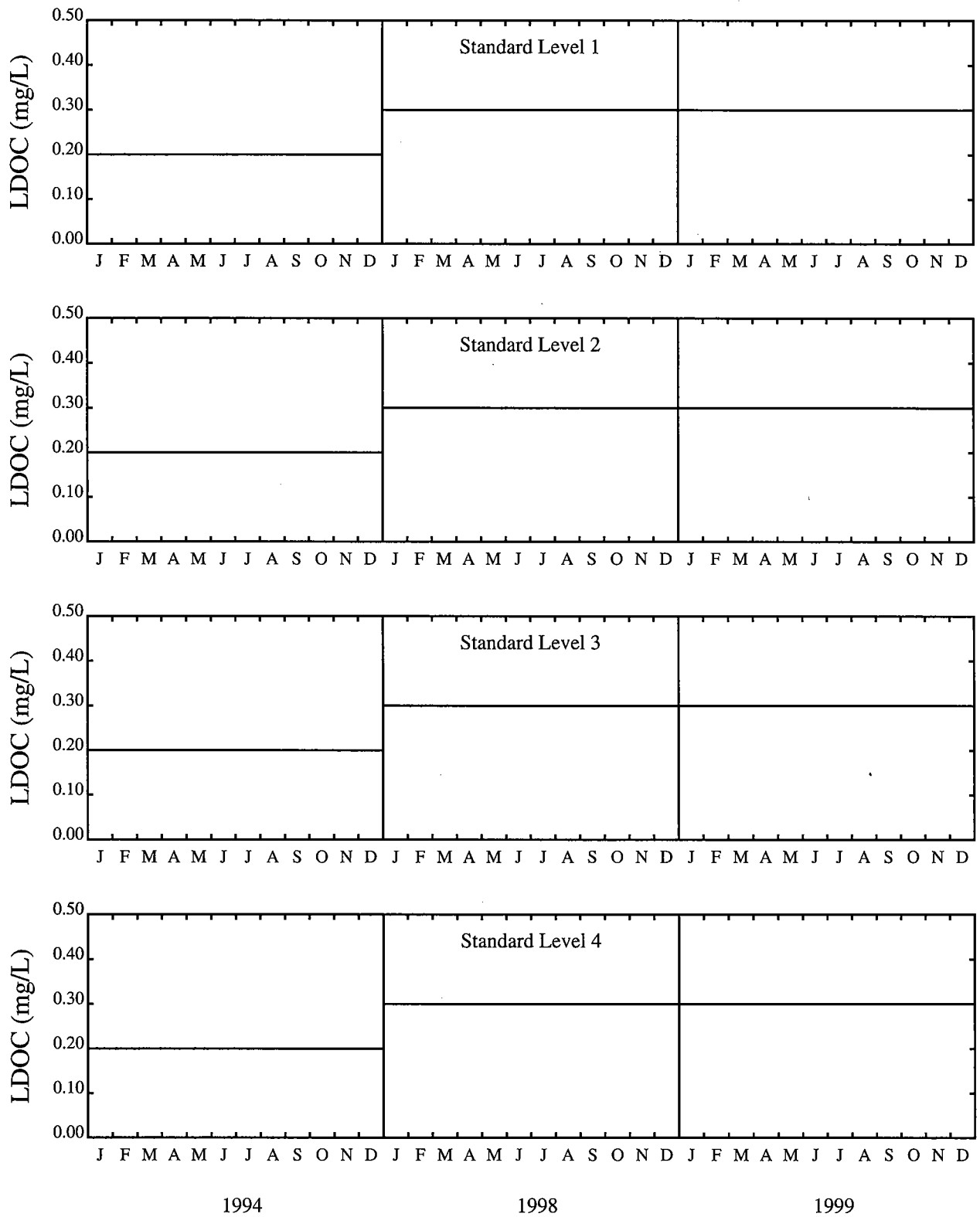


Figure 4-32. Assigned LDOC Boundary Conditions for 1994, 1998 and 1999

Table 4-1. Far Field to Near Field Ratios

Standard Level 1				Standard Level 2			
Month	DO sat	% DO sat	DO	Month	DO sat	% DO sat	DO
Jan	0.98	0.99	0.985	Jan	0.98	0.98	0.97
Feb	0.985	1.00	0.985	Feb	0.98	0.99	0.97
Mar	0.99	1.005	1.000	Mar	1.00	0.97	0.97
Apr	1.02	1.005	1.03	Apr	1.005	1.005	1.01
May	1.02	1.01	1.03	May	1.005	1.025	1.03
June	1.02	1.01	1.03	June	1.005	1.045	1.05
July	1.01	1.00	1.005	July	1.00	1.04	1.035
Aug	1.00	0.99	0.98	Aug	0.99	1.035	1.02
Sept	0.995	0.995	0.985	Sept	0.99	1.03	1.015
Oct	0.99	0.995	0.985	Oct	0.985	1.03	1.015
Nov	0.985	0.995	0.985	Nov	0.985	1.01	0.98
Dec	0.98	0.995	0.985	Dec	0.98	0.995	0.97
Standard Level 3				Standard Level 4			
Month	DO sat	% DO sat	DO	A constant ratio of 0.97 was used between Level 4 and Level 3 for DO.			
Jan	0.98	1.01	0.98				
Feb	0.98	1.01	0.99				
Mar	0.995	1.01	1.00				
Apr	0.985	1.045	1.03				
May	1.00	1.05	1.05				
June	1.01	1.06	1.07				
July	1.01	1.035	1.05				
Aug	1.005	1.025	1.03				
Sept	1.001	1.06	1.075				
Oct	1.02	1.10	1.12				
Nov	1.00	1.05	1.055				
Dec	0.98	1.01	0.99				

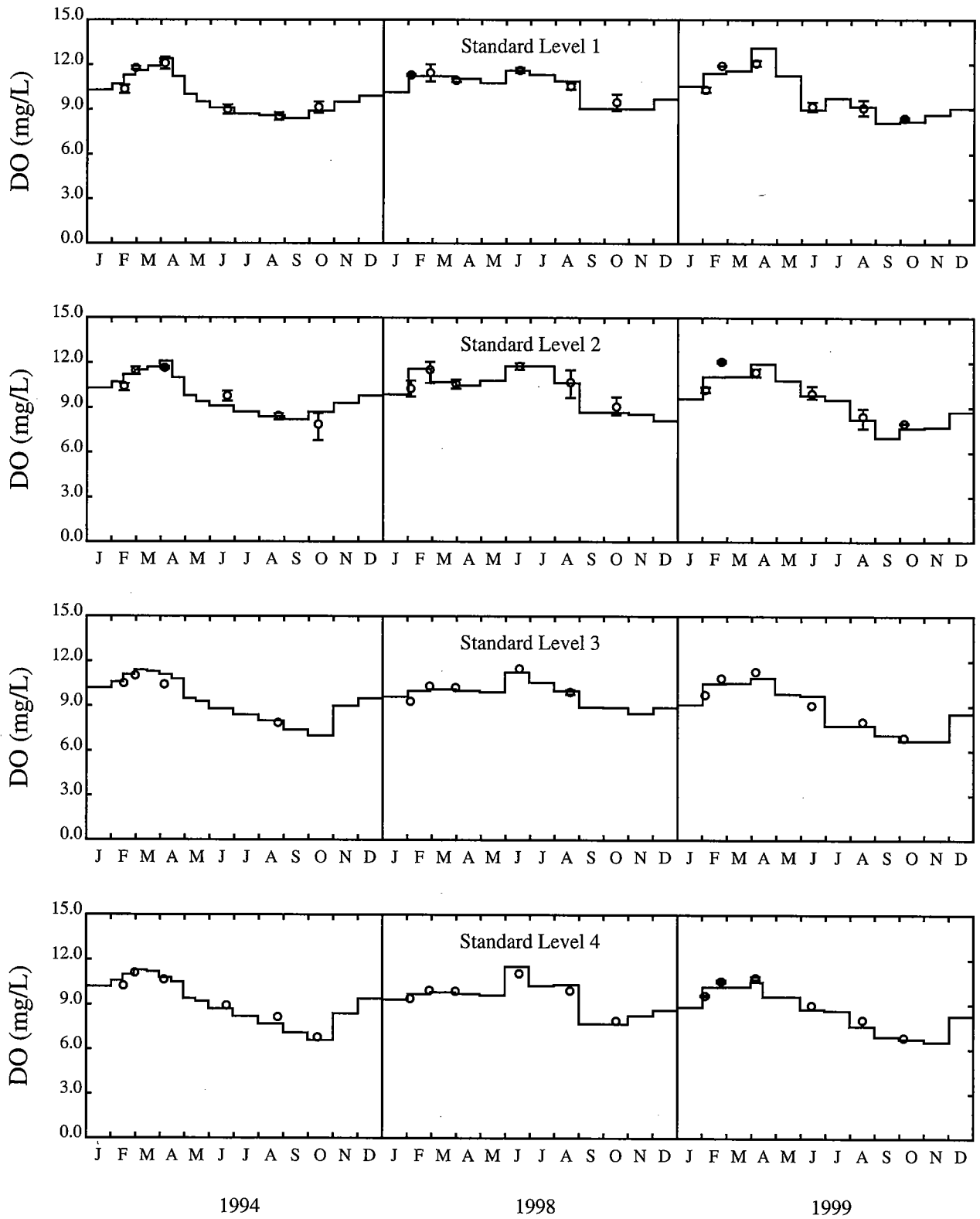


Figure 4-33. Assigned DO Boundary Conditions for 1994, 1998 and 1999

4.1.3 Time Variable Inputs

Figure 4-34 presents the wind, solar irradiance, and fraction of daylight information supplied to the model. The wind data were obtained from the Boston Buoy 44013, which is operated by NOAA. The wind data are used to determine the reaeration coefficient. The solar irradiance data were provided by the Woods Hole Oceanographic Institution. Solar irradiance data are required because phytoplankton require light energy for growth. The daily fractions of daylight, which are dependent on the latitude and the declination of the sun as a function of the time of year, were calculated using a method developed by Duffie and Beckman (1970).

4.2 SPATIAL WQ MODEL VERSUS DATA COMPARISONS

In previous modeling analyses, the model was calibrated by adjusting model coefficients and parameters as well as adjusting boundary conditions for the year to year variation that occurs within the Gulf of Maine. The modeling effort presented here was approached as a model verification. The model coefficients and parameters were considered "sacred" and, therefore were unchanged from the previous modeling work. The boundary conditions and loadings were changed to reflect the conditions that occurred in 1998 and 1999.

The following section will present model versus data comparisons at six stations located throughout Massachusetts and Cape Cod Bays in order provide a spatial presentation of how well the model reproduces the data. The same six stations will be presented for each state-variable presented. The stations include F23, N10, N04, N07, F01 and F06.

Figure 4-35 presents the model to data comparison for surface chlorophyll in 1998. At station F23, at the mouth of Boston Harbor, the model reproduces the data fairly well through August. In October, the model is over predicting the data. The model predicts the highest concentrations to occur during the summer, which is consistent with the data. At station N10, the model compares favorably with the data. The data indicate a bloom in the late summer that the model does not reproduce. The high chlorophyll concentrations measured at station N10 are not observed at the other five stations. At stations N04 and N07, the chlorophyll concentrations are lower than at N10, and the model is able to reproduce the difference in magnitude. At station F01, there is an indication of a spring bloom that is not observed at the other stations. The model is able to reproduce the spring bloom at F01 and does not predict it elsewhere. At station F06, the model compares favorably to the data as well. It is important to note that the model is able to reproduce the lack of a spring bloom in the near field. Initially, the model did predict a spring bloom, but this

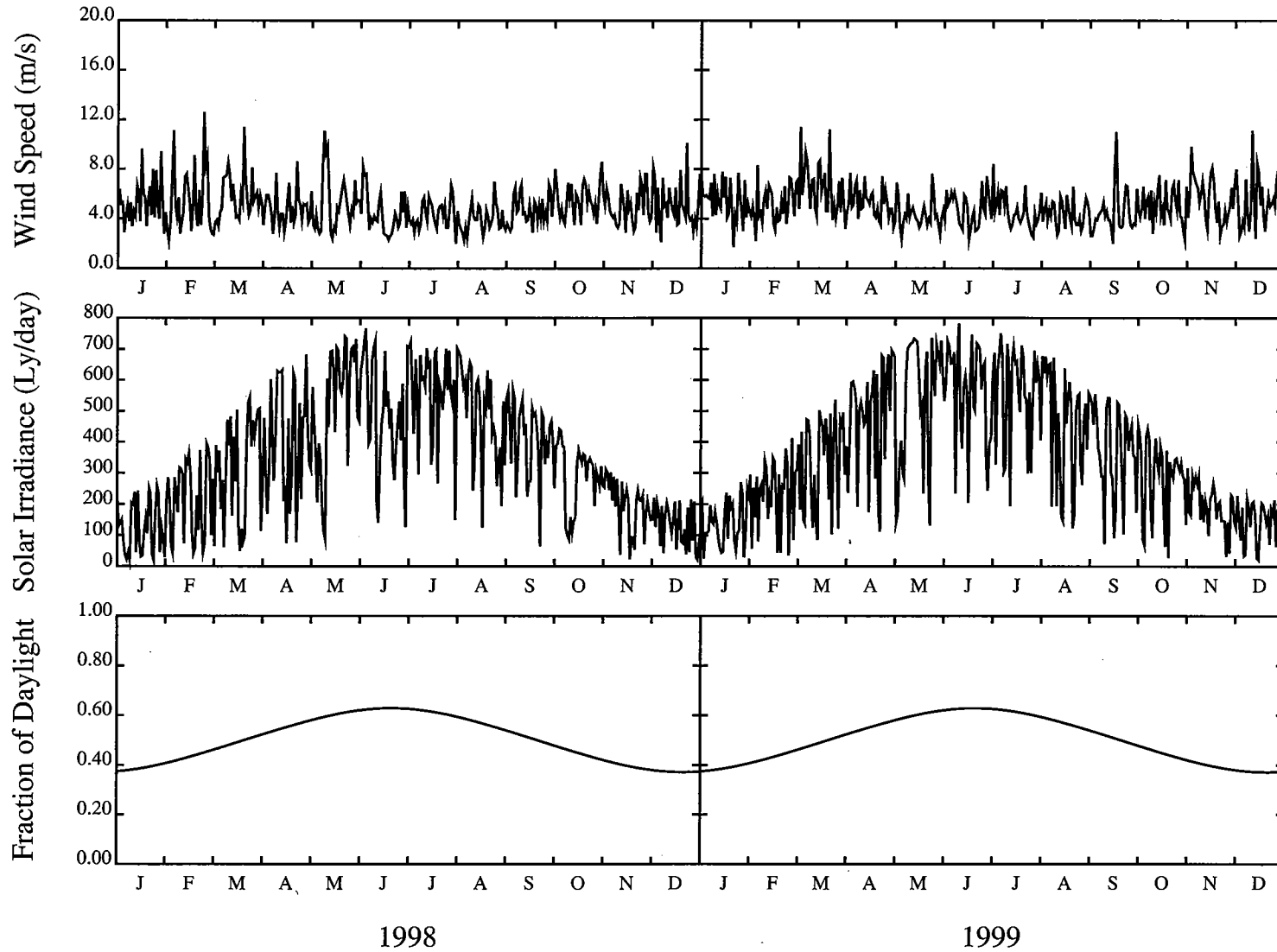


Figure 4-34. Time Variable Inputs

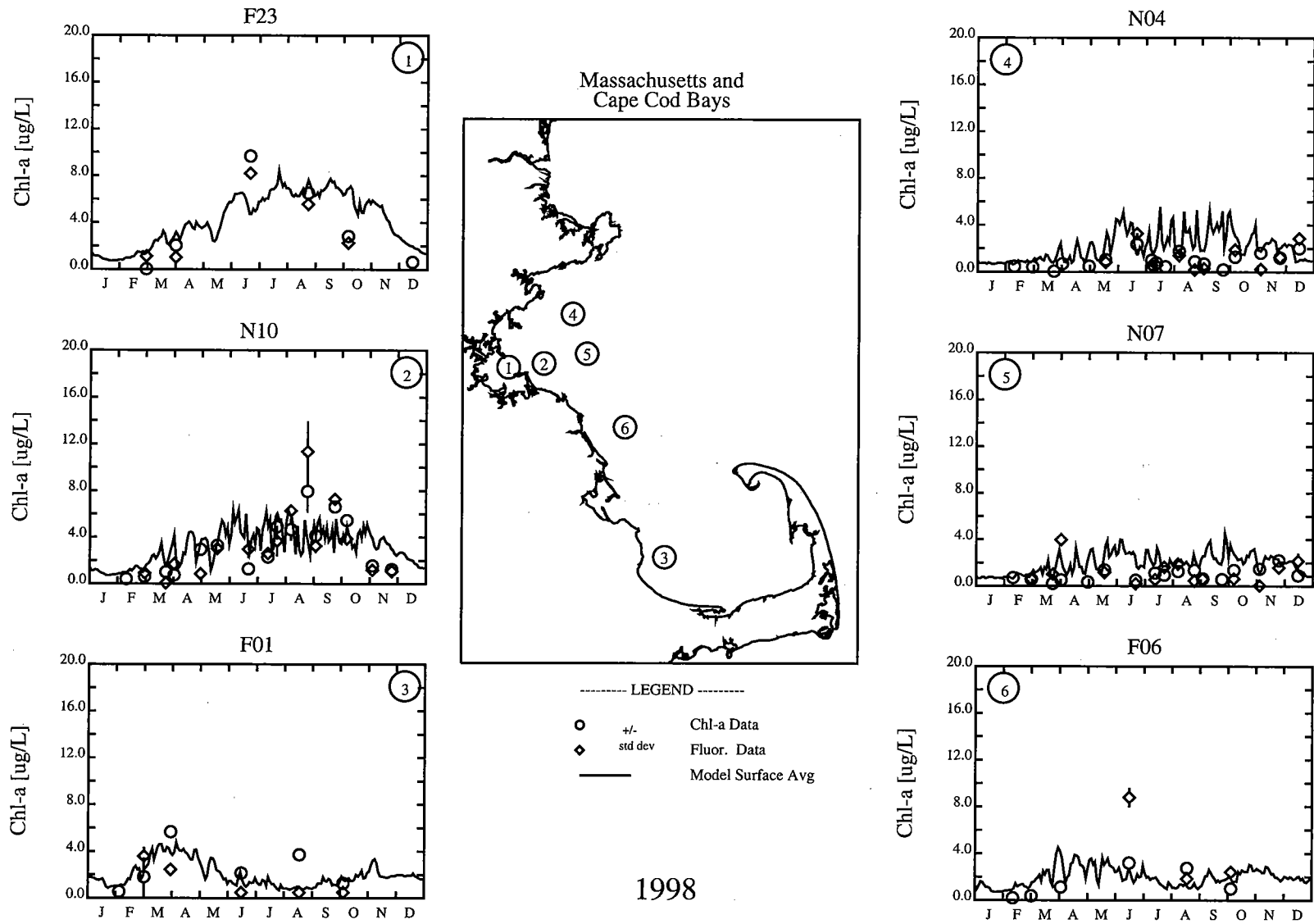


Figure 4-35. 1998 Model vs. Surface Chl-a Data

was remedied by reducing the algal concentration at the boundary during the spring. This reduction is supported by the available boundary data.

The 1999 model comparison to the chlorophyll data is presented in Figure 4-36. In 1999, both the model and the data show more of a spring bloom than was evident in 1998. The summer time periods are similar between both years with respect to both the model and the data. A fall bloom is apparent in the data. While the model does compute higher chlorophyll in the fall at stations N04 and N07, the model concentrations are somewhat lower than the data. The higher fall chlorophyll concentrations calculated by the model are primarily due to the influence of the boundary conditions. Aside from the spring bloom, the model results for chlorophyll in the years 1998 and 1999 are very similar.

The model comparison to POC data in 1998 is presented in Figure 4-37 along with estimates of phytoplankton biomass using cell abundance and an assumed biomass per cell. These estimates are presented as filled circles in this figure. At stations F23, N04, N07, and N10, the model versus data comparison is similar to that for chlorophyll-a. At station F23, the model predicts higher POC concentrations than were measured in August 1998, but the model compares favorably with the data collected in the near field. During the first three field surveys, at stations F01 and F06, the model compares favorably with the POC data, but during the last three surveys the POC data are higher than the model computes. Clearly, there is a large shift in the carbon to chlorophyll ratio during the year at these stations. Whether this reflects a shift in the phytoplankton themselves or the change in the carbon to chlorophyll ratio is due to another source of carbon is unclear. The estimated phytoplankton biomass indicates that most of the carbon in the winter and fall is not due to phytoplankton while a good portion of the summer POC is due to phytoplankton biomass.

In Figure 4-38, the model versus data comparison for POC in 1999 is shown. The measured POC concentrations tend to be much higher in 1999 than in 1998. The estimated phytoplankton biomass, however, does not appear to be greater, in fact it may be less. The model captures some of the POC concentration variation by calculating higher springtime concentrations than in 1998. The model greatly over estimates the summer/fall POC concentrations, and under predicts the POC concentrations at N07 in the spring, F06 in the fall, and for most of the year at F01. At station F01, the biomass indicates that most of the carbon is non-algal. This may indicate either that the biomass estimation is flawed, that there is another source of carbon that is unaccounted for, that there were measurement errors in POC data, or a combination of these factors.

Biogenic silica measurements were not taken during the earlier years that have been modeled (1989-1994), but have now been included in the HOM sampling program. These data provide some

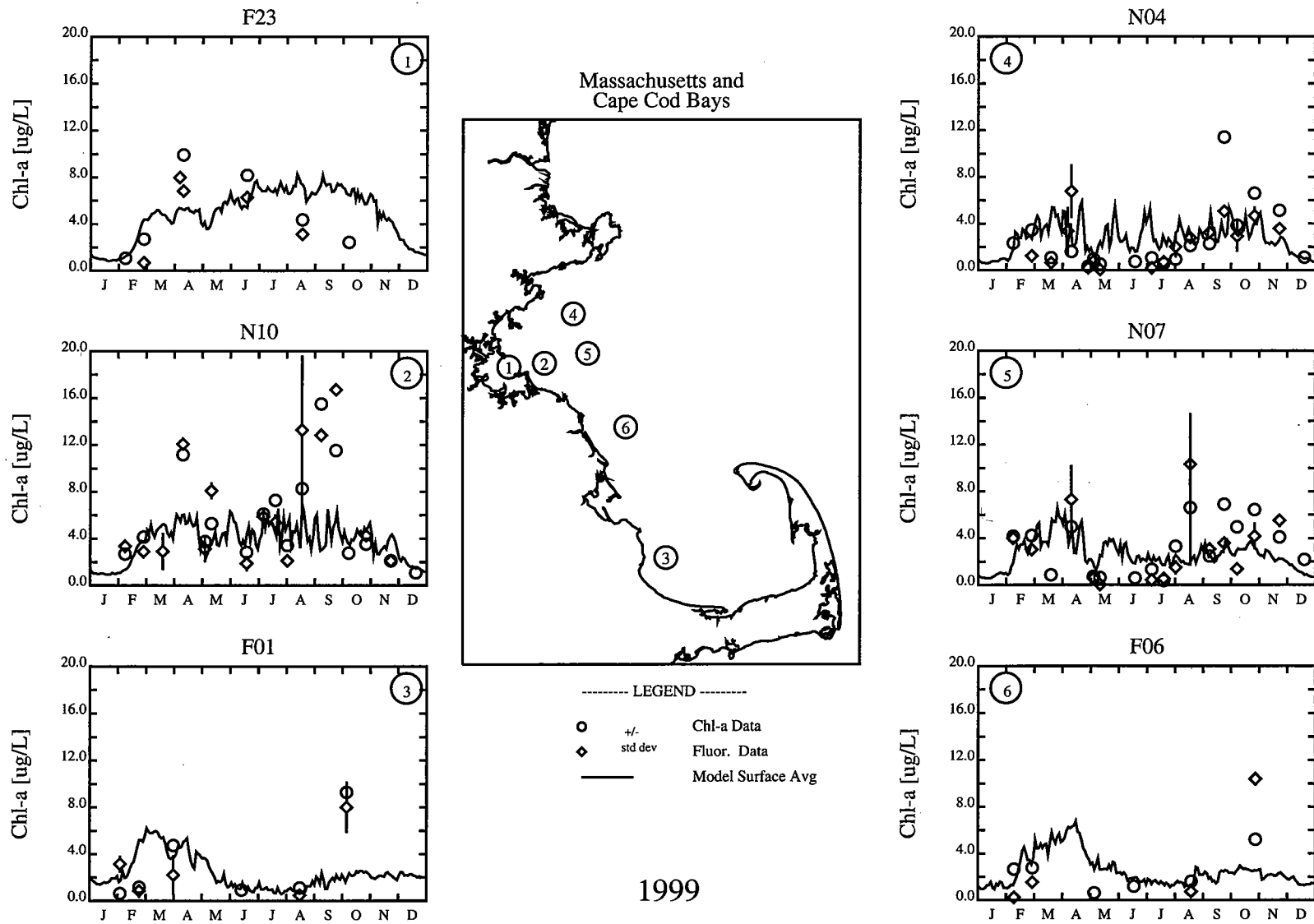


Figure 4-36. 1999 Model vs. Surface Chl-a Data

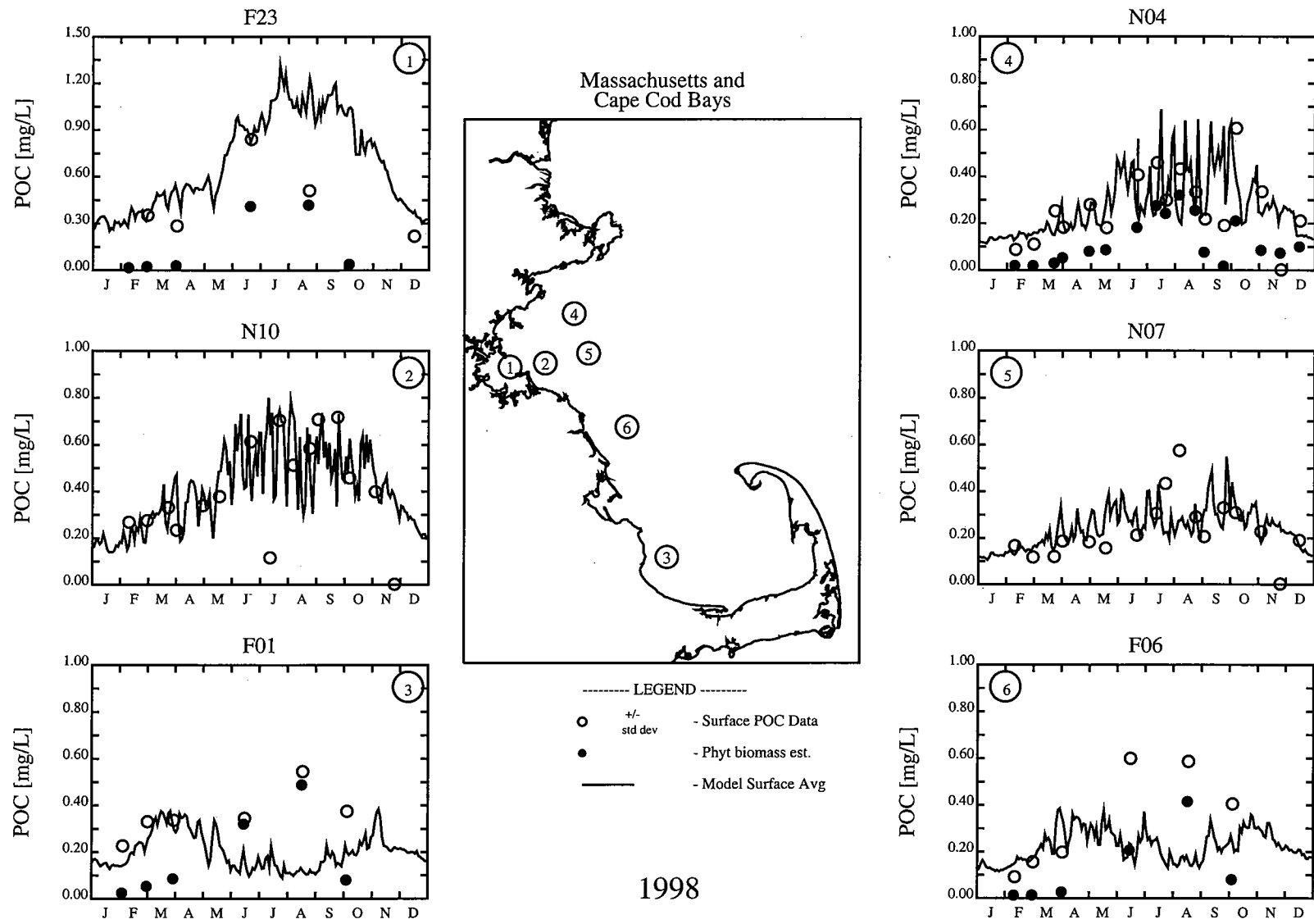
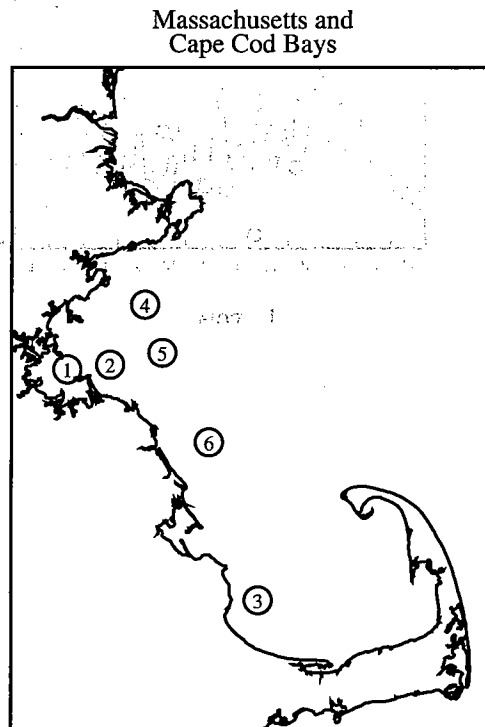
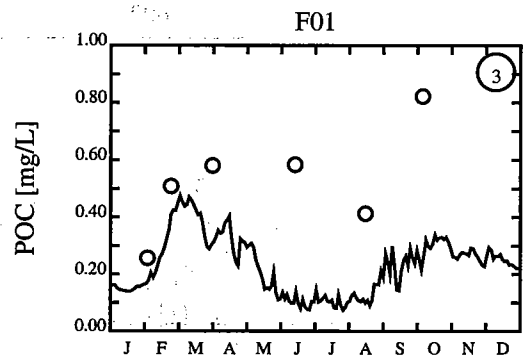
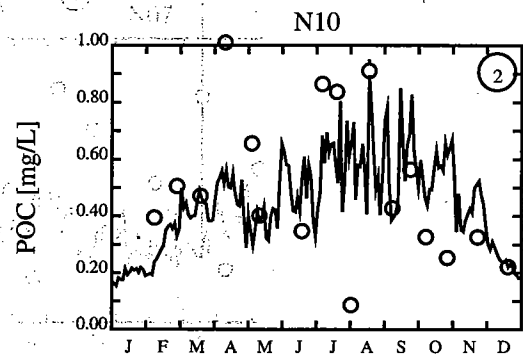
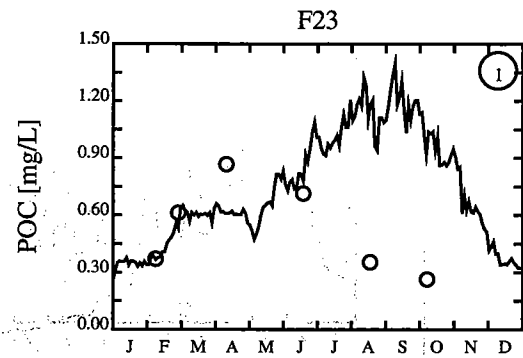


Figure 4-37. 1998 Model vs. Surface POC Data



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 ○ +/- - Surface POC Data
 - - - - - Model Surface Avg

1999

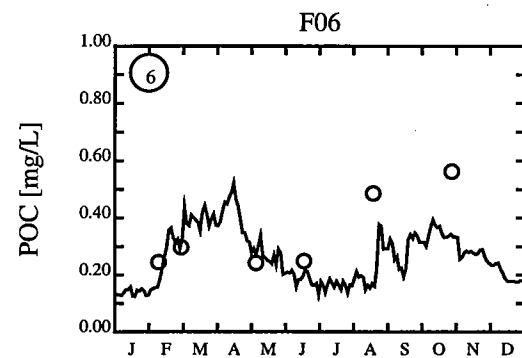
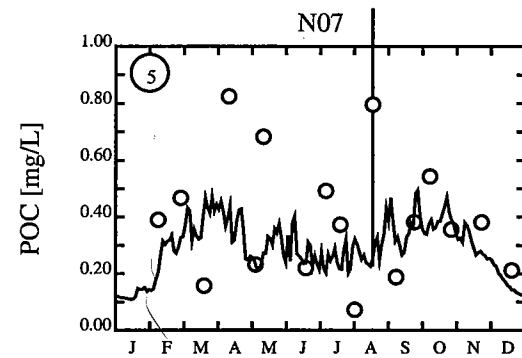
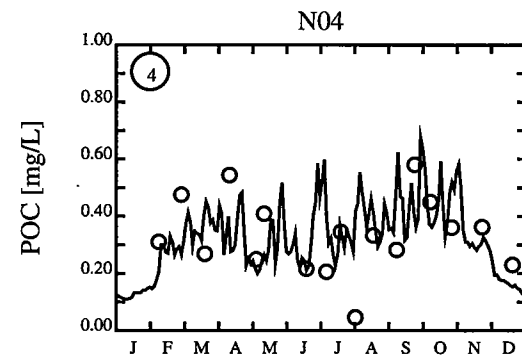


Figure 4-38. 1999 Model vs. Surface POC Data

insight as to the fluctuation of diatom populations and detrital silica. The model versus data comparison for biogenic silica in 1998 is presented in Figure 4-39. The model generally reproduces the magnitude of the BSi data. The one exception is station F23 where the model under predicts the data. It is possible that there is a greater loading of BSi from the riverine sources than is specified in the model. At station N10, the model under predicts the surface BSi data during the second half of the year, but reproduces much of the data during the remainder of the year. At stations F01, N04, N07 and F16, the model satisfactorily reproduces the BSi data. During 1999 (Figure 4-40), the model reproduces the BSi data fairly well. A feature that was present during 1999 and 1998 is a peak in BSi concentrations during the late winter. Aside from stations F23 and N10, the model does a fairly good job reproducing this feature. The model reproduces the BSi data during the remainder of the year, fairly well, at all six stations.

The model's ability to reproduce the inorganic nutrient data is usually related to how well the model is able to reproduce the phytoplankton biomass. When the model reproduces the phytoplankton biomass, the model results generally compare favorably to the inorganic nutrient data. The model to data comparison for DIP in 1998 is presented in Figure 4-41. In Boston Harbor (station F23), the model compares somewhat favorably to the data until October, when the computed DIP concentration is low. This corresponds to the period when the model is over predicting the phytoplankton biomass; thus, utilizing too much inorganic phosphorus. At station N10, the model reproduces the data for the first half of the year, but then under estimates both the surface and bottom data during the latter half of the year. At stations N04 and N07, the model reproduces the surface DIP well throughout the year. Except for a period in the fall, the model reproduces the bottom data fairly well. At station F01, the model under estimates the data for most of the year. The data is reproduced fairly well at station F06, with the exception of the bottom data collected during the summer.

The DIP data in 1999 are somewhat different from the 1998 data. In particular, the spring bottom water DIP concentrations are higher in 1999, and in general, the surface DIP concentrations during the summer are also higher. On exception to this is as station F23 where the springtime DIP concentrations are lower in 1999. The model is able to reproduce most of the differences between the two years with the exception of station F23 (Figure 4-42). However, overall the model compares very favorably to the 1999 DIP data.

The model to data comparison of DIN for 1998, presented in Figure 4-43, is remarkably similar to the DIP comparison. The comparison of the model results to the DIN is slightly less favorable, however. In general, the bottom DIN concentration is under predicted by a greater margin than the bottom DIP was under predicted. Overall, however, the model is able to reproduce

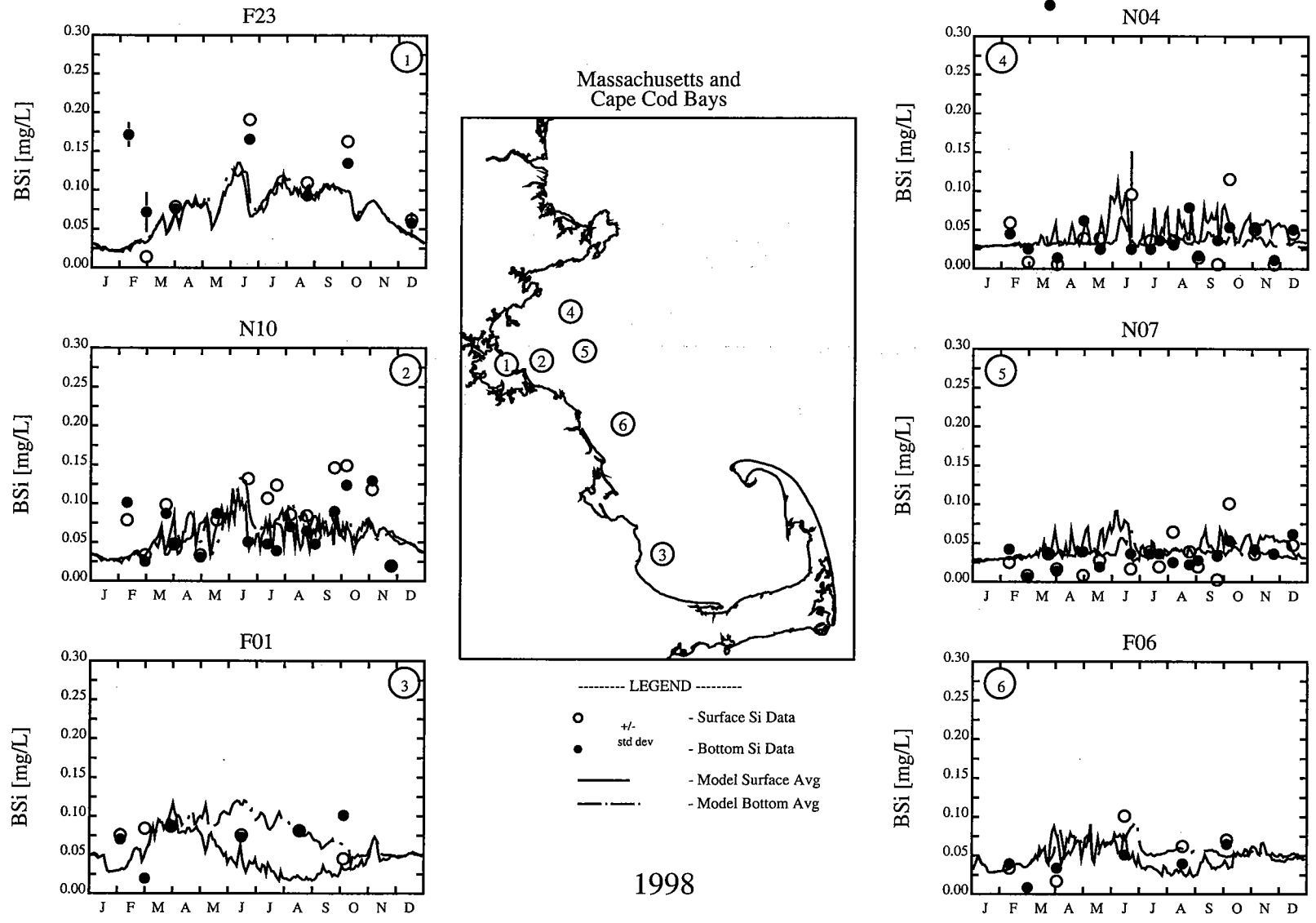


Figure 4-39. 1998 Model vs. Surface and Bottom BSi Data

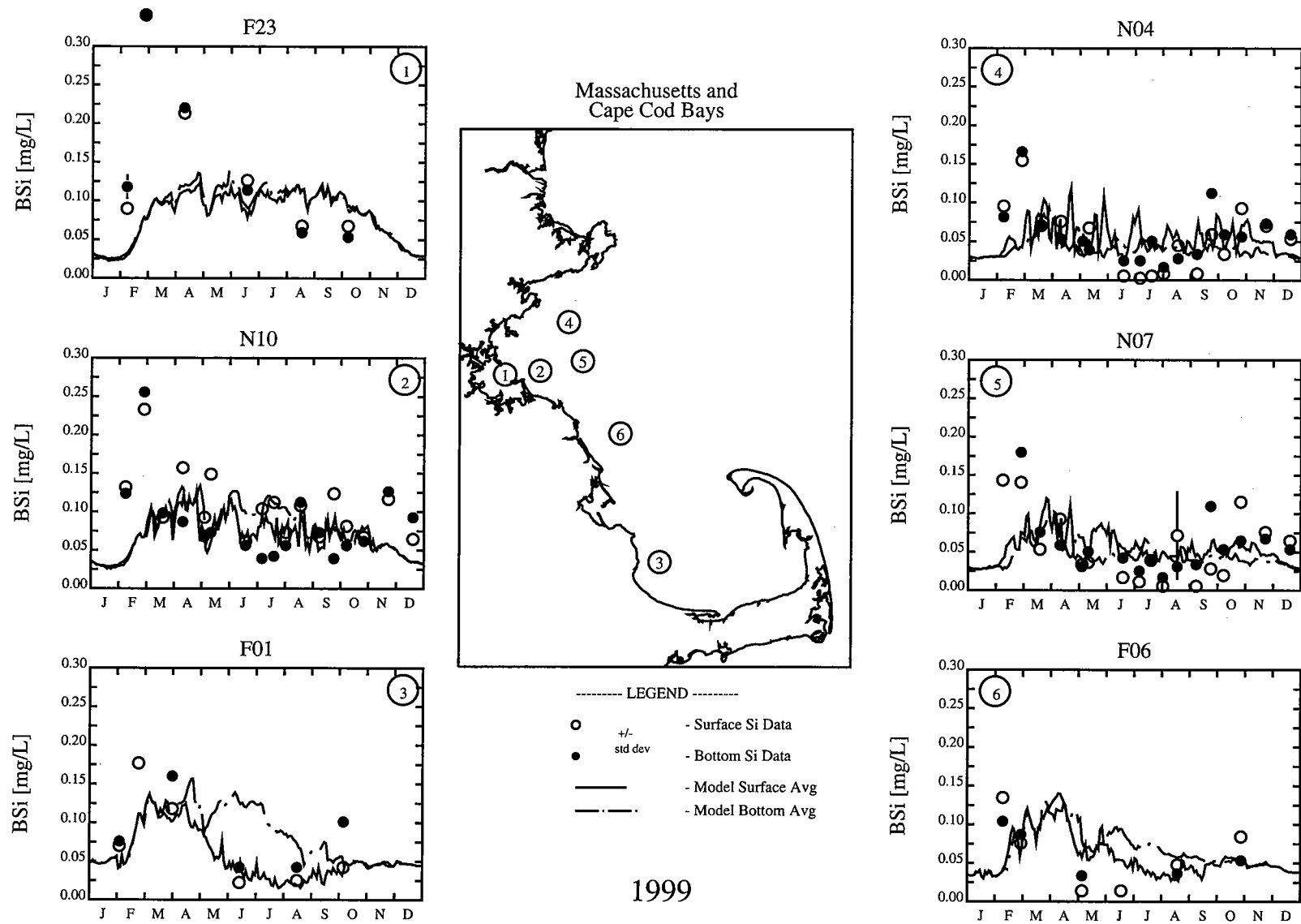


Figure 4-40. 1999 Model vs. Surface and Bottom BSi Data

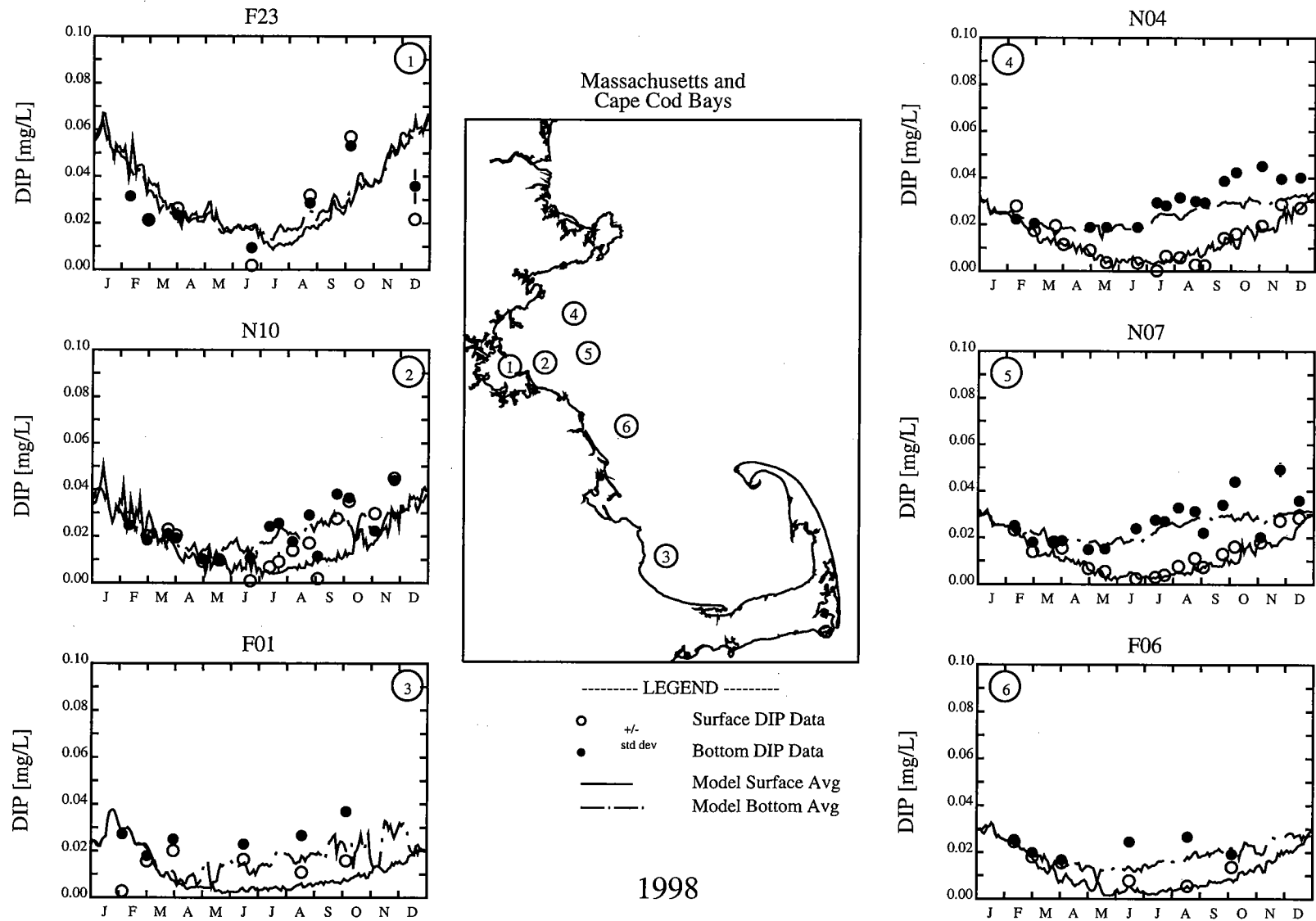
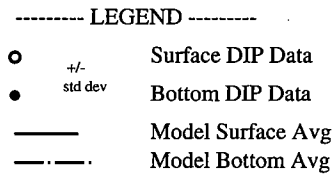
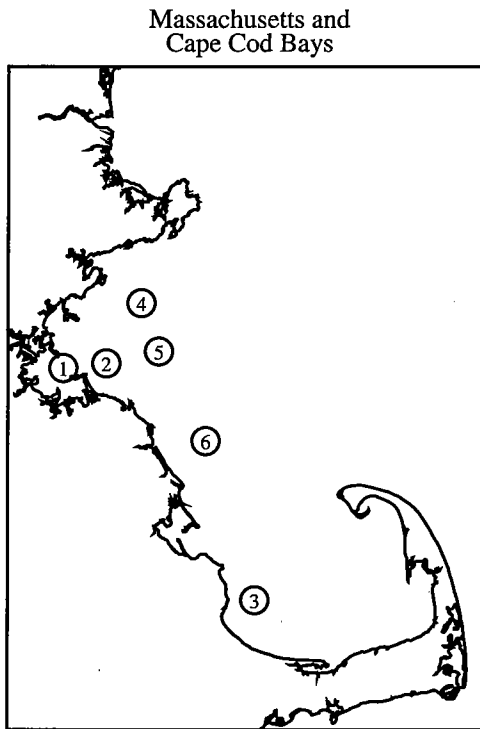
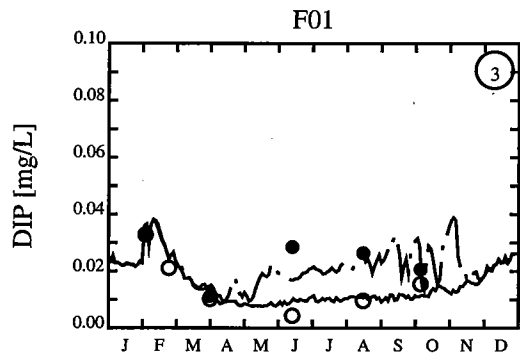
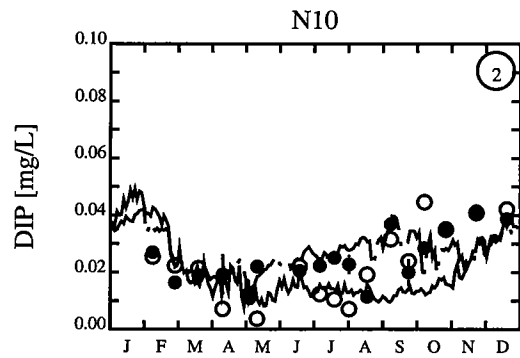
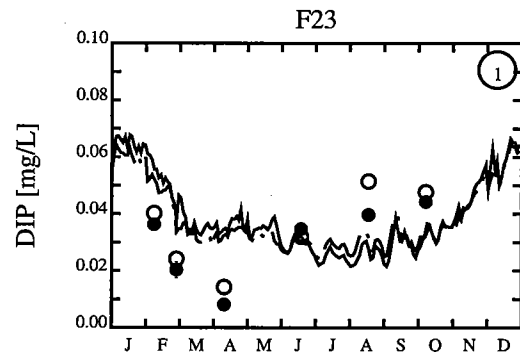


Figure 4-41. 1998 Model vs. Surface and Bottom DIP Data



1999

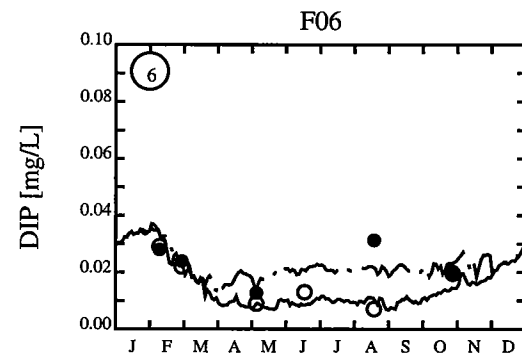
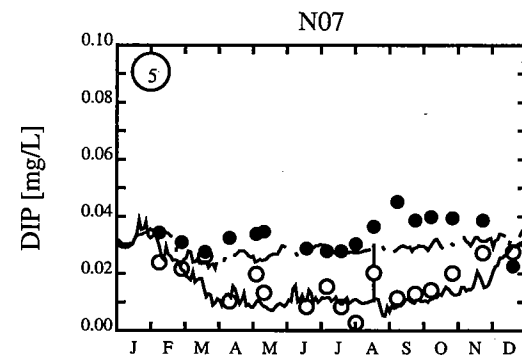
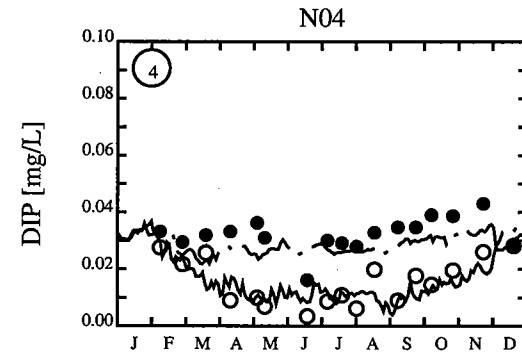


Figure 4-42. 1999 Model vs. Surface and Bottom DIP Data

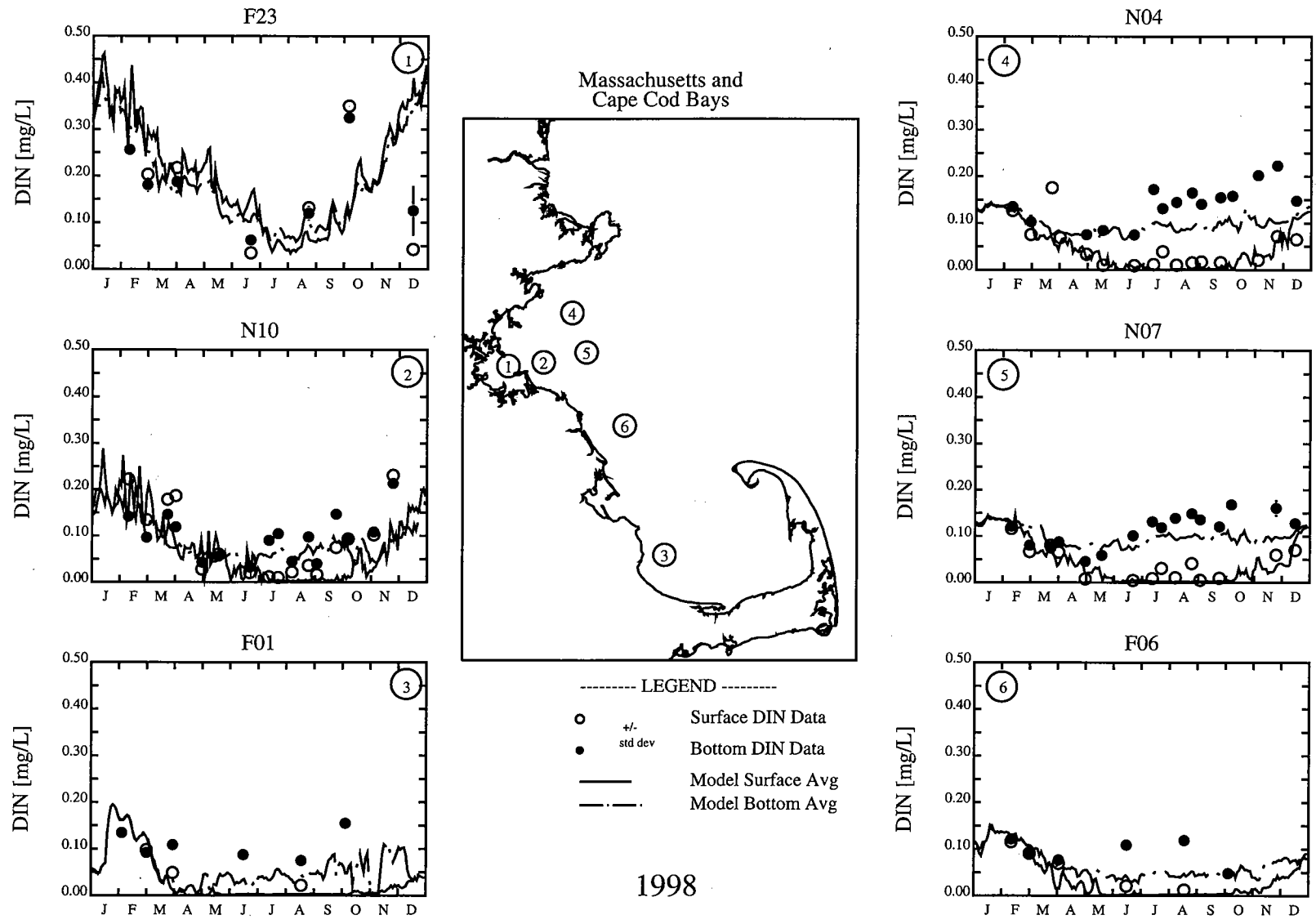


Figure 4.43. 1998 Model vs. Surface and Bottom DIN Data

the timing of the nitrogen limitation occurring during the spring and summer. In 1999 (Figure 4-44), the model is able to reproduce the more rapid decline in the DIN concentrations that occurred in the spring, but again has difficulty reproducing the higher bottom DIN concentrations at stations N04 and N07. While the model computes similar concentrations in Cape Cod Bay (station F01) and station F06 for both years, the model compares more favorably to the 1999 data.

The results of the model to data comparison for dissolved silica during 1998 are presented in Figure 4-45. In Boston Harbor, the model reproduces the timing of the silica uptake by diatoms to some degree, but generally under estimates the Si concentration. At station N10, there is quite a bit of scatter in the data, possibly due to tidal interaction with Boston Harbor. The model results are generally lower than the data at this station. At stations N04 and N07, the model comparison to the data is more favorable, but the bottom Si concentration is under predicted during the second half of 1998. The surface data compare very favorably to the model results. At stations F01 and F06, the model reproduces the data collected during the first three surveys, but is under stratified during the remainder of the year.

In 1999, the model does reproduce some of the differences in Si from 1998 as shown in Figure 4-46. The poor calibration at station F23 remains, but the model does reproduce the more rapid decline in Si that was measured in 1999. The model is able to reproduce the decline in the Si concentration in February and March followed by the increase in April and the subsequent decline in the May/June time frame. This is especially evident at stations N10, N04, N07 and F06. The model also reproduces the higher surface Si concentrations observed in the fall of 1999.

An important part of the model's ability to project future conditions is its ability to determine which of the nutrients is potentially limiting to phytoplankton growth. Whether or not actual nutrient limitation occurs is dependent on the actual nutrient concentrations. Figure 4-47 presents the surface DIN/DIP for 1998. The DIN/DIP ratio indicates whether nitrogen or phosphorus is the potentially limiting nutrient. At a ratio less than 7.0, nitrogen is the potentially limiting nutrient. In general, both the data and model indicate that DIN is potentially limiting. The model is also able to reproduce the DIN/DIP ratio of greater than 7.0 that occurs at station F23; however, is unable to reproduce the potentially limiting phosphorus conditions at station N10. This ends up not being too much of an issue because the DIP concentrations at this time are higher than what would limit phytoplankton growth. The model does not reproduce the very high DIN/DIP that were recorded in June and July. These seem to be of short duration and are possible due to the high fresh water flows that occur during this period. In 1999, the data show that the bays system is primarily potentially nitrogen limited (Figure 4-48), and is more so than in 1998. The model is able to reproduce this feature.

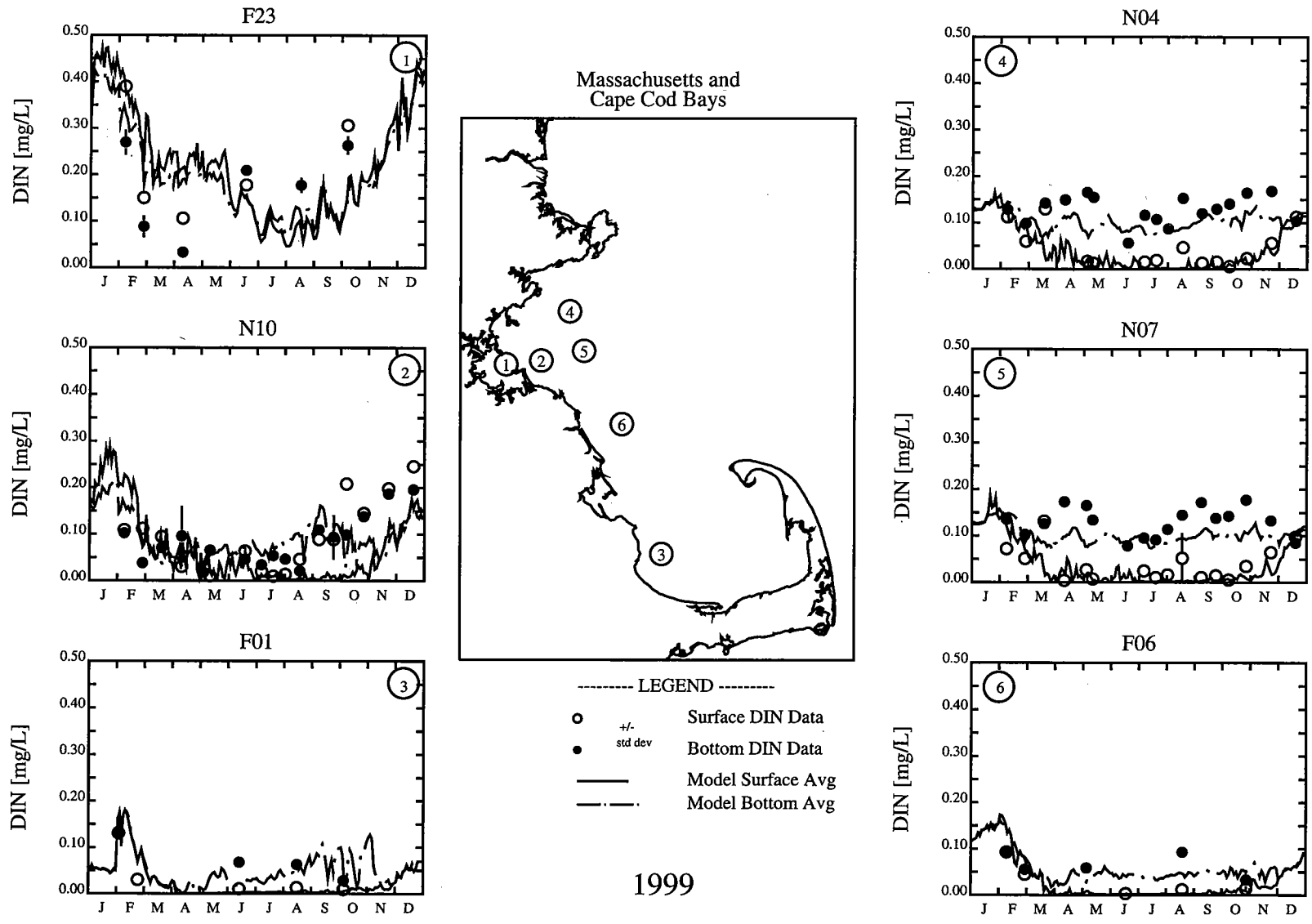


Figure 4-44. 1999 Model vs. Surface and Bottom DIN Data

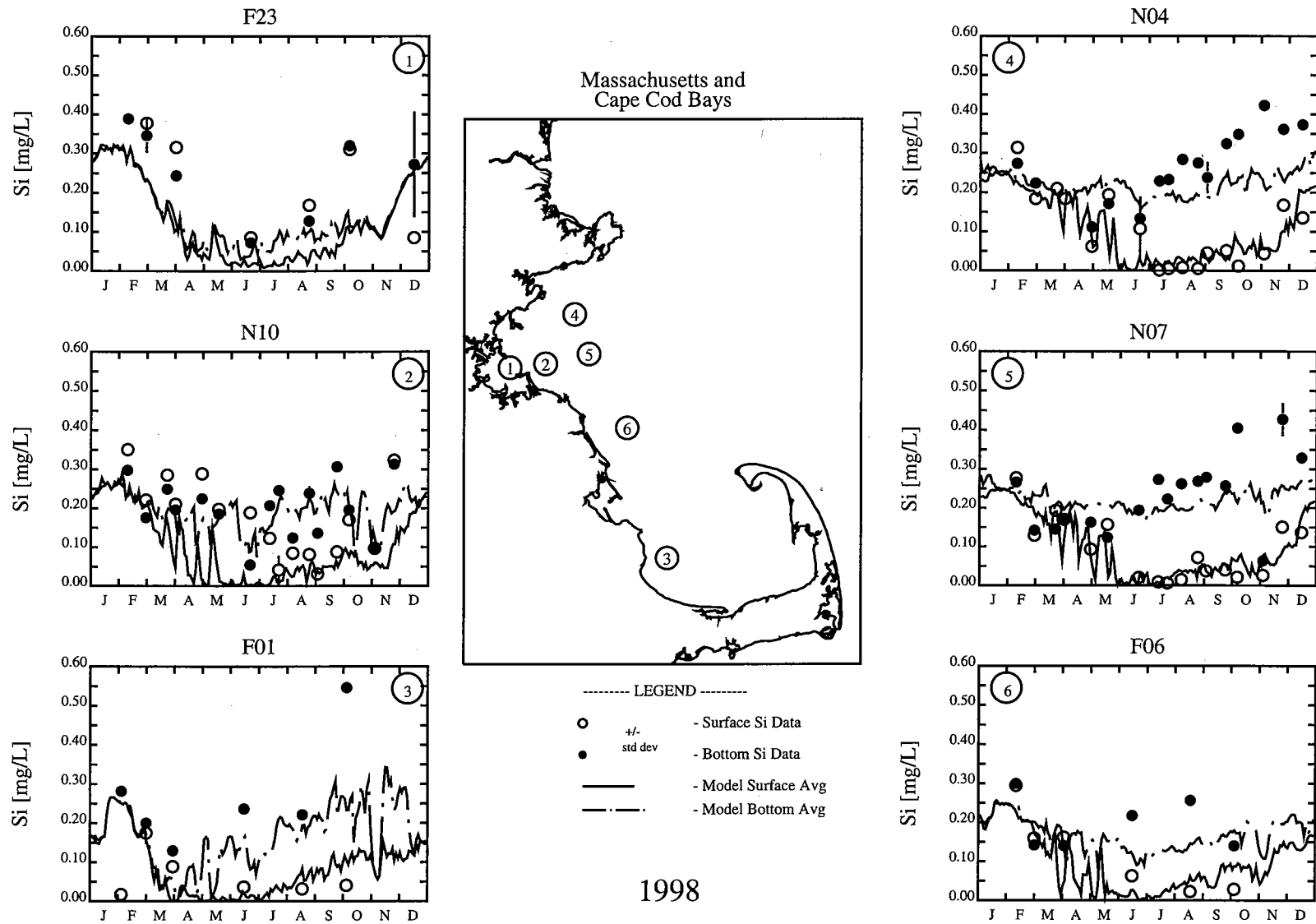


Figure 4-45. 1998 Model vs. Surface and Bottom Si Data

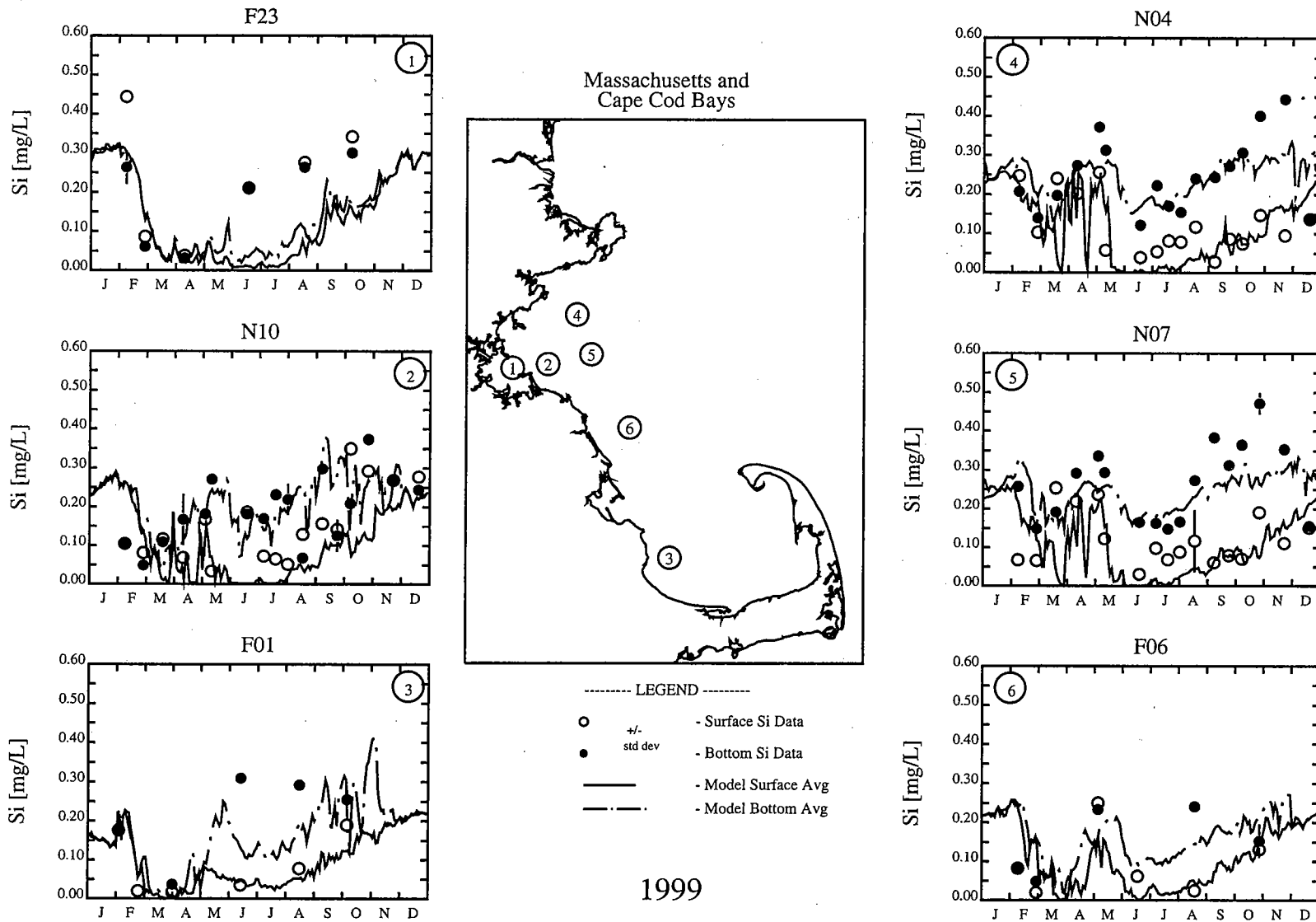


Figure 4-46. 1999 Model vs. Surface and Bottom Si Data

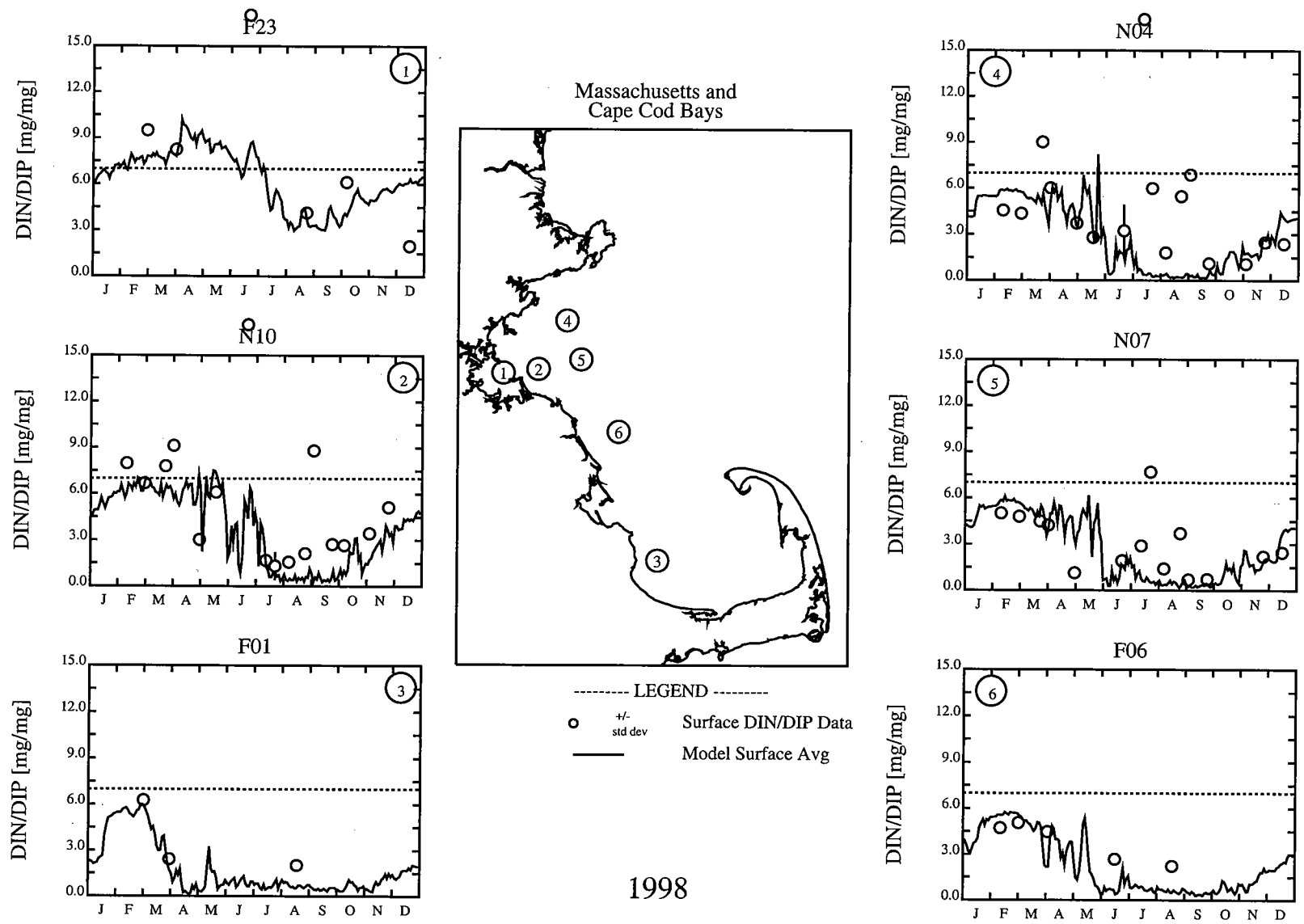


Figure 4-47. 1998 Model vs. Surface DIN/DIP Data

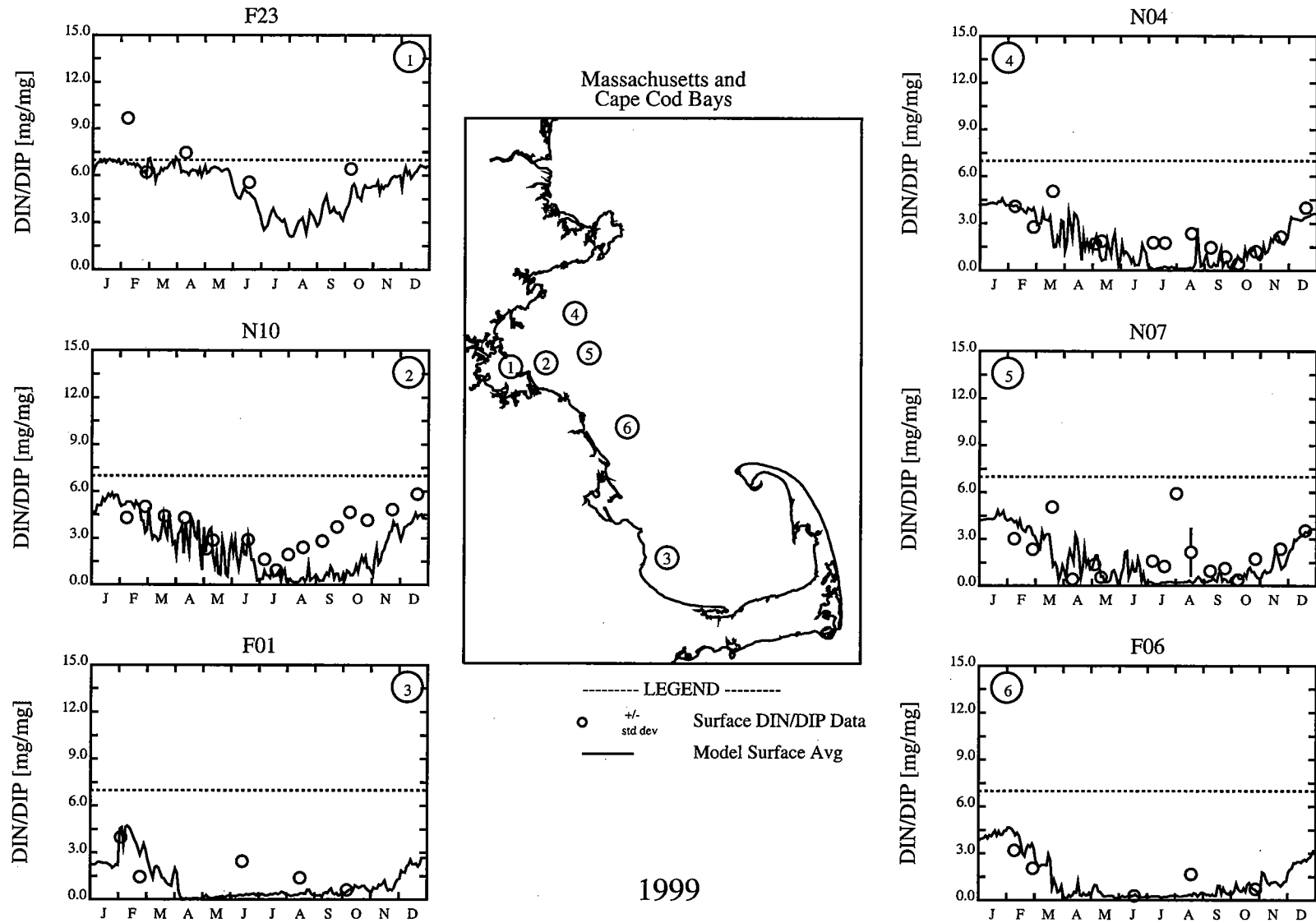


Figure 4-48. 1999 Model vs. Surface DIN/DIP Data

In Figure 4-49, a ratio of DIN/DSi less than 0.5 indicates potentially DIN limiting conditions. The model predicts potentially Si limiting conditions at stations F23 and N10 during the late spring and early summer that is not indicated in the data. During the rest of the year and at the remaining stations the model is able to reproduce the mostly nitrogen limiting conditions that occurred in 1998. In 1999, the model is able to reproduce the more potentially limiting silica conditions that occurred in February, but over estimates the duration of this condition at station F23 and sporadically predicts potentially silica limiting conditions at the near field stations (Figure 4-50). The model does reproduce the potentially nitrogen limiting conditions during the second half of the year at stations N04, N07, F01 and F06.

The model to data comparison for DO in 1998 is presented in Figure 4-51. In general, the model's ability to reproduce the DO concentrations is disappointing. While the model does go through many of the data points it is unable to reproduce some of the more important features observed in the data. During the summer, there are some very high DO concentrations at the surface that the model does not reproduce. The model does, however, match the high bottom DO concentrations measured at that time. The cause of the high DO concentrations is not entirely clear, because the concentrations are well above the saturation concentration (approximately 8.3 mg/L at the surface) and the algal biomass does not appear large enough to produce this much oxygen. The model also does not reproduce the fall bottom water DO concentrations. In the near field, the DO concentration appears to be strongly correlated to the DO concentration entering the bays near Cape Ann. During the fall period the data near the boundary does not indicate that there were concentrations low enough to justify lowering the boundary conditions specified in the model enough to reproduce the near field bottom DO concentrations. It would have been useful to have more data during this fall period to make sure the appropriate boundary conditions were assigned.

Figure 4-52 presents the model versus data comparison for DO in 1999. The comparison to the data at the near field stations is quite good, while at the far field stations the comparison is less favorable. The high DO concentrations observed in April at the surface are reproduced, and the low DO concentrations measured in October and November are also reproduced. The model also reproduces the near field conditions during the summer when the surface and bottom have similar DO concentrations.

The overall comparison of the water quality model results to the water quality data is fair, but it must be remembered that there was no attempt to calibrate the model using model coefficients and parameters. The model produces results that are similar to those produced in 1992 to 1994. Models in general are able to reproduce average conditions and have more difficulty reproducing extreme events. The data collected in 1998 and 1999 deviate somewhat from the data collected earlier. In some cases, such as POC, the data have changed dramatically. Therefore, it was

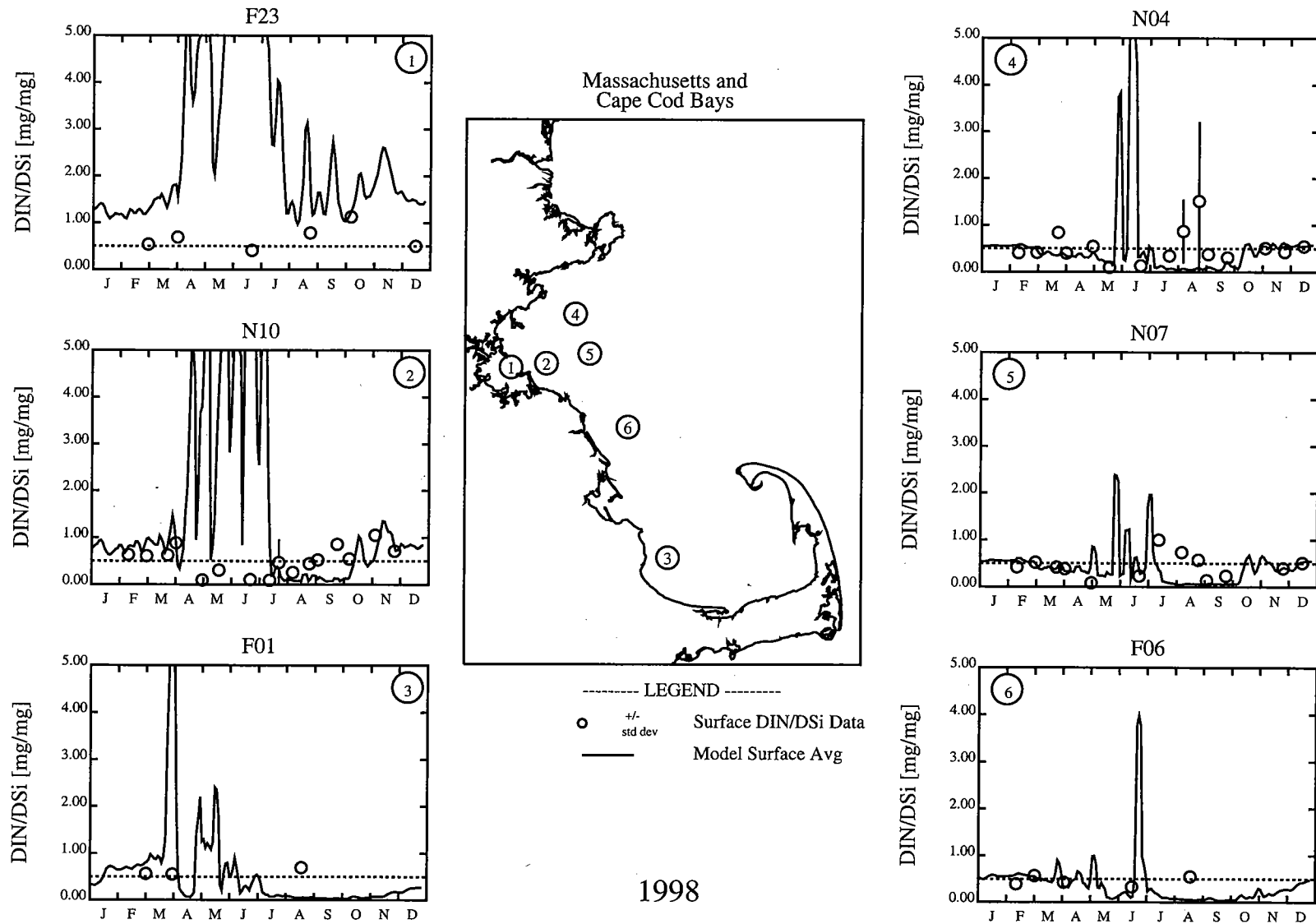
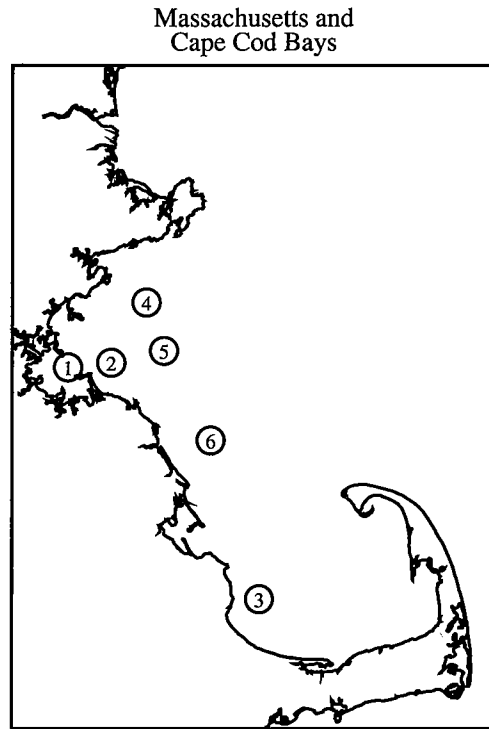
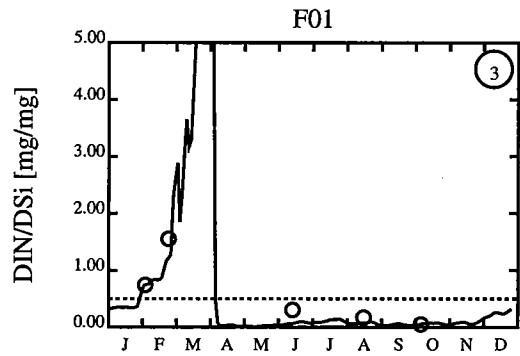
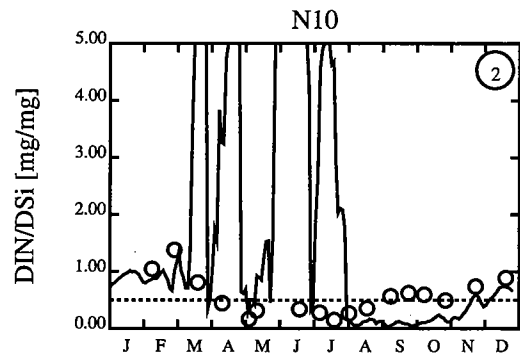
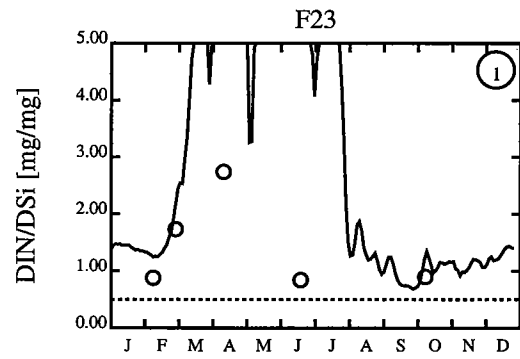


Figure 4-49. 1998 Model vs. Surface DIN/DSi Data



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1999

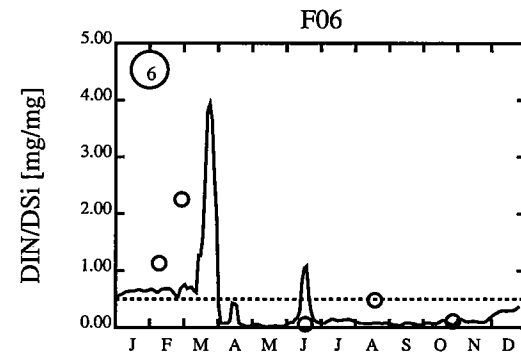
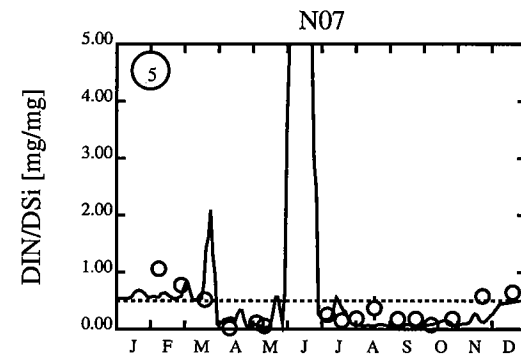
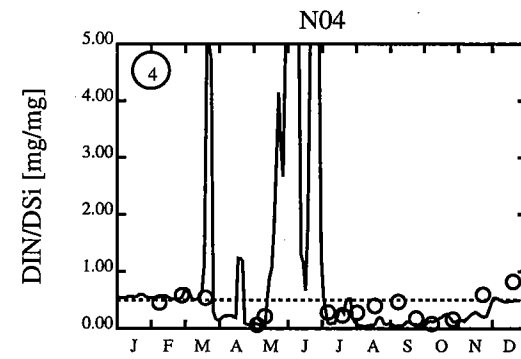
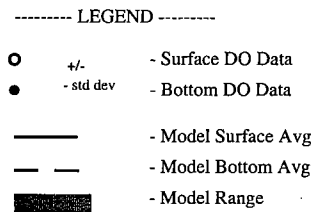
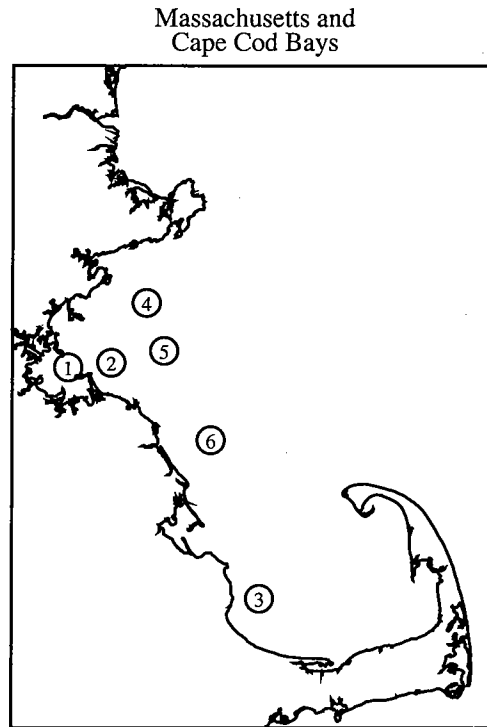
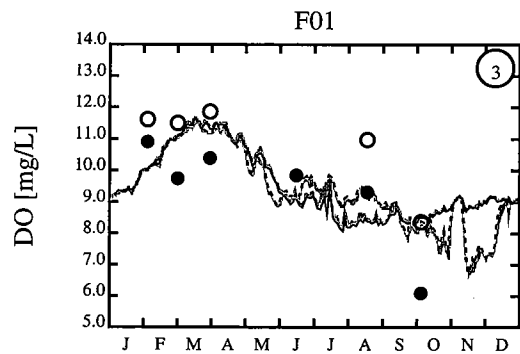
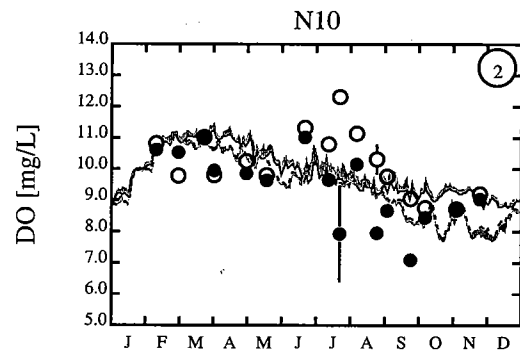
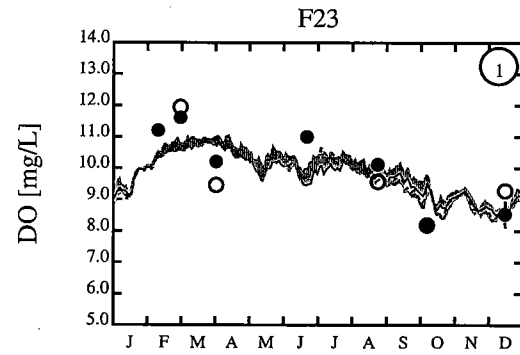


Figure 4-50. 1999 Model vs. Surface DIN/DSi Data



1998

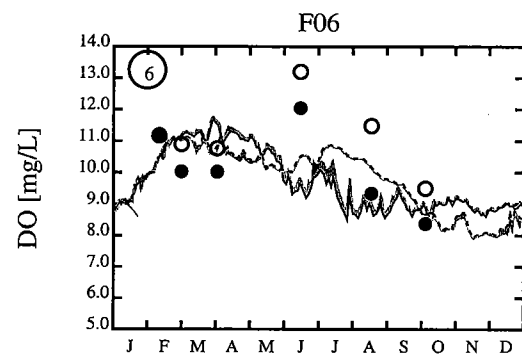
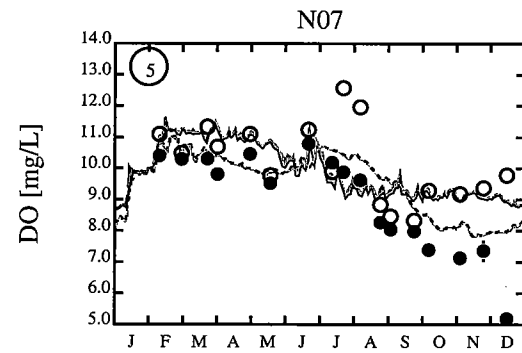
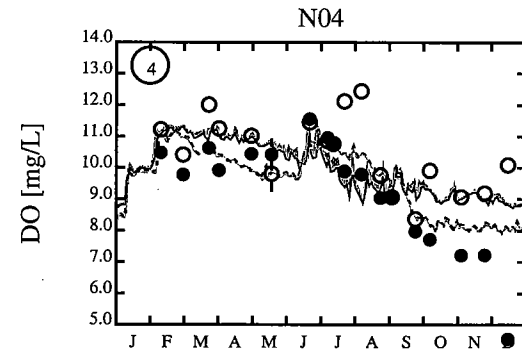


Figure 4-51. 1998 Model vs. Surface and Bottom DO Data

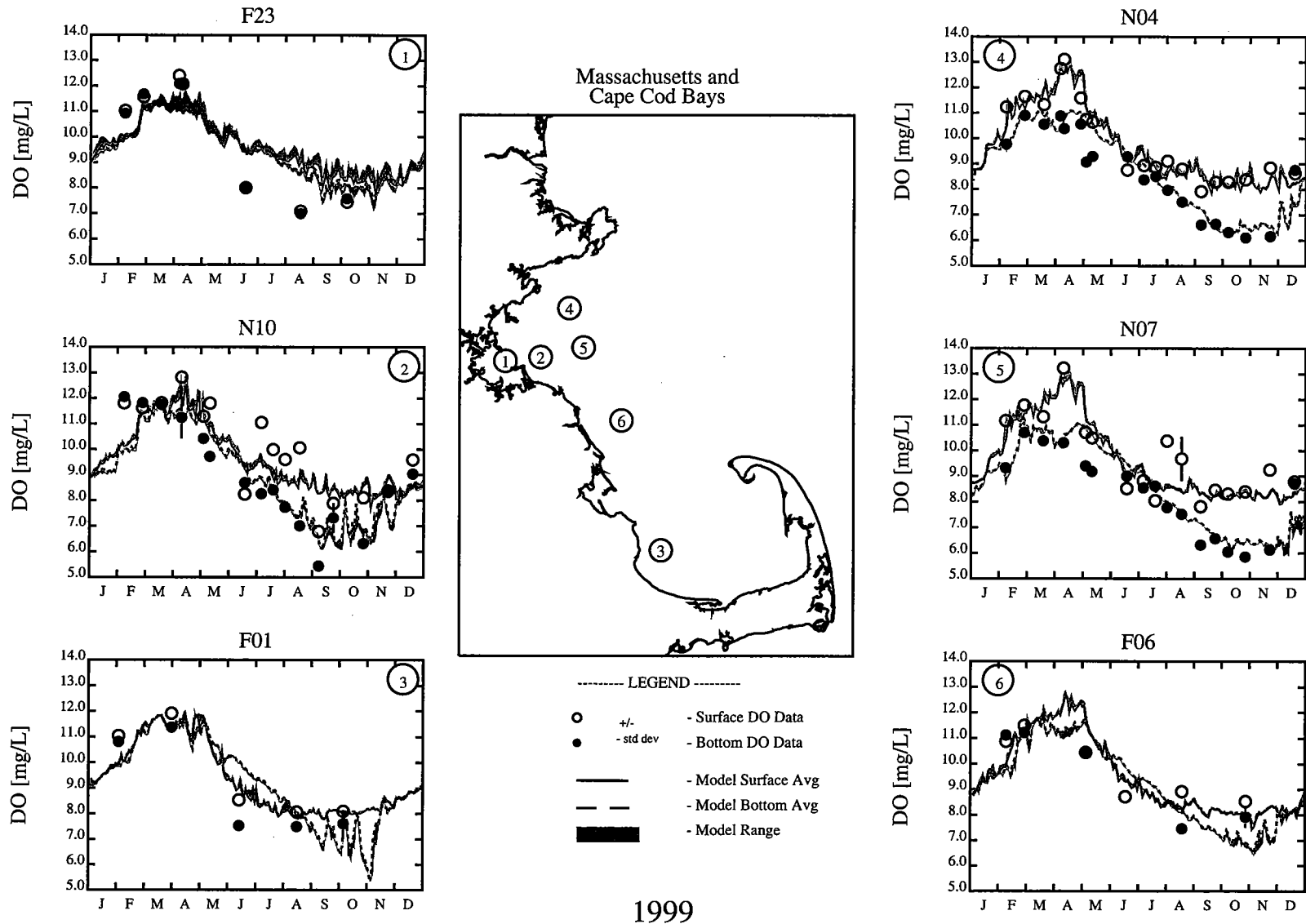


Figure 4-52. 1999 Model vs. Surface and Bottom DO Data

anticipated that the comparison of the model to the data for 1998 and 1999 would not be as good as earlier comparisons. However, there are cases where the model performs quite well.

4.3 PROBABILITY COMPARISONS

In this section probability figures will be presented comparing the model against the data. While temporal figures can present how well the model is able to reproduce various events that are observed in the data, probability figures can give an indication as to how well the model is able to reproduce the data on a seasonal basis. These probability figures present the percent of time that the model or data are less than a particular value. The vertical line in the middle of the figure represents the median value, and the vertical lines on either side of the median encompass two-thirds of the values although they only encompass one-third of the area on the plot. These figures will include seasonal distributions for the model and data at the near field stations, and annual distributions at both the near field and far field stations. The solid lines of the model results represent five-day averages of the model results. The dashed lines in some of these figures represent the maximum and minimum values that occurred during the five-day averaging periods.

Figure 4-53, presents the comparison of model and data probability distributions for surface chlorophyll in 1998. In general, the model results are higher than the data. 1998 was a "low chlorophyll" year. The model does not reproduce the lowest values that were measured in any season, and is lower than the highest values observed during any season. The model does capture the upper half of the far field data, but overall the fit is poor. In 1999 (Figure 4-54), the model compares more favorably to the data. The winter chlorophyll concentrations are higher for both the model and data in 1999. The model under predicts most of the winter data. In the spring and summer, the model is generally higher than the data. In the fall, the model under estimates the data. On an annual basis, the model reproduces the median of the data at the near field and far field stations fairly well, but does not reproduce the range. While chlorophyll is one indicator of algal biomass, it is not the best because algae can adjust their carbon to chlorophyll ratio depending on the ambient conditions.

Figures 4-55 and 4-56 present probability distributions of surface POC for 1998 and 1999, respectively. In 1998, the winter median POC concentration is low (between 0.1 and 0.15 mg/L). Despite over predicting the chlorophyll, the model does a fair job reproducing the POC data. The 1999 winter median POC concentration is much higher, at approximately 0.4 mg/L. The model reproduces the 1998 winter data better than the 1999 winter data. During the spring the data in 1999 is higher than the 1998 POC data. The model does predict higher POC concentrations during the spring of 1999 than the spring of 1998. The model over estimates the spring of 1998 data, and

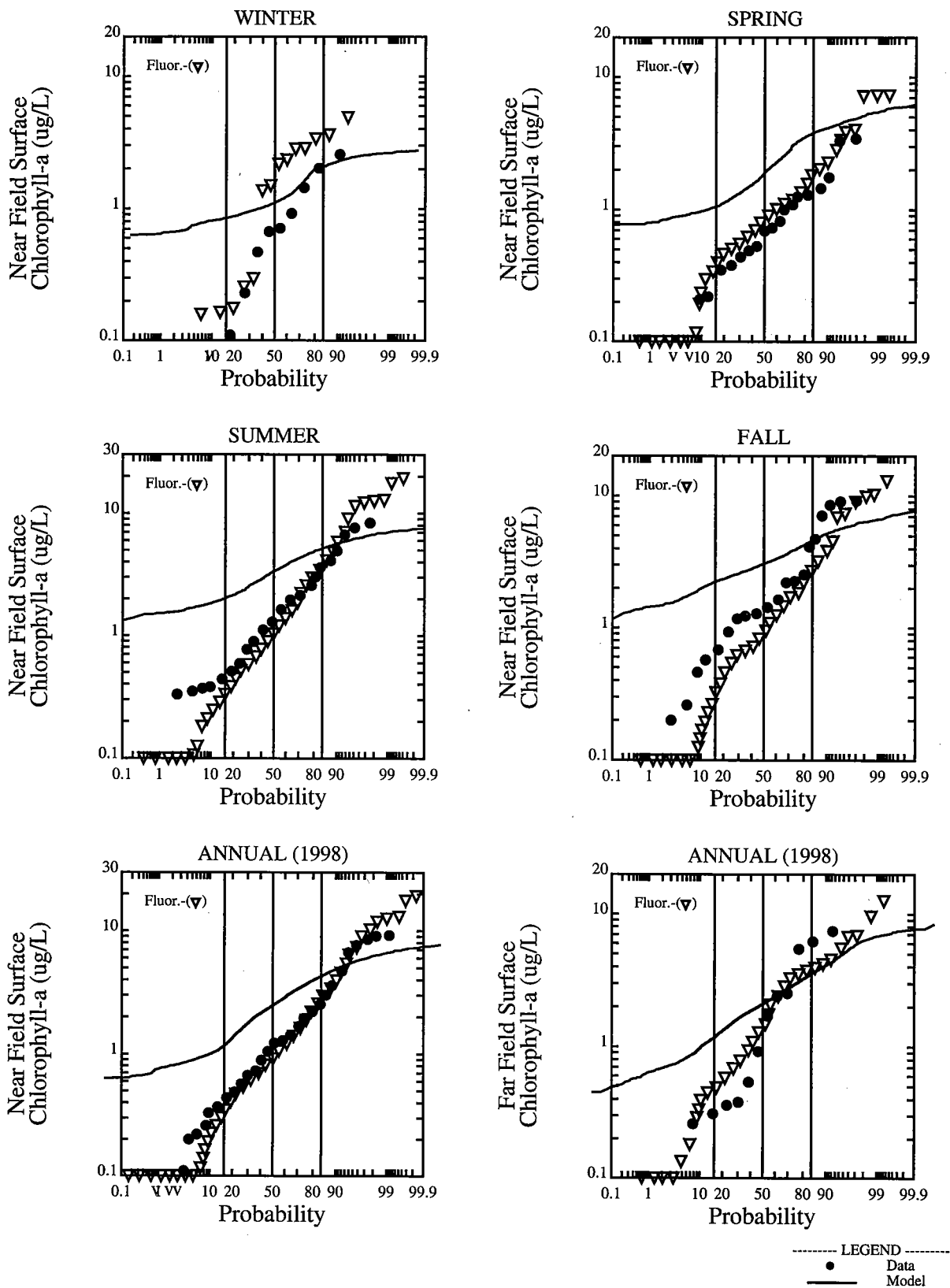


Figure 4-53. Model vs. Data Probability Comparisons for 1998 Surface Chlorophyll

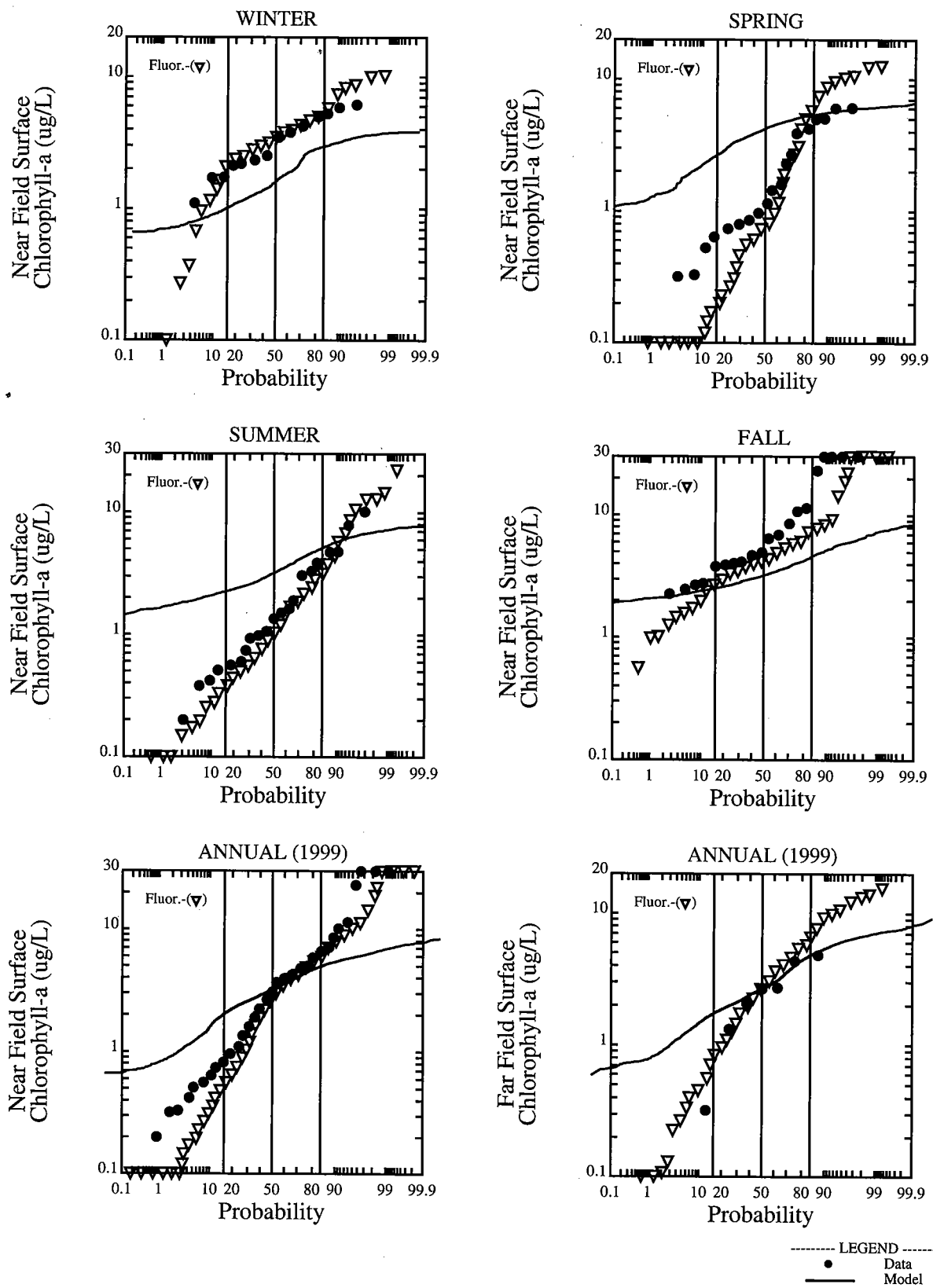


Figure 4-54. Model vs. Data Probability Comparisons for 1999 Surface Chlorophyll

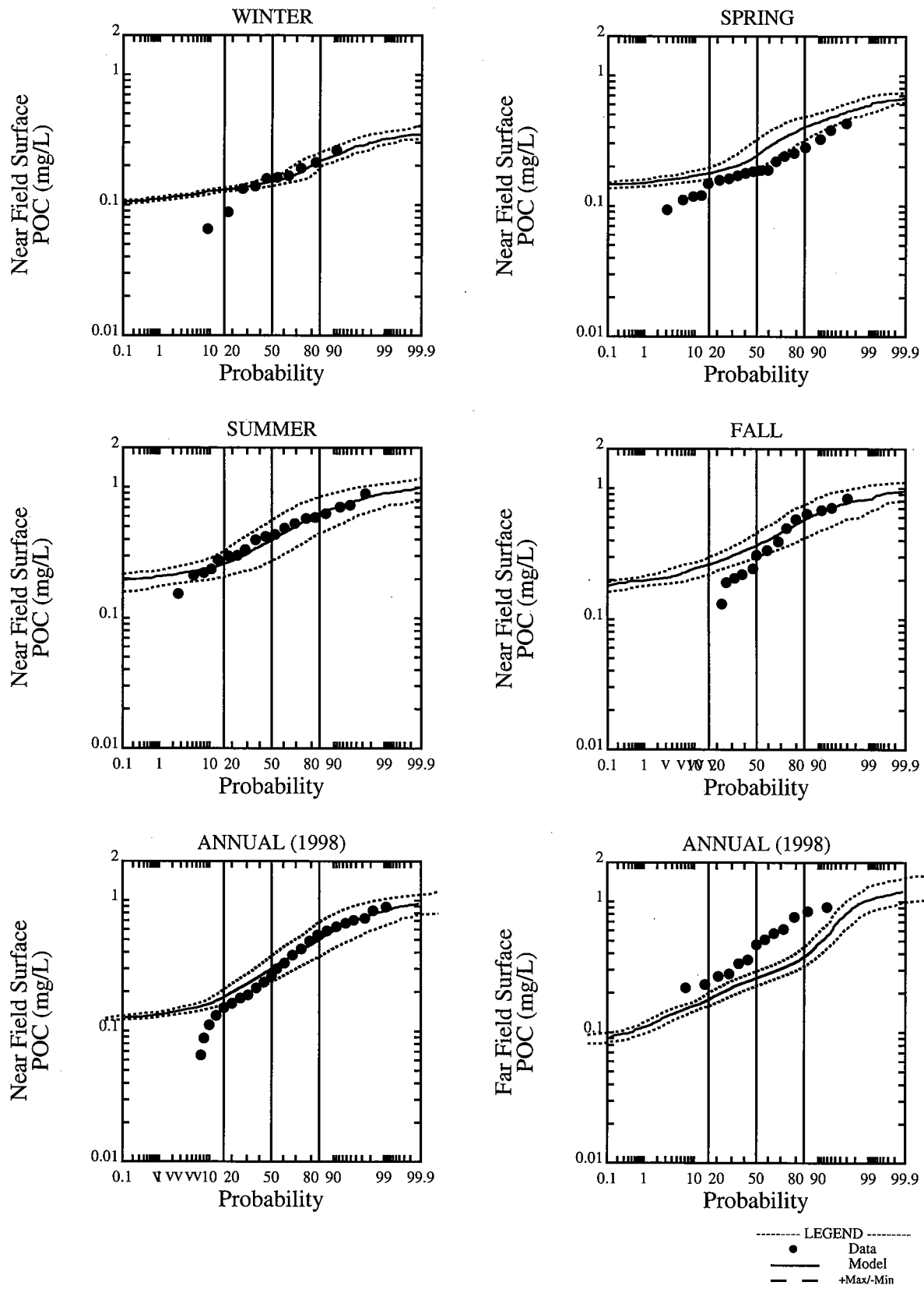


Figure 4-55. Model vs. Data Probability Comparisons for 1998 Surface POC

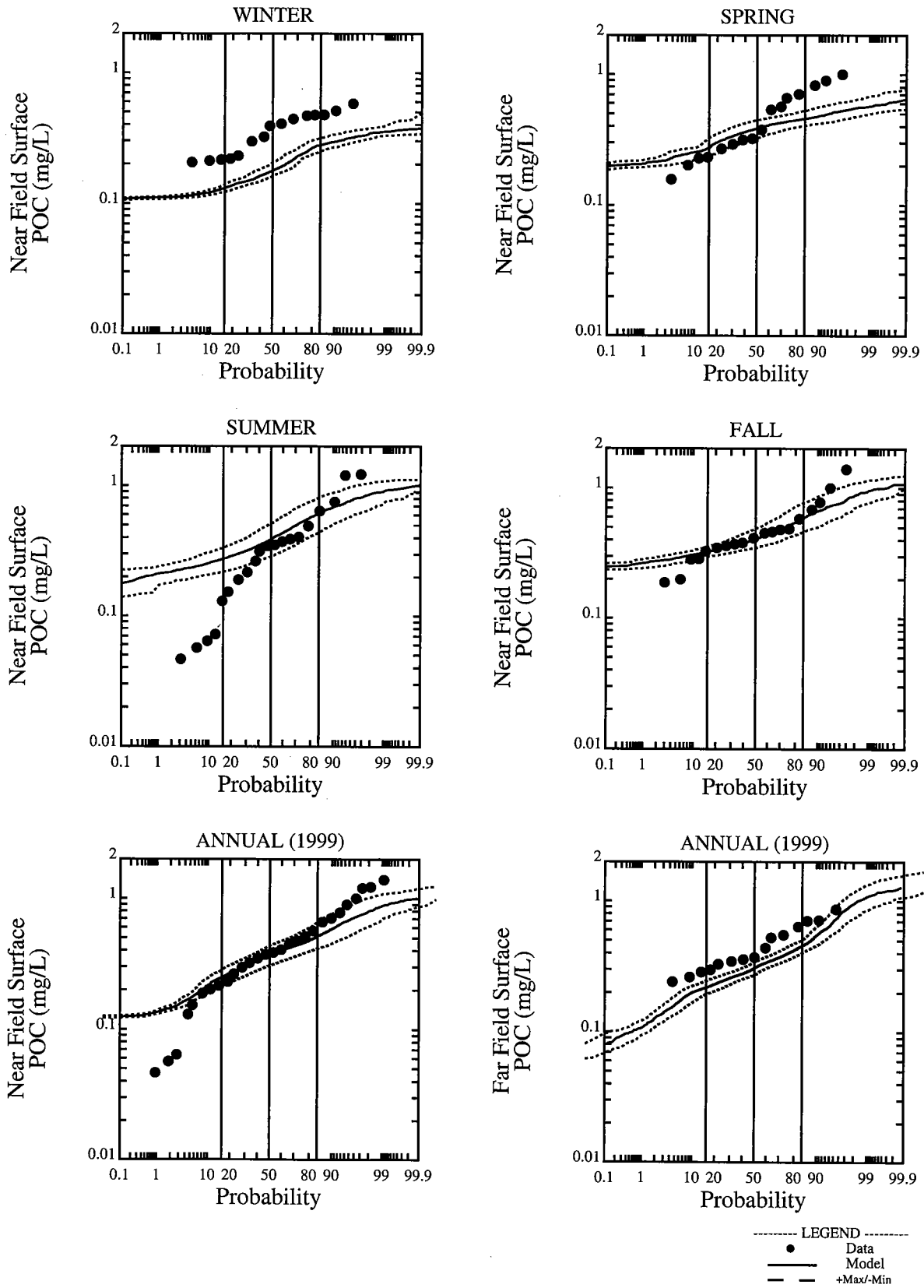


Figure 4-56. Model vs. Data Probability Comparisons for 1999 Surface POC

does a fair job reproducing the 1999 data. During the summer the data are more similar between the two years except for the extreme values. The model matches the summer POC data very well. During the fall, the model reproduces the data well except for a few low values in the fall of 1998. The model calculates higher POC concentrations in the fall of 1999 than the fall of 1998 as was observed in the data. On an annual basis the model reproduces the near field POC data fairly well, but under estimates the far field POC data.

Based on the model's ability to reproduce the chlorophyll data and the POC data, it is not difficult to conclude that during some periods the model would reproduce the carbon to chlorophyll ratio data very well and in others, not so well. Figures 4-57 and 4-58 present the carbon to chlorophyll ratios for 1998 and 1999, respectively. The data have an enormous range from 1.0, in the fall of 1998, to greater than 10,000, in the winter of 1998. In 1998, the model's fit to the data is not very good, although the summer and fall are reproduced fairly well. In 1999, the model reproduces the annual carbon to chlorophyll ratio distribution fairly well, but it misses some of the seasonality.

The probability distributions for the surface PO_4 data and model results in 1998 and 1999 are presented in Figures 4-59 and 4-60, respectively. In general, the model compares favorably to the data in both 1998 and 1999. The 1998 data tend to be lower than 1999 data during the summer and fall. The model is able to reproduce the seasonal and annual differences.

The surface DIN concentration probability data and model results are shown in Figures 4-61 and 4-62 for 1998 and 1999, respectively. The DIN concentration data are quite similar for 1998 and 1999 especially during the summer and fall. The model results are also quite similar except for low values calculated during the spring. The model under predicts the measured DIN concentrations during the summer for both years, although the model results are similar to those computed in 1994. As pointed out in Section 3.2.7 the DIN concentrations in 1998 and 1999 were much higher in the near field than during the years that were modeled previously (1992-1994). During the remainder of the year the model matches the near field DIN data fairly well. The model underestimates the DIN data at the far field stations.

In Figures 4-63 and 4-64, the model versus data probability comparisons are presented for dissolved silica for the years 1998 and 1999, respectively. The data tend to be higher during the winter and spring of 1998 and during the summer and fall of 1999. In general, the model reproduces the silica data fairly well during the winter and fall, but under predicts the spring and summer DSi concentrations, especially during the summer of 1999. In part, this is probably due to the fact that the model was calibrated to years when diatom blooms were evident during the spring

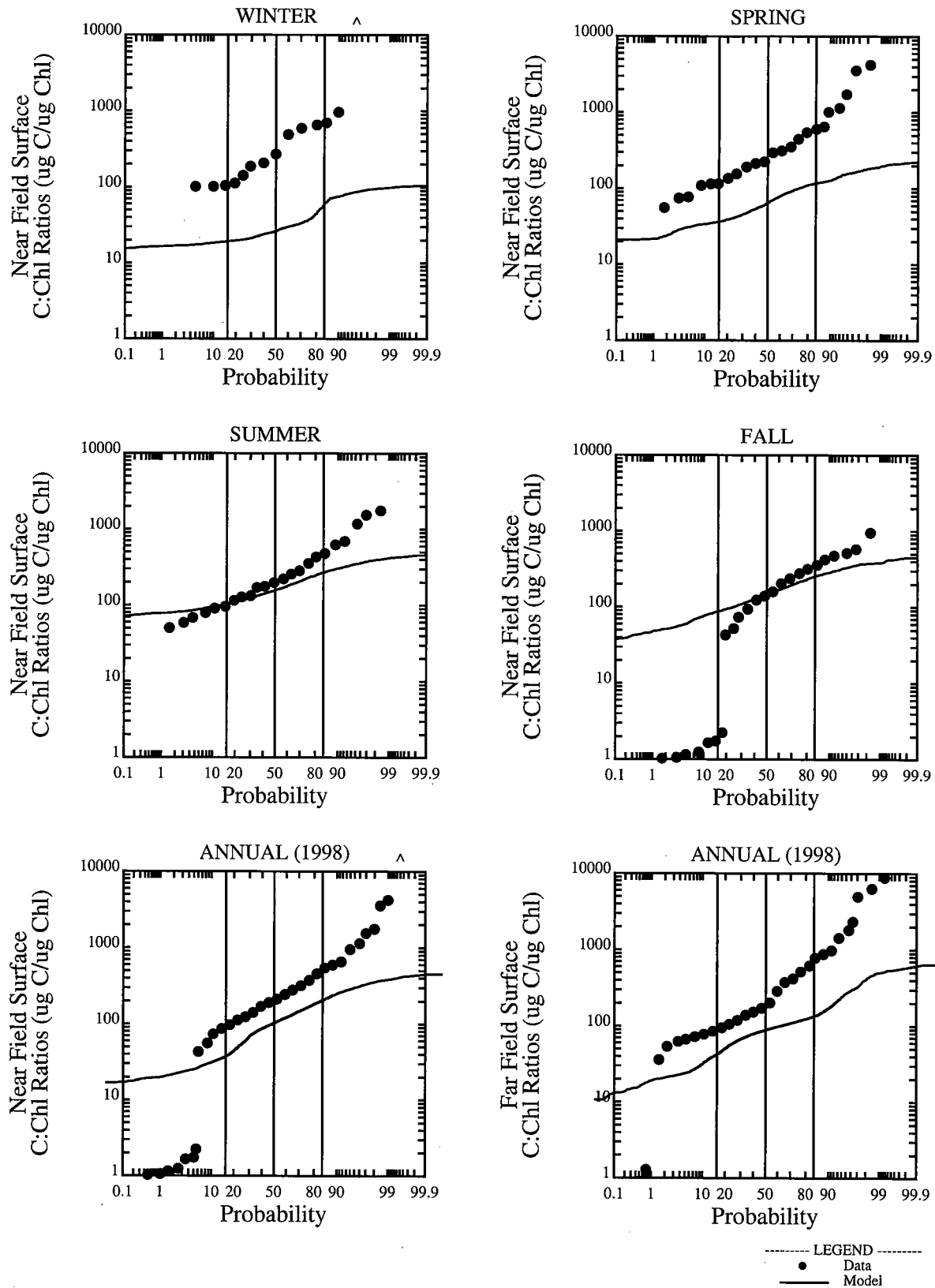


Figure 4-57. Model vs. Data Probability Comparisons for 1998 Surface C:Chl

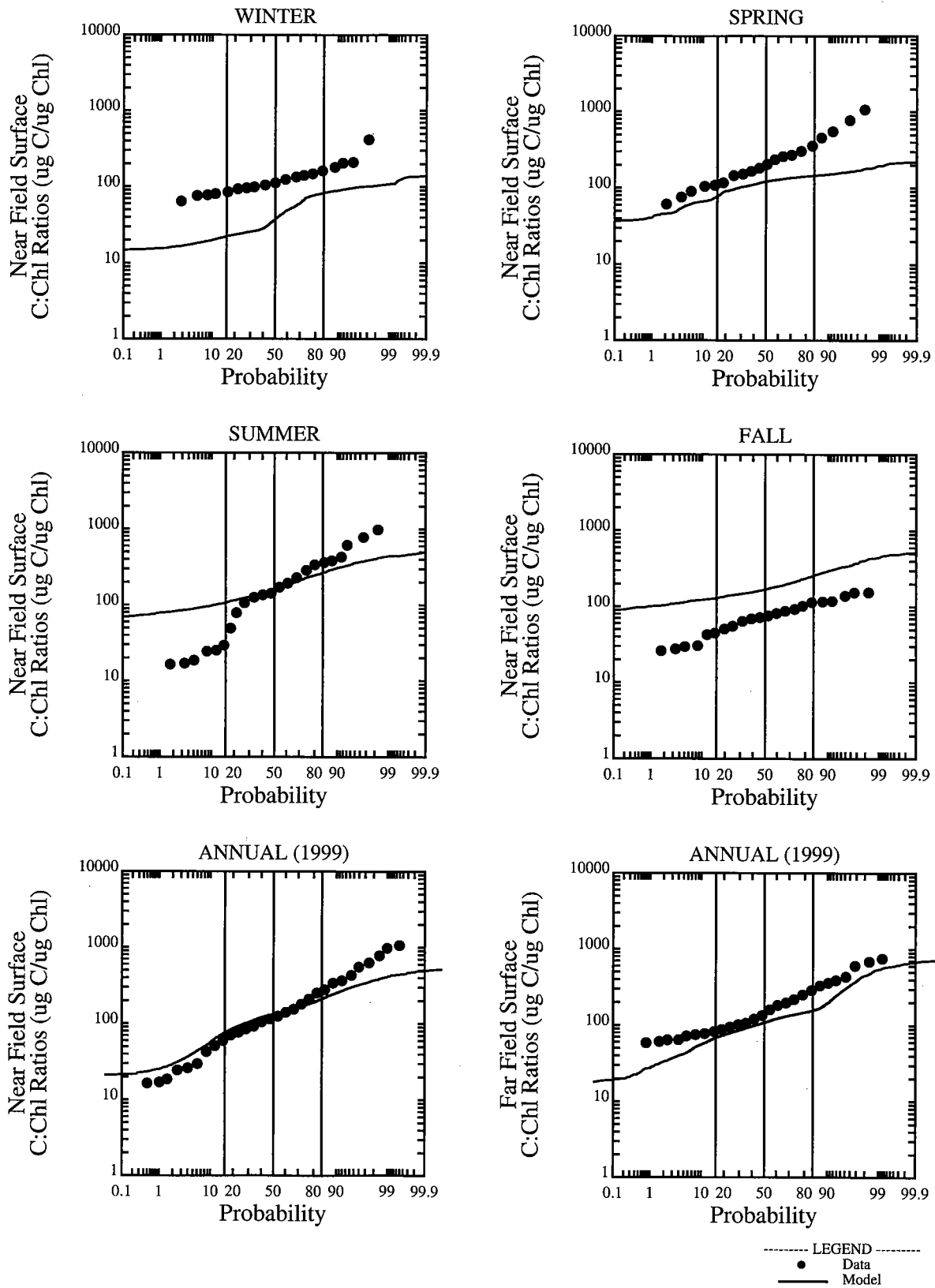


Figure 4-58. Model vs. Data Probability Comparisons for 1999 Surface C:Chl

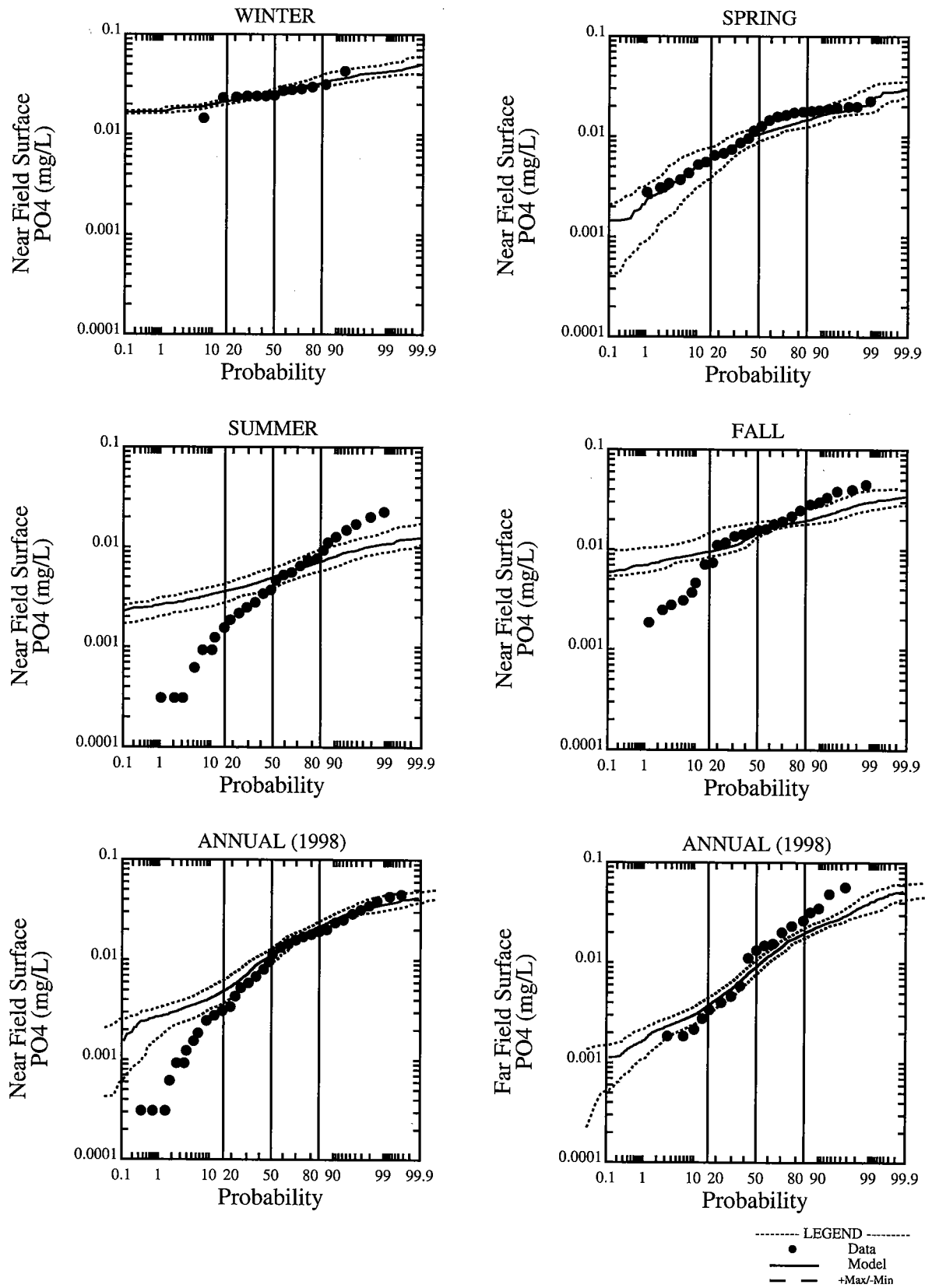


Figure 4-59. Model vs. Data Probability Comparisons for 1998 Surface PO4

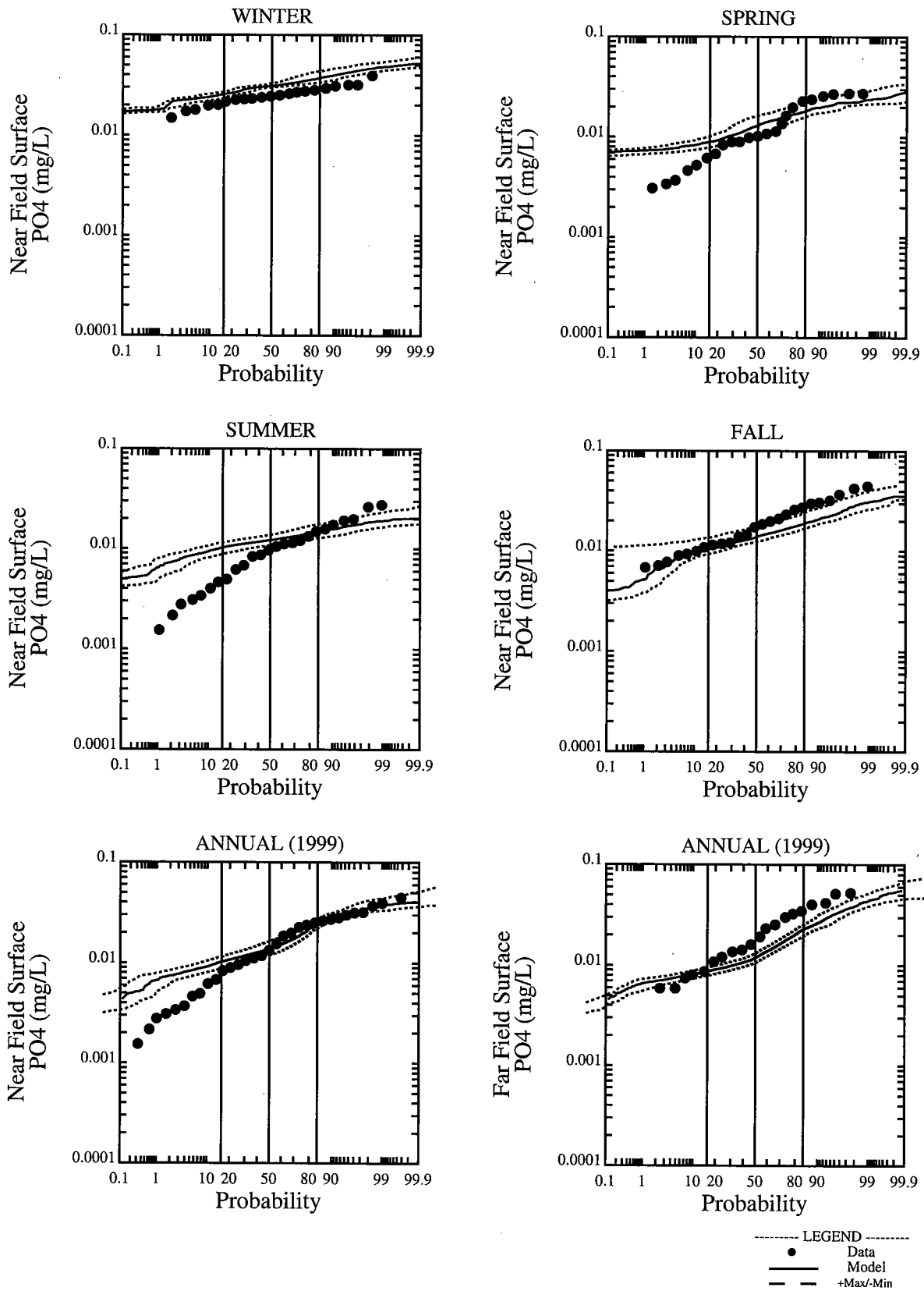
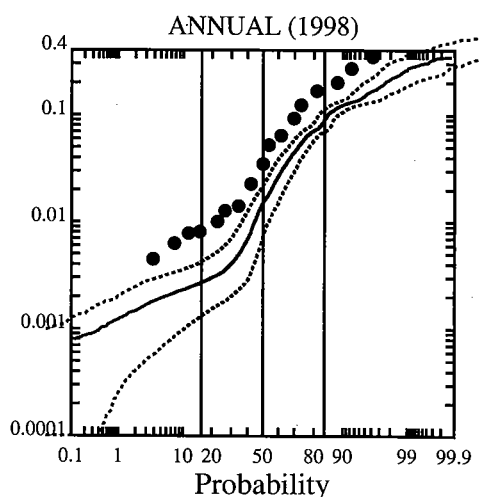
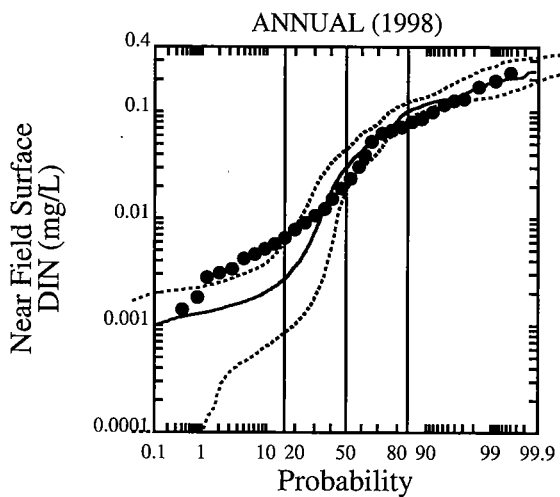
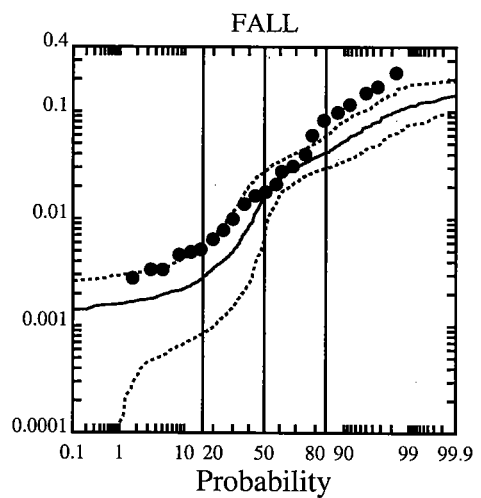
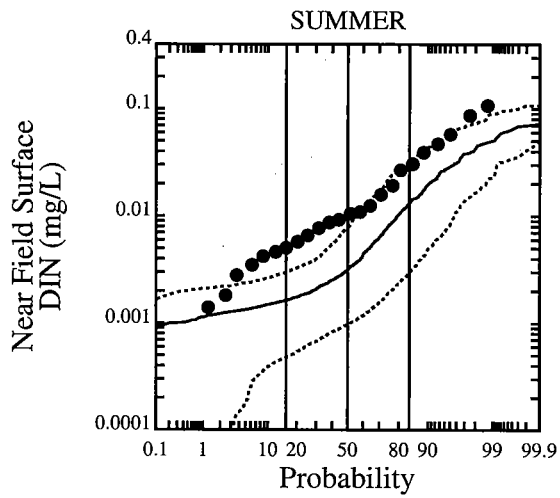
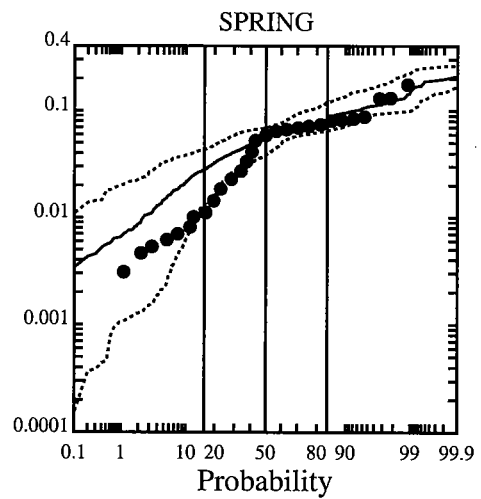
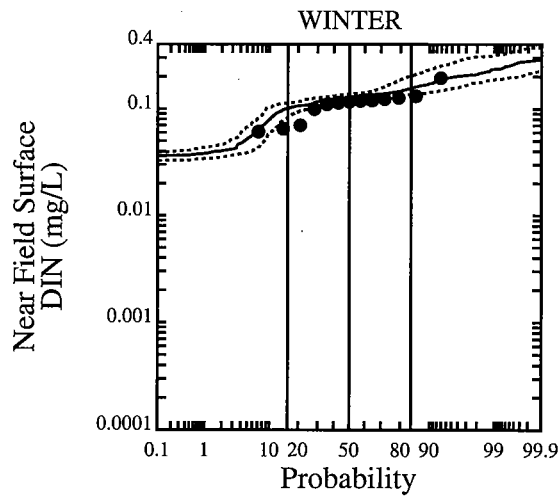


Figure 4-60. Model vs. Data Probability Comparisons for 1999 Surface PO4



----- LEGEND -----
 • Data
 — Model
 - - - Max/Min

Figure 4-61. Model vs. Data Probability Comparisons for 1998 Surface DIN

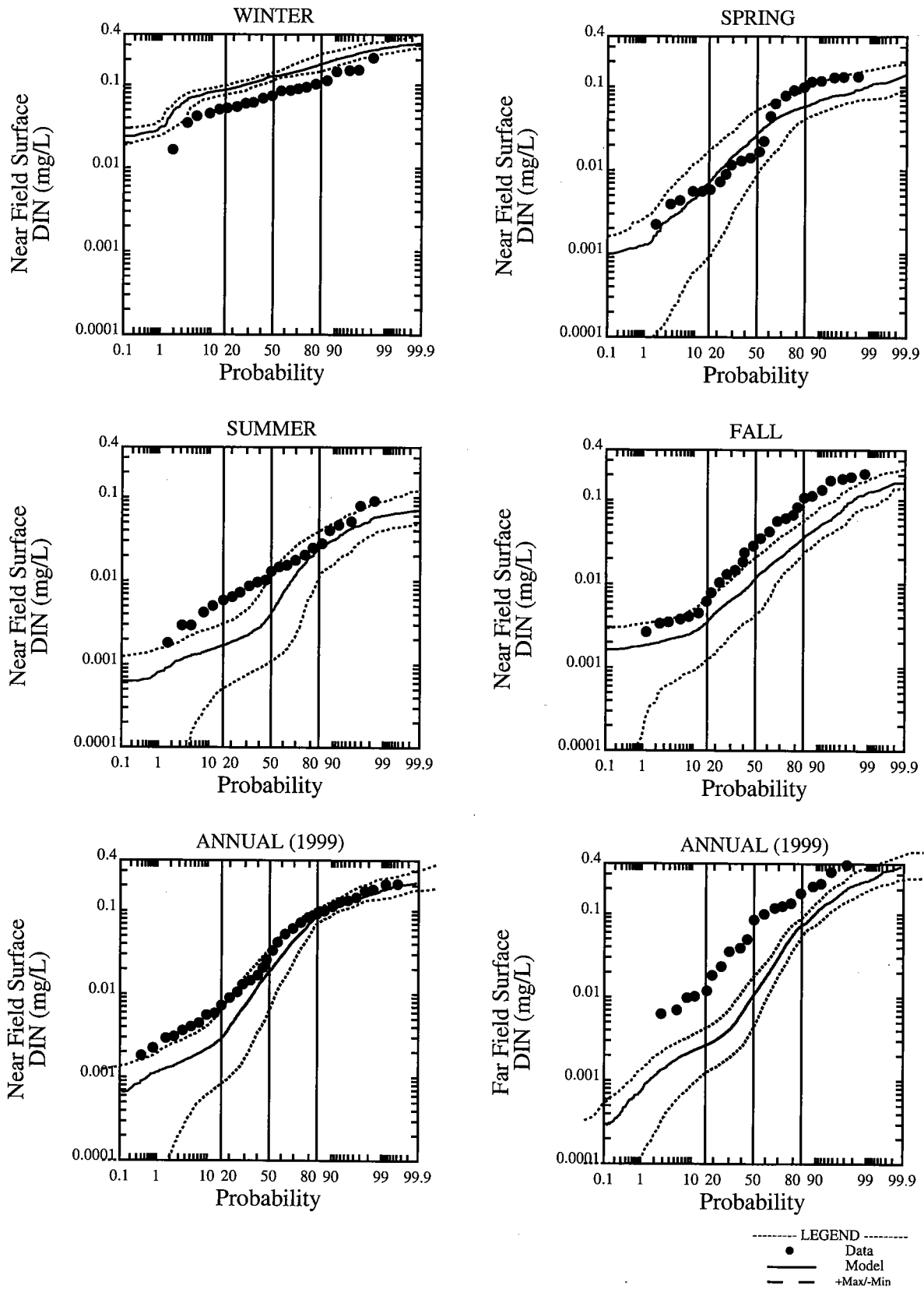


Figure 4-62. Model vs. Data Probability Comparisons for 1999 Surface DIN

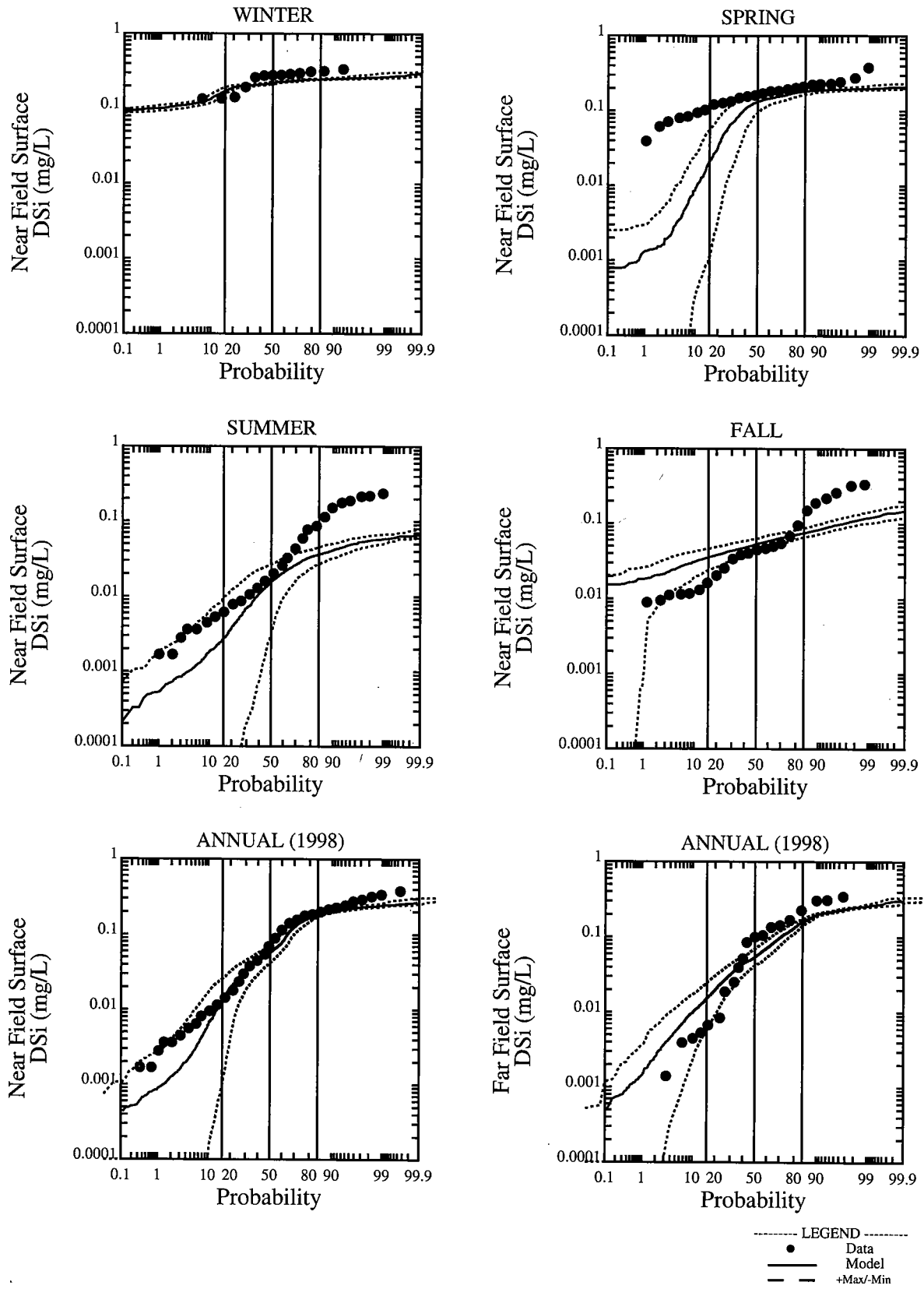


Figure 4-63. Model vs. Data Probability Comparisons for 1998 Surface DSi

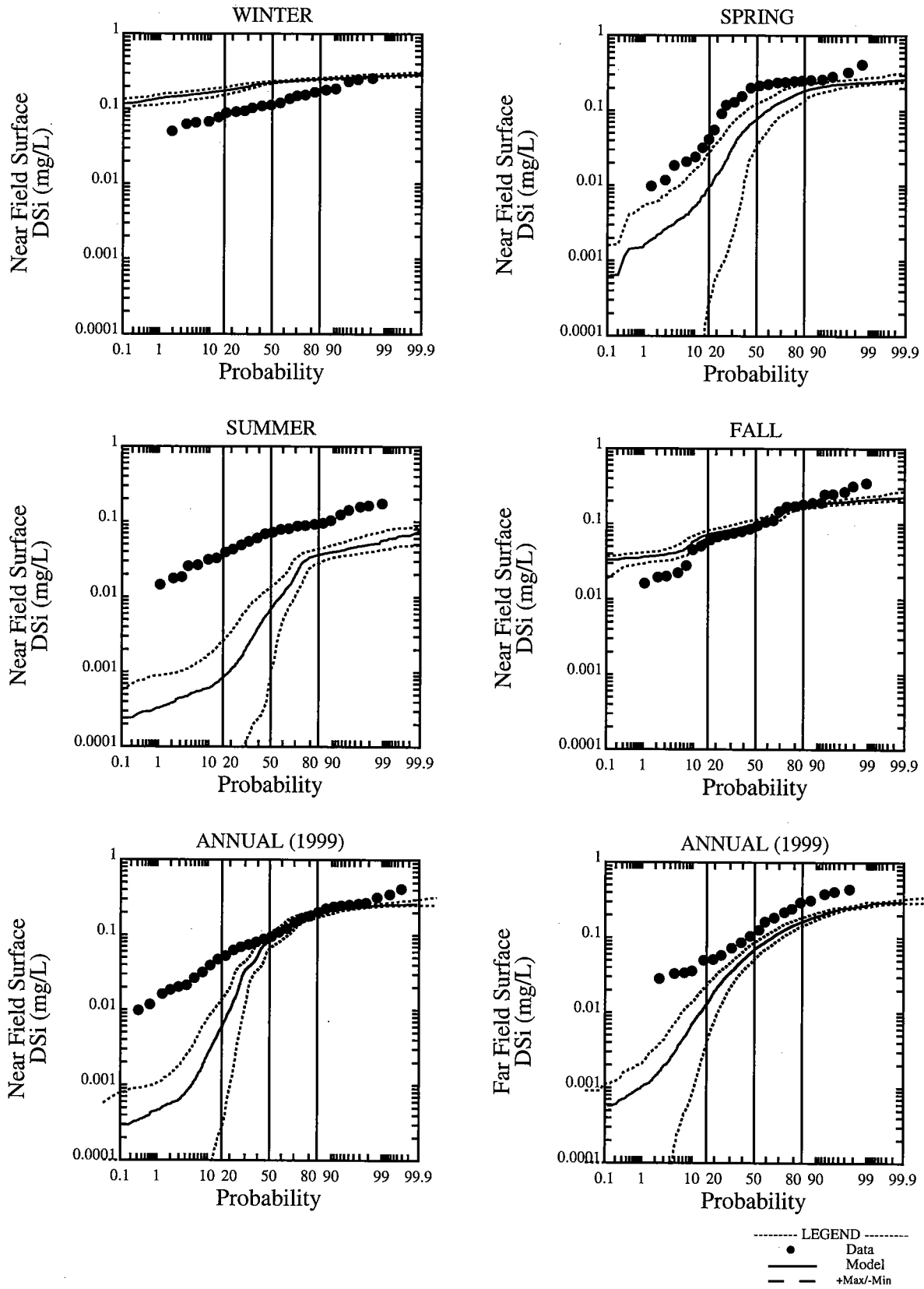


Figure 4-64. Model vs. Data Probability Comparisons for 1999 Surface DSi

period. During 1998 and 1999, spring blooms were less apparent. The model compares more favorably to the 1998 surface silica data than the 1999 data.

The DO probability distributions are presented in Figures 4-65 and 4-66 for 1998 and 1999, respectively. The model compares to the winter and spring data of 1998 quite favorably, but slightly over estimates the summer and fall data in the near field. The model overestimates the summer and fall minimum DO concentrations during 1998. The model is able to reproduce much of the far field data distribution. In 1999, the model matches the seasonal data fairly well except for the lowest fall DO measurements. The model is late in predicting the fall turnover and therefore misses the December DO concentrations. The model matches the DO concentrations below the annual median quite well at the far field stations, but under estimates the higher concentrations.

4.4 PRIMARY PRODUCTIVITY

Another measure of the water quality model's ability to reproduce the processes that occur in Massachusetts and Cape Cod Bays is the comparison to the primary productivity. In 1998 and 1999, primary productivity was measured at three stations: F23, N04 and N18. Primary productivity was measured six times at station F23 during each of the far field sampling events and seventeen times at stations N04 and N18 during each of the near field sampling events. In 1998 and 1999, ^{14}C techniques were used to measure primary productivity. In general, measured productivity was low in 1998 (Libby et al. 1999) and more consistent with previous years in 1999 (Libby et al. 2000).

Figure 4-67 presents the 1998 areal productivity data with the monthly average model results for gross primary productivity (GPP) and the net primary productivity (NPP). At station F23, the model results are substantially higher than the data except for early February. At the near field stations, the model does over estimate the primary productivity, but the NPP is a fair approximation of the fall productivity data. In Figure 4-68, the 1999 model versus data comparison is presented. Again, the model over estimates the productivity at station F23, but in this case it is only the second half of the year that is over estimated. At the near field stations, the model comparison to the 1999 data is quite good. The model reproduces the higher production measured during the spring and fall, but misses the high productivity measured in August at station N18.

The model is able to compute some differences between the two years. The spring productivity computed by the model in 1998 is somewhat less than was computed in 1999. This feature was observed in the data as well. Clearly, there are processes occurring in the vicinity of station F23 that the model is not able to reproduce. There are more nutrients available in Boston Harbor than in the near field area which should fuel more phytoplankton growth. There also

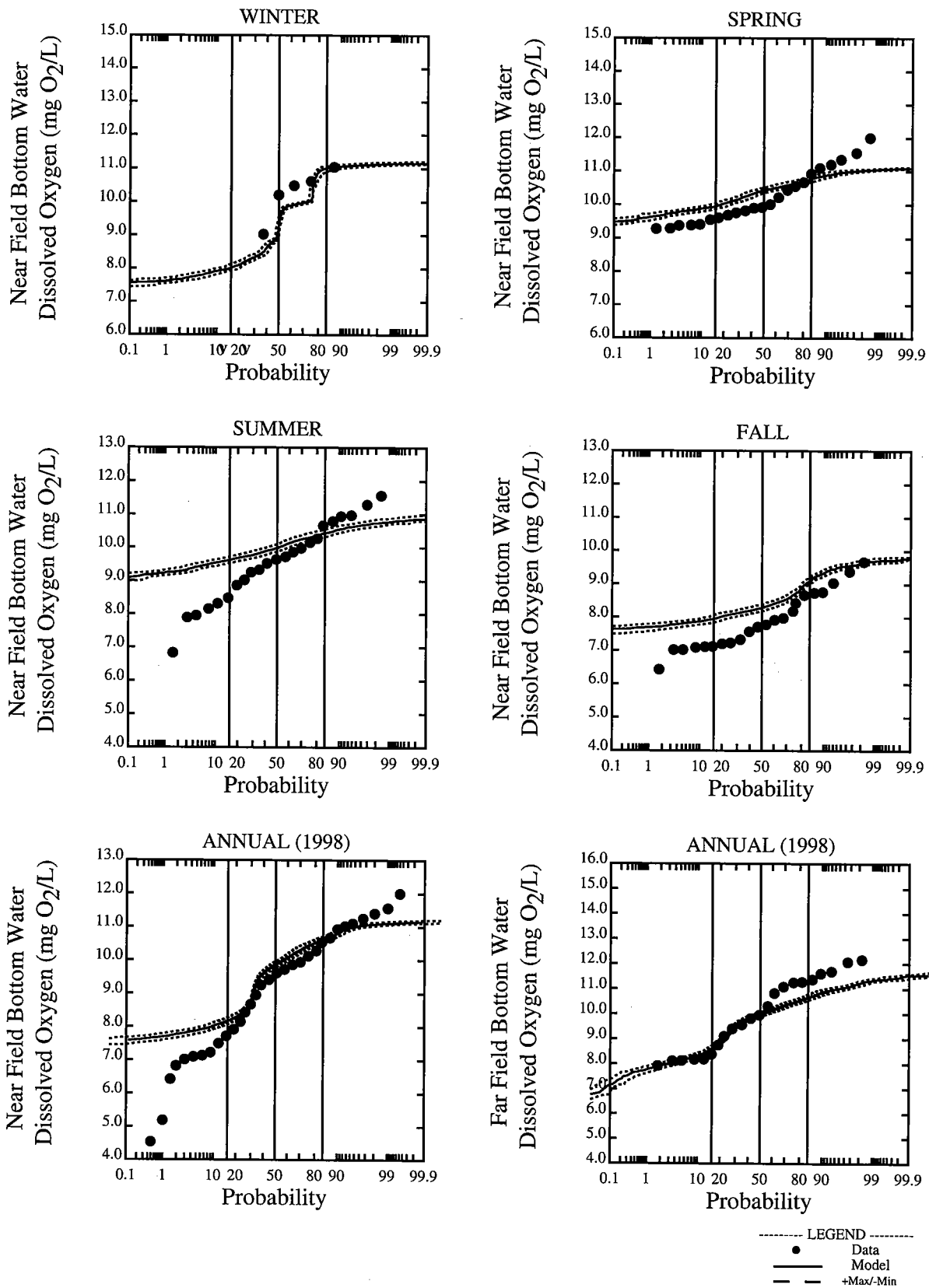


Figure 4-65. Model vs. Data Probability Comparisons for 1998 Bottom DO

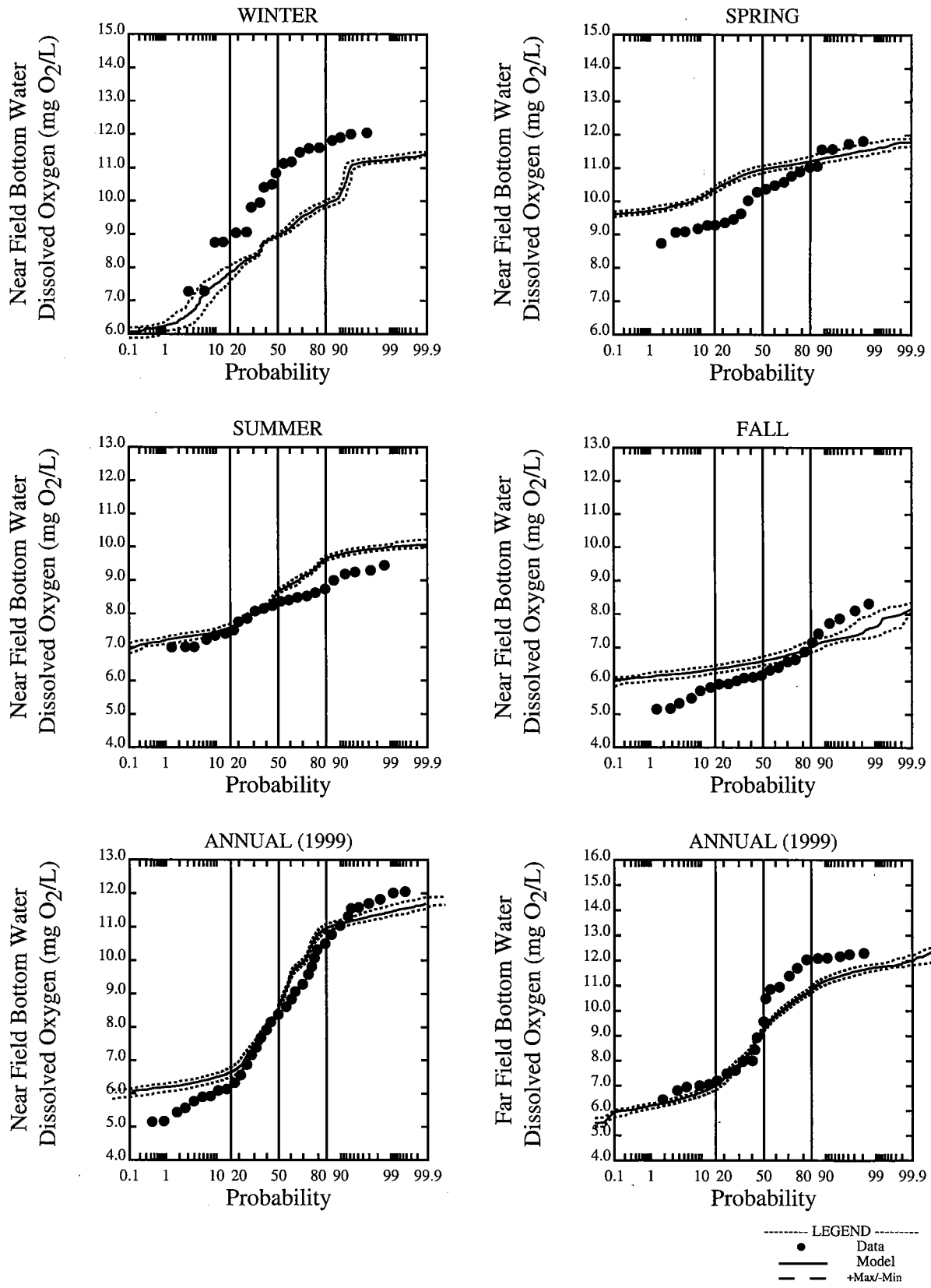


Figure 4-66. Model vs. Data Probability Comparisons for 1999 Bottom DO

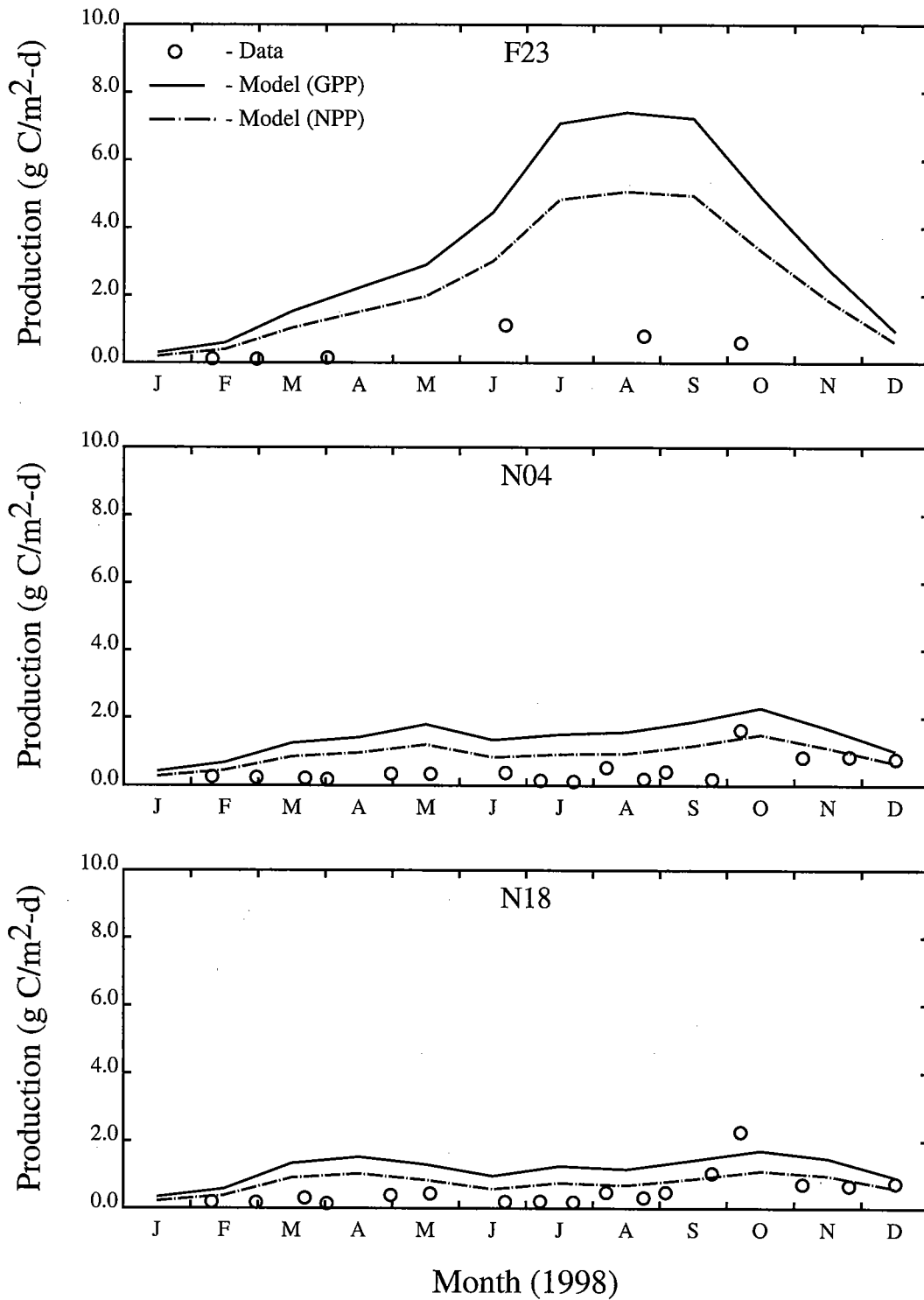


Figure 4-67. 1998 Primary Productivity Comparison

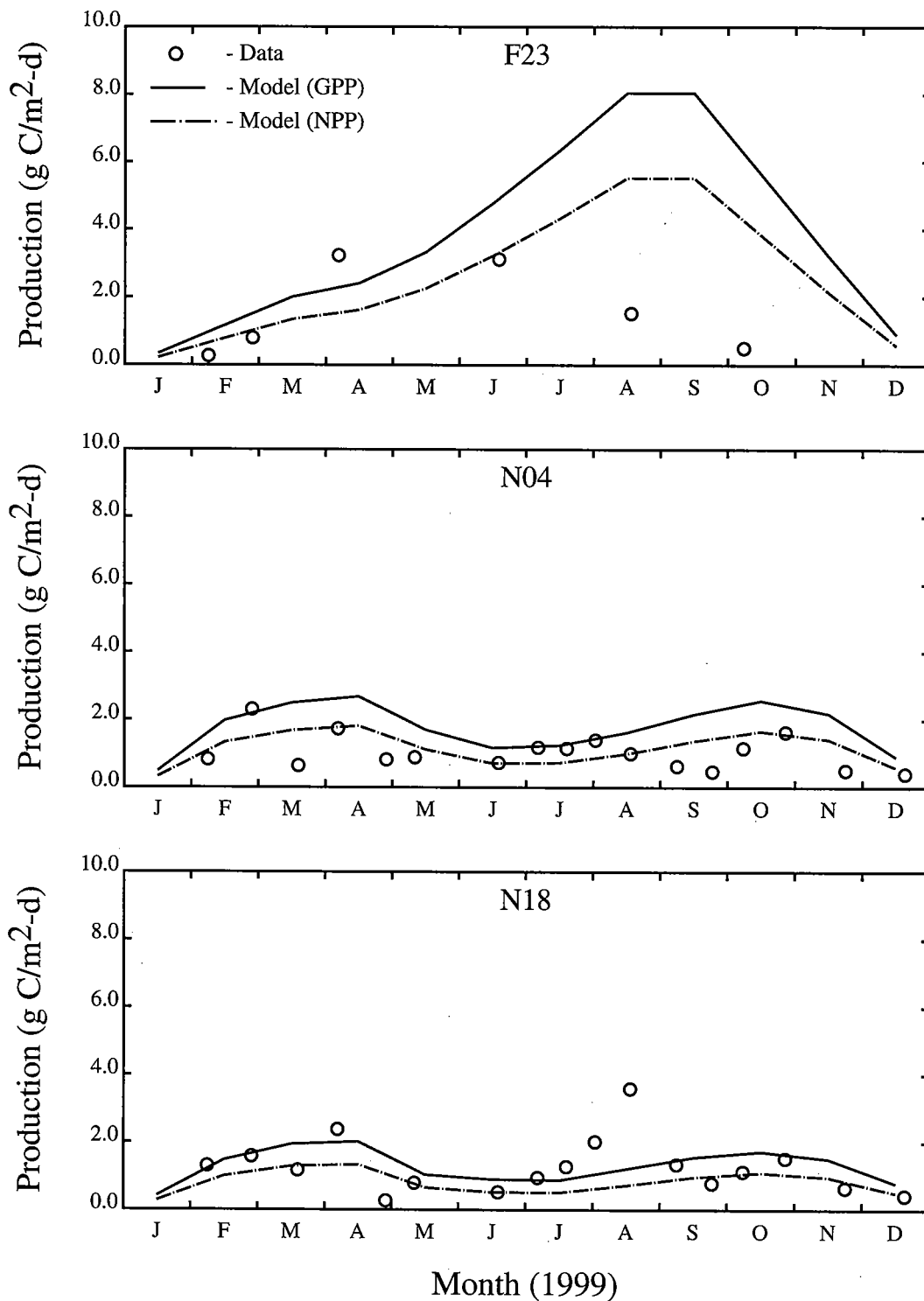


Figure 4-68. 1999 Primary Productivity Comparison

appears to be enough light to allow Boston Harbor to be productive. However, the data indicate that productivity is cropped during the second half of the year. There are several possible reasons for the reduced productivity in the harbor, but at this point they are purely speculative. One possibility for this discrepancy could be that the model has a higher residence time than actually exists in Boston Harbor and this gives more time for algae to grow in the model. Another reason could be that zooplankton grazing reduce the algal population. Zooplankton are not explicitly modeled in BEM. A third reason could be possible toxicity in the harbor that is not accounted for in the model.

4.5 CARBON DEPOSITION

The deposition of organic matter drives the diagenesis process occurring in the sediment. During the period from 1992 to 1999 there was an observed increase in the POC concentration measured in Massachusetts and Cape Cod Bays as well as the Gulf of Maine in general. This increased POC could translate into additional POC being deposited to the sediment, which could in turn increase the sediment SOD and affect benthic communities in the bays. BEM includes a sediment model that keeps track of the sediment POC in three reactivity classes, G1, G2 and G3. G1 is the most reactive class, followed by G2, which is less reactive, and G3, which is essentially inert. The largest component of the POC (which includes phytoplankton) that reaches the sediment is G1 carbon. However, because G3 carbon is inert, G3 carbon composes the majority of the sediment carbon. The following section presents figures showing the annual average flux of POC to the sediment (JPOC) and the resulting G1 carbon (POC1) and total carbon (POC) in the sediment for the years 1994, 1998, and 1999.

Figure 4-69 presents the annual average carbon flux to the sediment in $\text{mg}/\text{m}^2\text{-d}$ during 1994. The highest fluxes are observed in Boston Harbor due to inputs from WWTPs, rivers, and the deposition of the relatively high phytoplankton concentrations computed by BEM. In the bay proper, the highest deposition rates are computed along the western shore into Cape Cod Bay and along the northern shore. The lowest JPOC fluxes are computed near the northern boundary. The G1 POC concentrations presented in Figure 4-70, closely match the distribution of the JPOC fluxes in Figure 4-69. In Boston Harbor, the G1 POC concentrations are generally greater than 0.35 mg C/g sediment. Near the northern boundary the G1 POC concentrations are less than 0.05 mg C/g sediment.

The total POC sediment concentration for 1994 is presented in Figure 4-71. The figure shows that the total POC concentration is two orders of magnitude greater than the G1 POC concentration although the distribution is similar. The highest concentrations were computed in western Boston Harbor, and in the bays the highest sediment POC concentrations were computed along the coast.

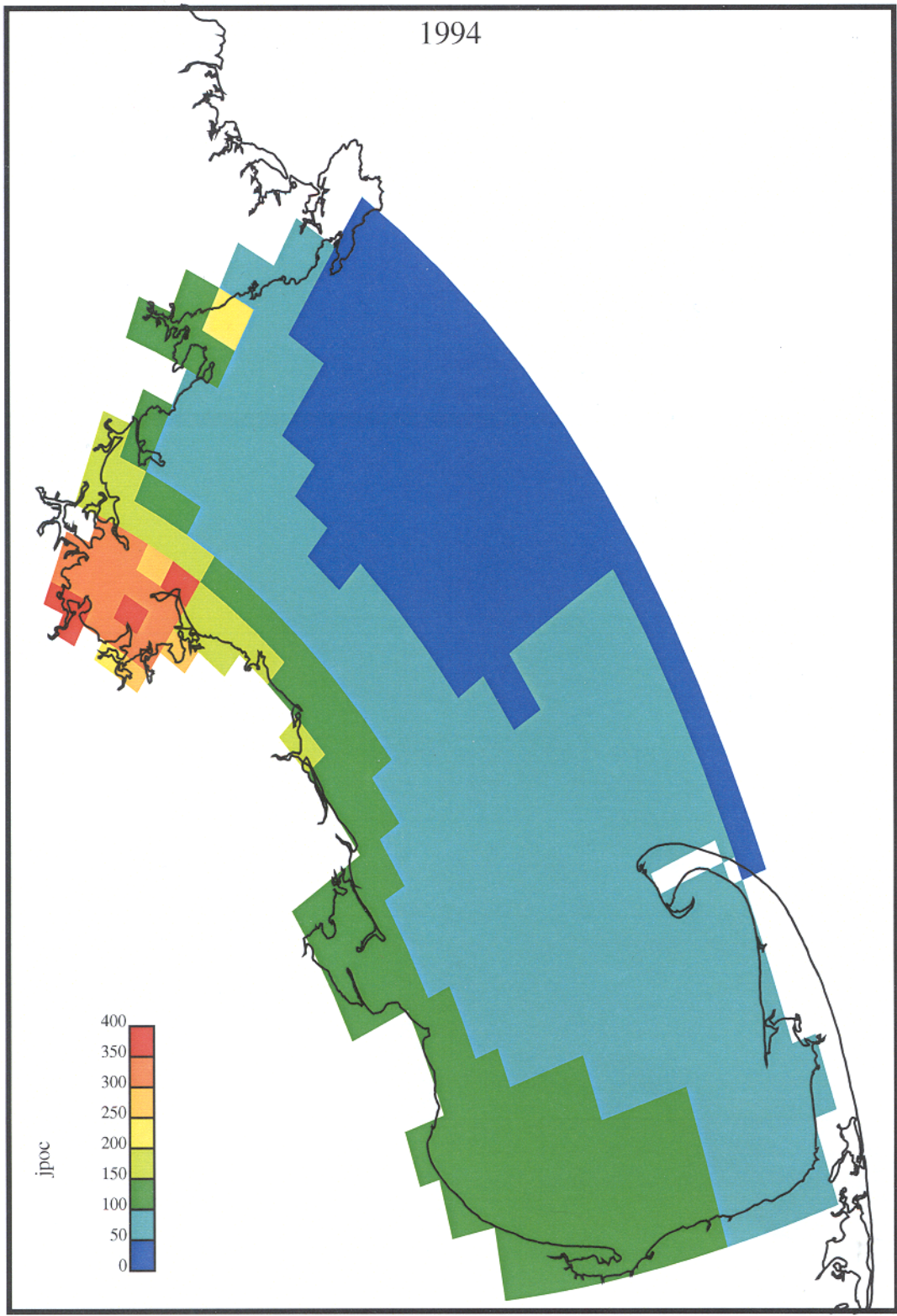


Figure 4-69. 1994 Computed Annual Average Carbon Depositional Flux ($\text{mg}/\text{m}^2\text{-d}$)

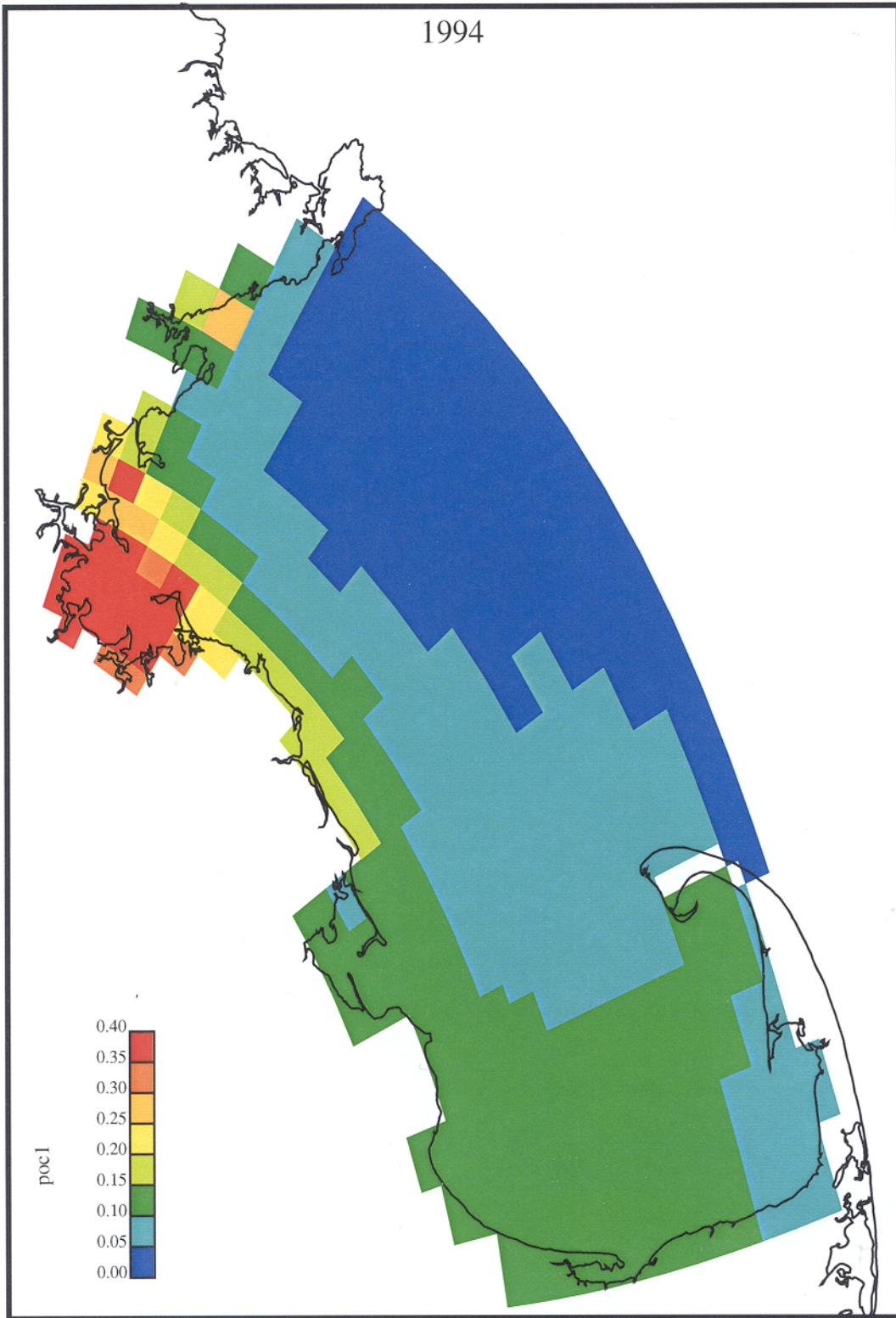


Figure 4-70. 1994 Computed Annual Average Sediment G1 Carbon (mg C/g sediment)

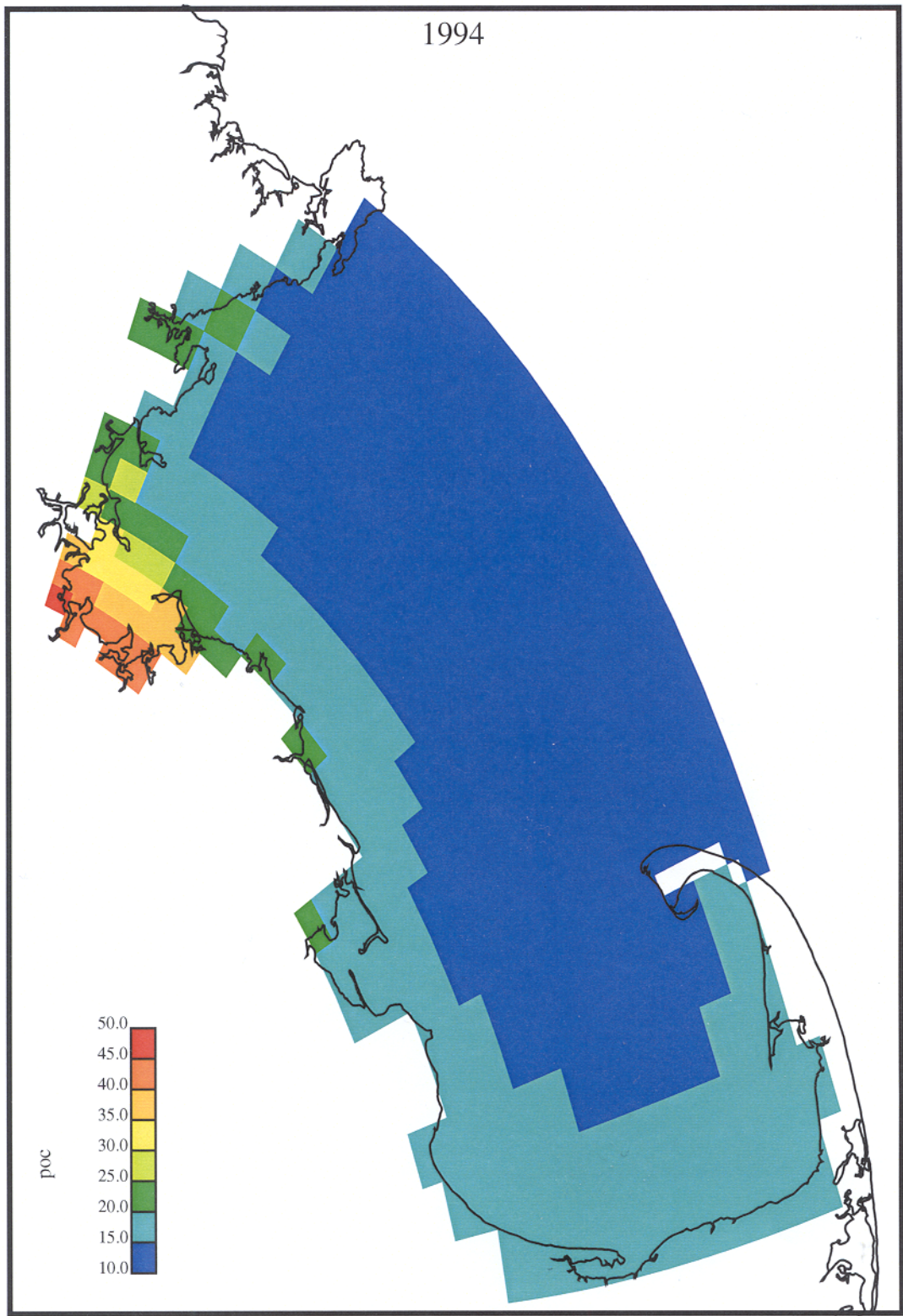


Figure 4-71. 1994 Computed Annual Average Sediment POC (mg C/g sediment)

The POC depositional flux for 1998 is presented in Figure 4-72, recall that BEM was run on an aggregated grid for 1994 and a fine grid in 1998. The JPOC in Boston Harbor is similar for the two years, but the finer grid is able to provide a bit more resolution. It is also apparent that the JPOC has increased in the bays. Higher JPOCs are computed along the western coast, in Cape Cod Bay, north of Race Point and in northeastern Massachusetts Bay during 1998. As a consequence, there is an increase in the G1 POC in the bays as shown in Figure 4-73. It is interesting to note, that the model computes lower G1 POC concentrations in Boston Harbor during 1998 than during 1994, but this is not an artifact of grid aggregation on the 1994 results. However, despite the increased JPOC in 1998, the total POC concentration in the sediment is very similar between the two years (Figure 4-74).

During 1999 (Figure 4-75), the carbon deposition increases over the 1998 rates, with the exception of the vicinity around Nut Island due to the transfer of the WWTP effluent from Nut Island to Deer Island. The changes in G1 POC concentrations from 1998 to 1999 follow the computed changes in JPOC (Figure 4-76). Figure 4-77 shows once again, despite the increase in the G1 POC from 1998 to 1999, the total POC is computed to be very similar between the two years.

4.6 SPATIAL SEDIMENT MODEL VERSUS DATA COMPARISONS

Figure 4-78 presents the model versus data comparison for JPO_4 in 1998. No flux measurements were taken at the Massachusetts Bay stations in 1998. Near the Inner Harbor (station BH02), the model does not match the high July JPO_4 measurement. During the remainder of the year the model computed fluxes are closer to the data. At stations BH03 and BH08A, the model compares favorably with the flux data, reproducing the higher fluxes observed during the warmer months. The model predicts very low, almost constant, phosphate fluxes at the Massachusetts Bay (MB) stations. These low PO_4 fluxes seem quite reasonable based on the data collected in 1999 (Figure 4-79). In 1999, the model computes higher JPO_4 than for 1998, at least during the summer and fall. One area where the model does not match the data in 1999 is at station MB03. While the model does compute small fluxes out of the sediment, the data show a small flux into the sediment. Overall, the model compares quite favorably with the 1999 data.

The ammonia flux model versus data comparison for 1998 is presented in Figure 4-80. The measured fluxes indicate the highest NH_4 fluxes occurred during the early summer in Boston Harbor. While the model reproduces this early peak, it extends the duration of the peak into September, while the data indicate a decline during August. While the model reproduces the general shape and magnitude of the data, it generally over estimates the fluxes during the latter portion of the year. The model calculates low ammonium fluxes at the MB stations.

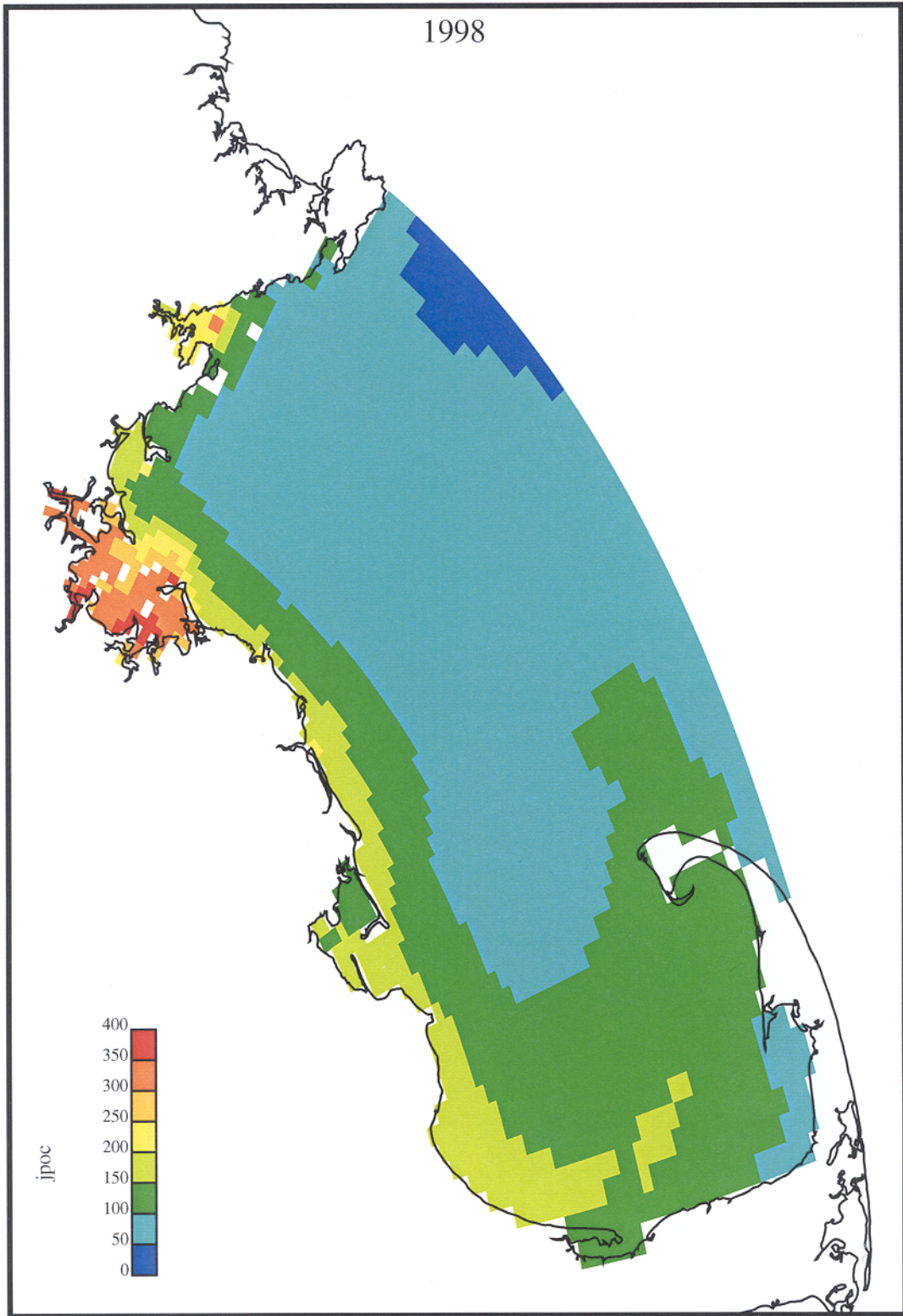


Figure 4-72. 1998 Computed Annual Average Carbon Depositional Flux (mg/m²-d)

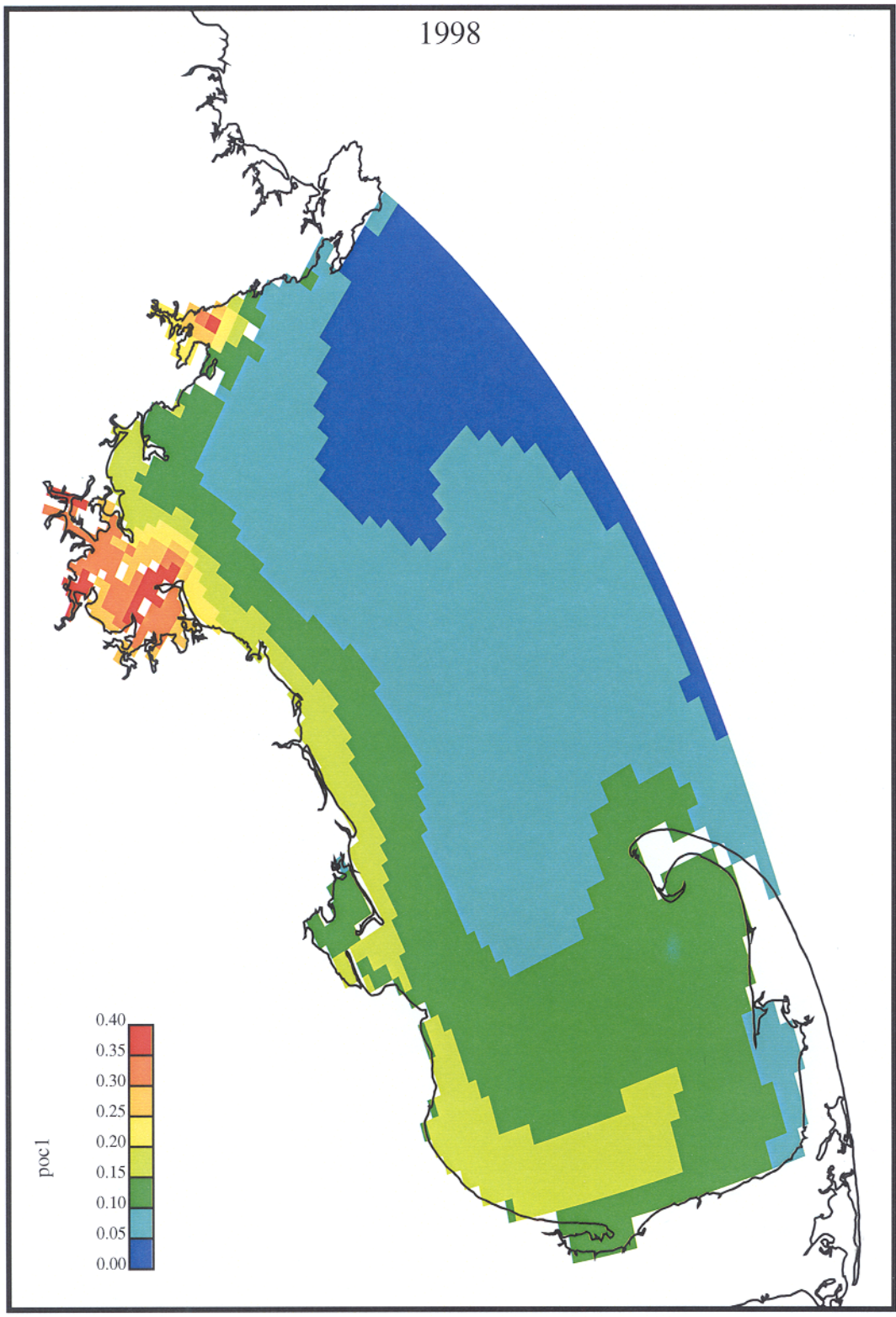


Figure 4-73. 1998 Computed Annual Average Sediment G1 Carbon (mg C/g sediment)

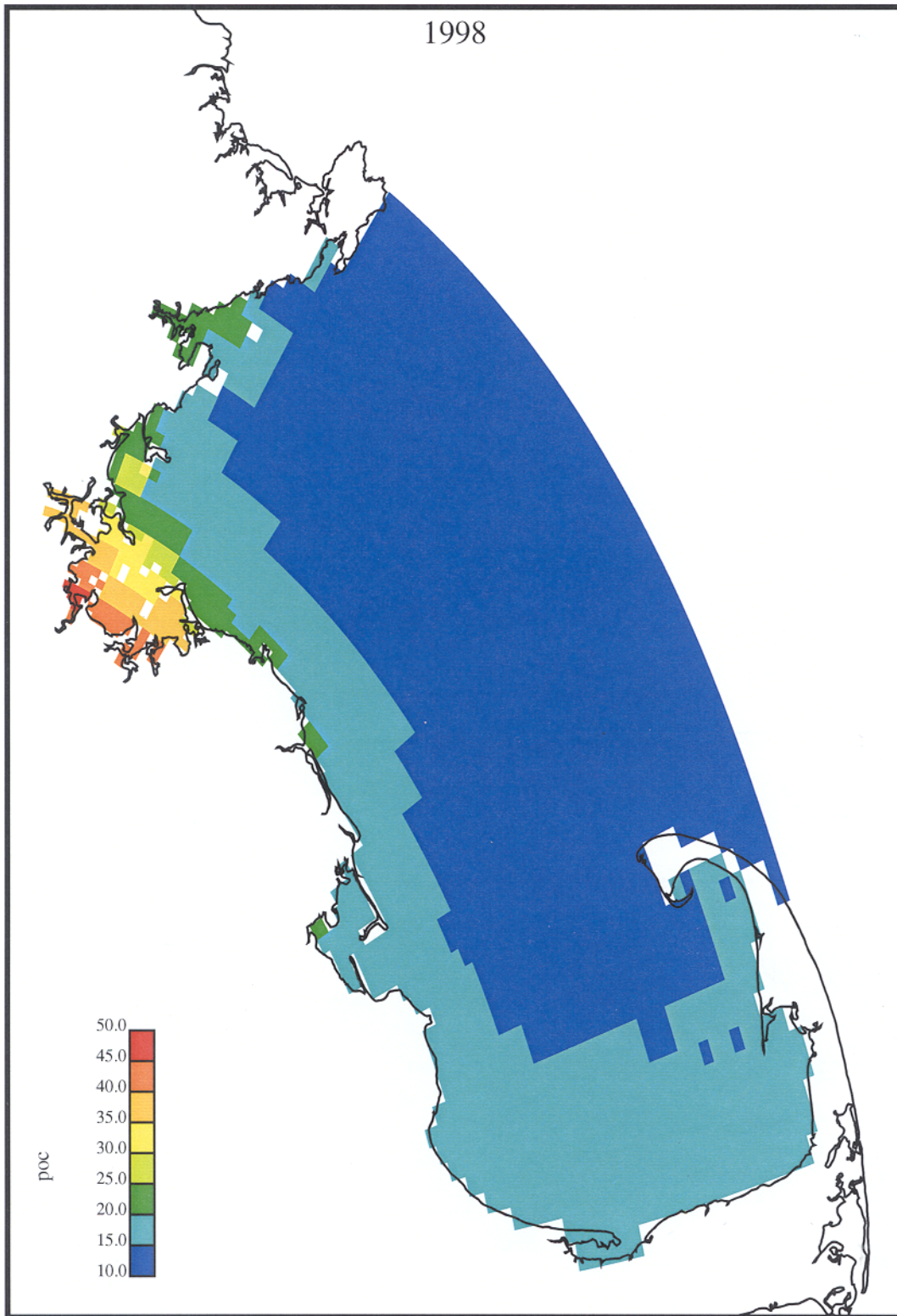


Figure 4-74. 1998 Computed Annual Average Sediment POC (mg C/g sediment)

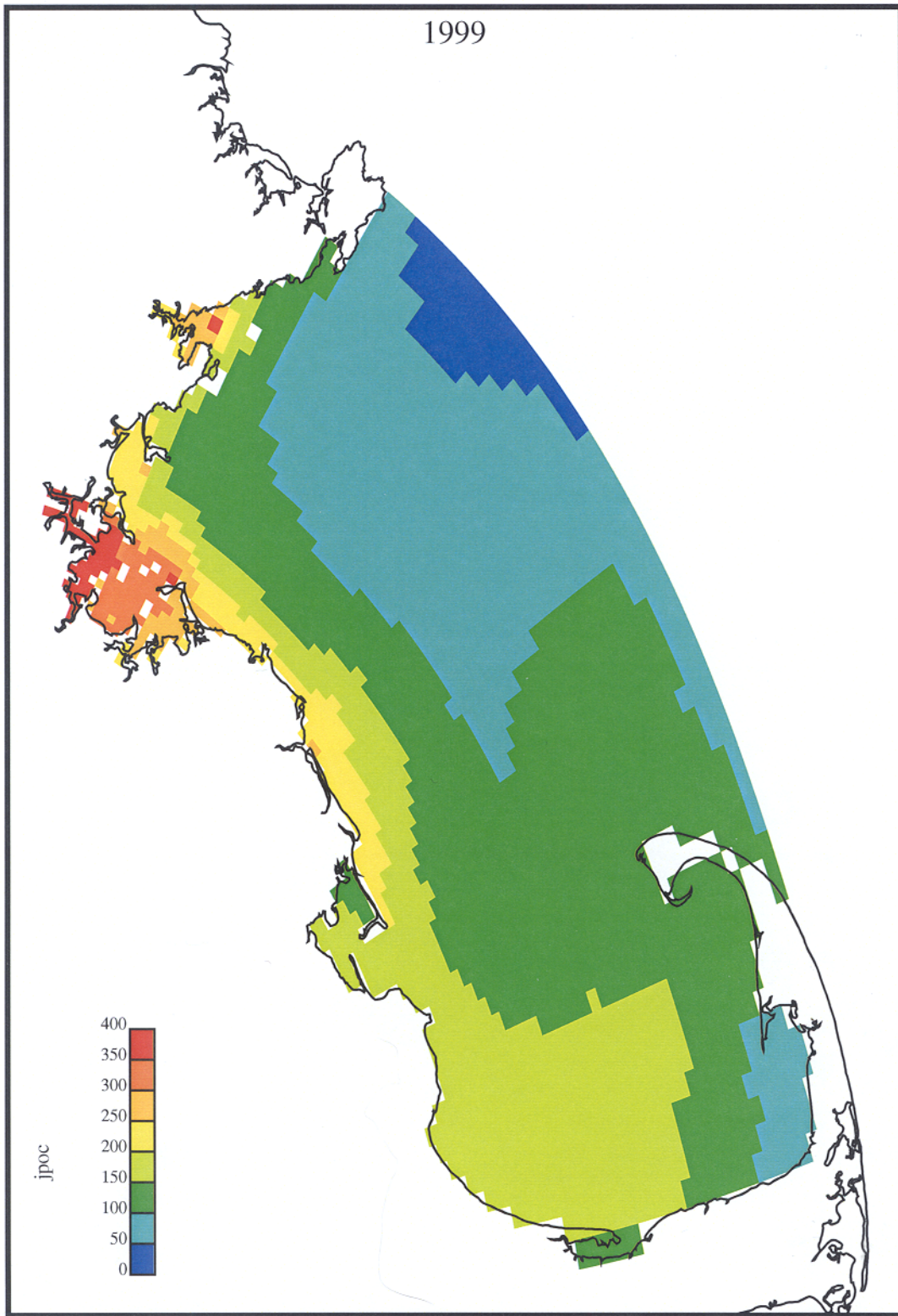


Figure 4-75. 1999 Computed Annual Average Carbon Depositional Flux ($\text{mg}/\text{m}^2\text{-d}$)

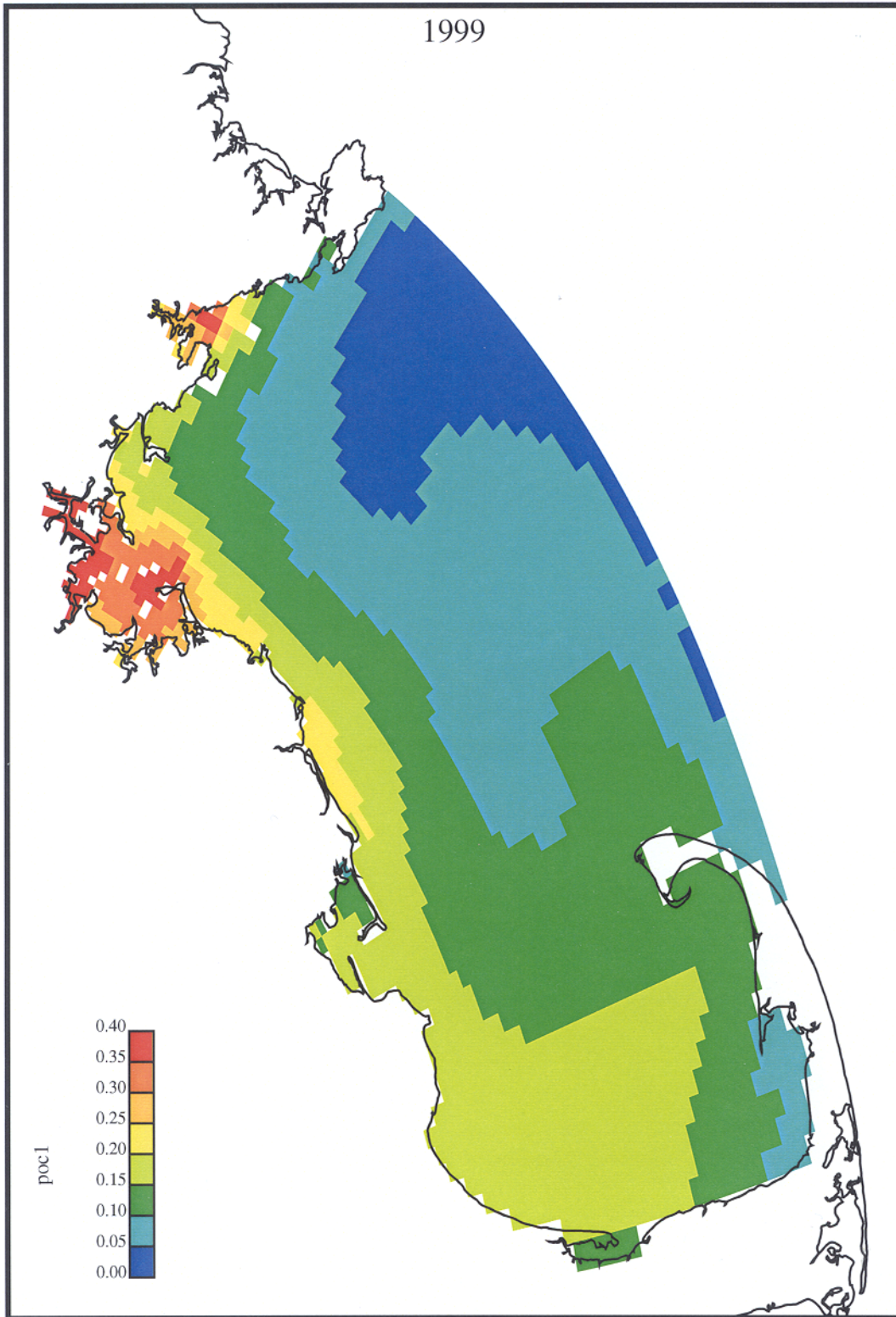


Figure 4-76. 1999 Computed Annual Average Sediment G1 Carbon (mg C/g sediment)

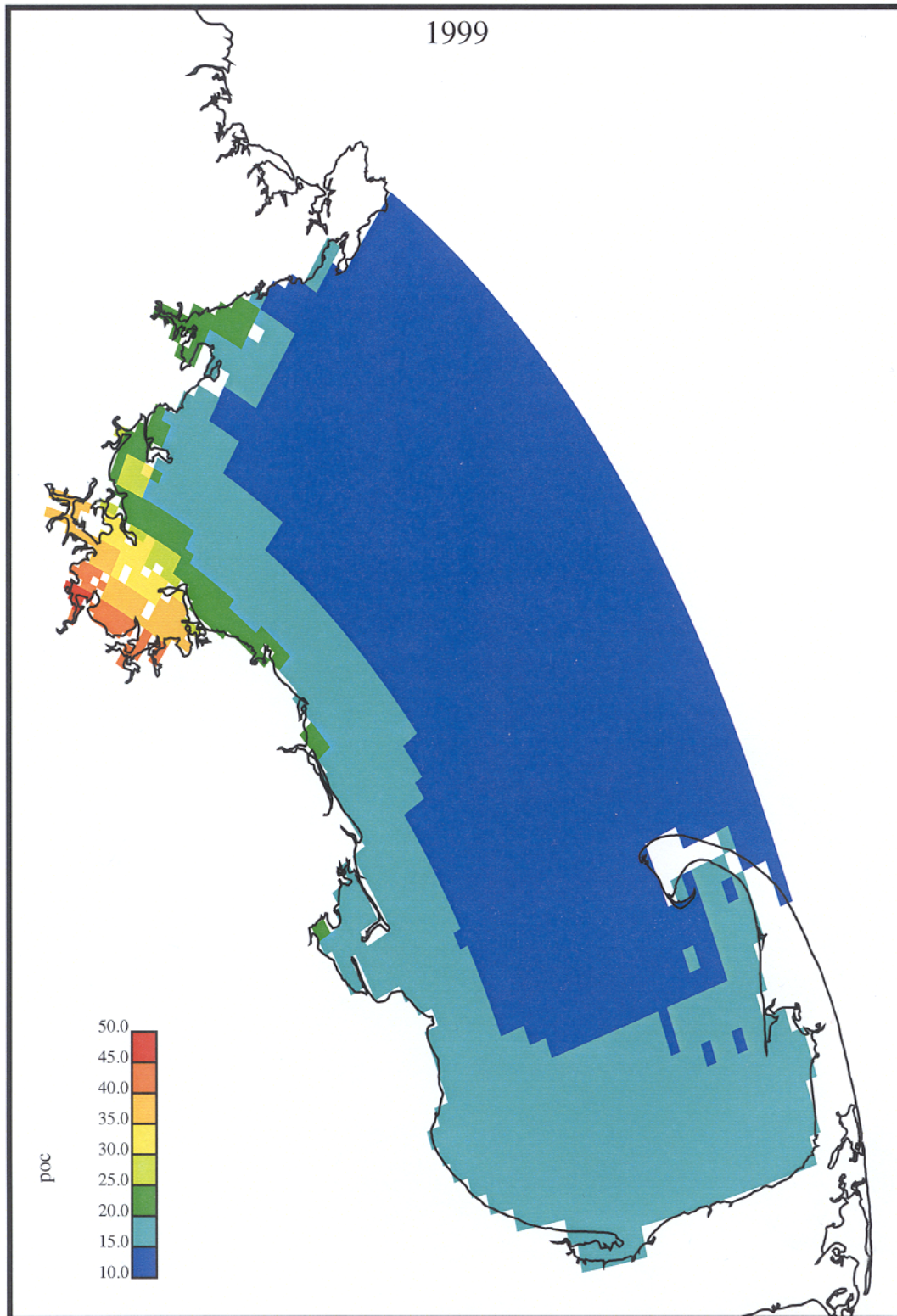
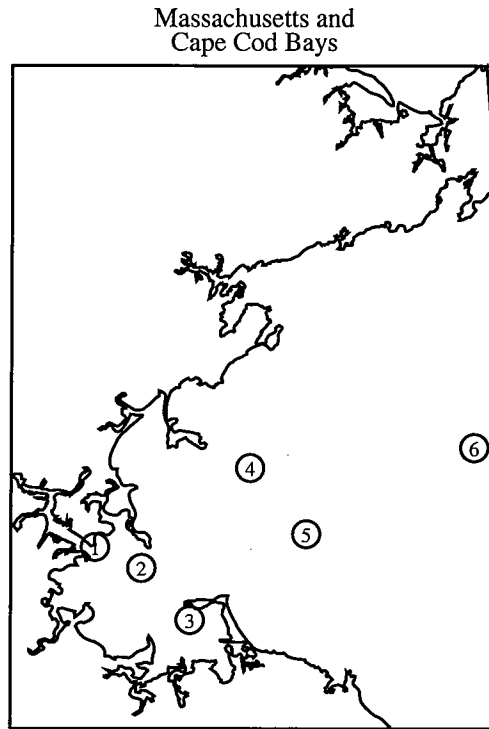
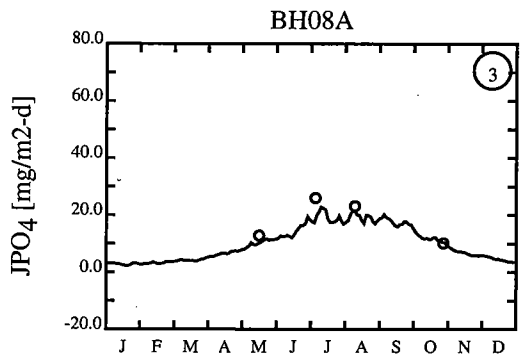
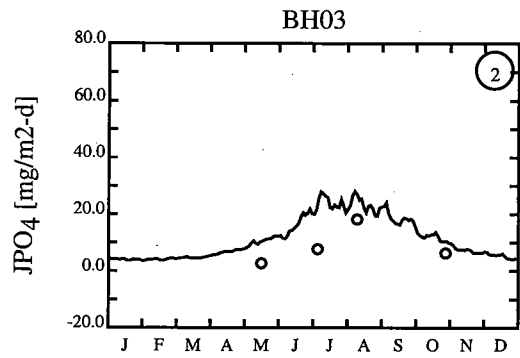
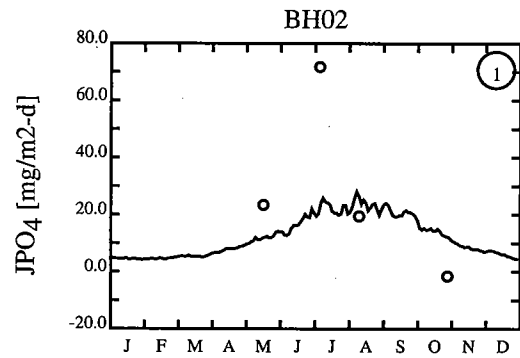


Figure 4-77. 1999 Computed Annual Average Sediment POC (mg/m²-d)



----- LEGEND -----
 ○ - JPO₄ Data
 — - Model Avg

1998

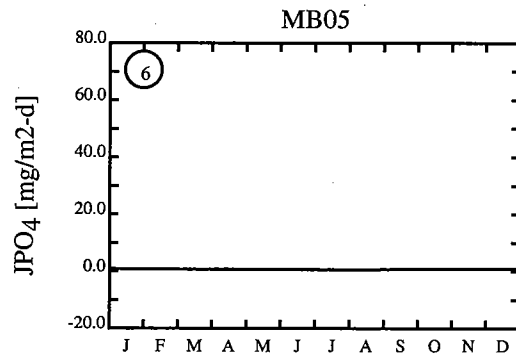
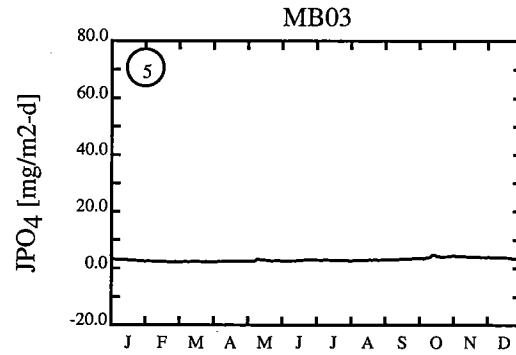
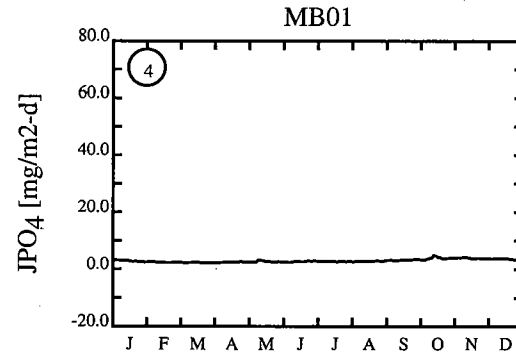


Figure 4-78. 1998 JPO₄ Model vs. Data Comparisons

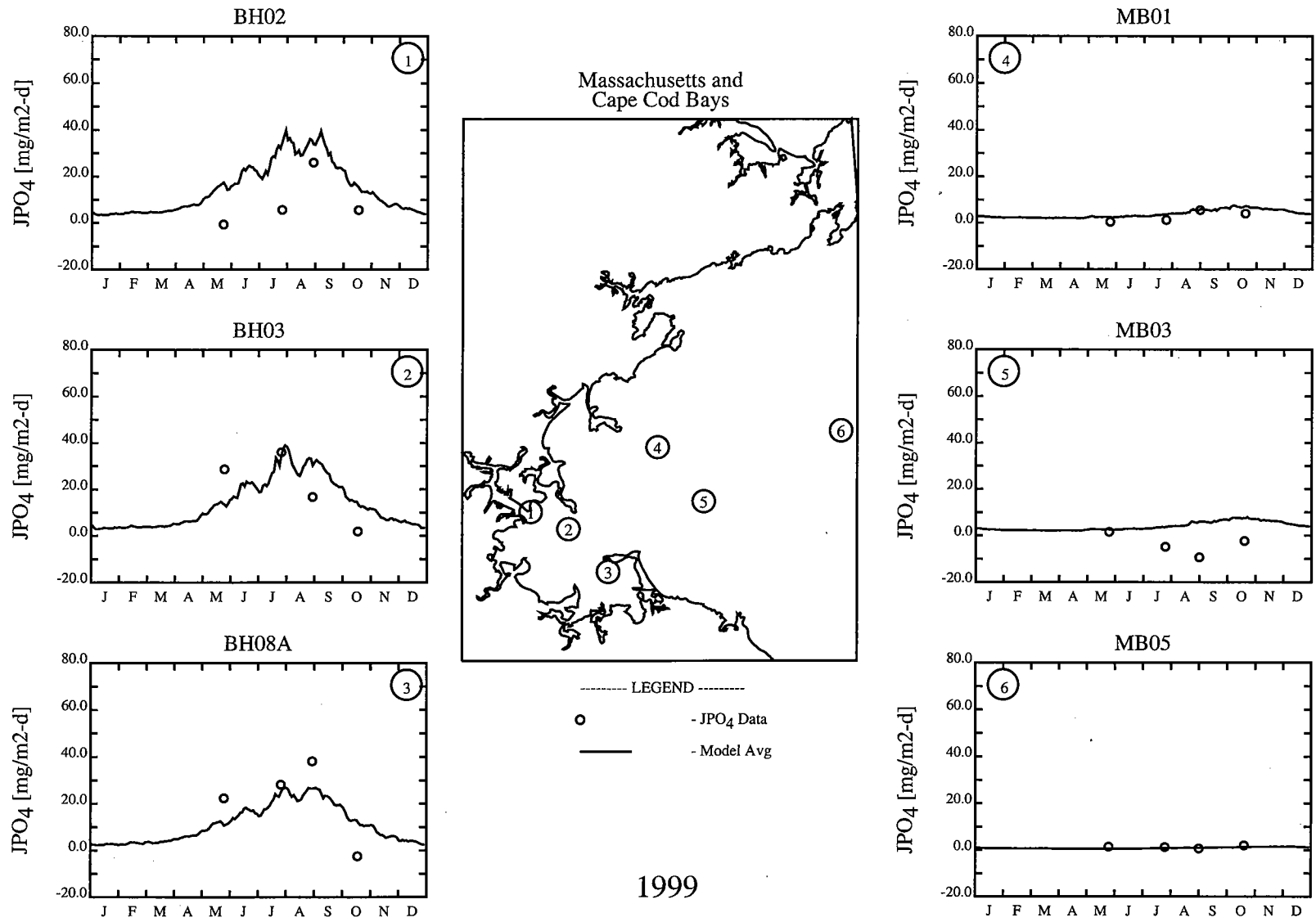


Figure 4-79. 1999 JPO₄ Model vs. Data Comparisons

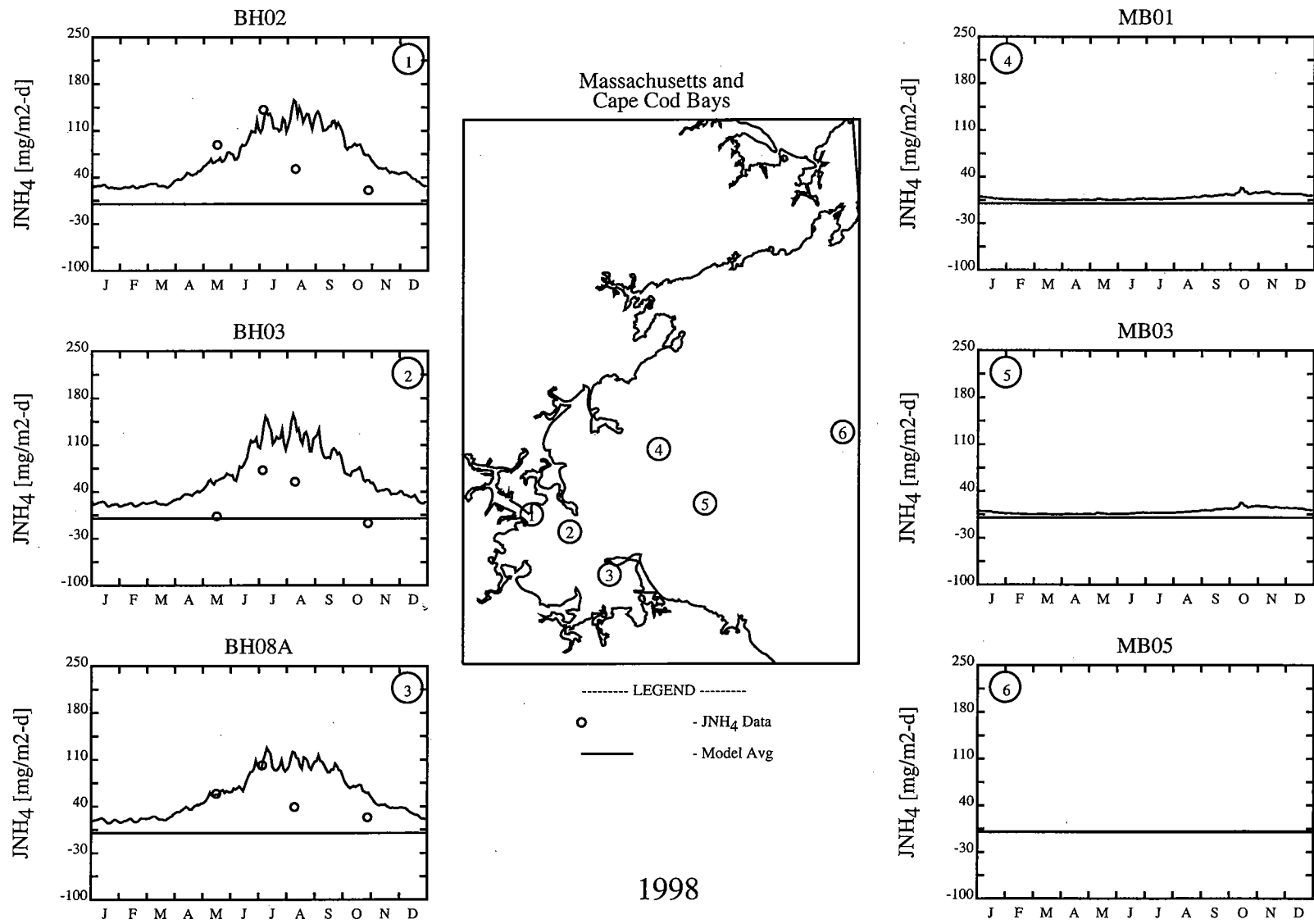


Figure 4-80. 1998 JNH₄ Model vs. Data Comparisons

The 1999 ammonia flux comparison is shown in Figure 4-81. The model computes higher JNH_4 in 1999 than in 1998. Since the measured ammonia fluxes in northern Boston Harbor during 1999 are not appreciably higher than the 1998 fluxes, the fluxes at stations BH02 and BH03 are over estimated. At stations BH08A, MB01, MB03 and MB05 the model does a good job reproducing the measured fluxes.

The 1998 model versus data comparison for the nitrate flux is presented in Figure 4-82. Both the model and data show fluxes out of the sediment during the May to October period. At stations BH02 and BH03 the model compares favorably with the data. The model under predicts the data at station BH08A. Very small nitrate fluxes are predicted at the MB stations. The 1999 comparison, as shown in Figure 4-83, is also quite favorable. The model is able to reproduce the spatial distribution of the nitrate fluxes. However, the fluxes at station BH08A are under predicted in both years.

The model does not compare very favorably to the limited denitrification flux data in 1998 (Figure 4-84). In general, the model under predicts the data. The model calculates higher denitrification fluxes at the MB stations. At the Boston Harbor (BH) stations, the model calculates a smaller denitrification rate during the warmer months than in the cooler months. Figure 4-85 shows that the model also under predicts the sparse data collected in 1999 for denitrification.

The silica flux comparison between the model and data for 1998 is presented in Figure 4-86. With the exception of a measurement in July at station BH02 and a measurement in October at station BH03, the model compares very favorably to the flux measurements taken at these two stations. The model under estimates the silica fluxes at station BH08A. Smaller JSi of 50-60 $\text{mg/m}^2\text{-d}$ are calculated at stations MB01 and MB03 than in Boston Harbor while the JSi at station MB05 is approximately 30 $\text{mg/m}^2\text{-d}$. The model estimates higher silica fluxes in 1999 (Figure 4-87), but tends to under predict the silica flux in general. The comparison to the data at station BH02 is favorable.

The model to data comparison for SOD in 1998, Figure 4-88, is similar to that for JNO_3 and JSi . The model compares favorably to the data at stations BH02 and BH03, but the SOD at station BH08A is under estimated. The SOD at station MB01 and MB03 is calculated to be considerably lower than at the BH stations and the SOD at station MB05 is approximately half of what is calculated at the other MB stations. In 1999 (Figure 4-89), both the model and data SOD are higher than for 1998. The model compares favorably to the data at station BH02. At the remaining stations the model under estimates the SOD. In general, the model reproduces the spatial differences in the SOD.

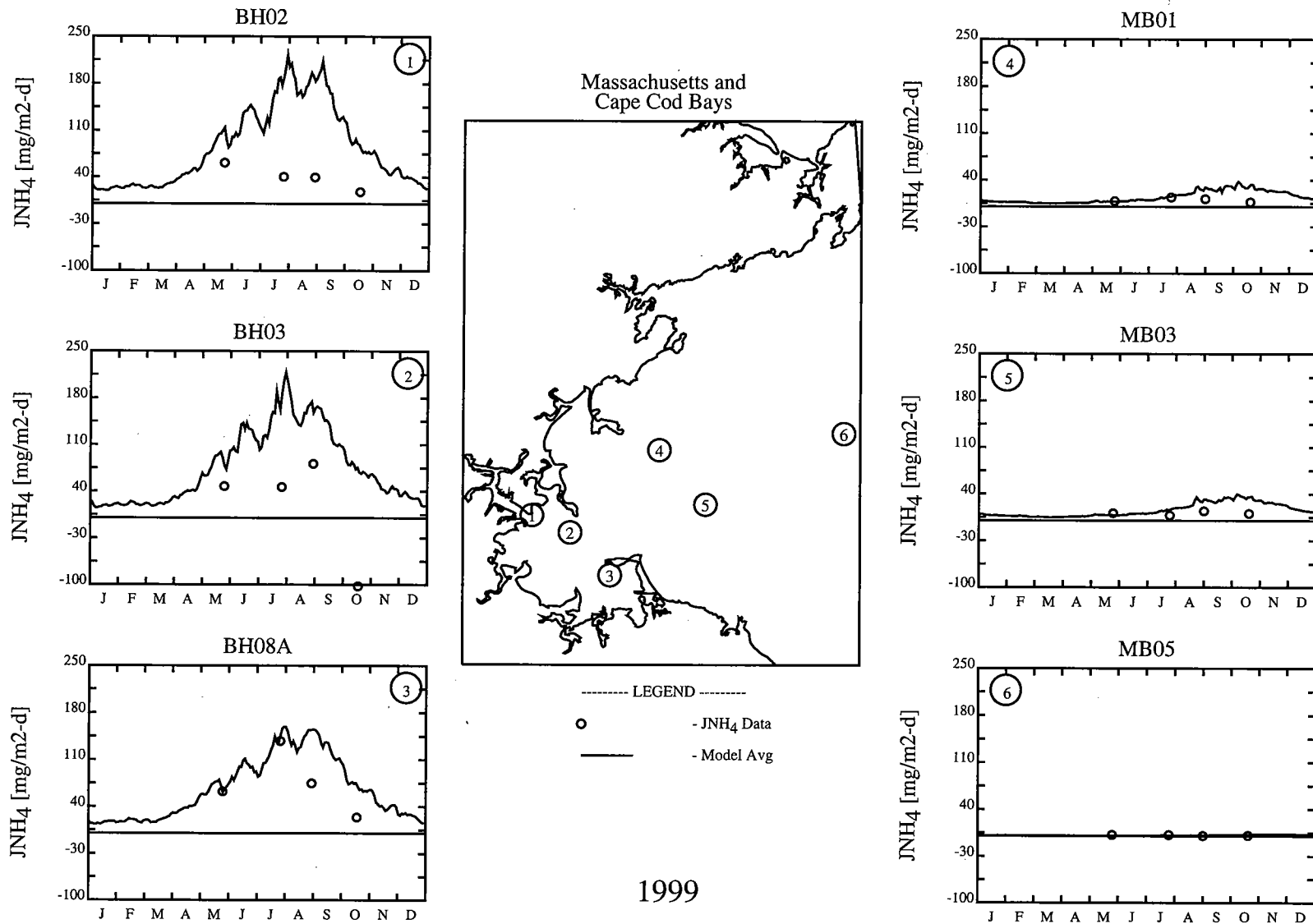


Figure 4-81. 1999 JNH₄ Model vs. Data Comparisons

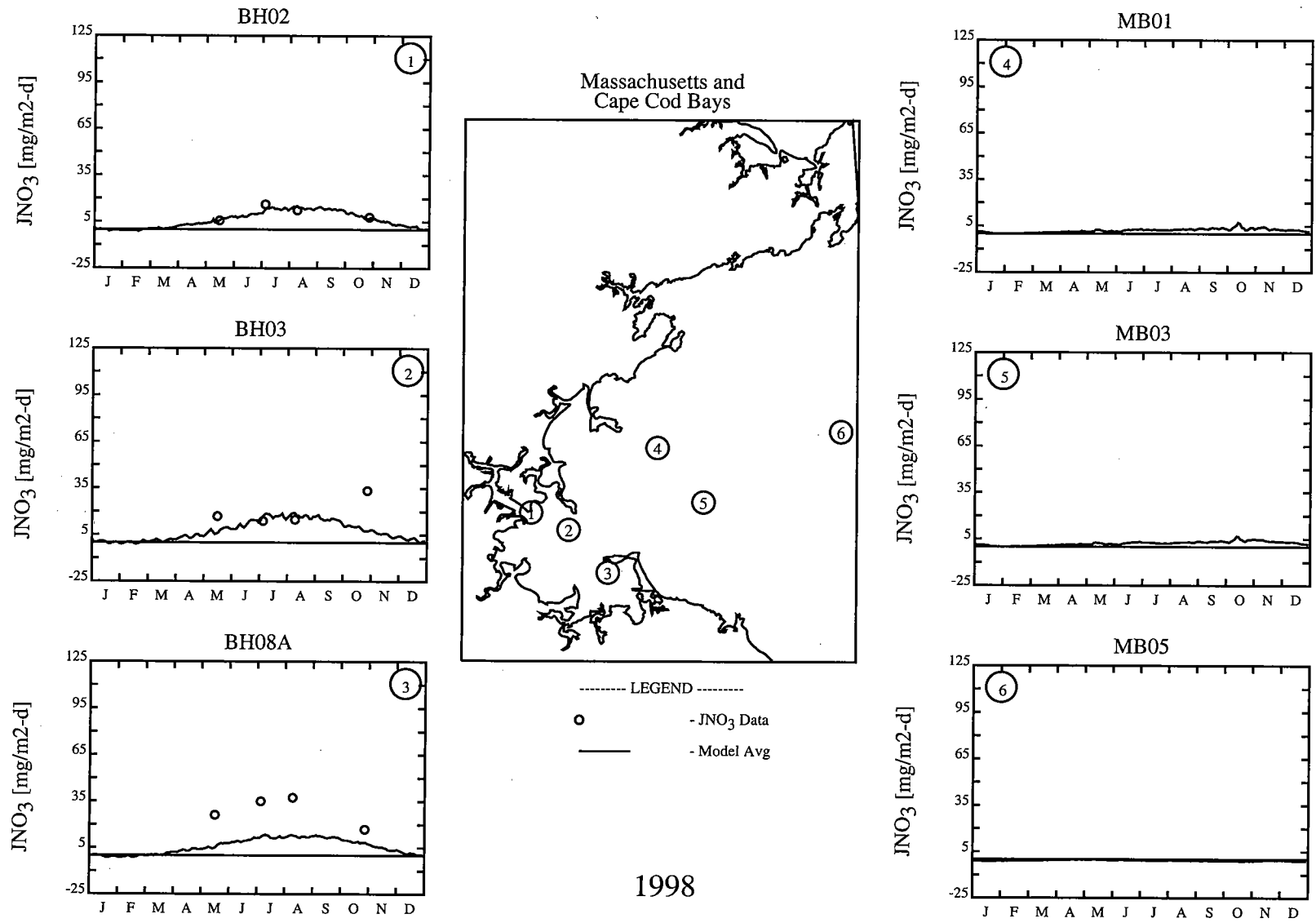


Figure 4-82. 1998 JNO₃ Model vs. Data Comparisons

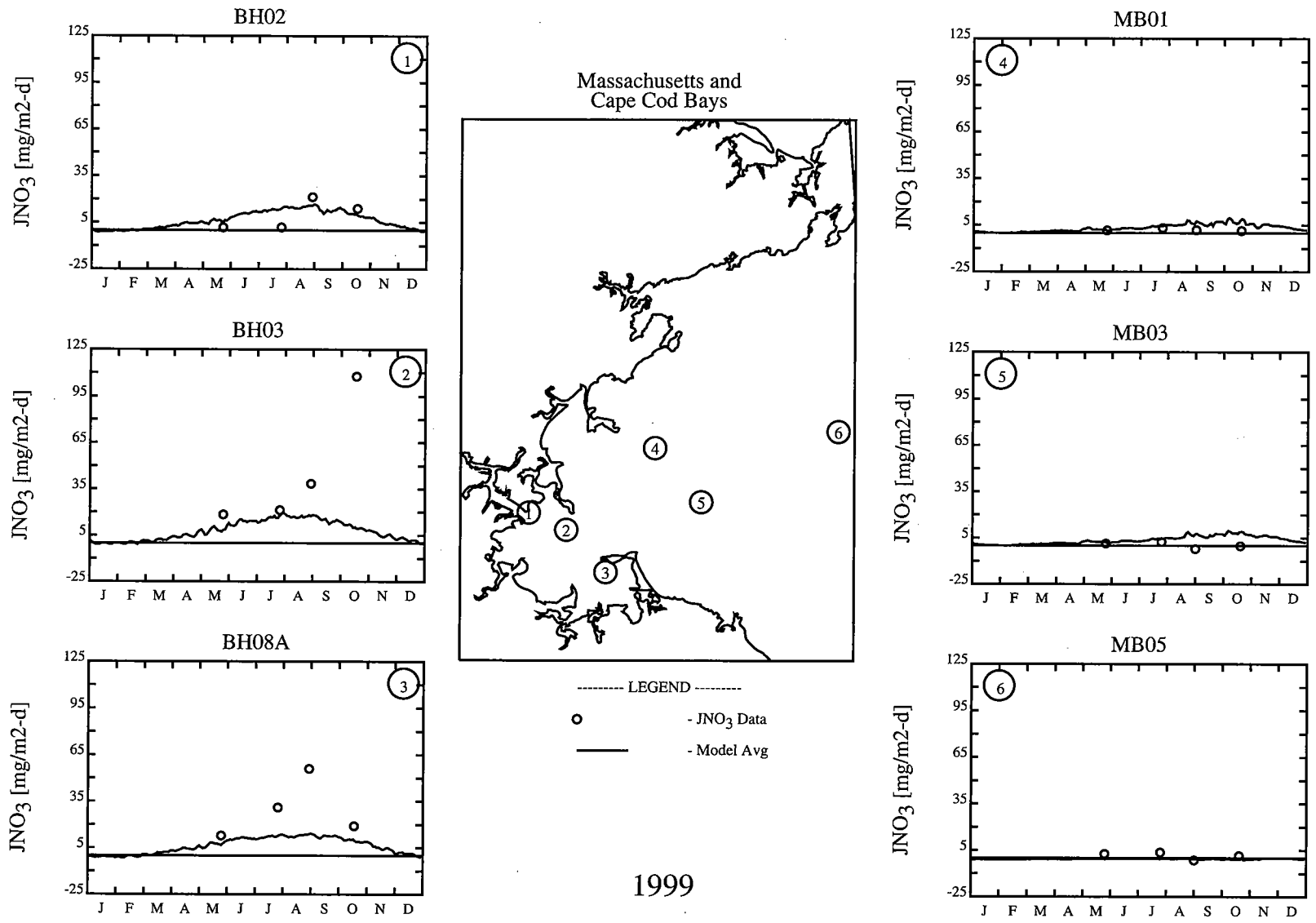


Figure 4-83. 1999 JNO₃ Model vs. Data Comparisons

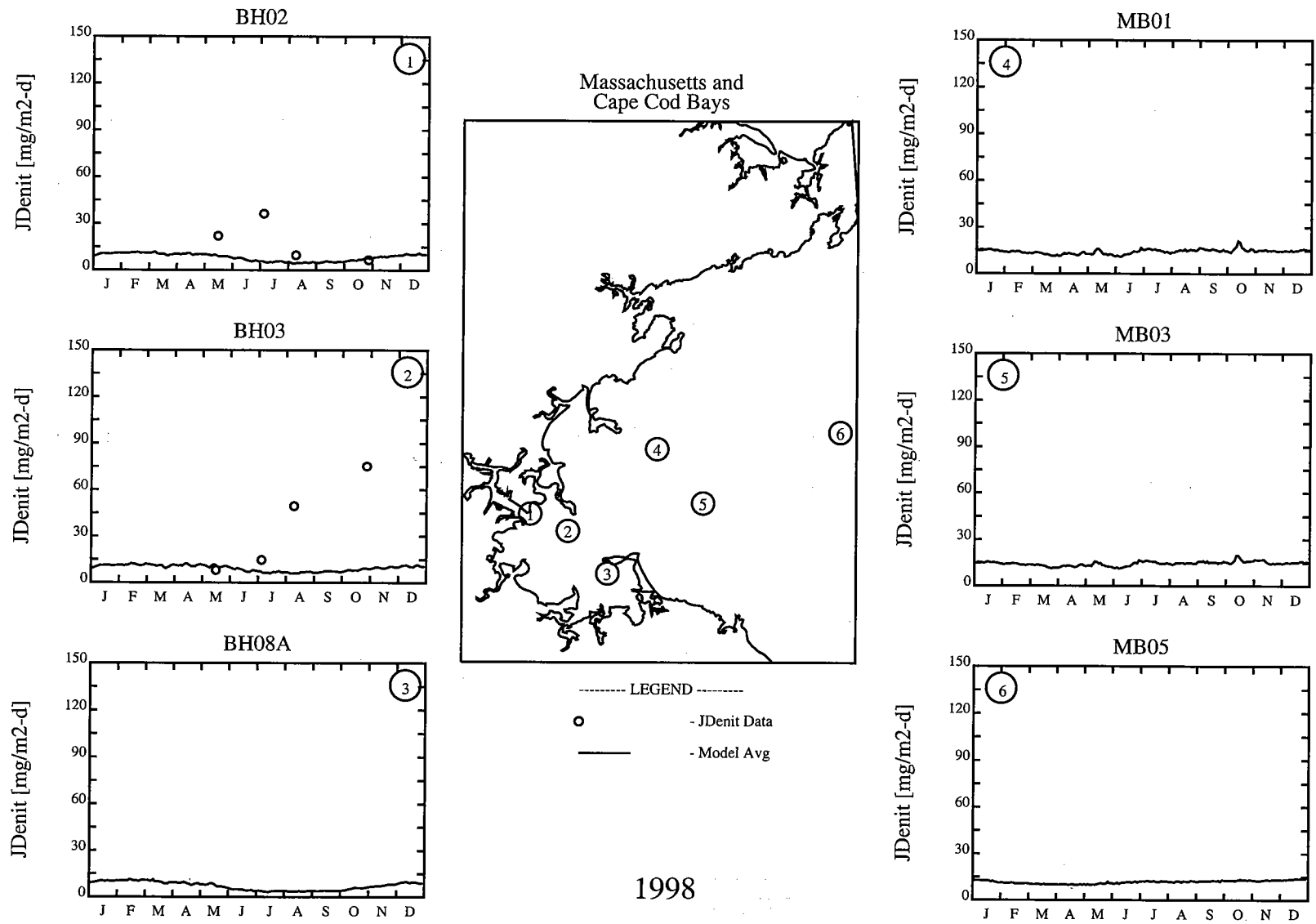


Figure 4-84. 1998 Denitrification Rate Model vs. Data Comparisons

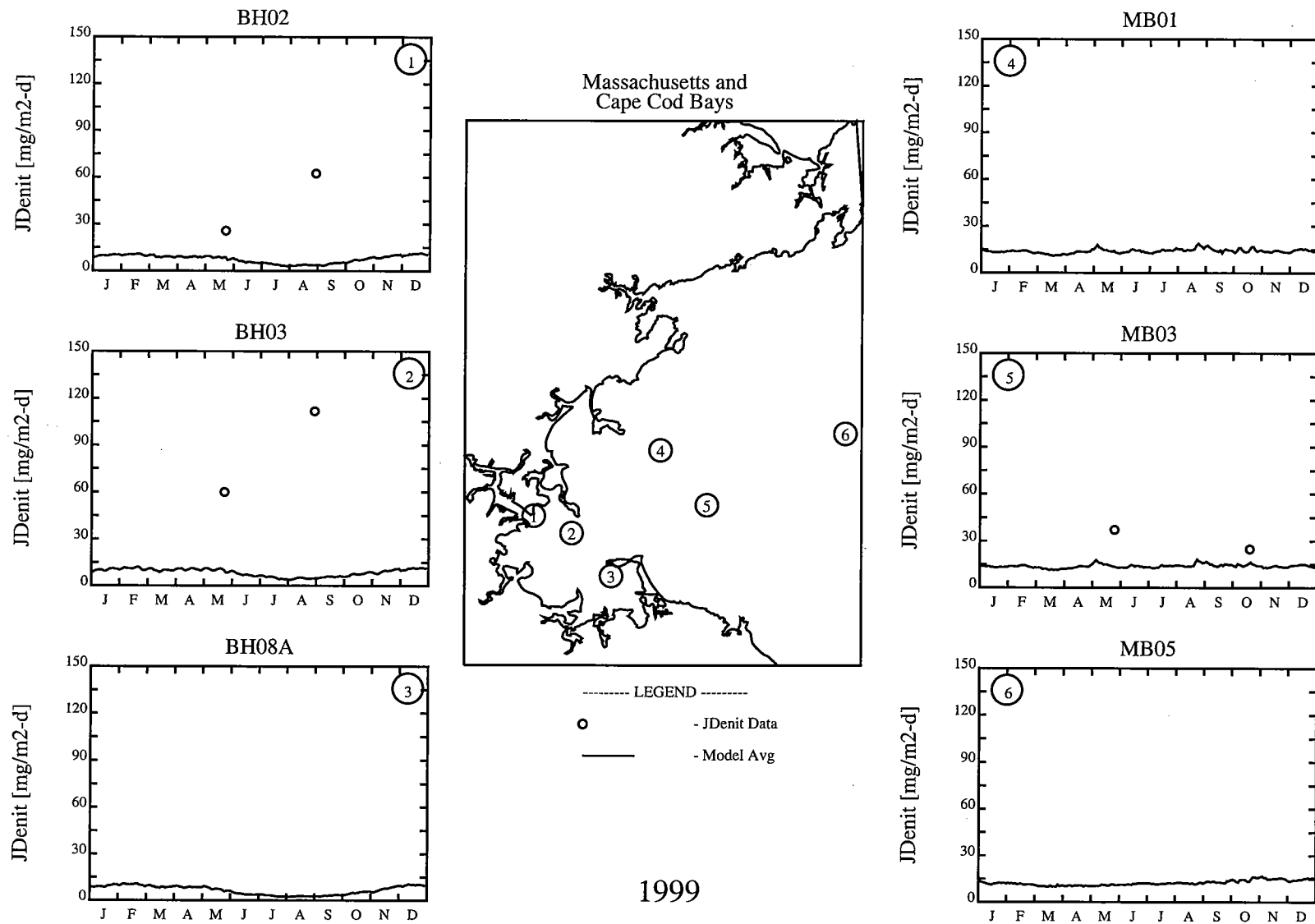


Figure 4-85. 1999 Denitrification Rate Model vs. Data Comparisons

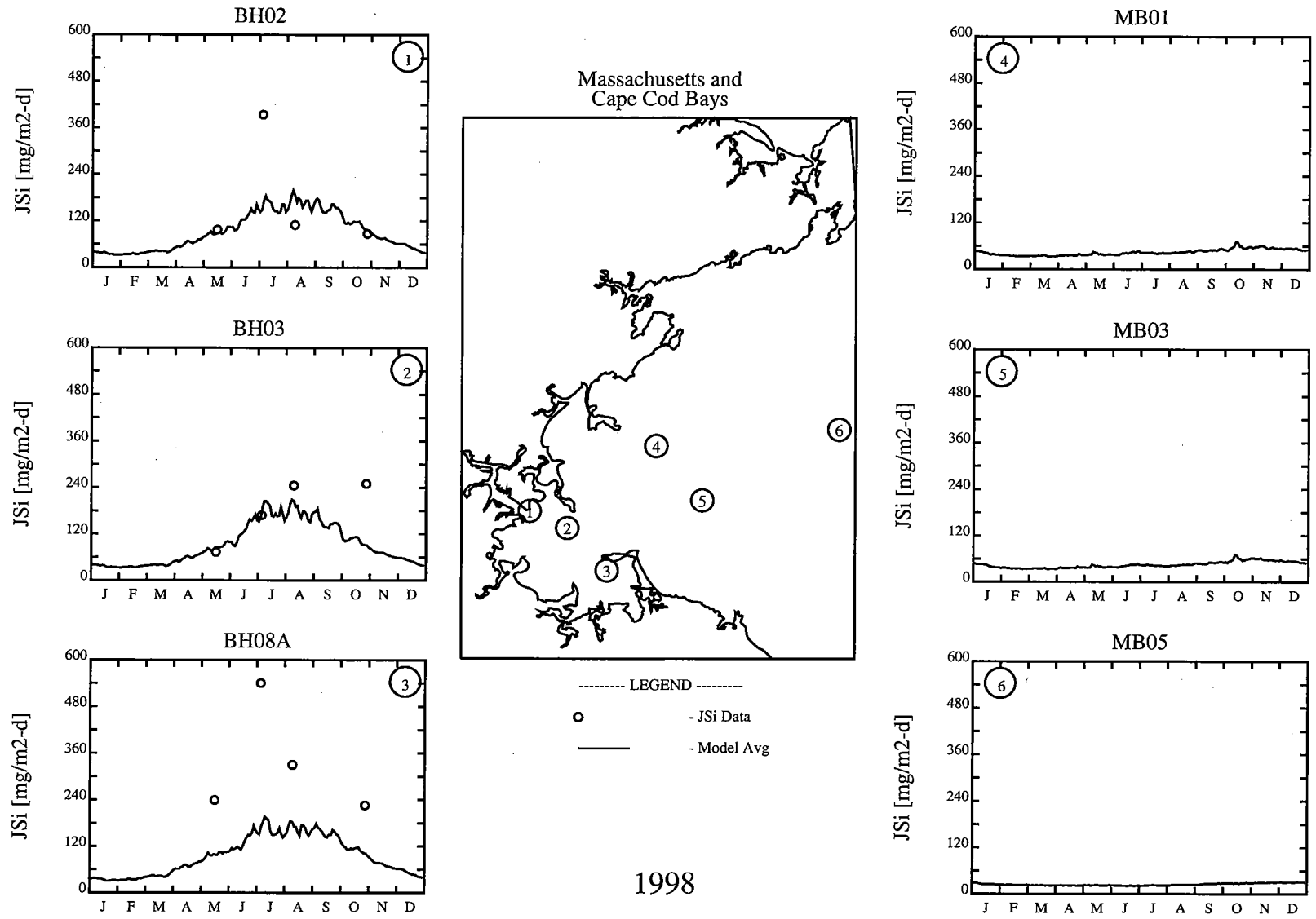


Figure 4-86. 1998 JSi Model vs. data Comparisons

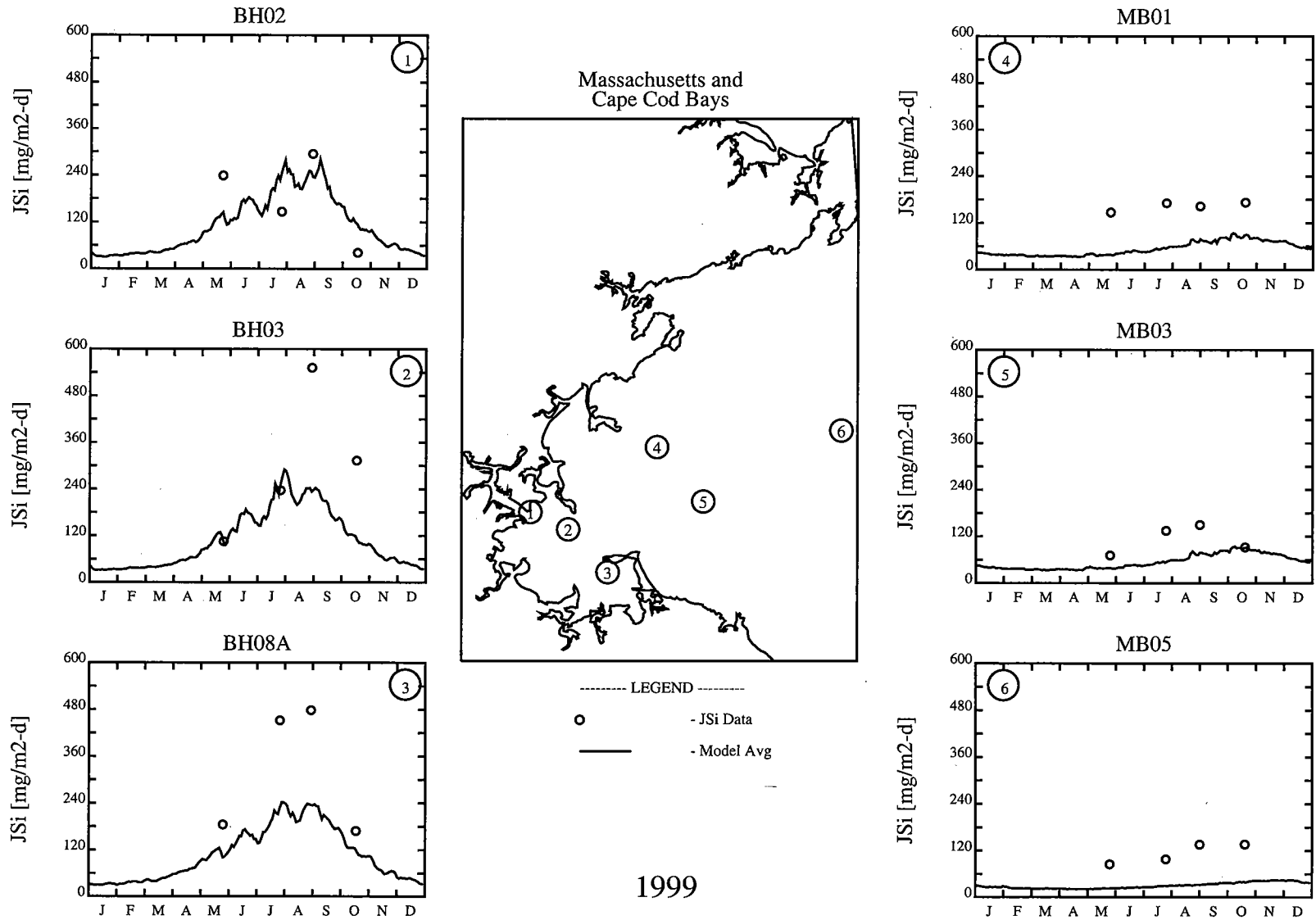


Figure 4-87. 1999 JSi Model vs. Data Comparisons

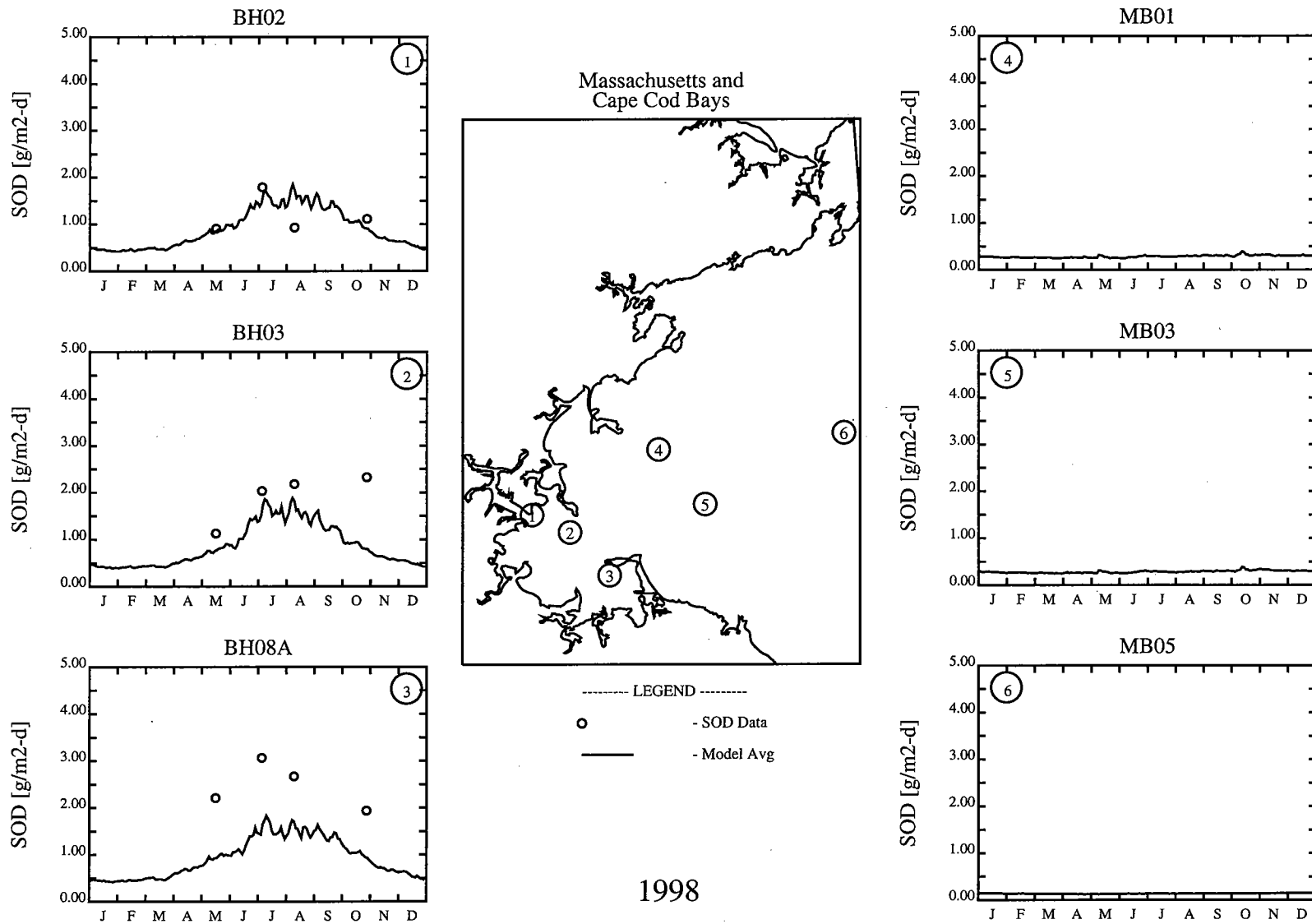


Figure 4-88. 1998 SOD Model vs. Data Comparisons

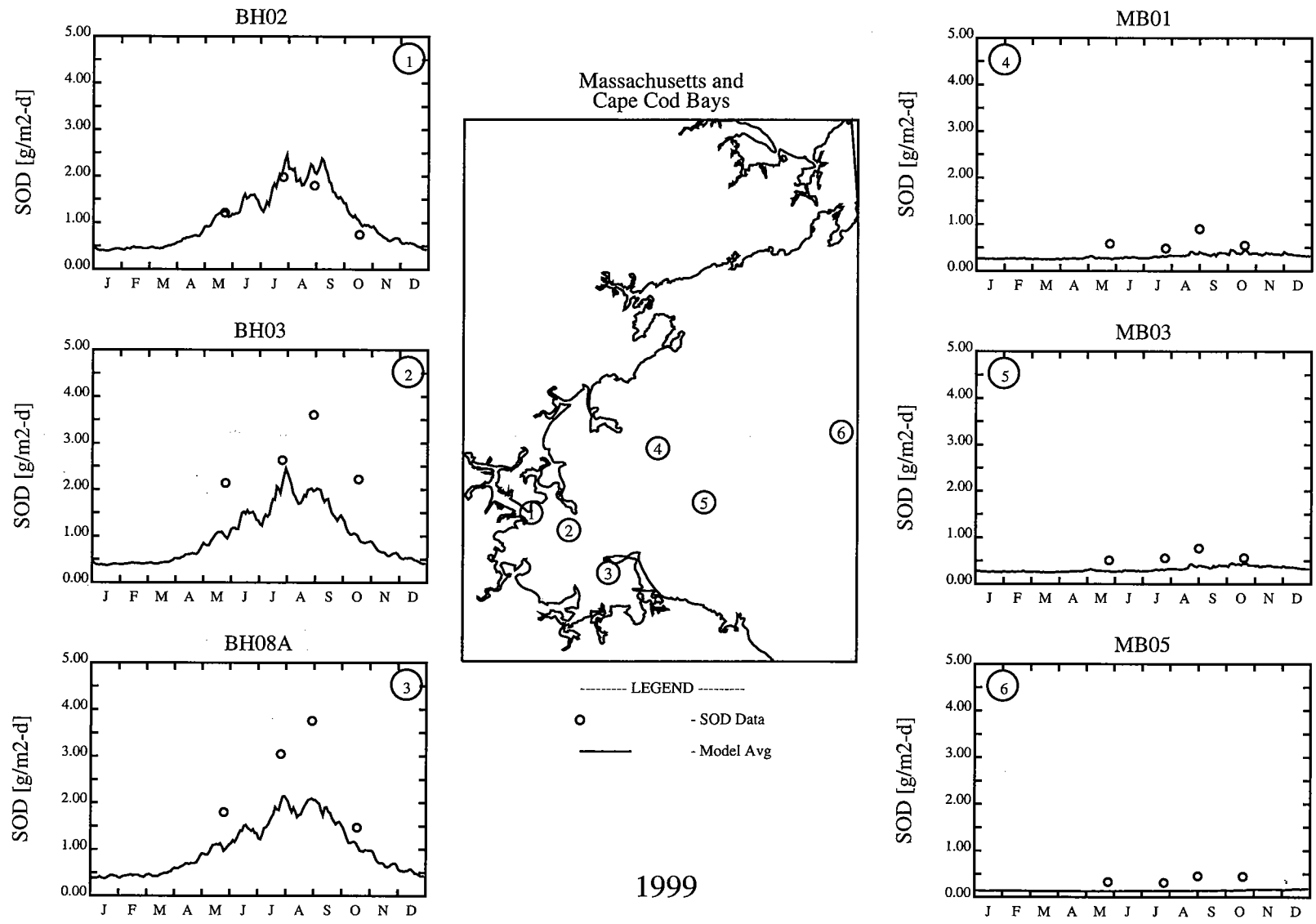


Figure 4-89. 1999 SOD Model vs. Data Comparisons

In general, the model compares favorably with the sediment flux data. It must be remembered that the sediment can be quite heterogeneous, so that measurements at a particular location may not be representative of the area in which the core was taken. It does appear from the data, however, that there is a difference between northern Boston Harbor and southern Boston Harbor. The model does not compute much of a difference between these two sections. This may indicate that the model allows too much mixing between the north and the south or the sites chosen for coring are simply in different depositional zones.

SECTION 5

MODEL COMPARISON WITH AN ADDITIONAL ALGAL GROUP

Based on the results of an earlier modeling analysis (HydroQual, 2001c) 1998 and 1999 were also run with a model containing a third algal group representing a fall diatom group. The addition of the third algal group produced similar changes to the model results in 1998 and 1999 although the data indicate that 1998 and 1999 were fairly different in terms of water quality. In the figures that follow, the calibration and third algal group results will be present with different line types. The third algal group model results will be presented as black lines. The calibration results will be displayed as gray lines, if the report is printed in black and white, or red lines if the report is printed in color.

Figures 5-1 and 5-2 present the chlorophyll results for the years 1998 and 1999, respectively. In 1998, small increases in the chlorophyll concentration over the calibration chlorophyll concentrations were computed in Boston Harbor and the near field stations. At stations F01 and F06, the chlorophyll concentrations are nearly twice that computed for the calibration during the fall. The result of the increased chlorophyll concentrations throughout Massachusetts and Cape Cod Bays is a poorer comparison to the 1998 data than the calibration. In 1999, the model responds in the same way as it did in 1998. However, due to the differences in the data between the two years, the changes to the 1999 calibration improve the model results' comparison to the data at stations N04, N07, F01, and F06.

While the addition of the third algal group noticeably changes the chlorophyll concentration results, the changes to the POC concentrations are smaller (Figures 5-3 and 5-4). Overall, the fall POC concentrations are slightly lower with the additional algal group. The differences are more noticeable in Boston Harbor and the near field despite the fact that the chlorophyll differences were larger in the southern portion of the bays.

The biogenic silica results for 1998 and 1999 (Figures 5-5 and 5-6, respectively) indicate a small increase in the fall due to an increase in the diatom biomass. The largest increases were computed in the southern portion of the bays. These changes in the BSi concentrations do not improve the model's comparison to the data.

Figures 5-7 through 5-10 present the comparison results for the calibration and third algal group for DIP and DIN in 1998 and 1999. Since the changes to POC were small and the third algal

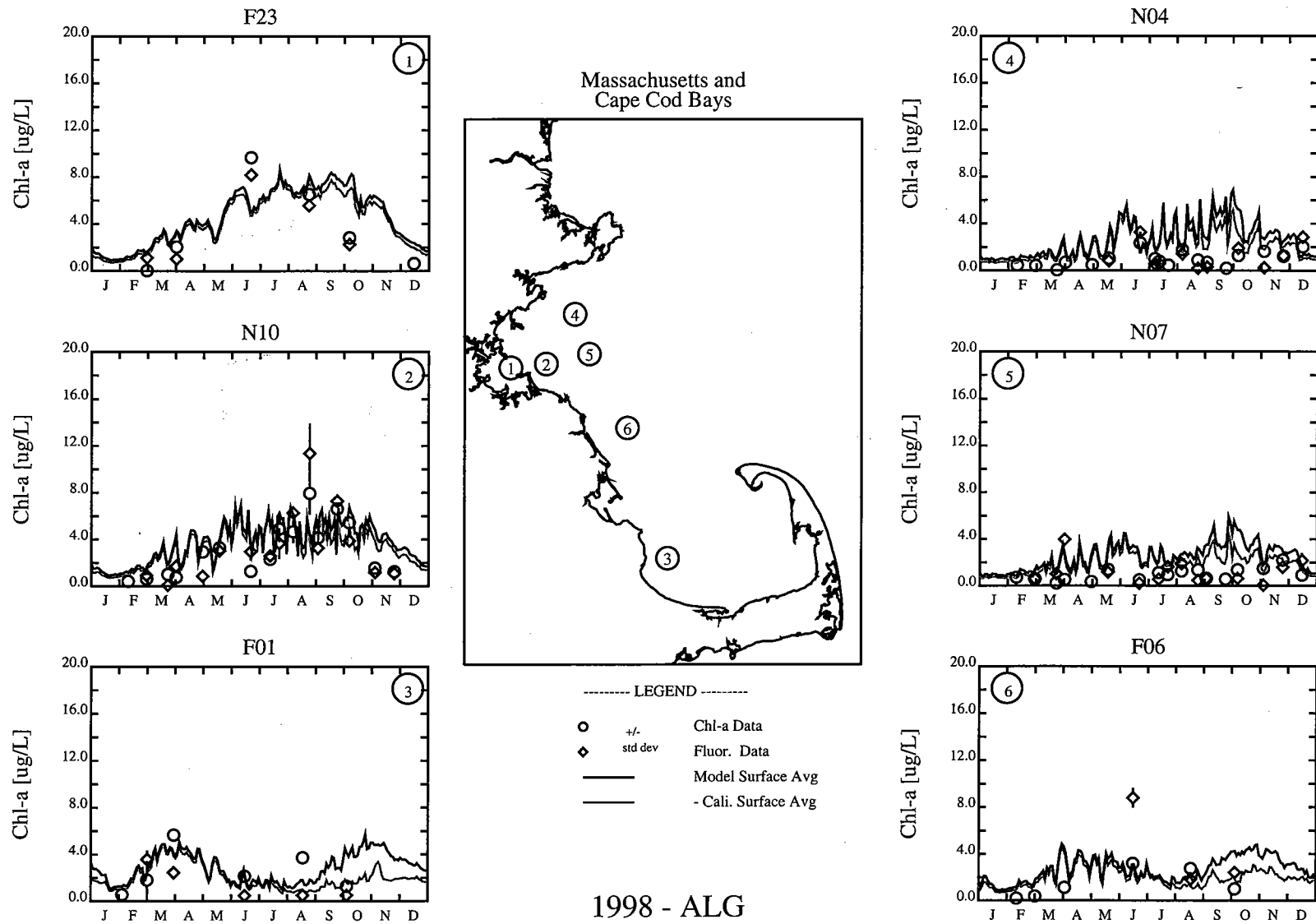


Figure 5-1. 1998 Three Algal Group Model vs. Surface Chlorophyll Data

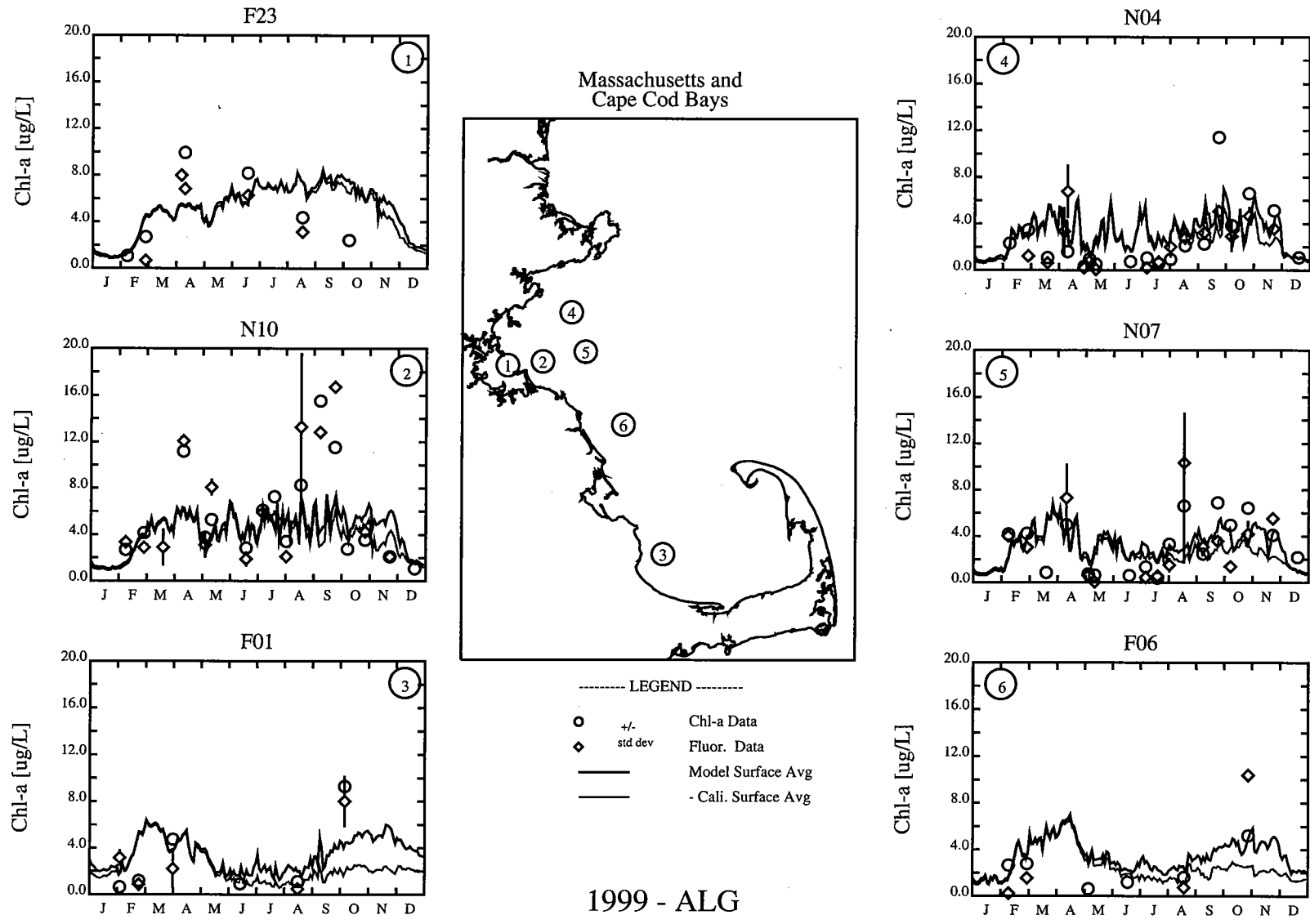


Figure 5-2. 1999 Three Algal Group Model vs. Surface Chlorophyll Data

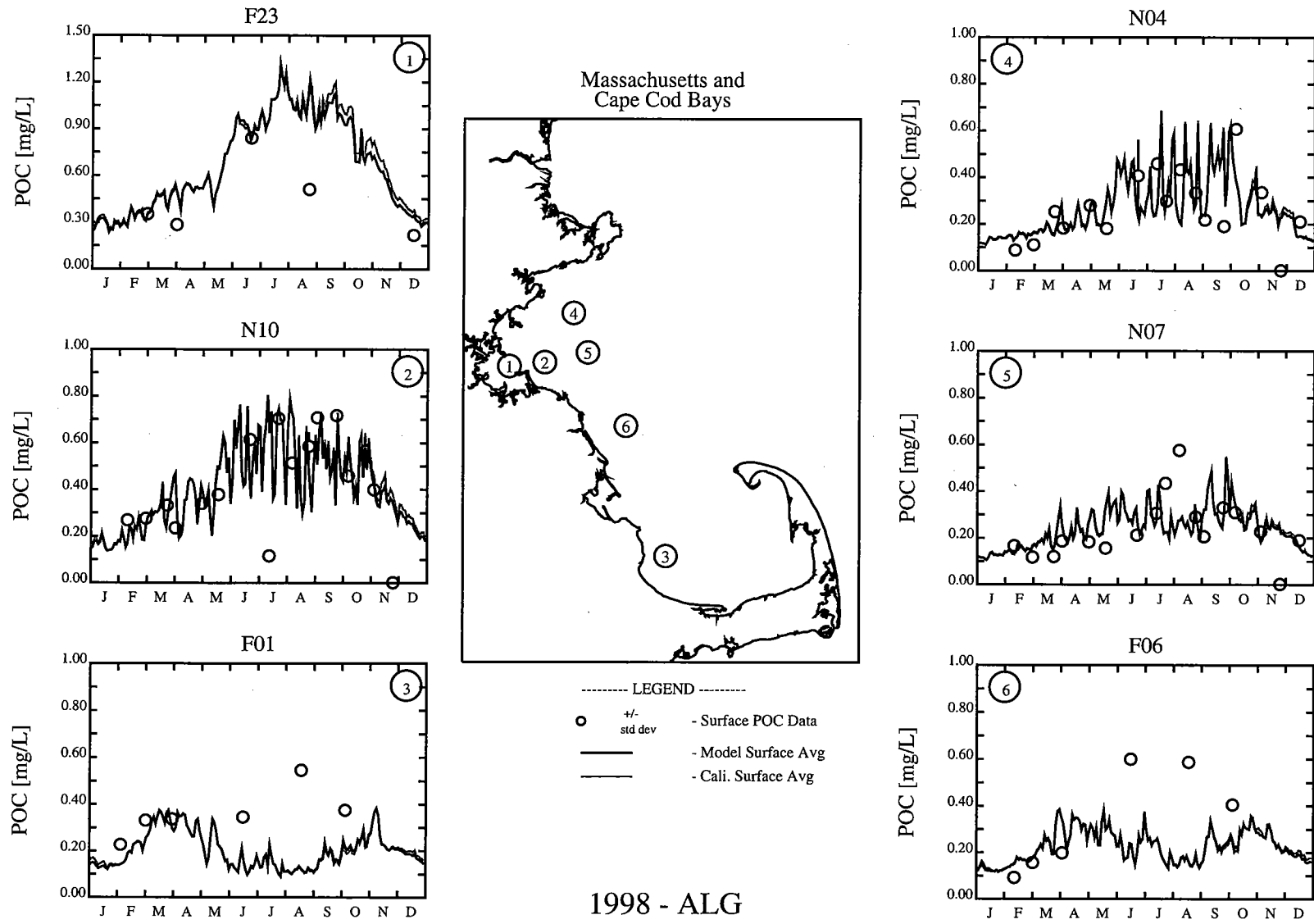


Figure 5-3. 1998 Three Algal Group Model vs. Surface POC Data

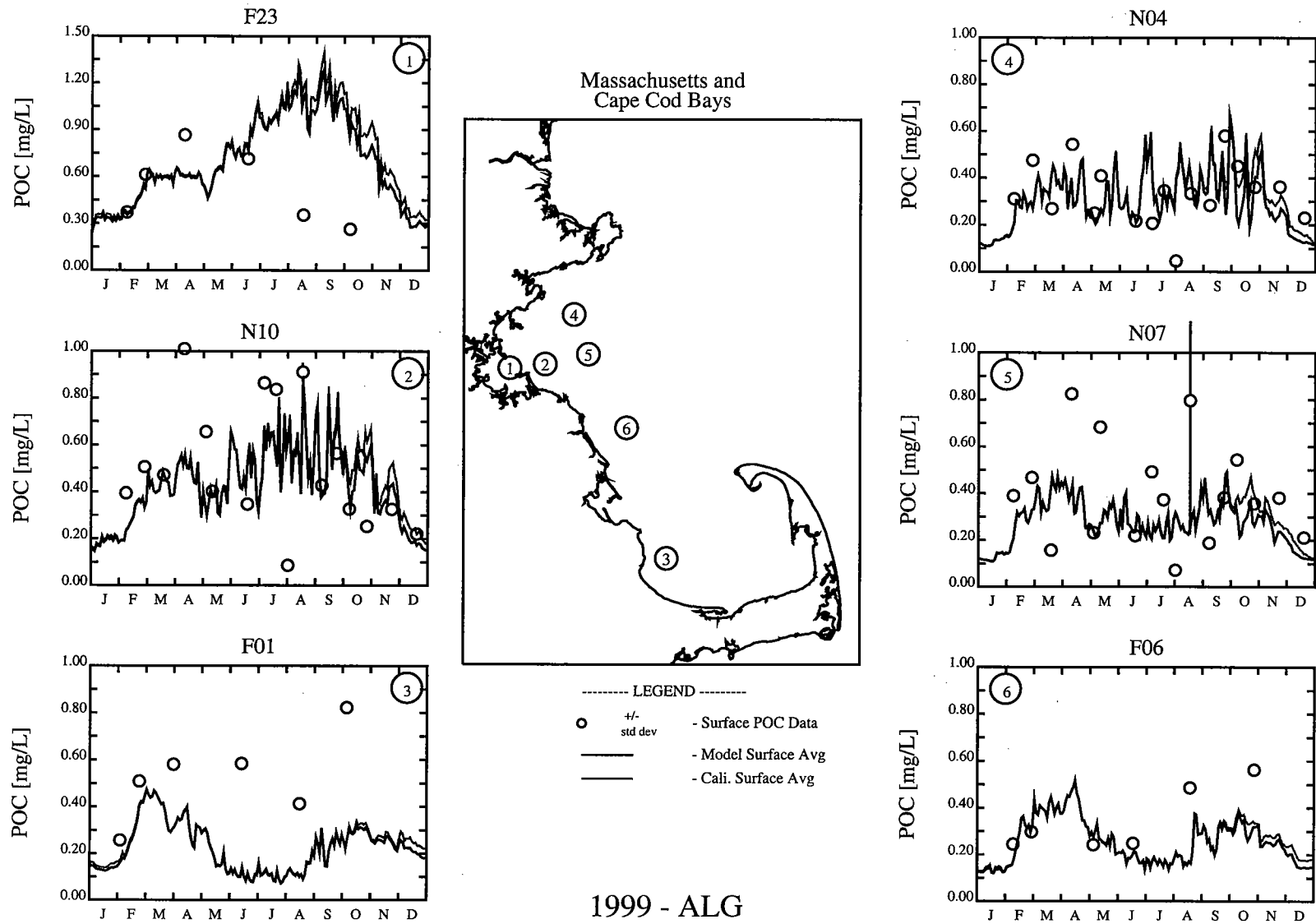


Figure 5-4. 1999 Three Algal Group Model vs. Surface POC Data

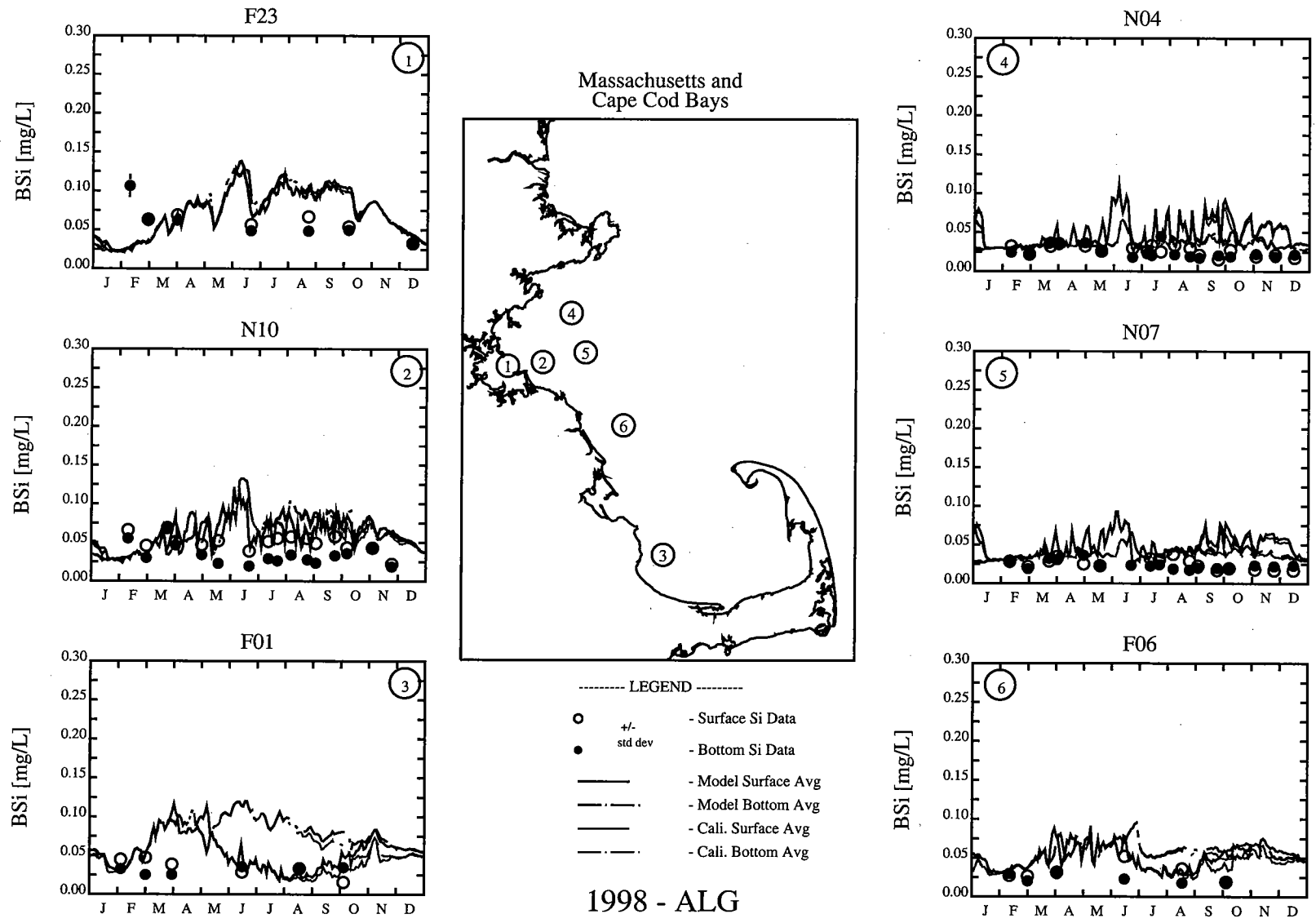


Figure 5-5. 1998 Three Algal Group Model vs. Surface and Bottom BSi Data

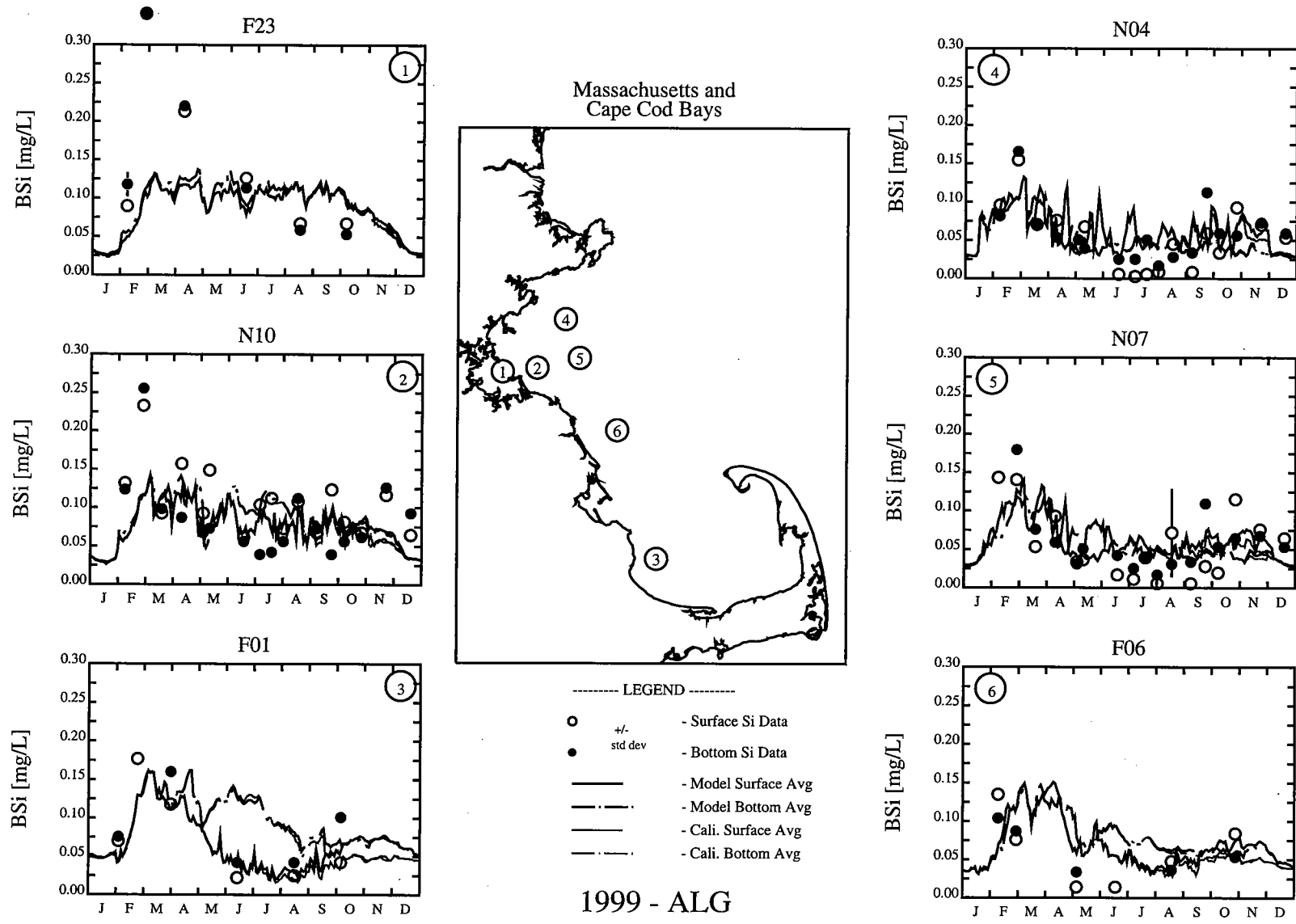


Figure 5-6. 1999 Three Algal Group Model vs. Surface and Bottom BSi Data

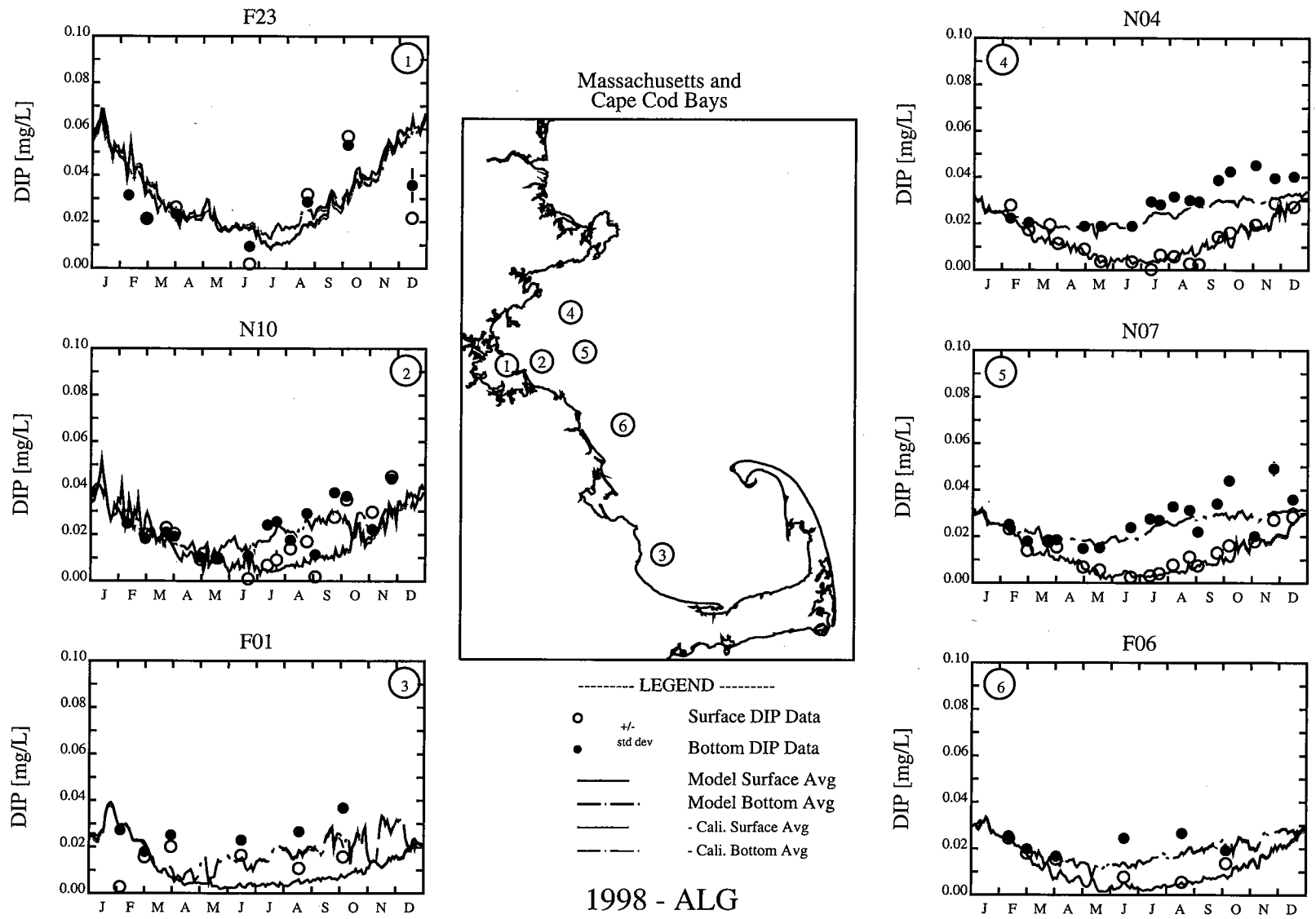


Figure 5-7. 1998 Three Algal Group Model vs. Surface and Bottom DIP Data

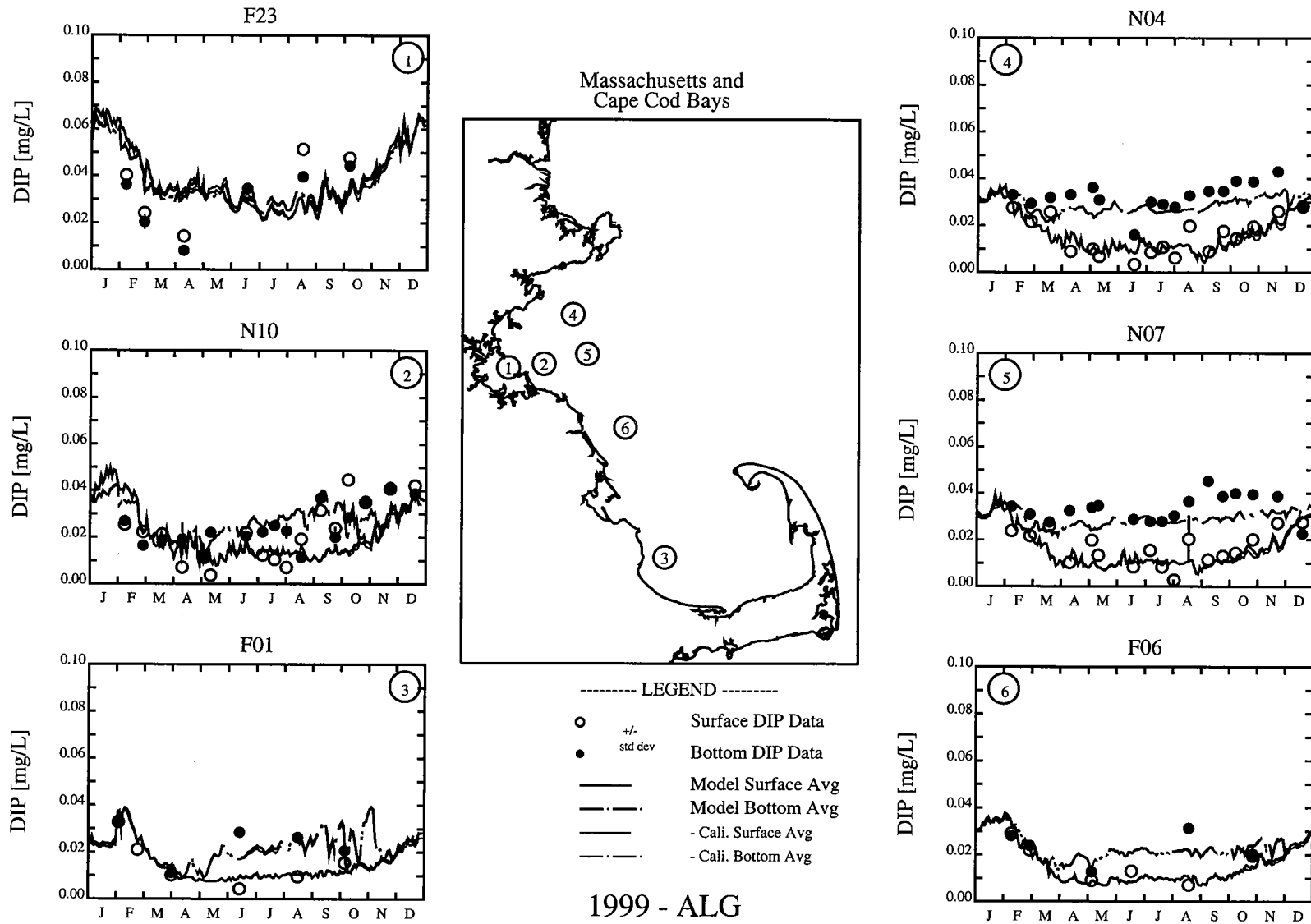


Figure 5-8. 1999 Three Algal Group Model vs. Surface and Bottom DIP Data

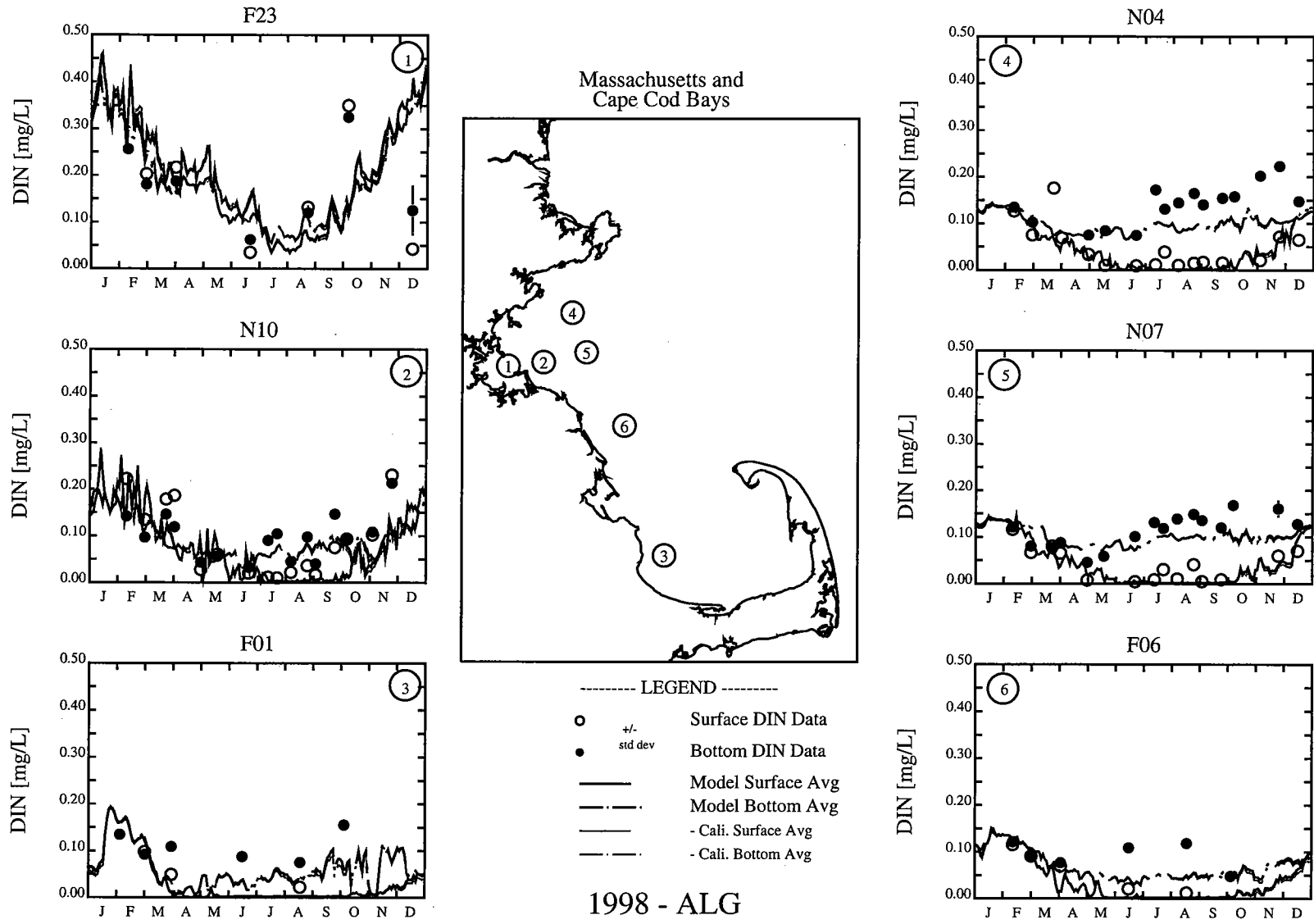


Figure 5-9. 1998 Three Algal Group Model vs. Surface and Bottom DIN Data

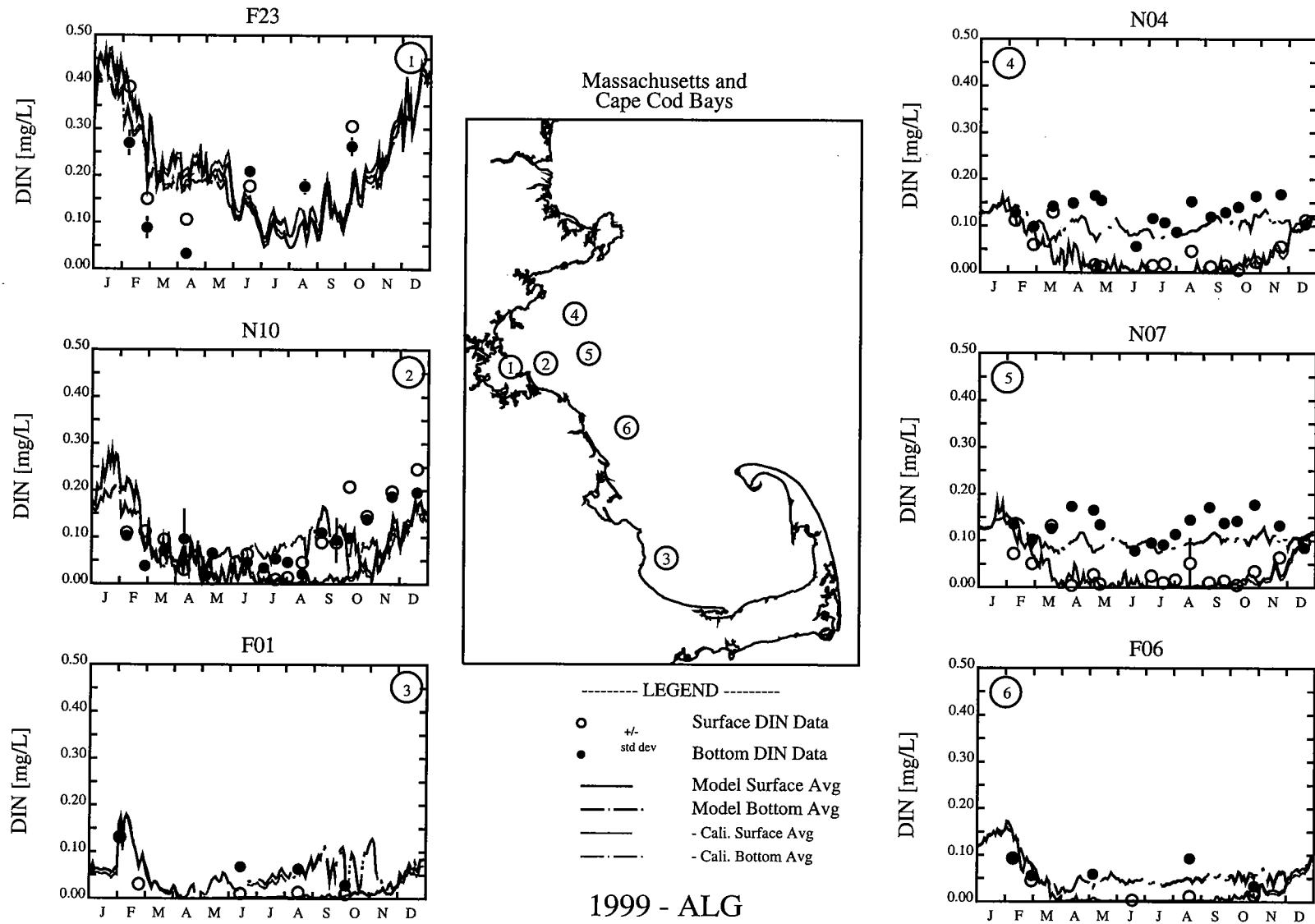


Figure 5-10. 1999 Three Algal Group Model vs. Surface and Bottom DIN Data

group has the same C:N and C:P ratios as the summer group, the effect of adding a third algal group on the DIP and DIN concentrations is small. The overall comparison between the model and data is very similar for the two runs for both DIP and DIN.

The summer assemblage and the third algal group (a fall diatom group) do not have the same C:Si ratio, so the change in dominance from the summer assemblage to the fall diatom group in the third algal group run did have an impact on the dissolved silica model results. With the exception of stations F23 and N10, the model's surface results compare more favorably to the data with the fall diatom group than without it for 1998 (Figure 5-11). The calibration results at the surface tended to be high during the fall and by adding the third algal group the surface concentrations were decreased. Figure 5-12 shows that the addition of the third algal group has mixed results for 1999. The results for the third algal group are less favorable at stations F23, N10 and F01. At the remaining stations it is unclear whether or not the model compares more favorably to the data.

Ultimately, the effect that the addition of the third algal group has on dissolved oxygen is small for both years as shown in Figures 5-13 and 5-14, respectively. The small change in algal biomass did little to change the DO concentrations due to changes in photosynthesis, respiration and biological oxidation of detrital biomass.

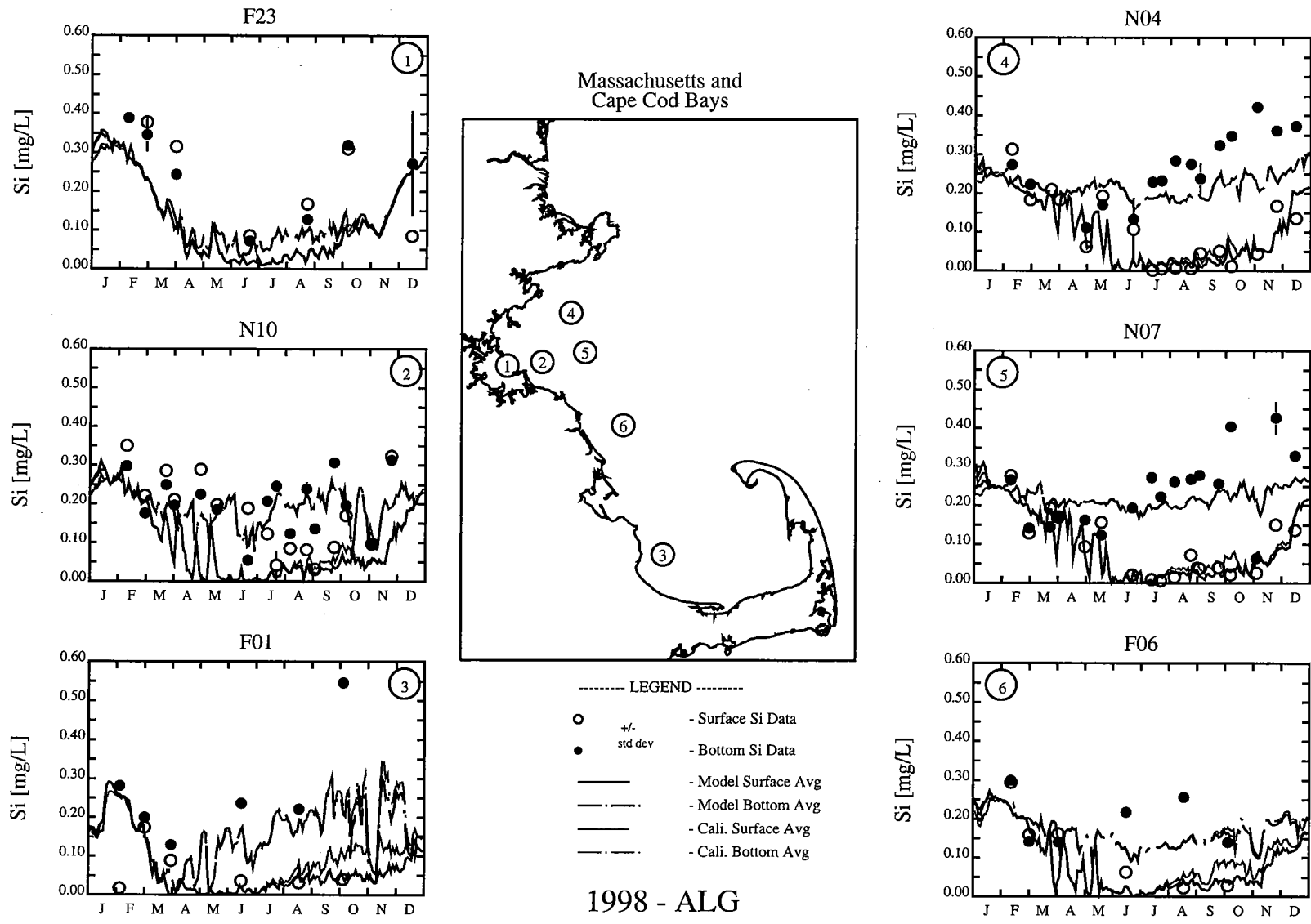


Figure 5-11. 1998 Three Algal Group Model vs. Surface and Bottom Si Data

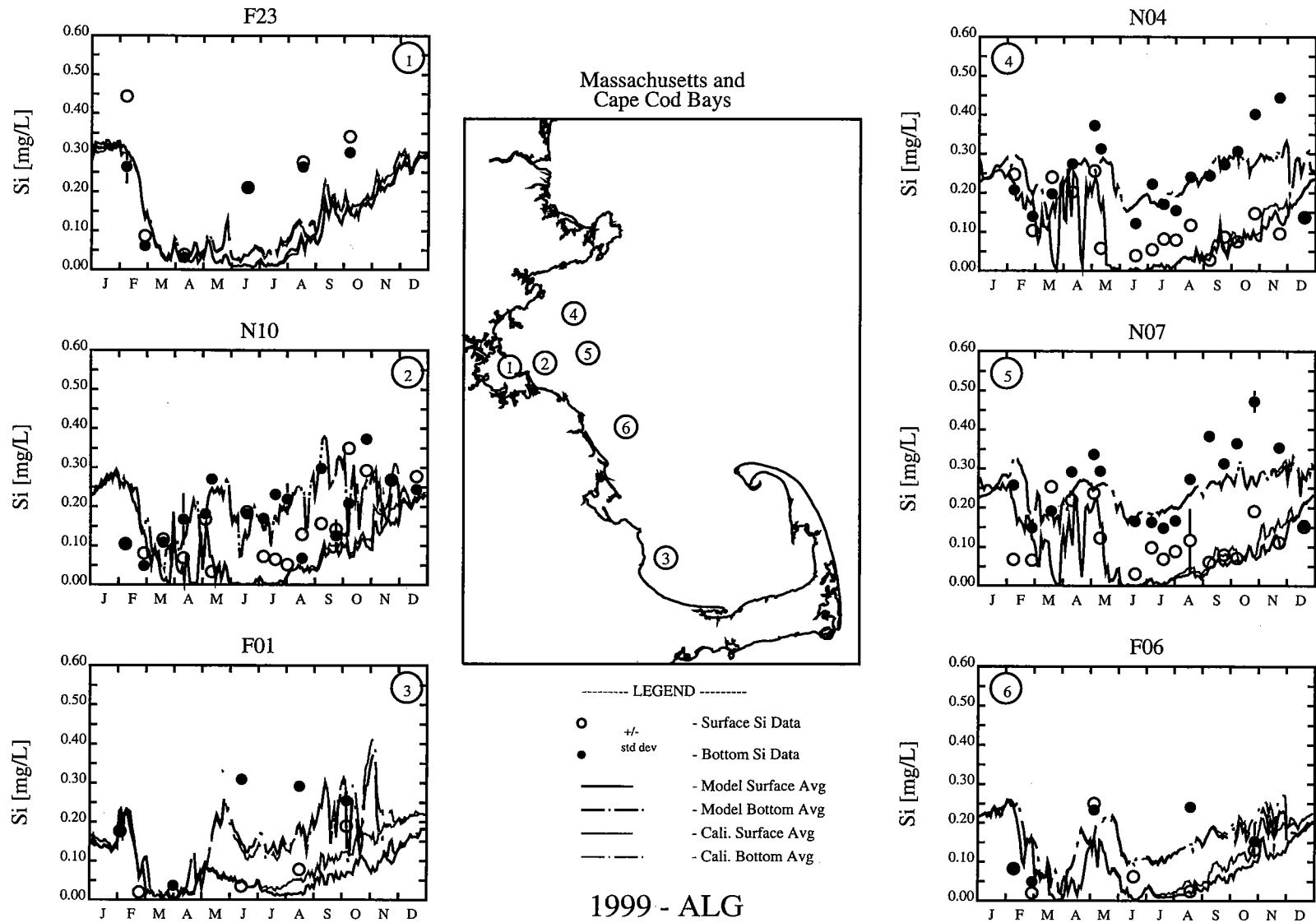


Figure 5-12. 1999 Three Algal Group Model vs. Surface and Bottom Si Data

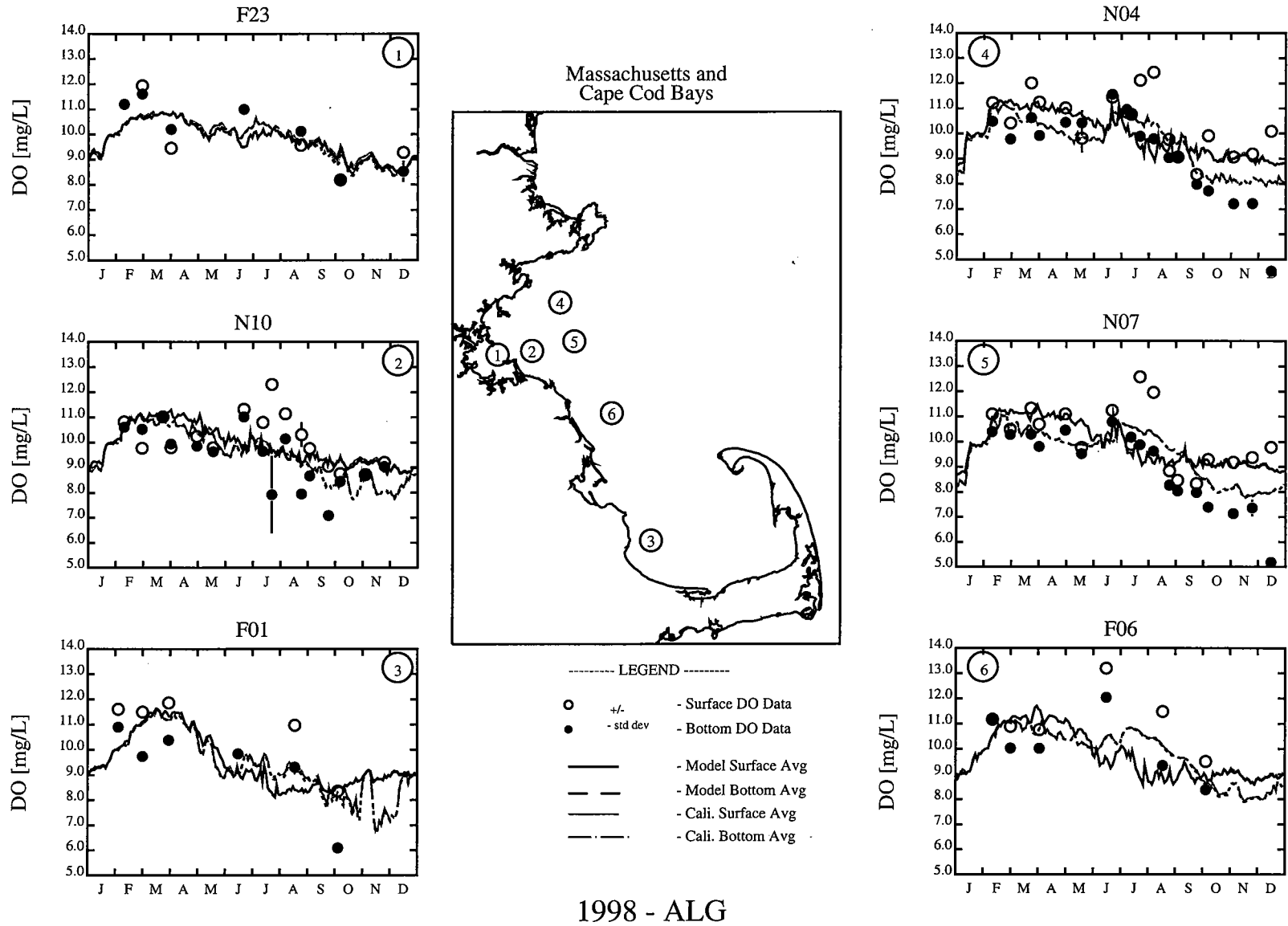
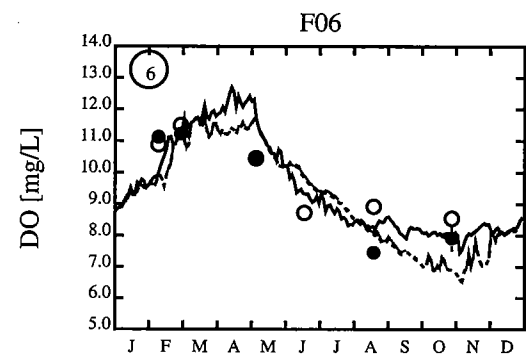
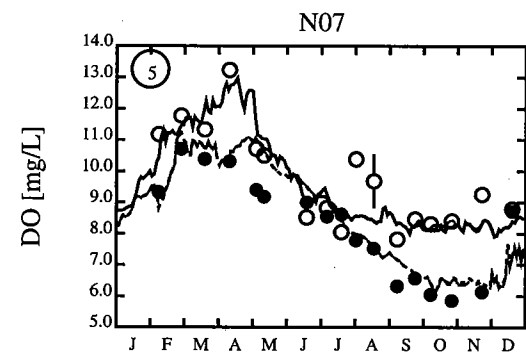
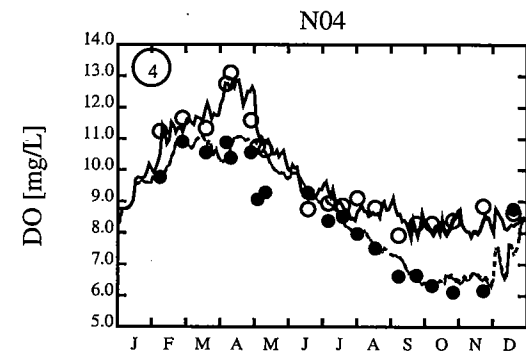
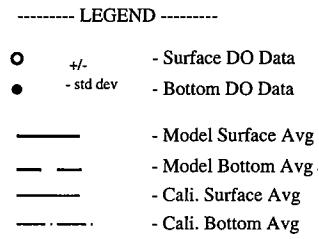
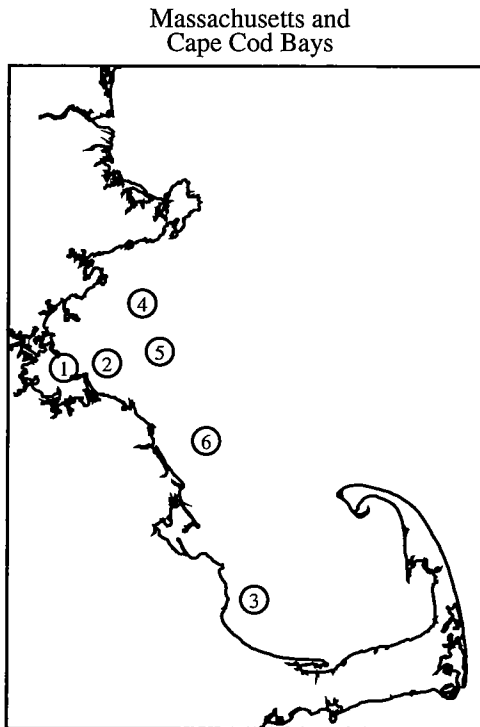
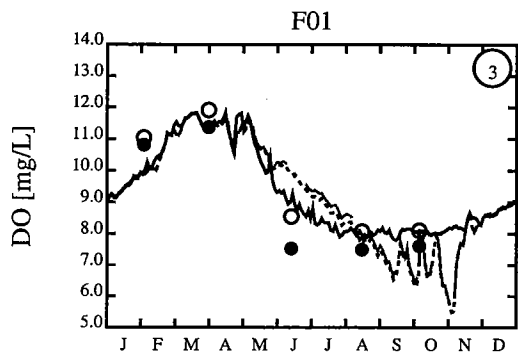
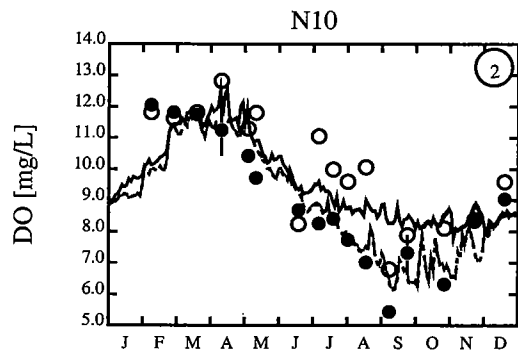
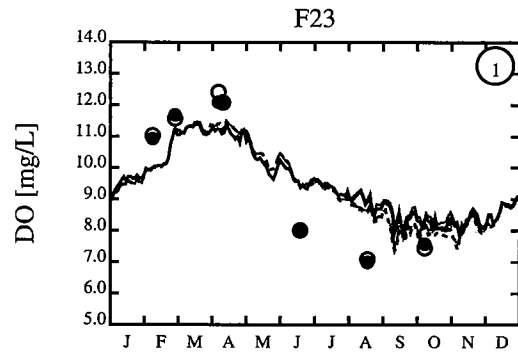


Figure 5-13. 1998 Three Algal Group Model vs. Surface and Bottom DO Data



1999 - ALG

Figure 5-14. 1999 Three Algal Group Model vs. Surface and Bottom DO Data

SECTION 6

RECYCLING SENSITIVITY

In an attempt to explain the large increase in POC observed within Massachusetts and Cape Cod Bays during the late 1990s without an associated increase in inorganic nutrients, a hypothesis was put forward at the October, 2002 progress meeting (which included participants from MWRA, Battelle, HydroQual, and the University of Massachusetts at Boston) that nutrient recycling had increased in the bays. Nutrient recycling includes the conversion of particulate and dissolved organic nutrients into inorganic nutrients that are available for uptake by phytoplankton. One possible cause for the increased recycling is the reduction of metals from the MWRA effluent. It is thought that some metals may be toxic to the bacteria that convert organic nutrients to inorganic nutrients and therefore suppress recycling. For the purposes of this sensitivity the cause of the suppression of nutrient recycling is irrelevant. To determine how the model would react to increased recycling rates, the recycling rates for nitrogen and phosphorus were increased by ten percent. The results of the sensitivity showed virtually no difference in the model results. In an attempt to force the model to produce results that were different from the calibration, the recycling rates were increased by fifty percent over their original values. Table 6-1 presents the recycle rates used for the calibration and the two sensitivity runs.

Figure 6-1 presents the model results for POC in 1998 for both the calibration and the sensitivity conducted with fifty percent increases in the recycling rates. The model computes slightly higher POC concentrations for the sensitivity with more noticeable changes at stations F01 and F06. It is unrealistic to assume that the changes that have occurred to the MWRA effluent would cause a fifty percent change in the recycling rate throughout Massachusetts and Cape Cod Bays. Yet even with such a large change to the rates, only minimal impacts were observed in the model results. Based on the model results, a change to the recycle rates in Massachusetts and Cape Cod Bays does not account for the increased POC concentrations measured in the bays.

Table 6-1. Recycle Rates (l/d)

Description	Calibration	10% increase	50% increase
LPOP Hydrolysis Rate at 20°C	0.05	0.055	0.075
RPOP Hydrolysis Rate at 20°C	0.01	0.011	0.015
LDOP Mineralization Rate at 20°C	0.10	0.11	0.150
RDOP Mineralization Rate at 20°C	0.01	0.011	0.015
LPON Hydrolysis Rate at 20°C	0.05	0.055	0.075
RPON Hydrolysis Rate at 20°C	0.008	0.0088	0.012
LDON Mineralization Rate at 20°C	0.05	0.055	0.075
RDON Mineralization Rate at 20°C	0.008	0.0088	0.012

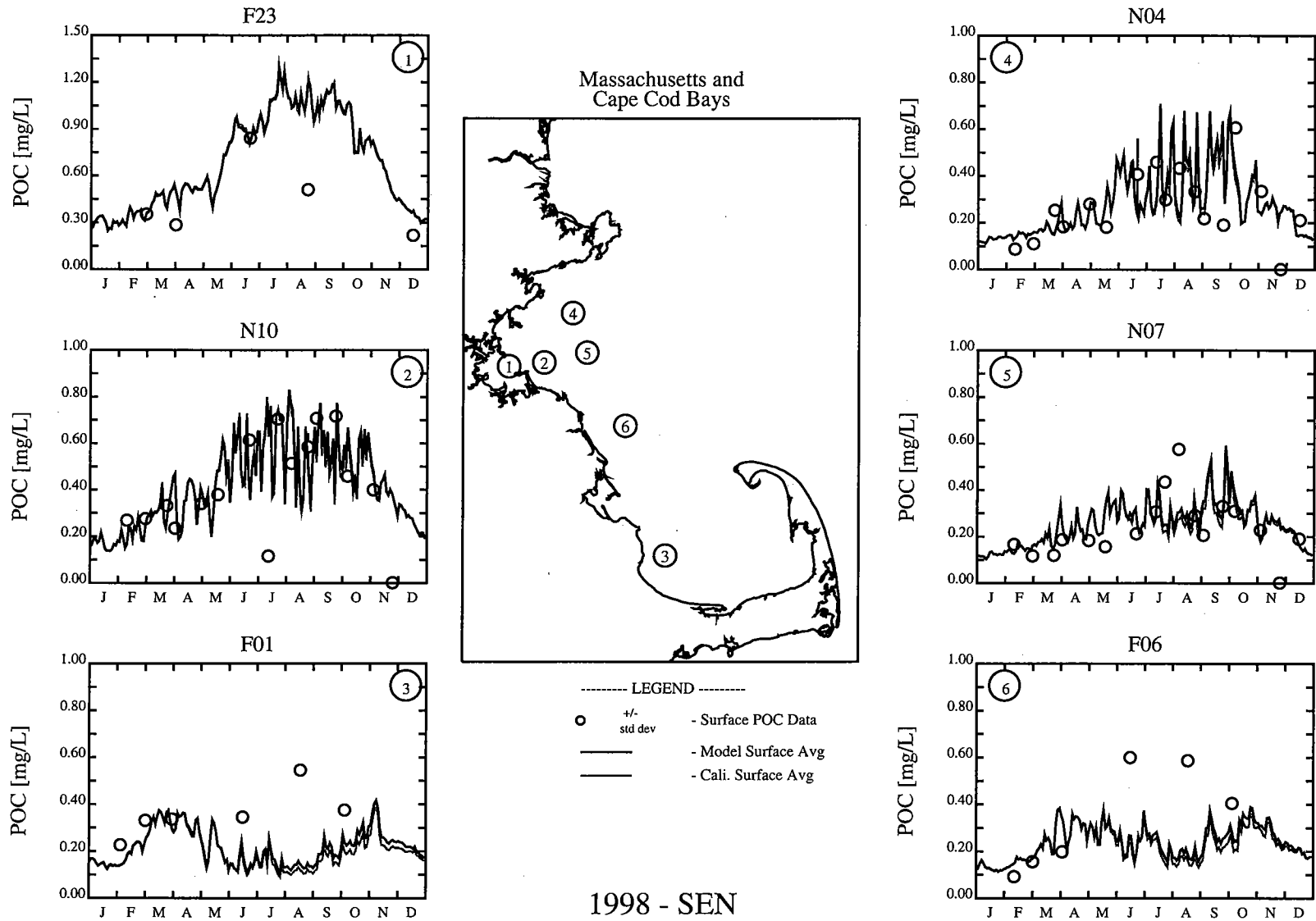


Figure 6-1. 1999 Model Results from the Recycle Rate Sensitivity vs. Surface POC Data

SECTION 7

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

In this analysis, BEM was set up and run for the years 1998 and 1999. Unlike previous analyses, BEM was run using the hydrodynamic model segmentation on the previous water quality model's spatial domain. No changes were made to the model coefficients chosen during the calibration process conducted for the period of 1992 through 1994. The modeling effort described in this report was an analysis to determine how well the previously calibrated BEM could reproduce the conditions that occurred in 1998 and 1999. In particular, the unique events that occurred in these years were the lack of a spring bloom in 1998 and low DO levels in 1999. In general, the model reproduces average year conditions, and with the aid of modifying the boundary conditions, based on representative data, the model can reproduce some of the unique events that occur during a particular year. In 1998, the model computes less of a spring bloom in than it computes in other years, but the model does compute increased productivity during this time, and more than was measured. The model is able to reproduce the observation that lower DO concentrations occurred in 1999, but it does not reproduce the lowest DO concentrations.

As sensitivities the model was also run with the addition of a third algal group, a representation of fall diatoms, and with increased nutrient recycle rates.

7.1 OBSERVATIONS/CONCLUSIONS

There was a dramatic decrease in the total carbon load from MWRA WWTPs from 1994 to 1998. The overall nutrient loading did not vary very much over this period.

1998 was a much wetter than average year. 1999 was drier than average.

POC and DOC concentrations in Massachusetts and Cape Cod Bays were higher in 1998 than previous years and much higher in 1999.

It is very important to adjust the boundary conditions in the model from year to year to account for the high degree of variability in the water quality observed in the Gulf of Maine.

The model overpredicts the productivity in Boston Harbor. The hydrodynamic model calibration may contribute to this over prediction.

Despite using the constants and parameters chosen for the 1992 – 1994 calibration, the model did a fair job of reproducing the water quality conditions in Massachusetts and Cape Cod Bays. It is possible that changes occurred to the bays between 1994 and 1998 that would warrant the use of modified constants and parameters.

The sparseness of data at the boundary could inhibit to the model's ability to reproduce the water quality data.

The addition of the third algal group did little to help or harm the model's comparison to the water quality data. The largest changes in the model results due to the inclusion of the third algal group were the small increase in chlorophyll during the fall and decreased Si concentrations during the fall.

The results of the recycle sensitivity do not point to the conclusion that increased recycling rates in the bays contribute to the increased POC concentrations observed in the bays.

7.2 RECOMMENDATIONS

The water quality model should continue to be applied and refined using the water quality data provided by the ongoing HOM depending on the long term goals set for the model. The model can readily be used to determine the impact of MWRA discharges in the near field and far field areas. With additional funding, additional state-variables can be added to the model, such as zooplankton, to gain a further understanding of the bays ecosystem.

More effort should be expended to improve the calibration of the fall diatom group. The initial calibration was based on data from 1993.

Sampling water quality data near the boundary should remain a priority.

The number of near field sampling stations appears to be excessive. Reducing the number of near field stations by up to 50 percent would not significantly reduce the amount of information gained from sampling all of the current near field stations. Near field stations could be reduced by evenly removing stations spatially, or by developing cross correlations between the stations and then removing redundant stations.

From the data, it appears that the fall algal blooms are becoming more common than spring blooms. It may be appropriate to shift one of the spring far field surveys to the fall in order to capture more of the fall bloom.

An effort should be made to determine what limits phytoplankton growth in Boston Harbor and then incorporate these processes into the model. The data indicate that phytoplankton biomass is suppressed during the second half of the year even though they are not temperature, nutrient or light limited. Currently, the model overestimates the phytoplankton in the harbor. As discussed in Section 4.4, the detention time in the harbor may be too long in the model. A dye study could be conducted and then reproduced in the model. A more thorough analysis of the zooplankton data could be conducted to determine how zooplankton biomass varies within the harbor and the bays. Modifications to the method of incorporating zooplankton in the model could be made. Finally, residual chlorine could be measured in the harbor to see if it is inhibiting phytoplankton growth.

SECTION 8**REFERENCES**

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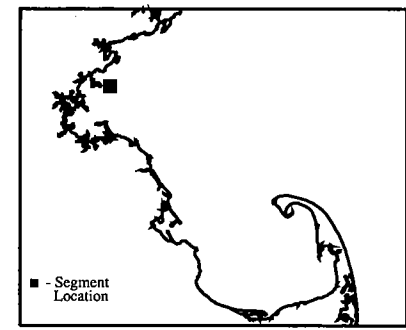
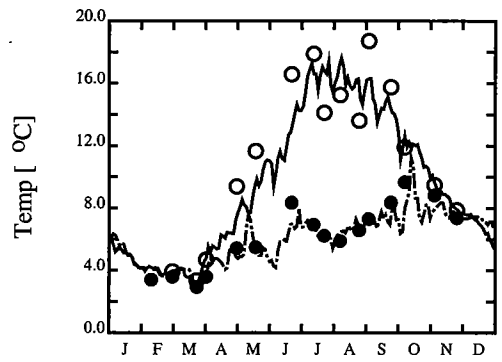
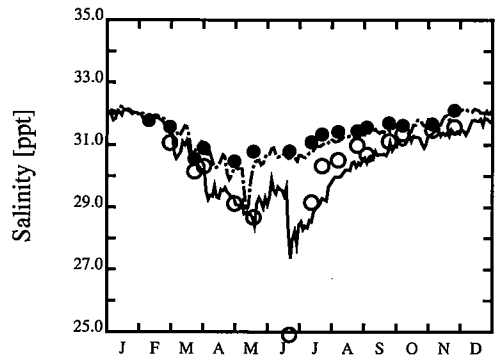
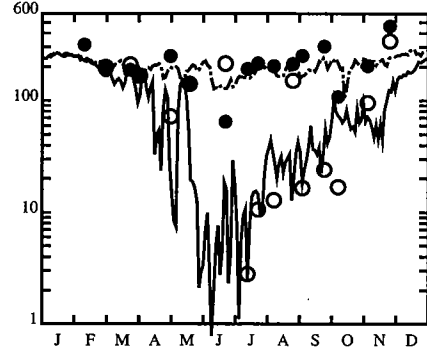
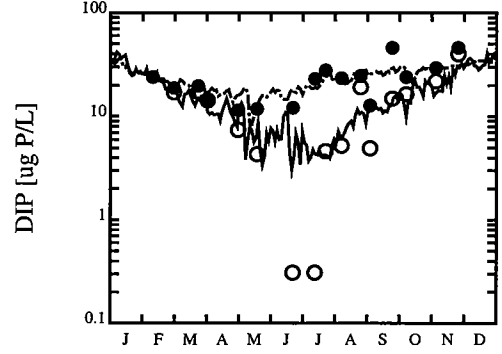
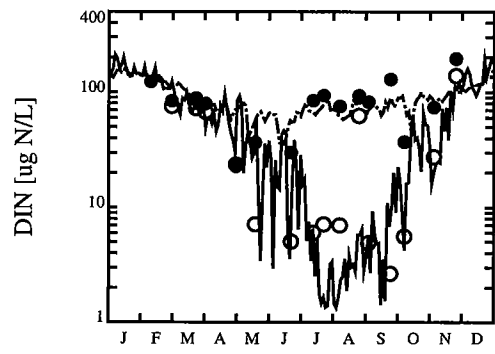
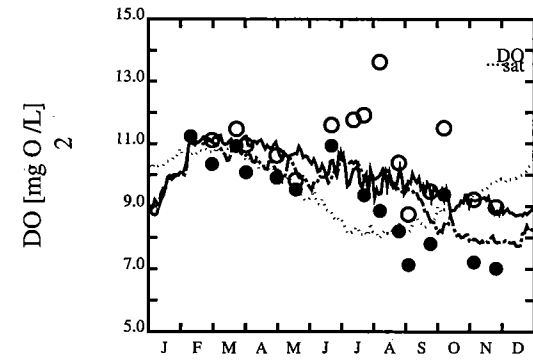
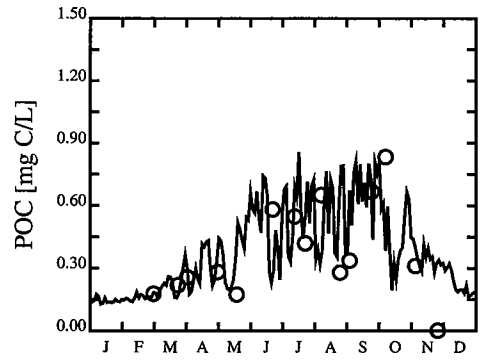
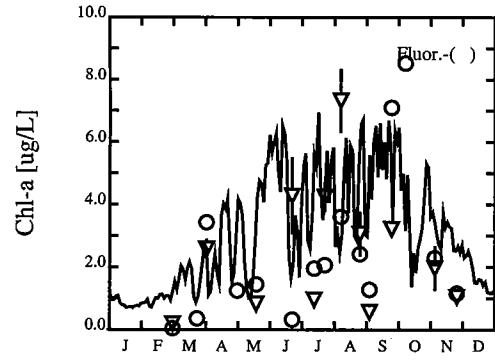
APPENDIX A

1998 RESULTS



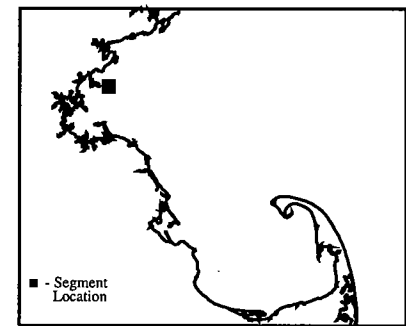
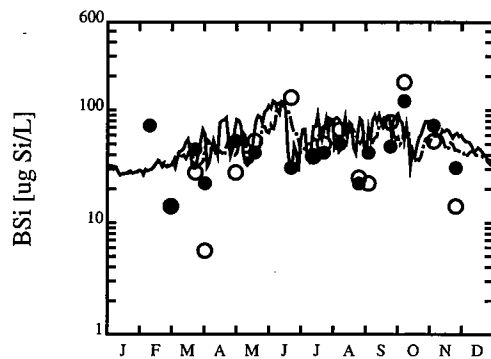
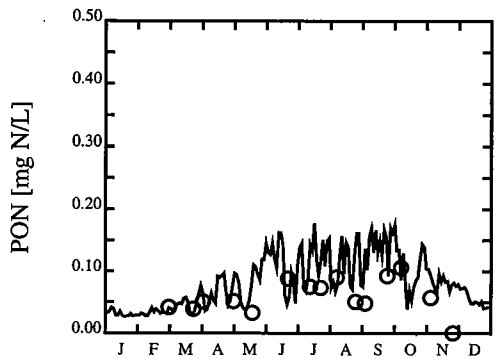
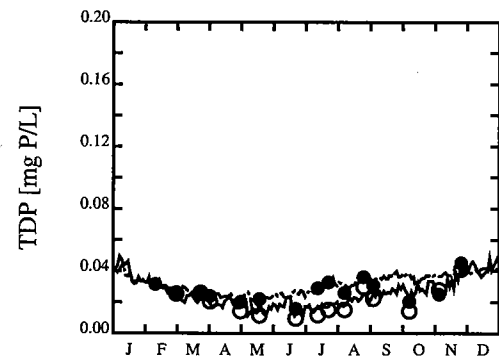
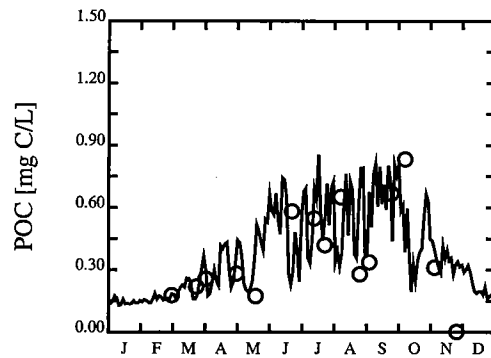
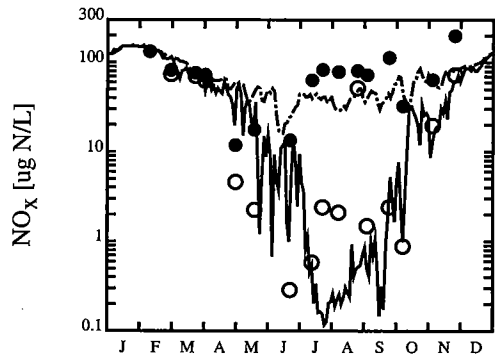
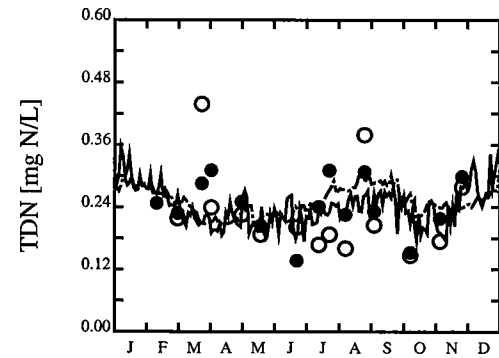
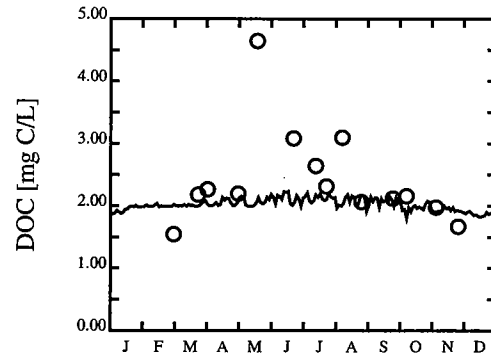
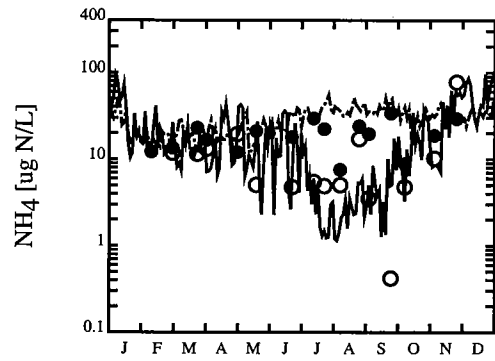
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Engineers & Scientists**

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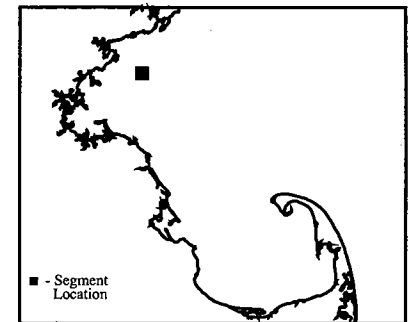
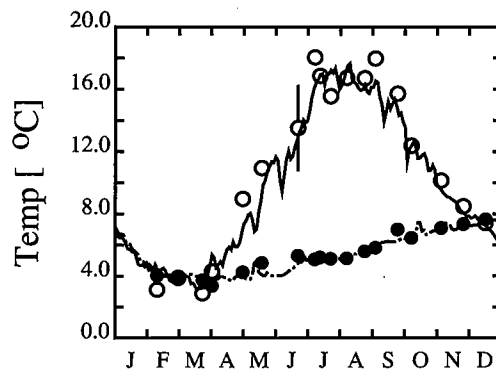
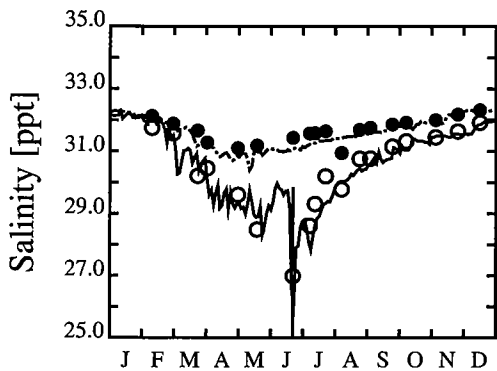
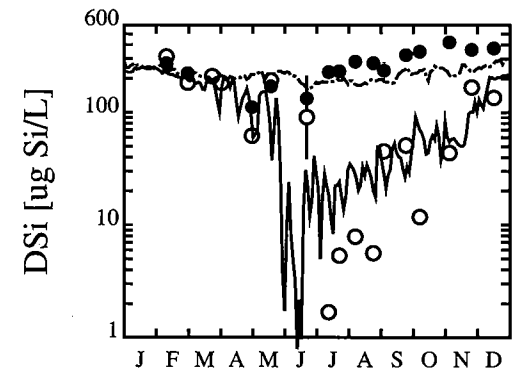
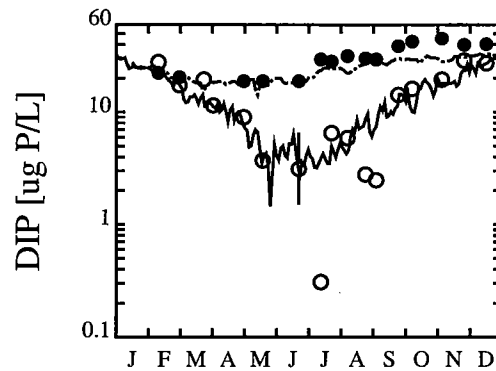
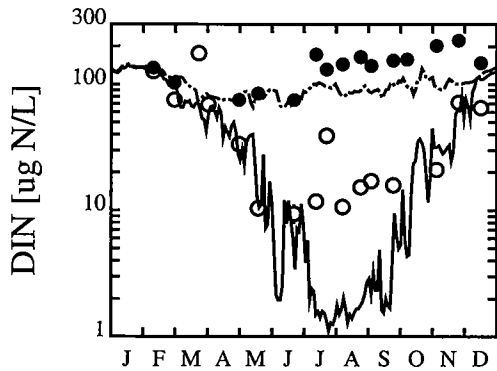
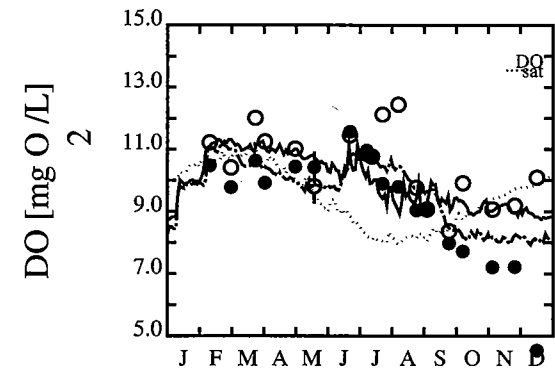
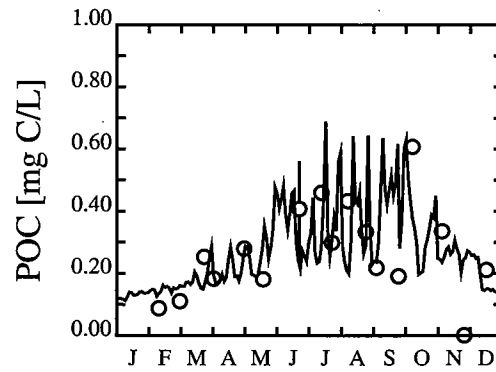
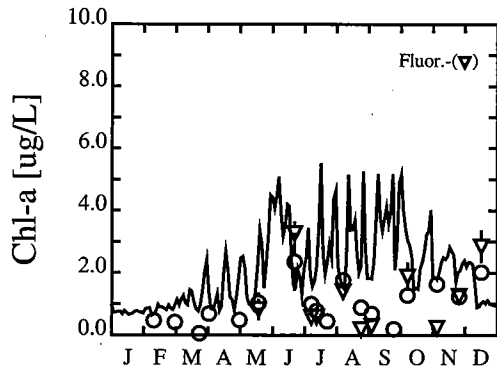
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 --- std.dev. Surface Model
 — Bottom Model

1998 Temporal Calibration Results for Grid Cell (30,53) Vs Data Station N01P



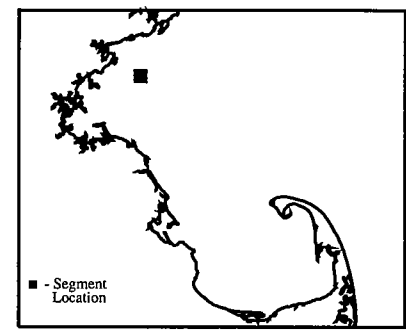
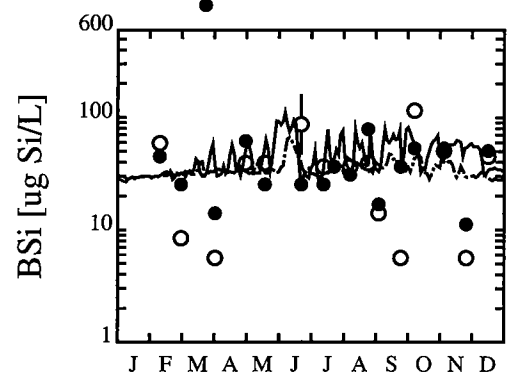
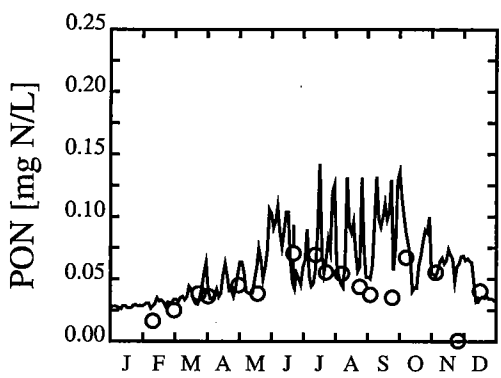
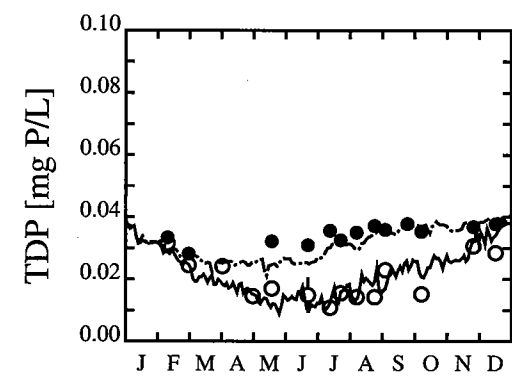
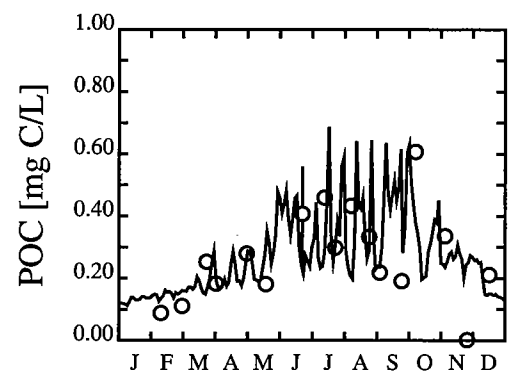
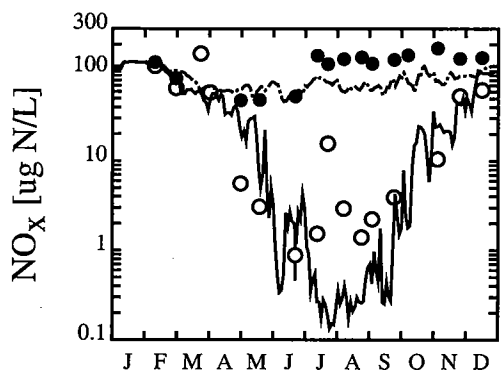
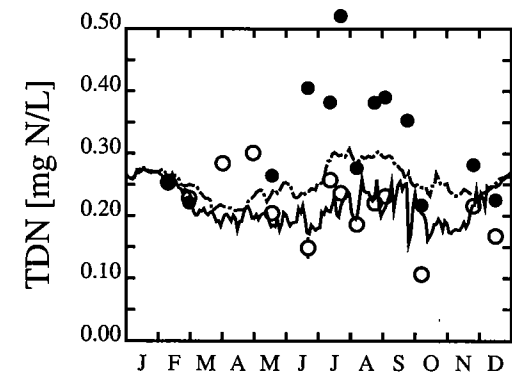
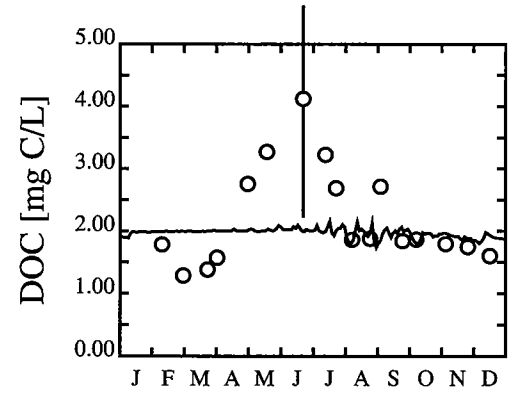
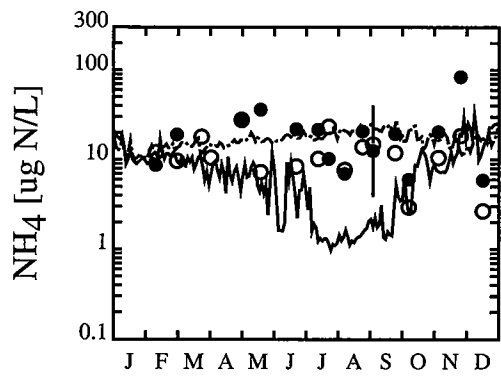
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - std dev Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for
 Grid Cell (30,53) Vs Data Station N01P



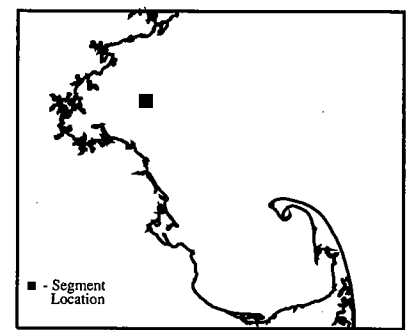
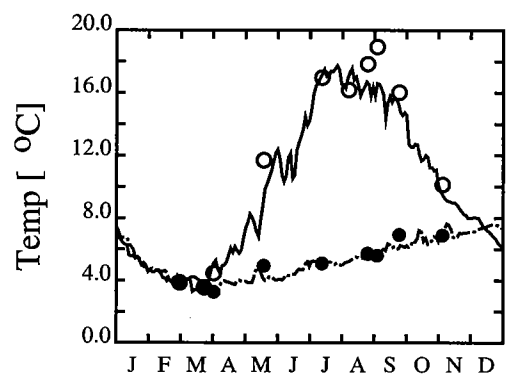
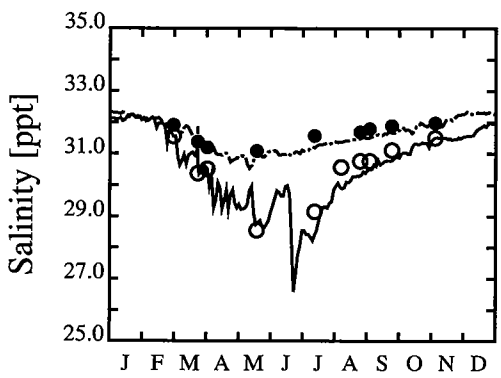
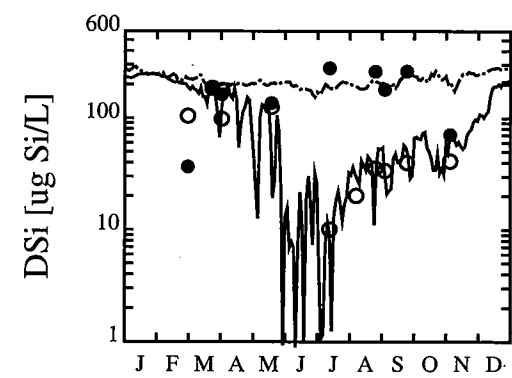
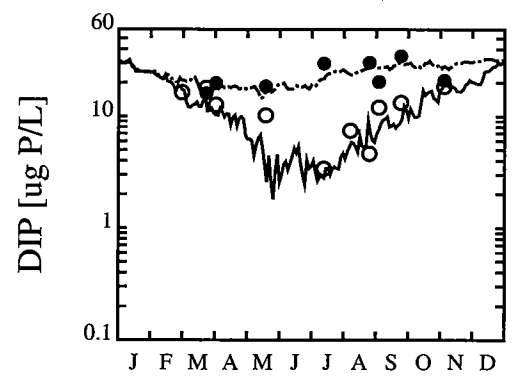
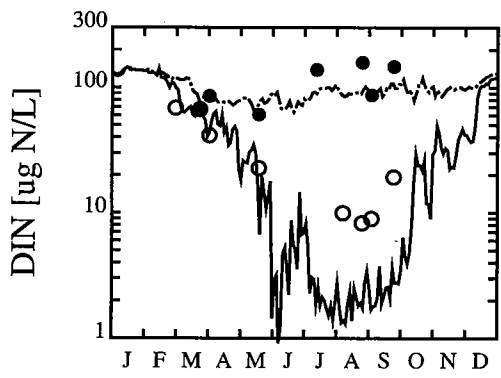
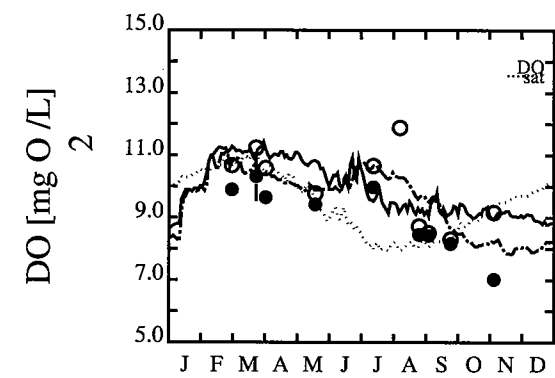
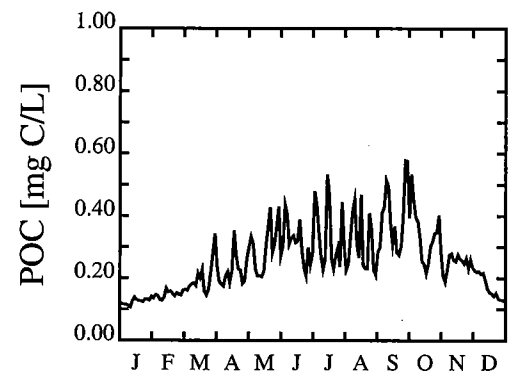
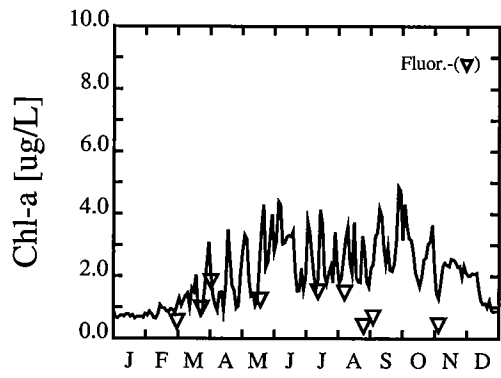
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std dev- Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for
 Grid Cell (37,48) Vs Data Station N04P



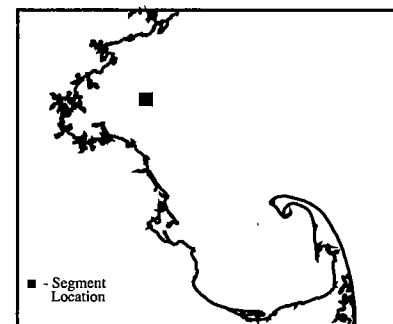
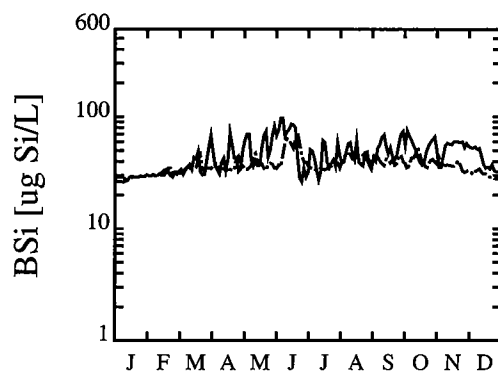
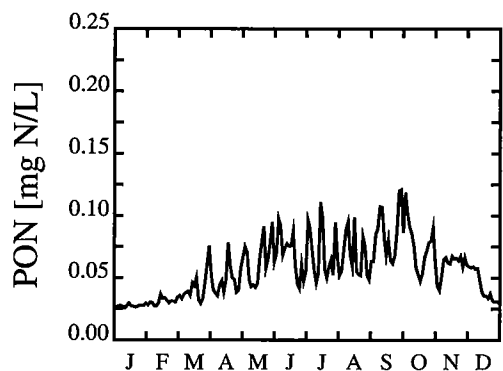
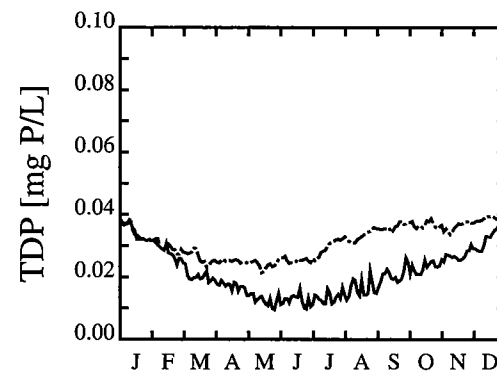
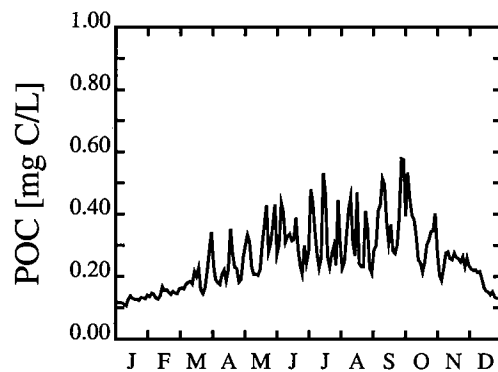
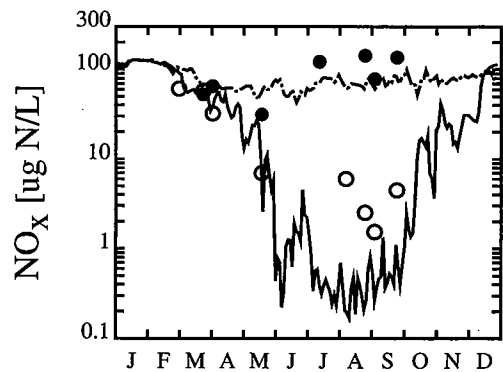
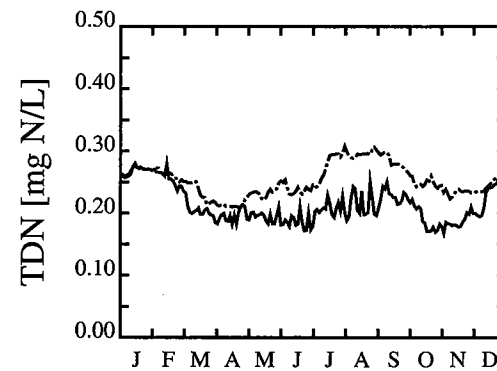
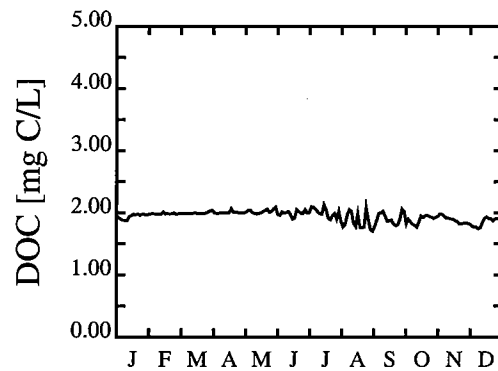
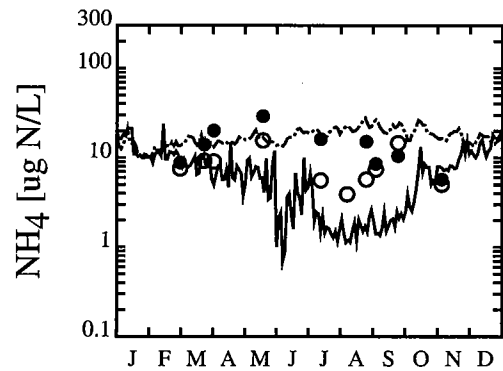
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev Surface Model
 --- Bottom Model

1998 Temporal Calibration Results for Grid Cell (37,48) Vs Data Station N04P



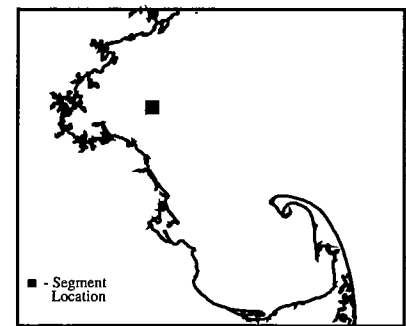
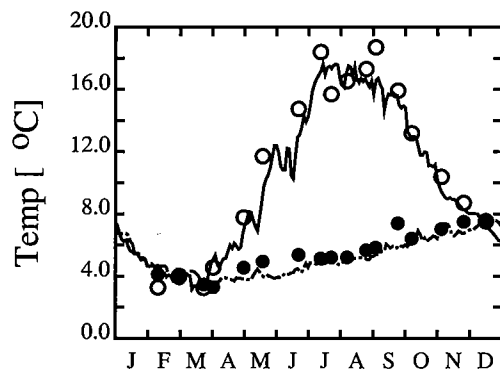
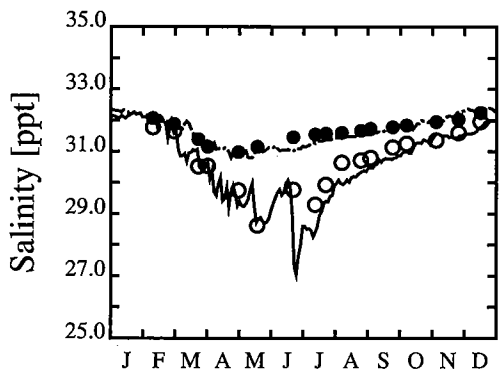
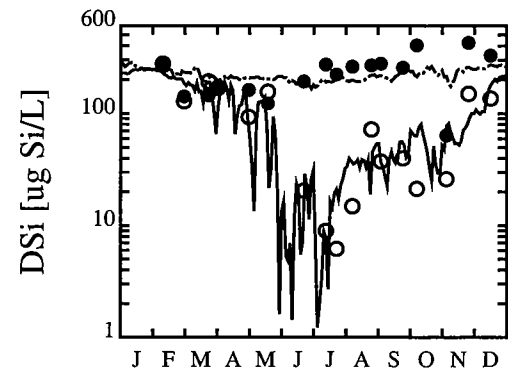
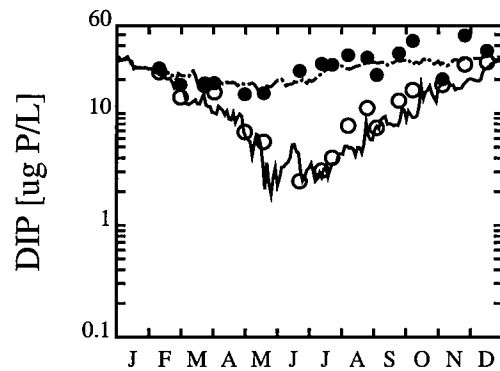
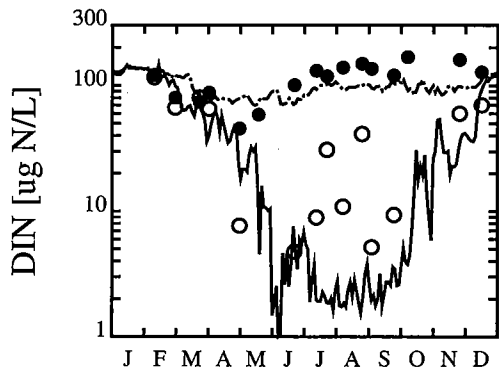
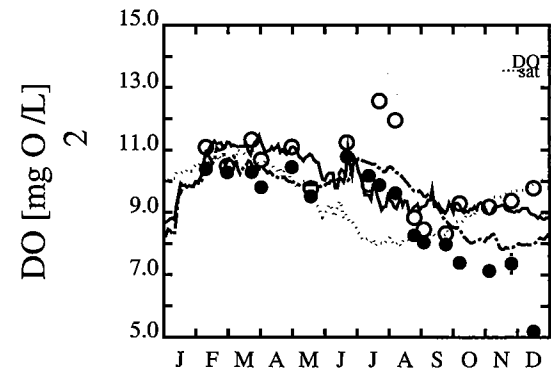
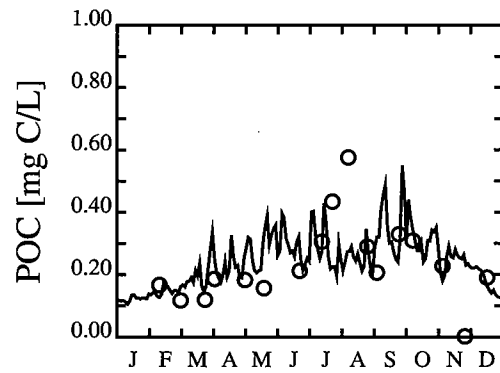
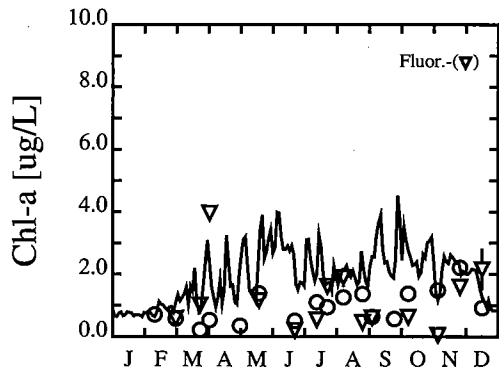
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std dev- Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (33,44) Vs Data Station N06



----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev- Surface Model
 - Bottom Model

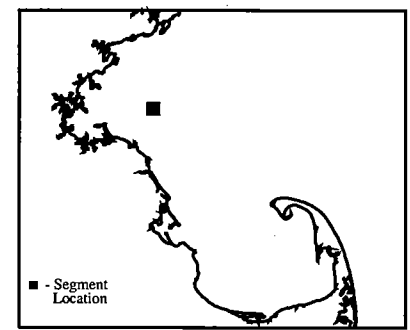
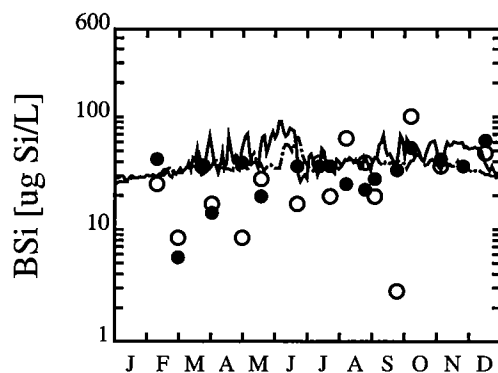
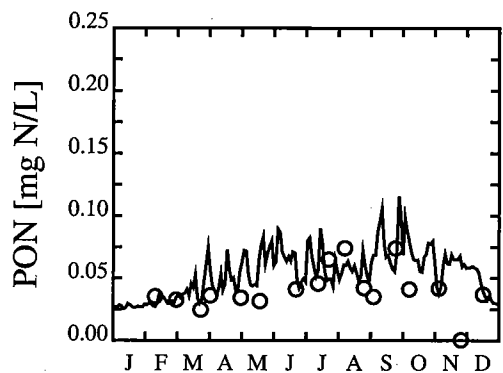
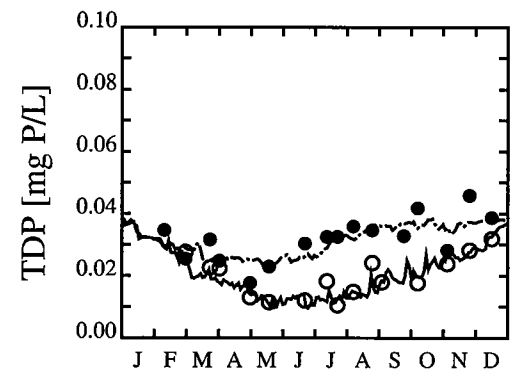
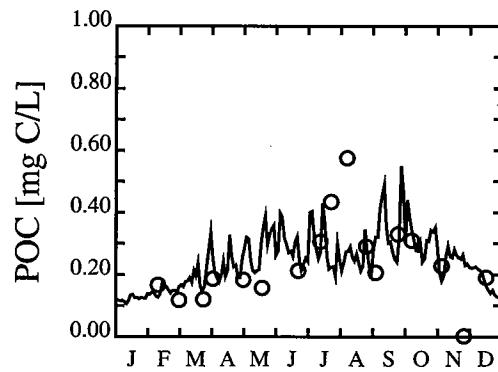
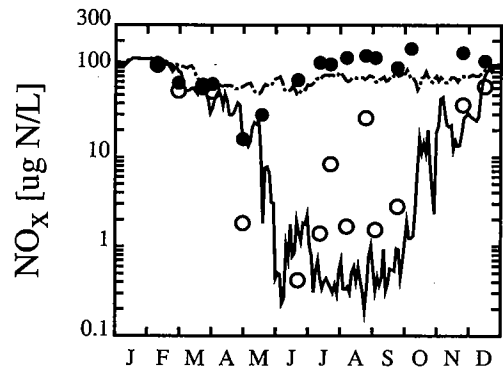
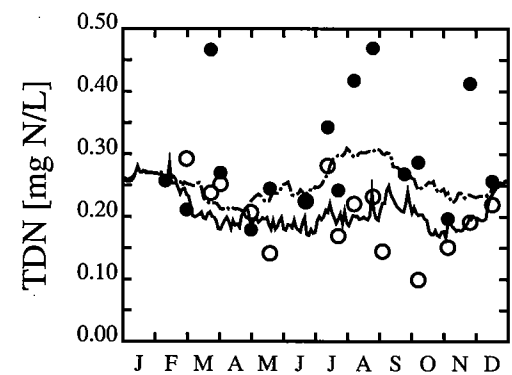
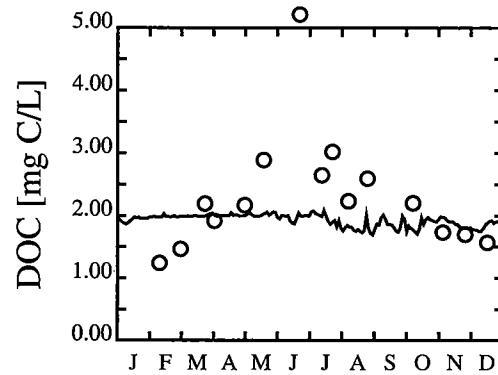
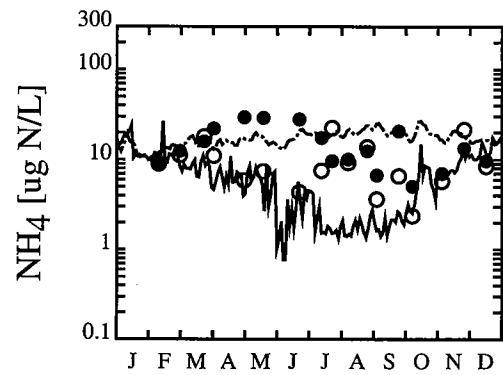
1998 Temporal Calibration Results for Grid Cell (33,44) Vs Data Station N06



LEGEND

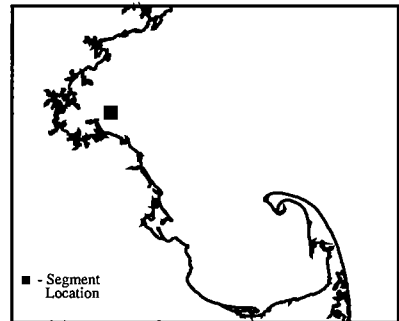
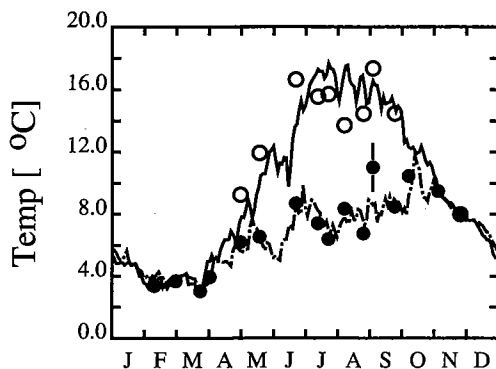
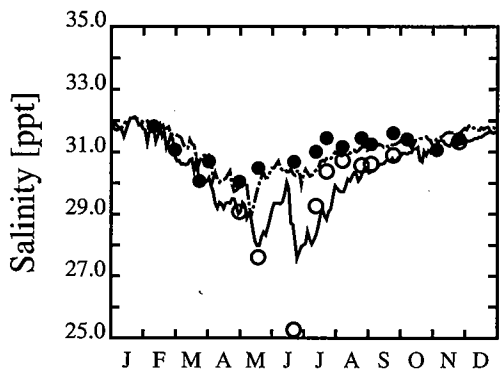
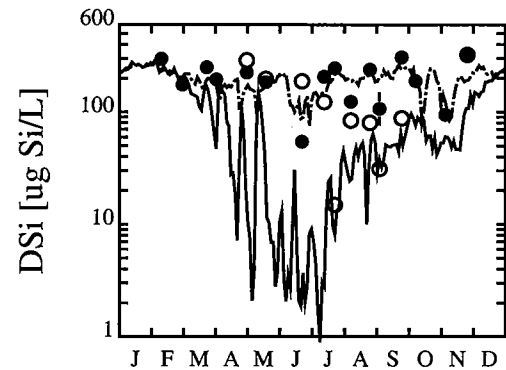
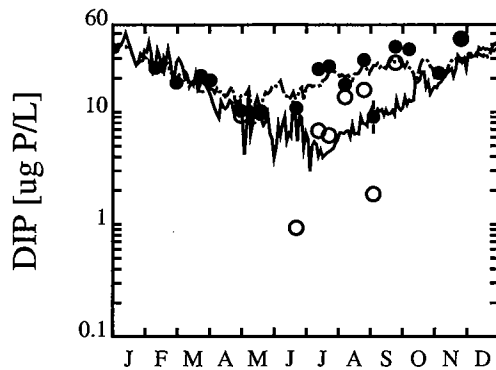
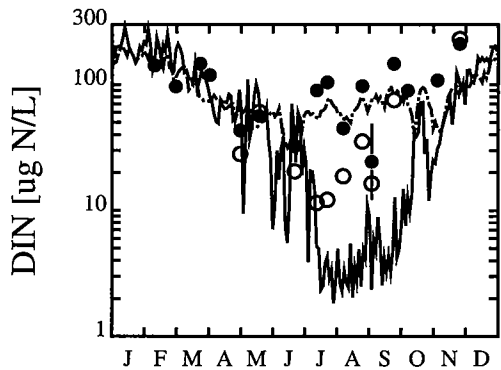
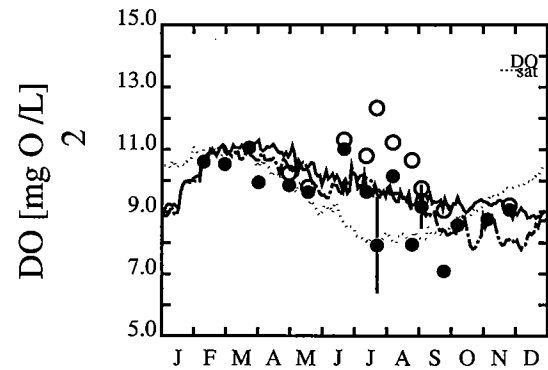
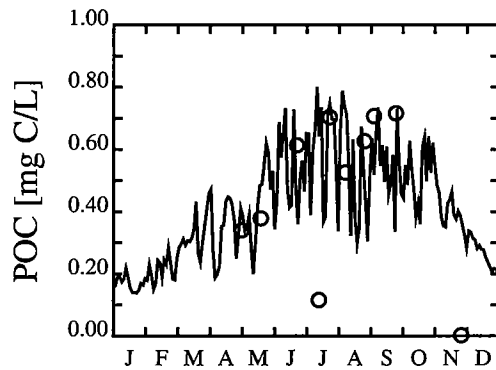
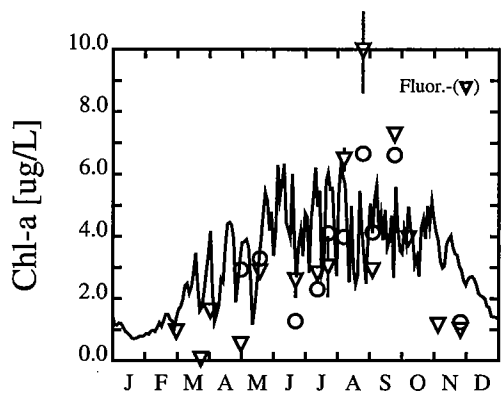
- +/- Surface Data
- Bottom Data
- std.dev. Surface Model
- Bottom Model

1998 Temporal Calibration Results for Grid Cell (32,42) Vs Data Station N07P



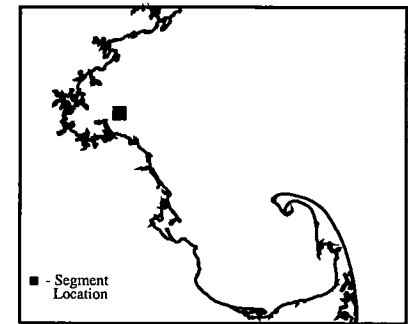
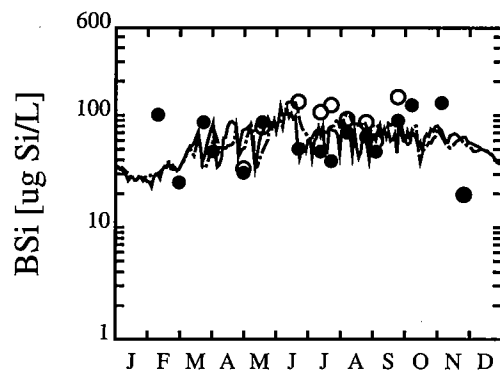
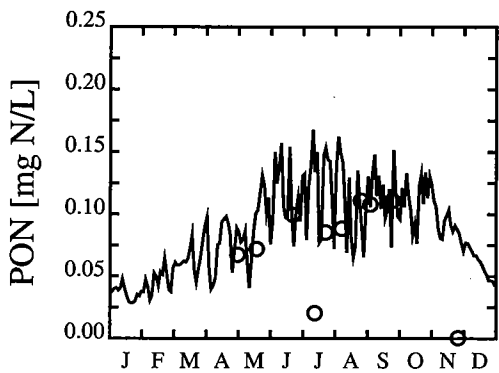
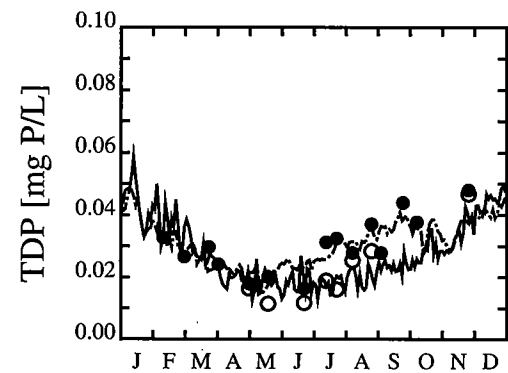
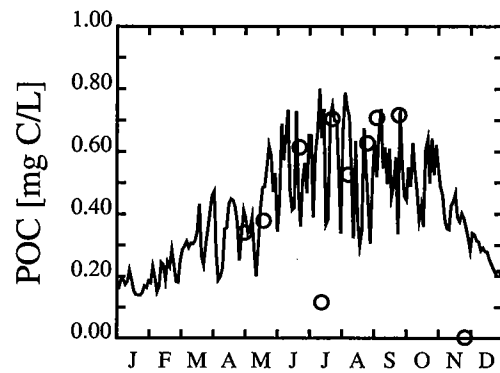
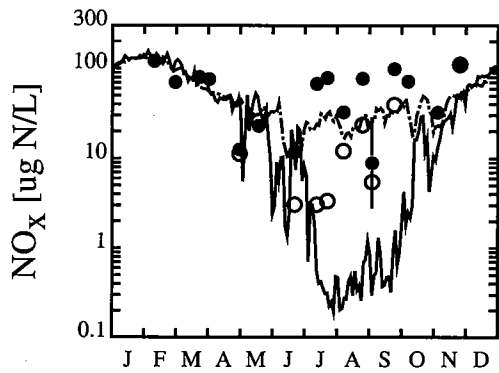
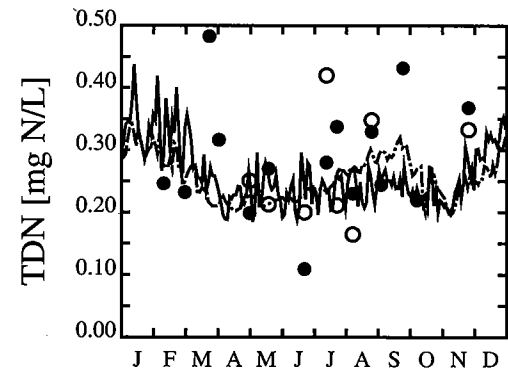
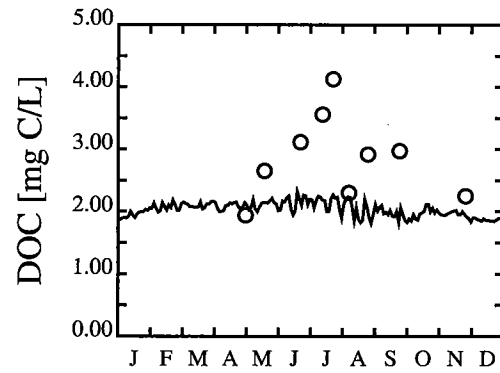
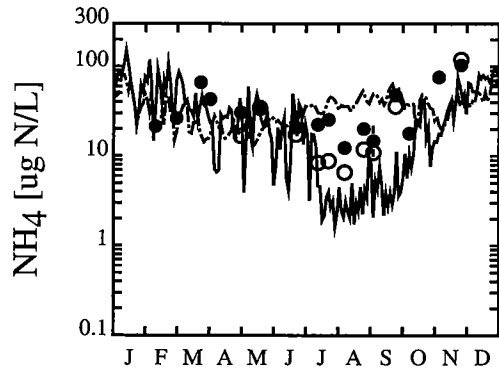
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - std.dev. Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (32,42) Vs Data Station N07P



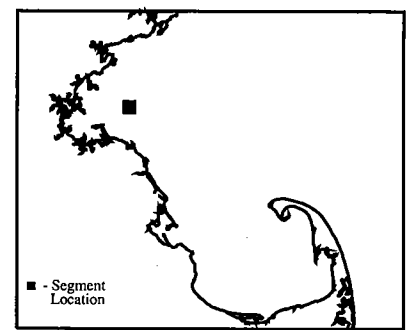
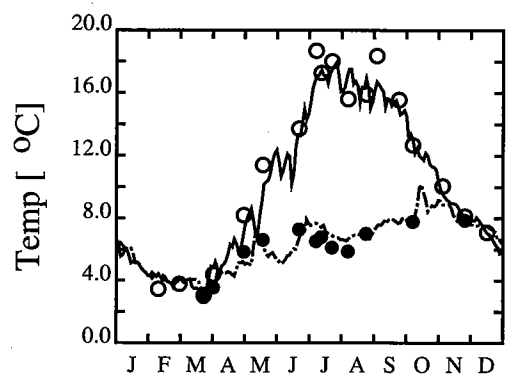
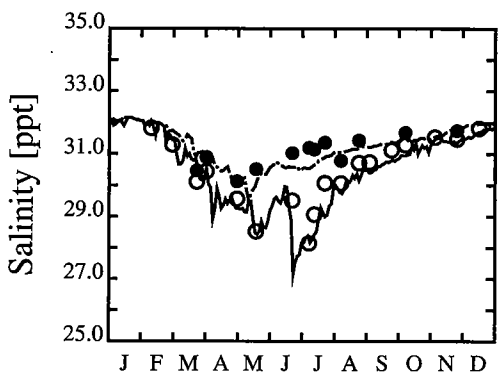
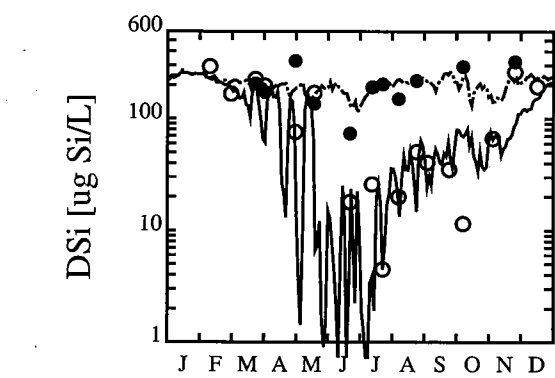
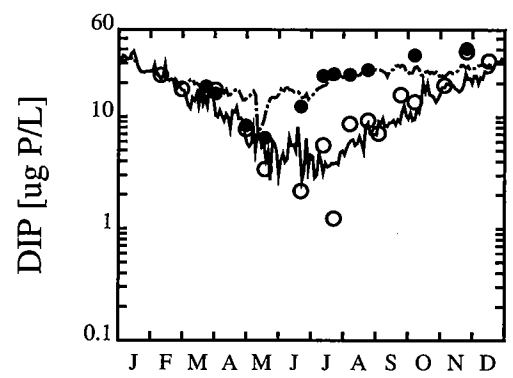
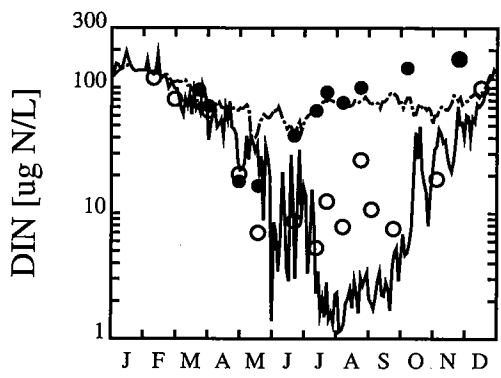
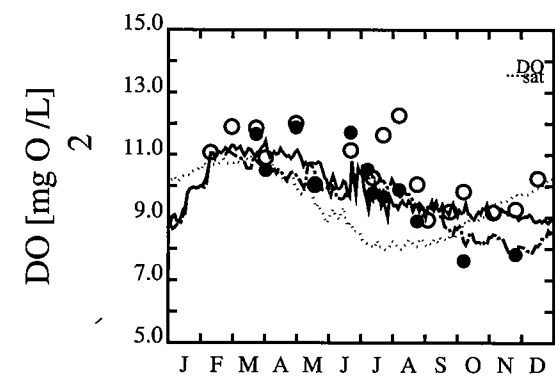
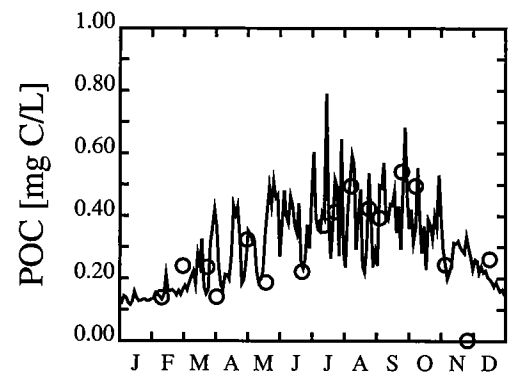
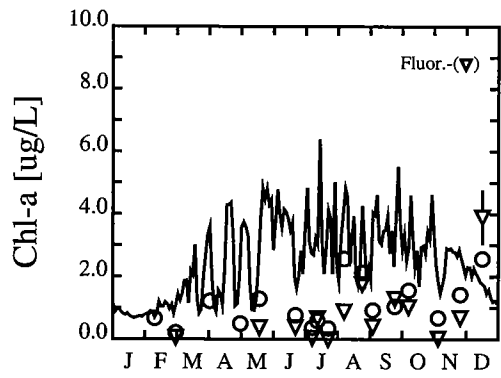
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev- Surface Model
 - Bottom Model

1998 Temporal Calibration Results for Grid Cell (24,47) Vs Data Station N10P



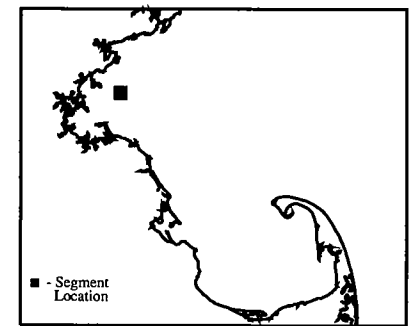
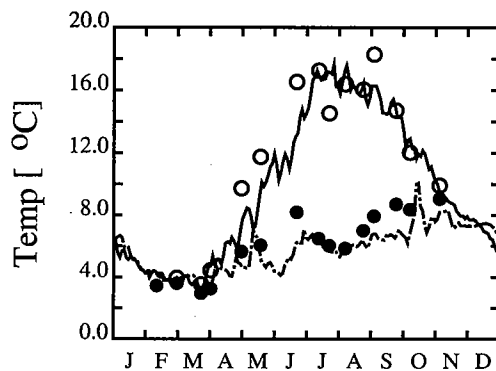
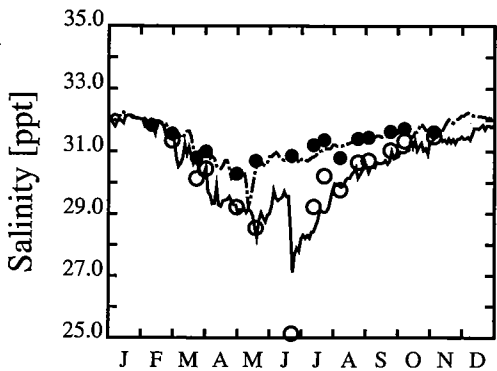
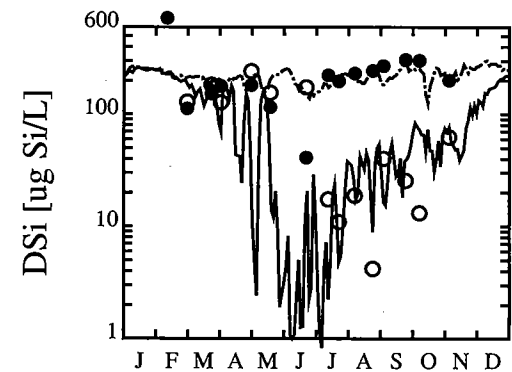
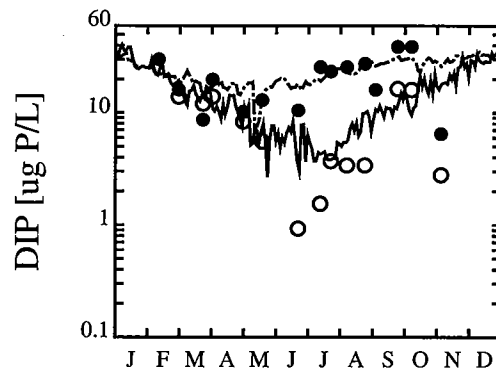
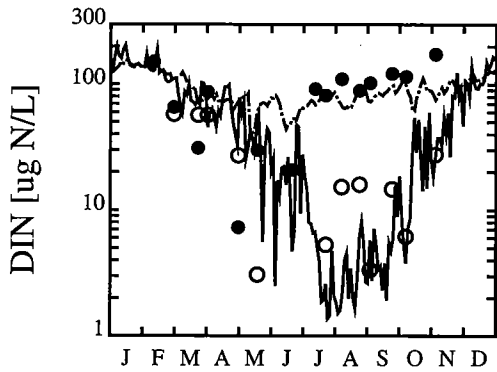
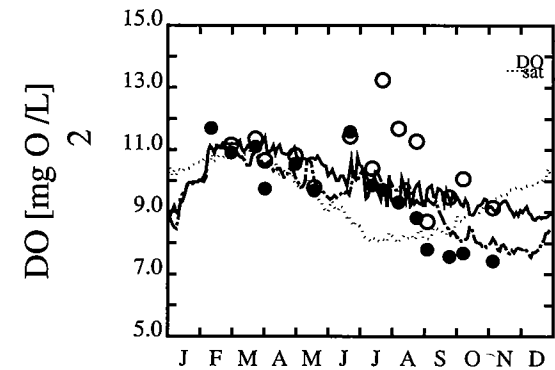
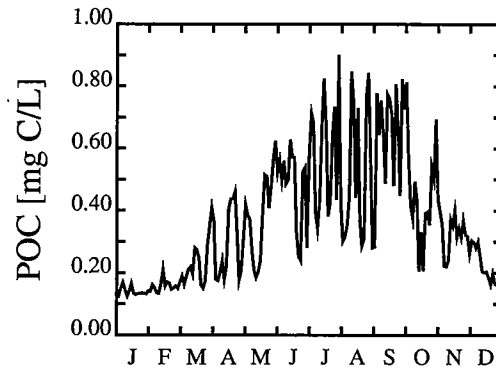
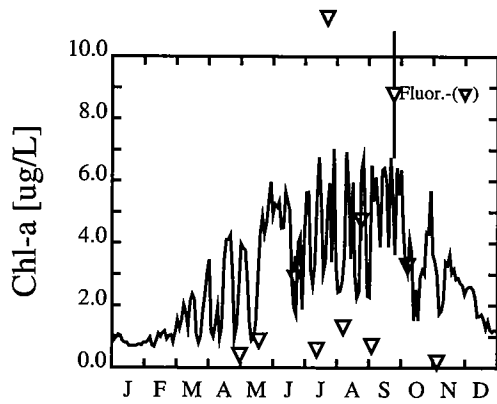
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - std.dev Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (24,47) Vs Data Station N10P



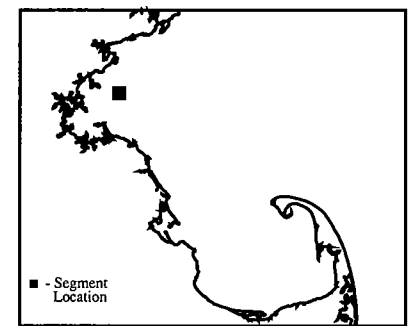
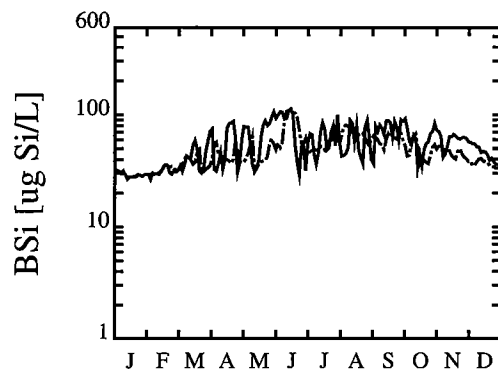
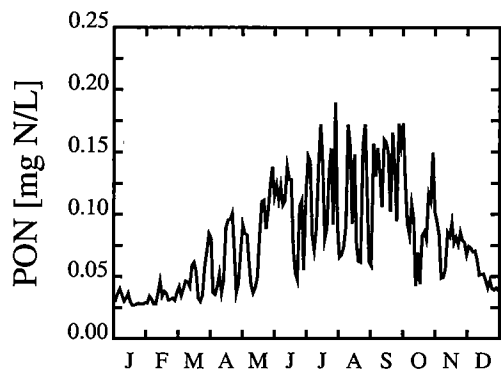
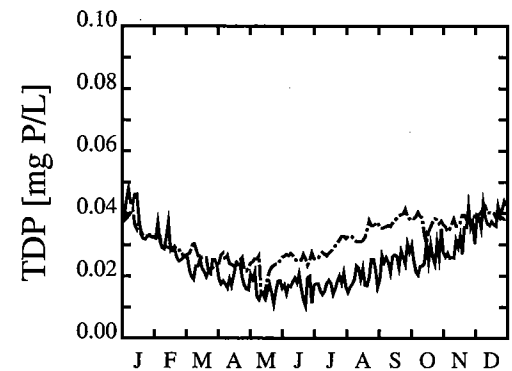
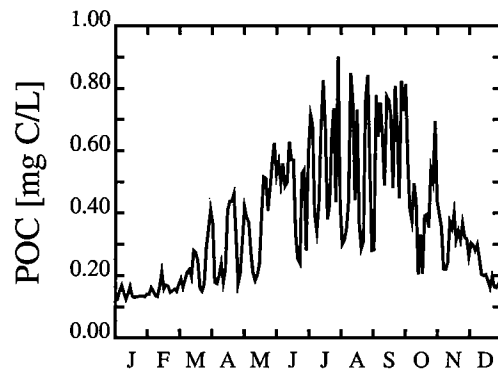
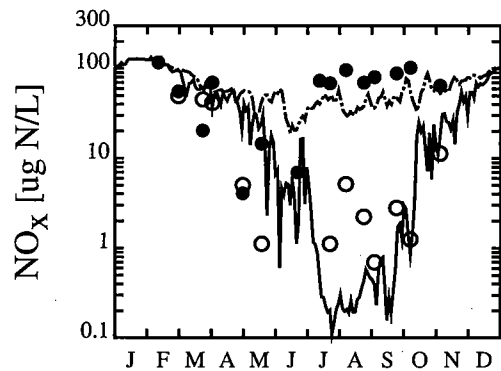
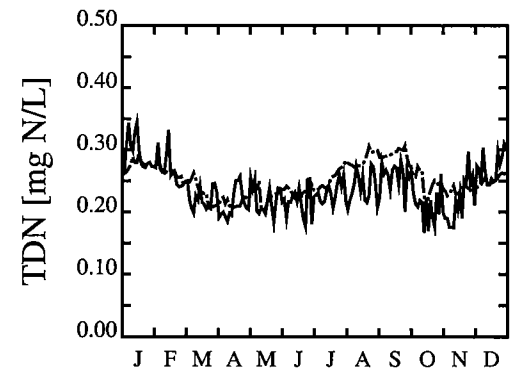
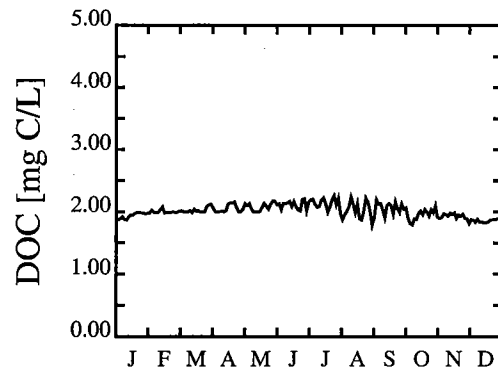
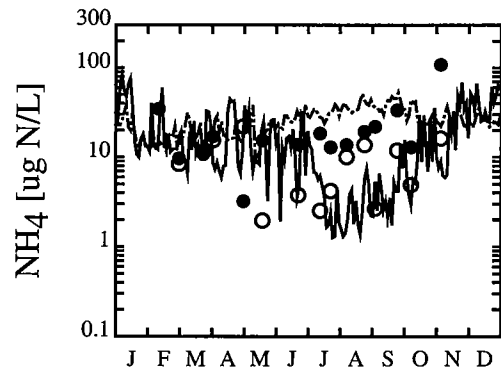
----- LEGEND -----
 ○ +/- Surface Data
 ● +/- Bottom Data
 - - - - - std dev. Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (29,46) Vs Data Station N18



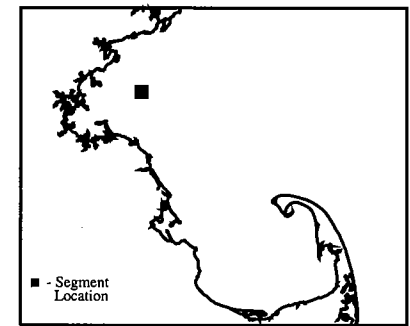
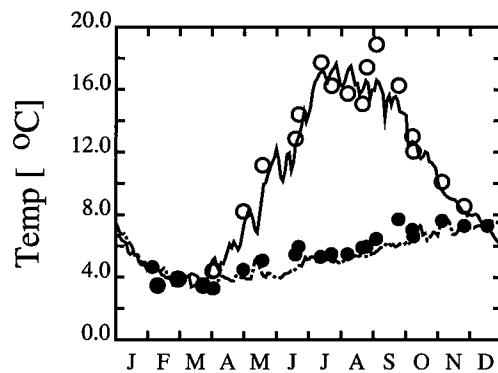
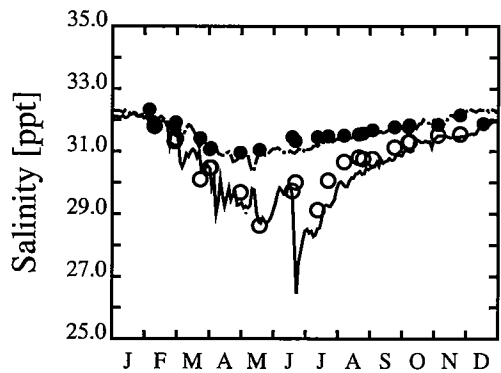
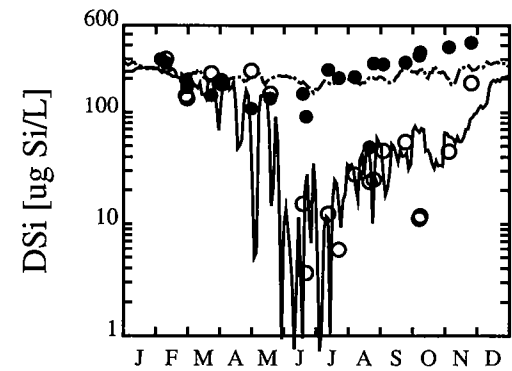
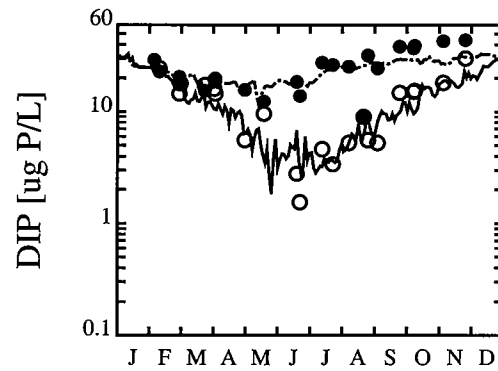
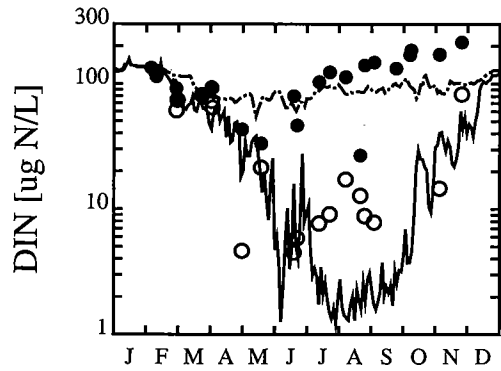
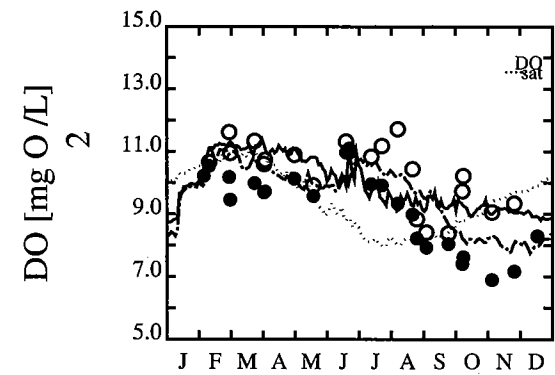
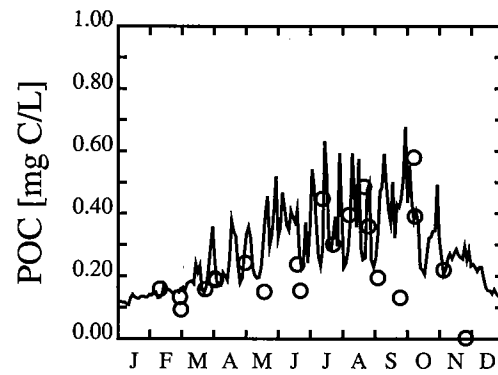
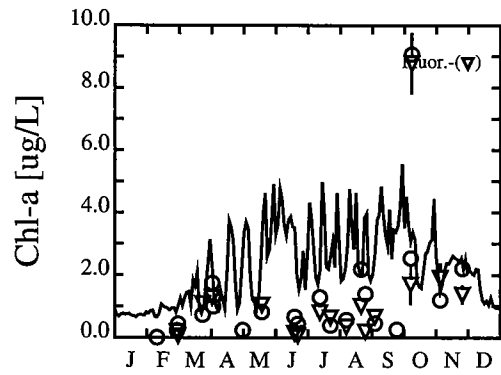
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev- Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (30,50) Vs Data Station N13



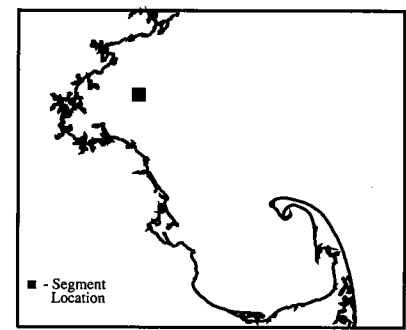
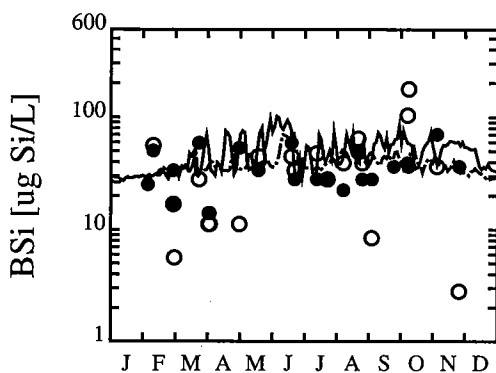
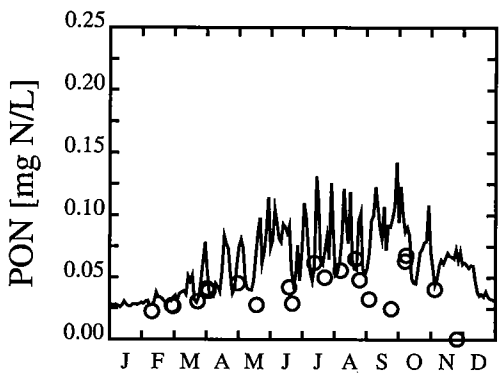
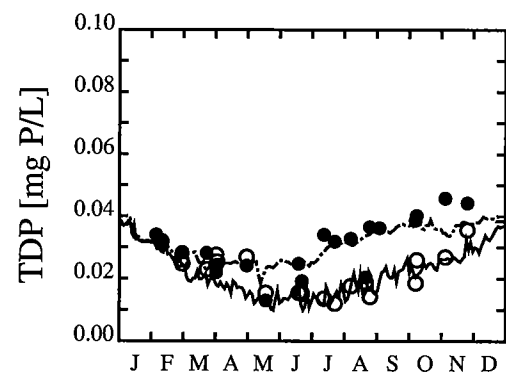
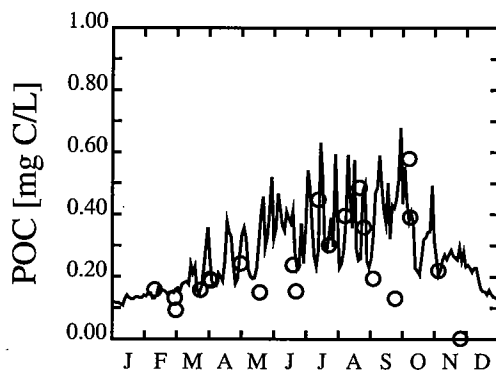
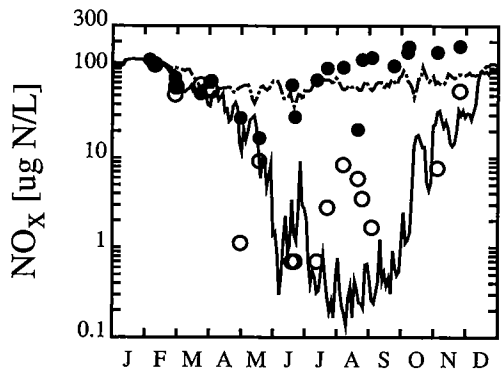
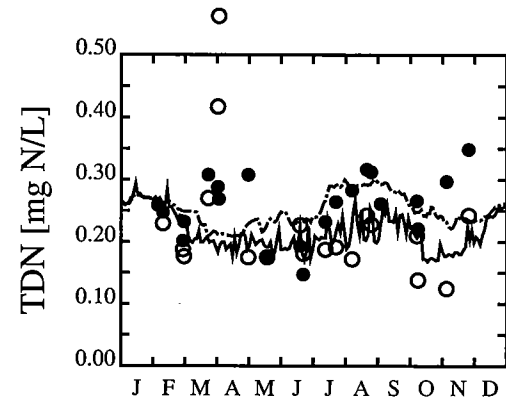
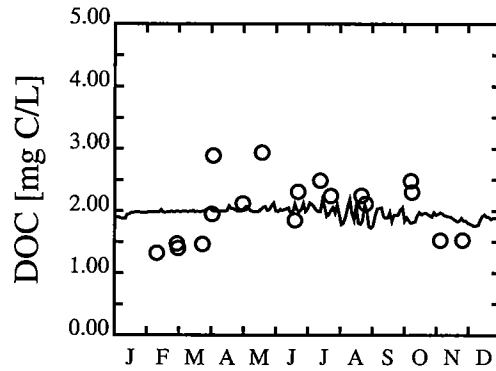
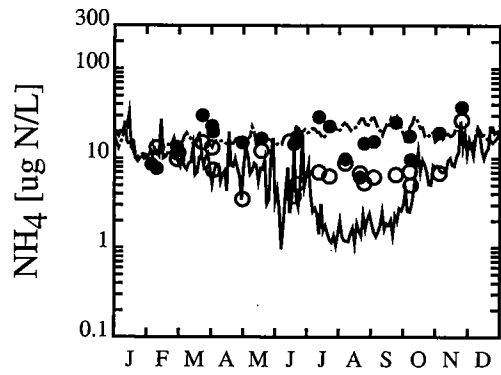
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 — std.dev. Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (30,50) Vs Data Station N13



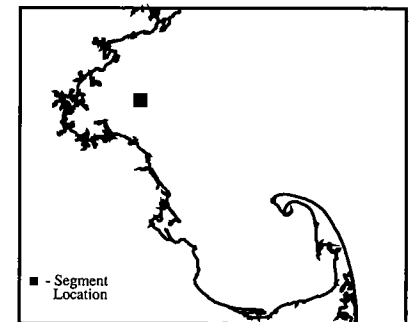
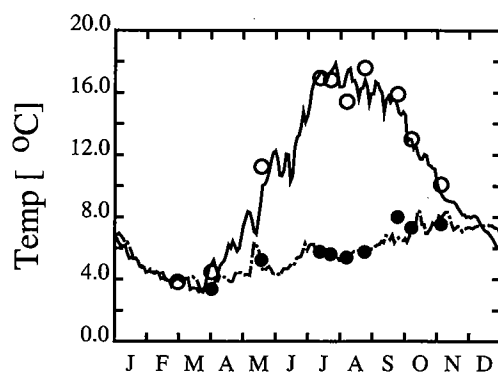
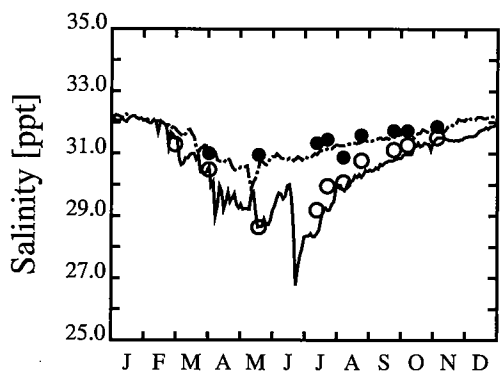
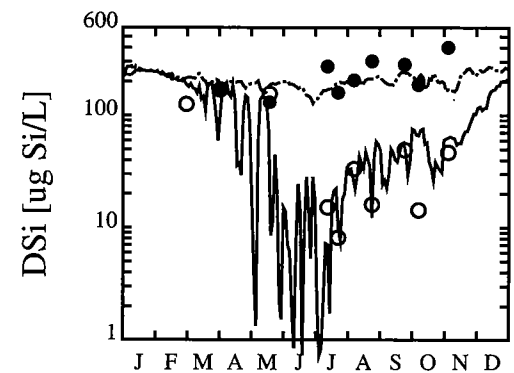
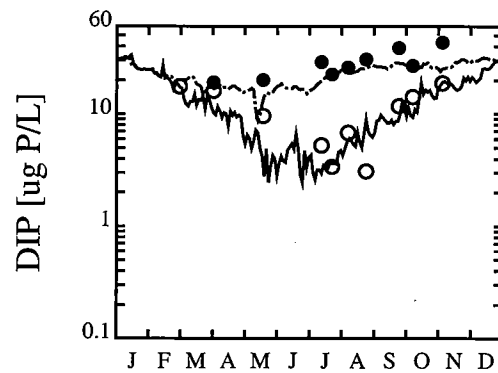
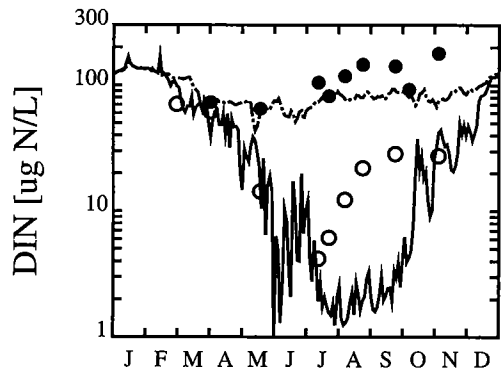
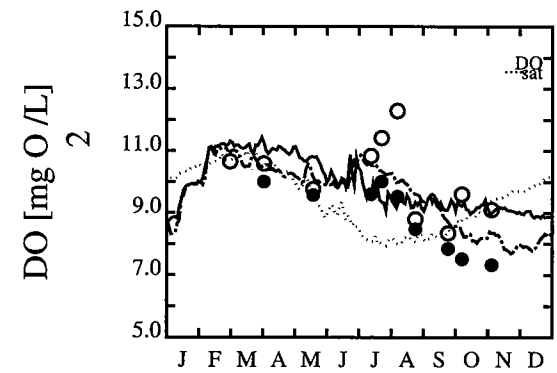
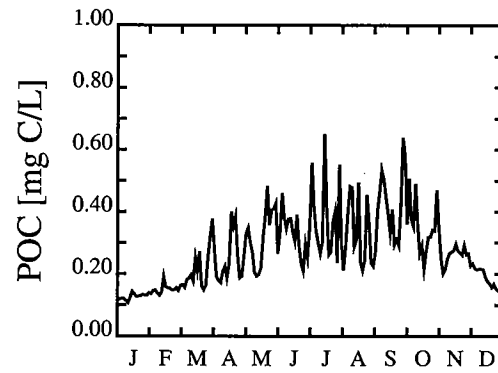
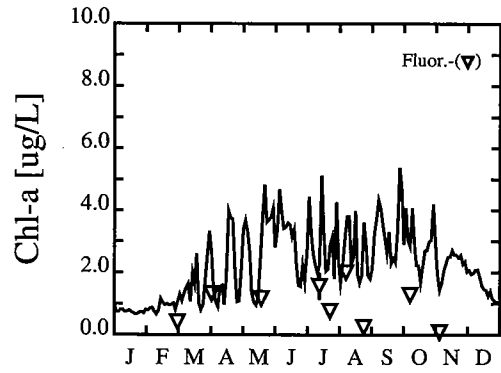
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev. Surface Model
 - Bottom Model

1998 Temporal Calibration Results for Grid Cell (33,46) Vs Data Station N16P



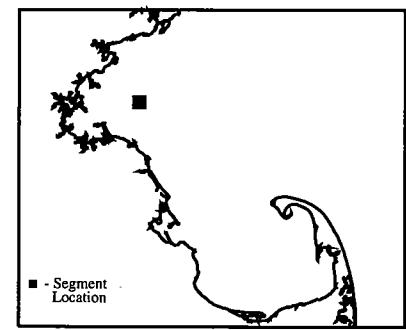
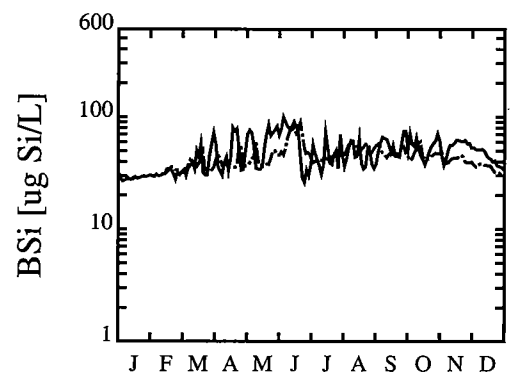
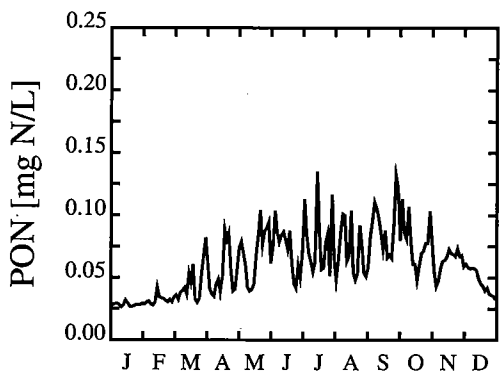
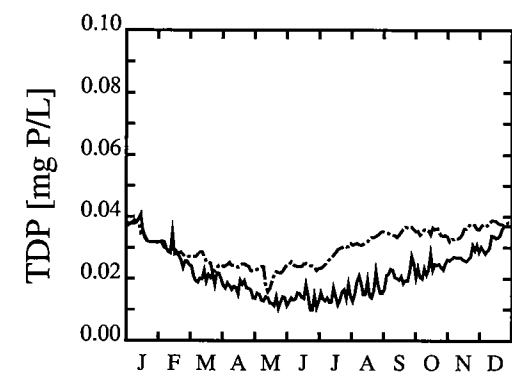
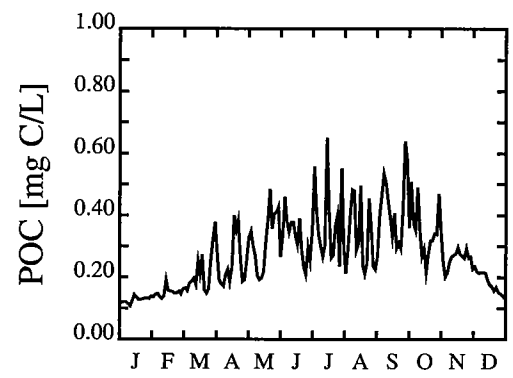
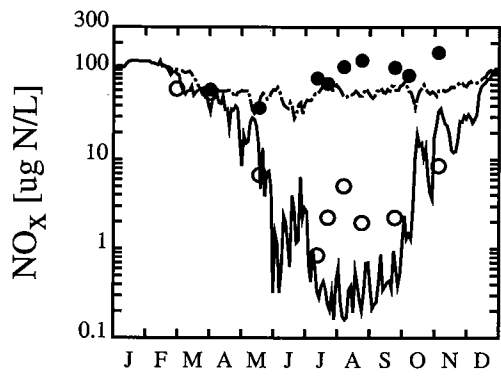
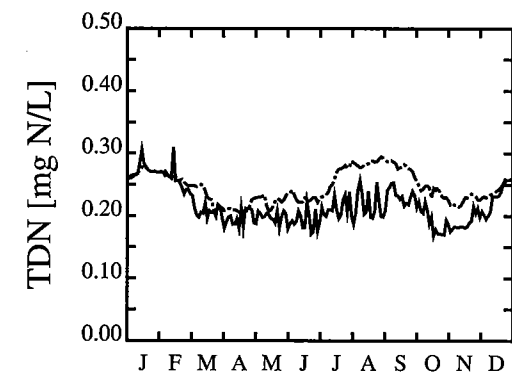
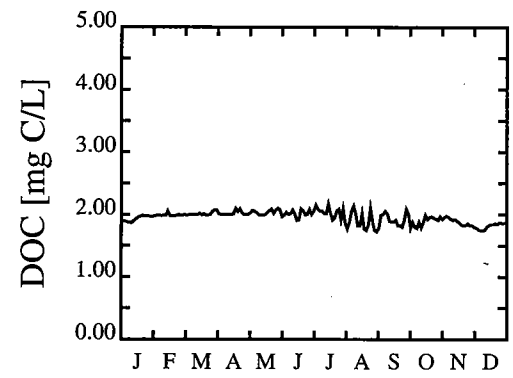
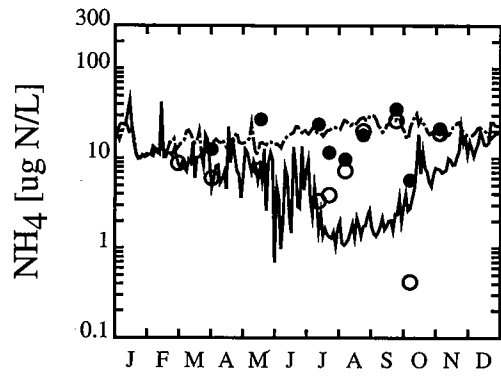
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 — std dev Surface Model
 - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (33,46) Vs Data Station N16P



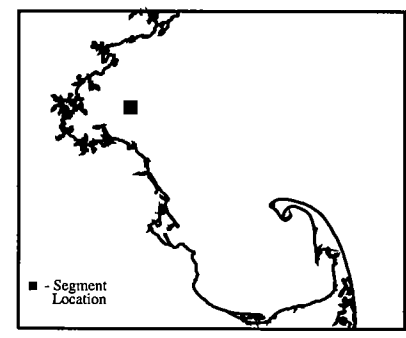
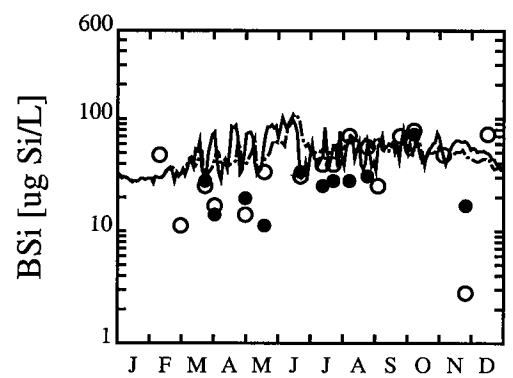
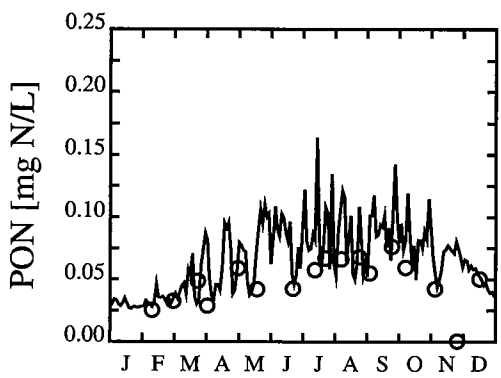
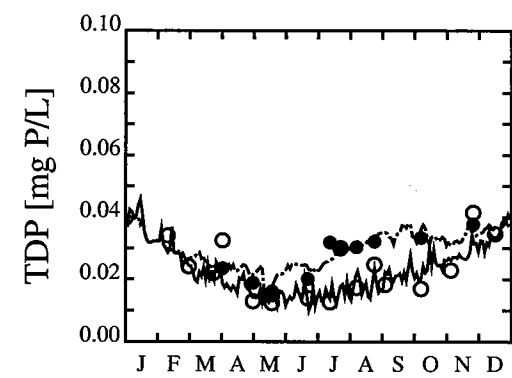
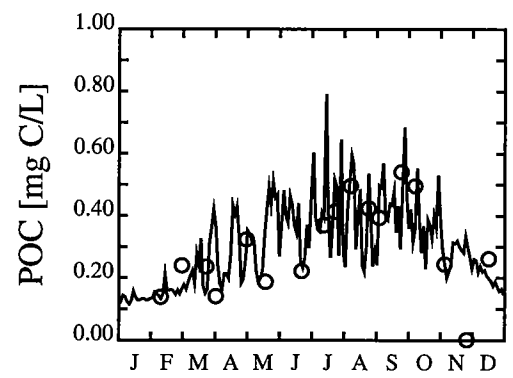
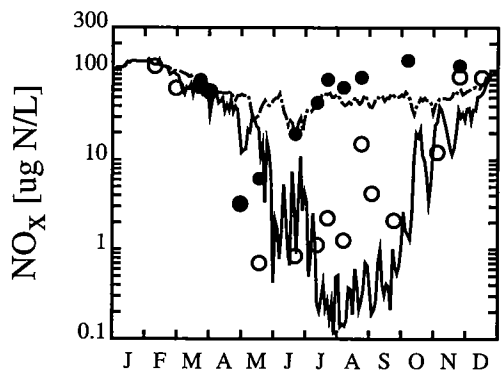
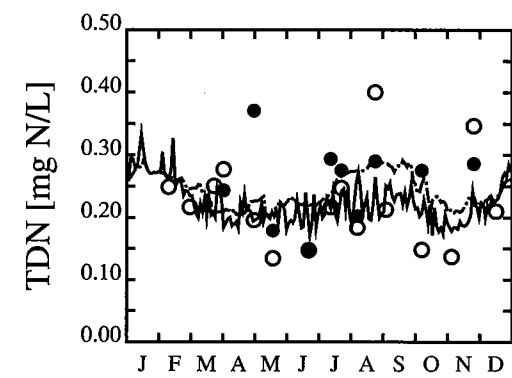
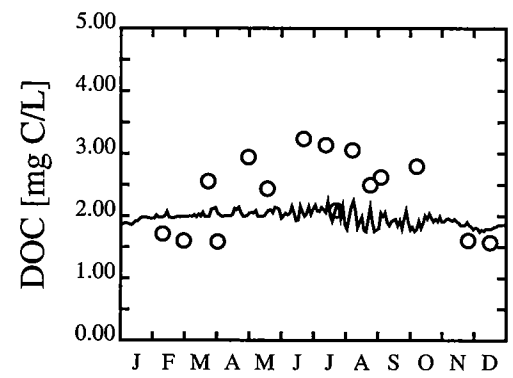
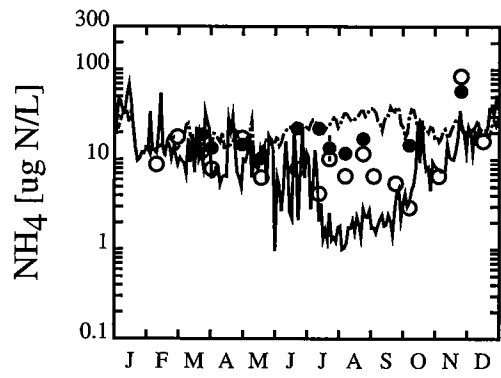
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std dev- Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (31,45) Vs Data Station N17



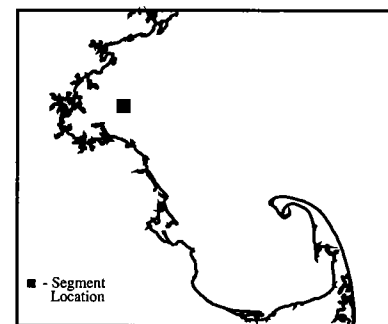
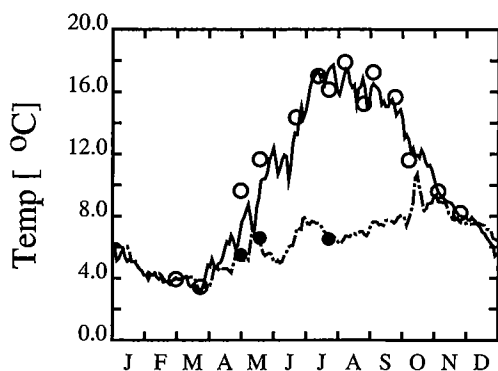
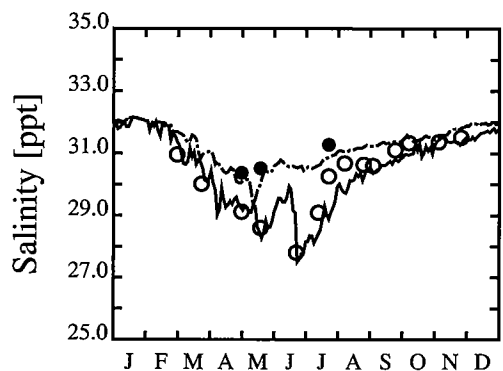
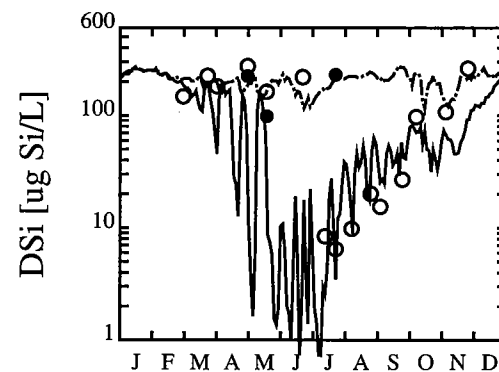
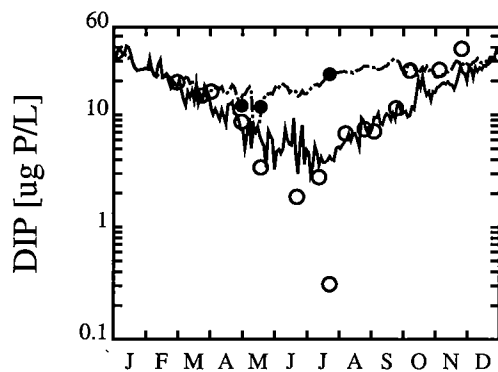
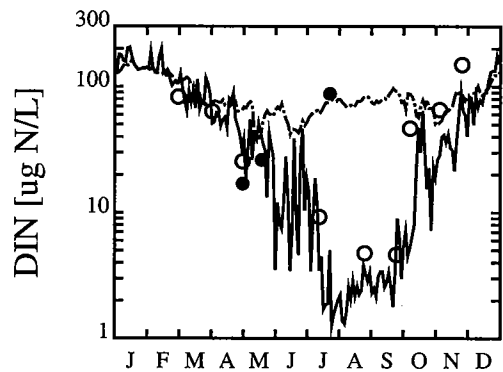
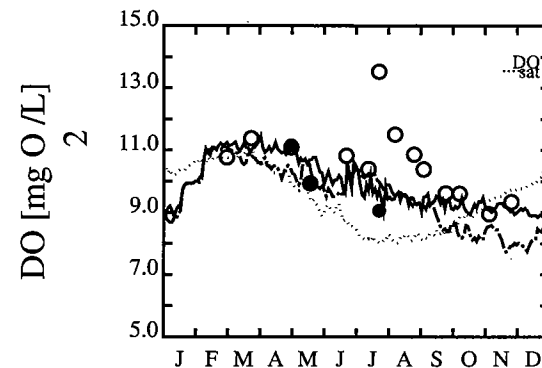
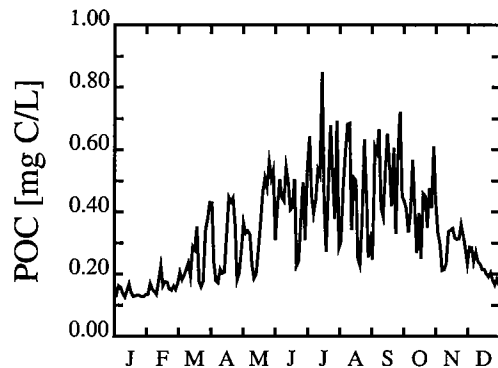
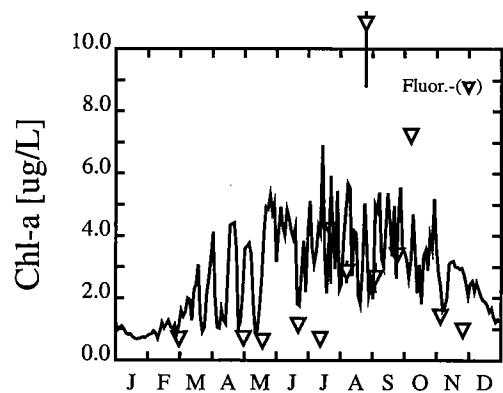
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 --- std.dev Surface Model
 ——— Bottom Model

1998 Temporal Calibration Results for Grid Cell (31,45) Vs Data Station N17



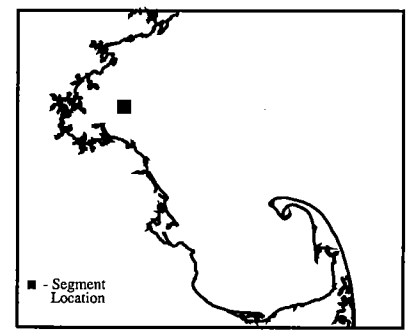
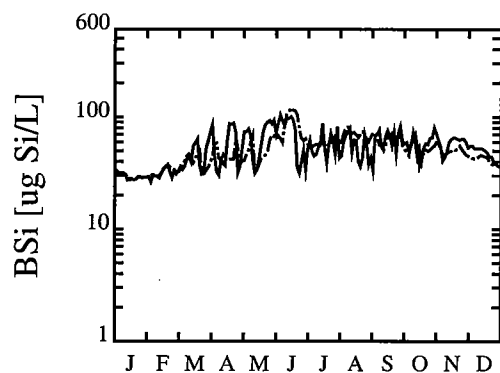
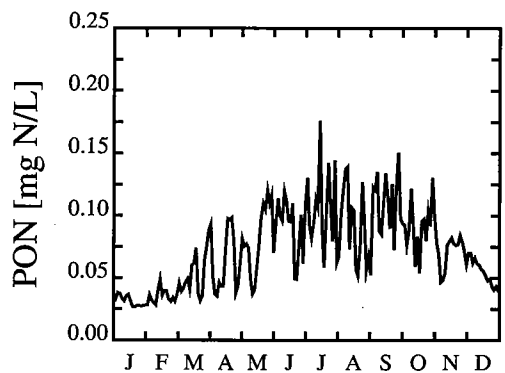
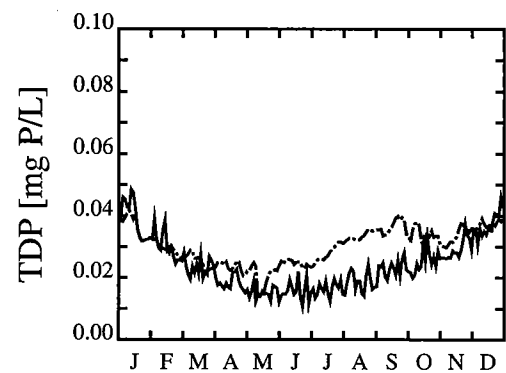
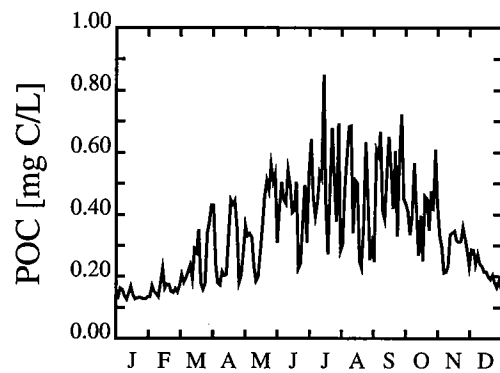
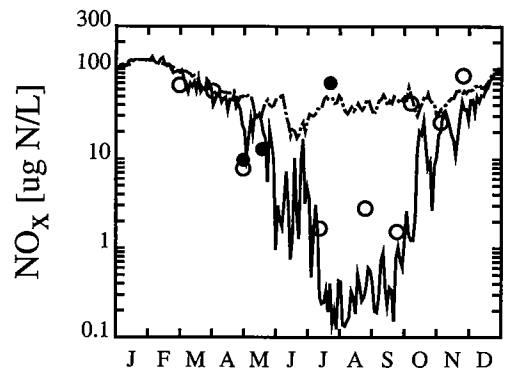
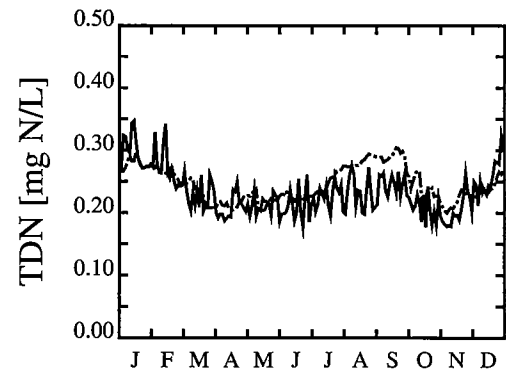
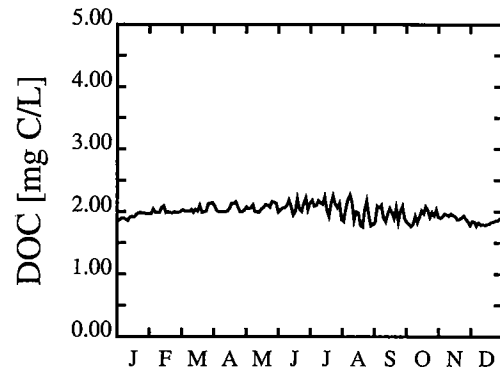
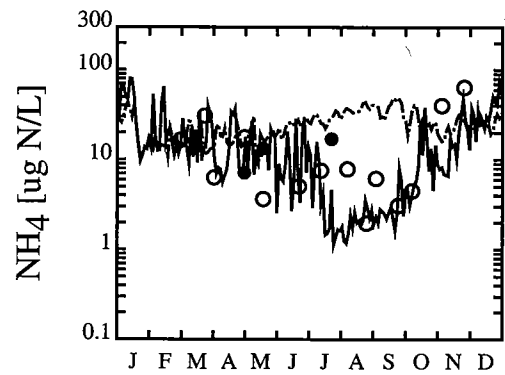
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 -std dev- Surface Model
 - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (29,46) Vs Data Station N18



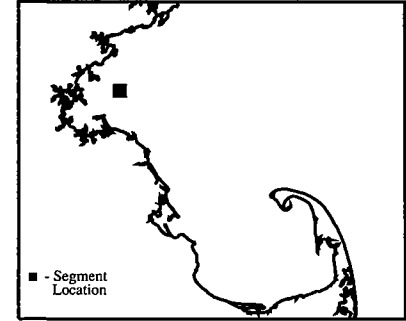
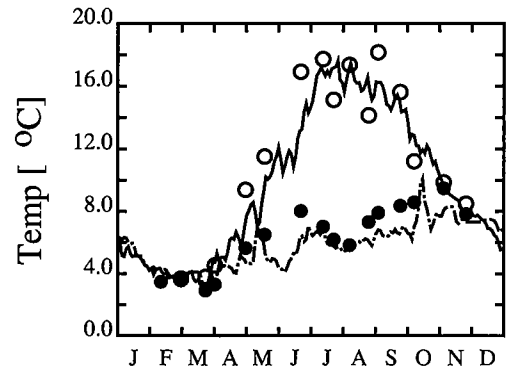
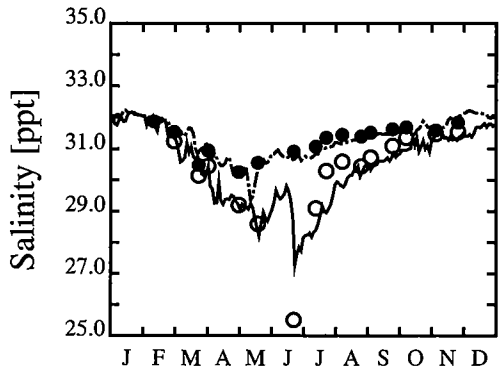
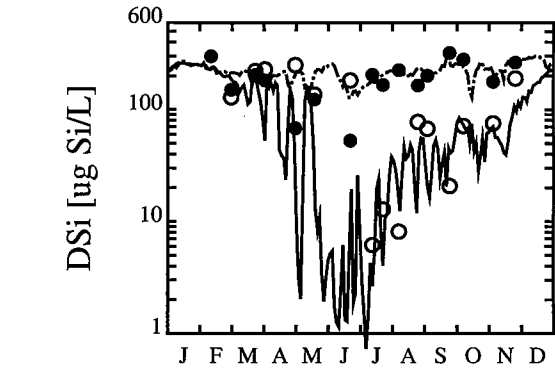
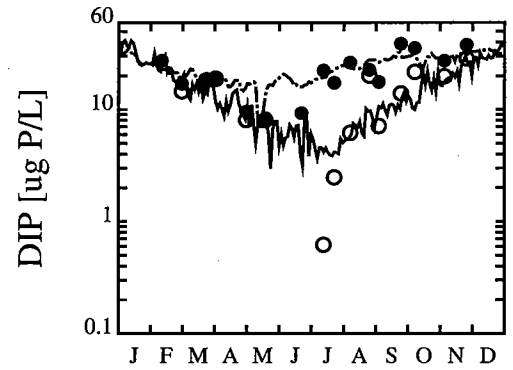
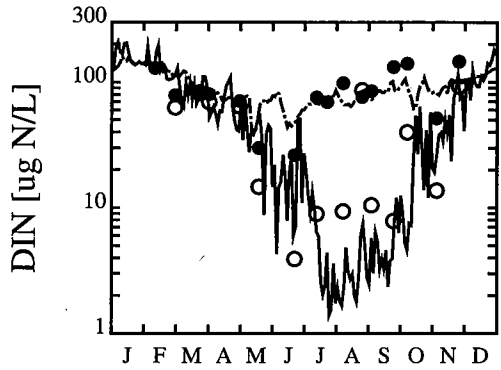
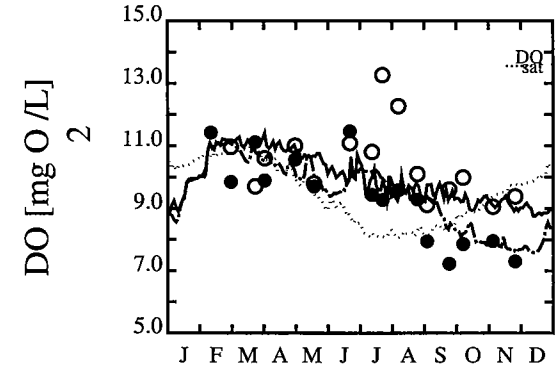
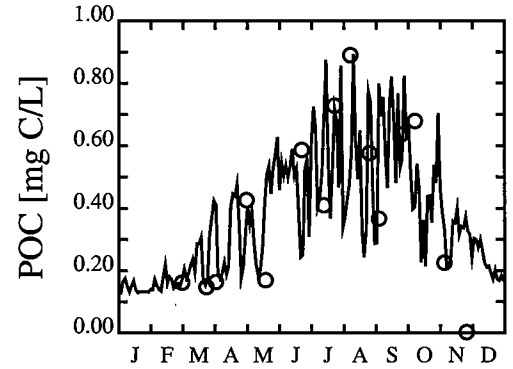
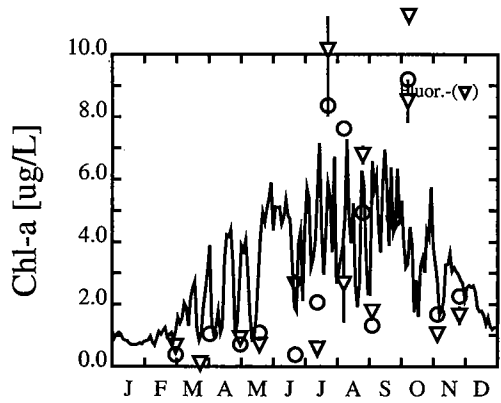
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 — std dev. Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (28,47) Vs Data Station N19



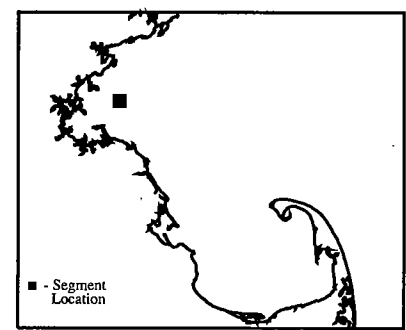
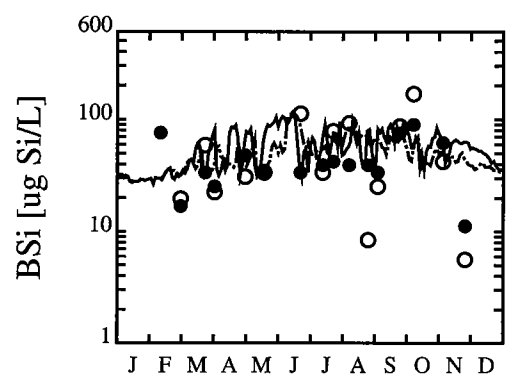
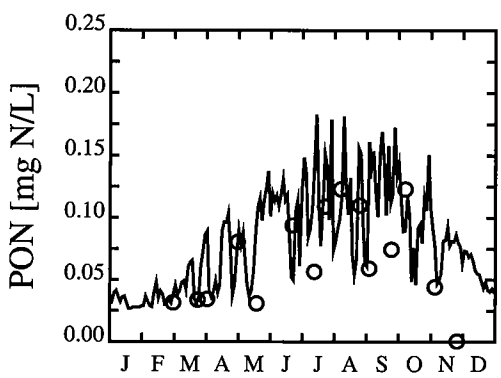
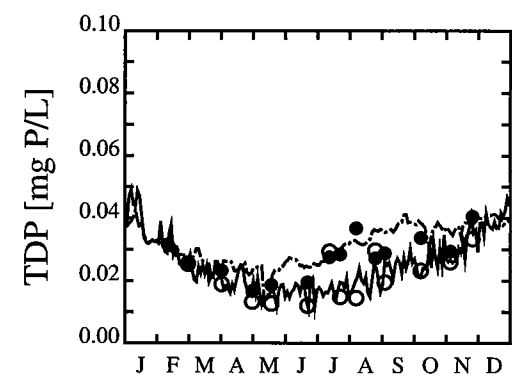
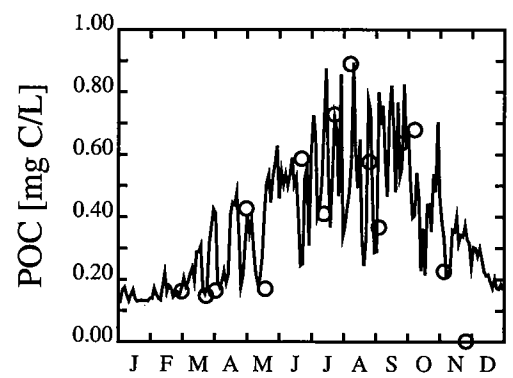
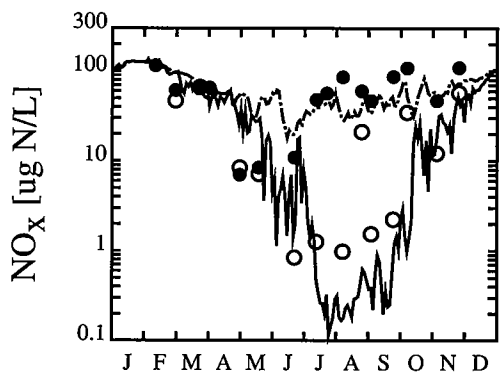
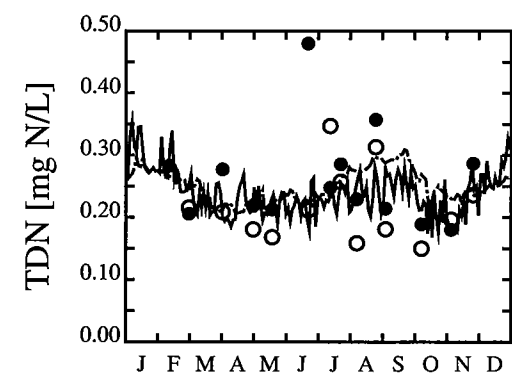
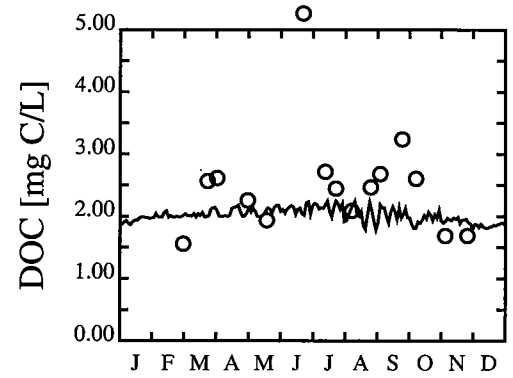
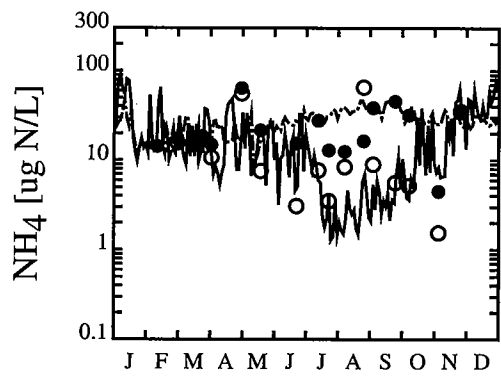
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 — std dev Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (28,47) Vs Data Station N19



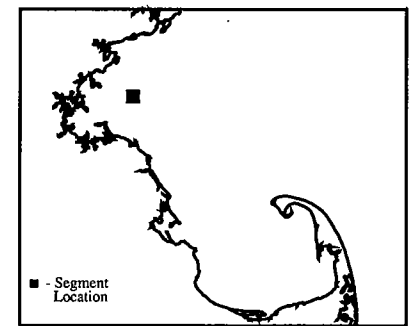
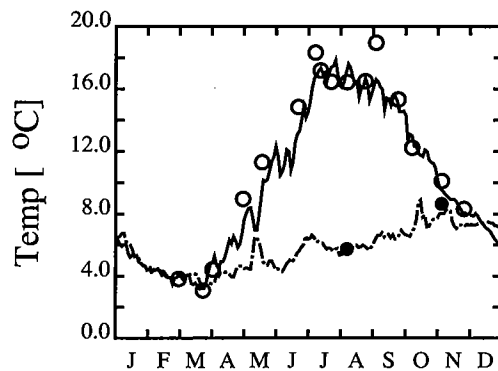
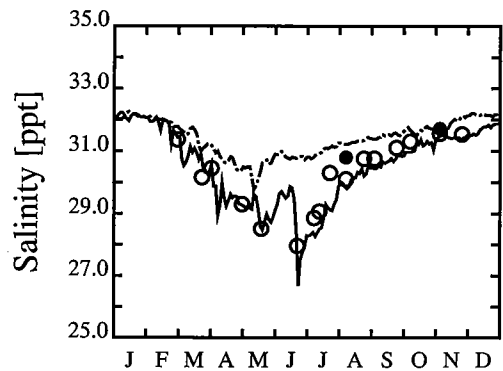
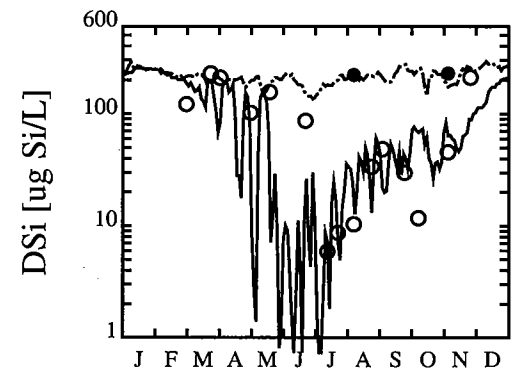
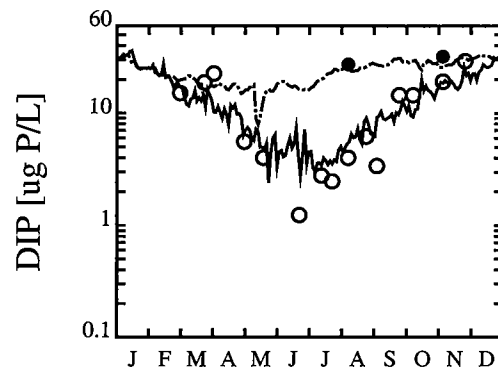
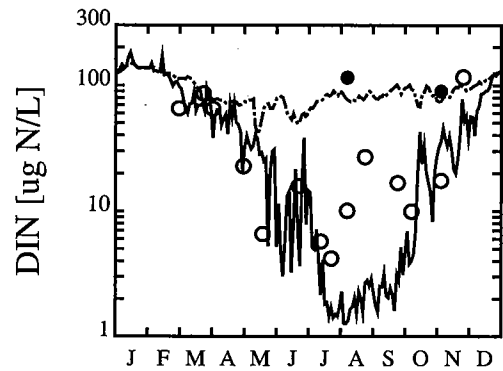
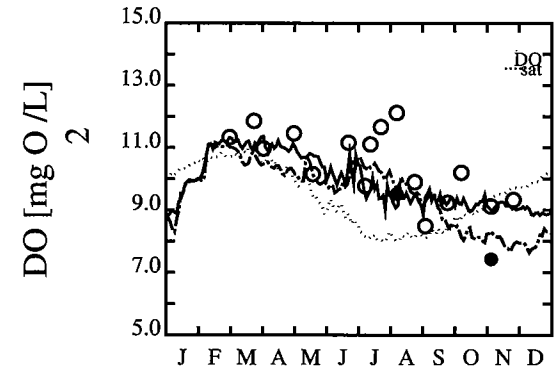
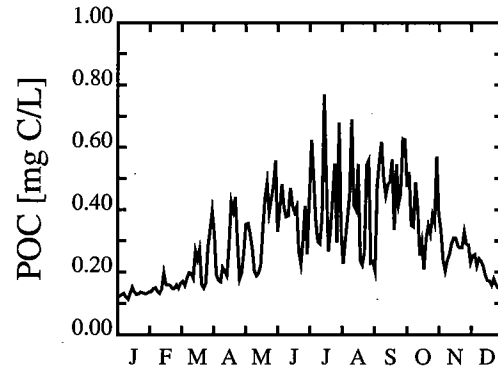
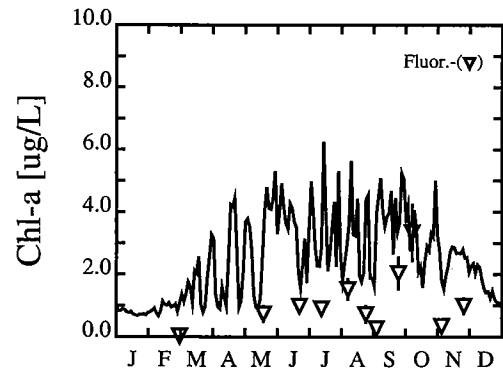
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 --- std.dev. Surface Model
 --- Bottom Model

1998 Temporal Calibration Results for Grid Cell (29,49) Vs Data Station N20P



----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - std.dev Surface Model
 - - - - - Bottom Model

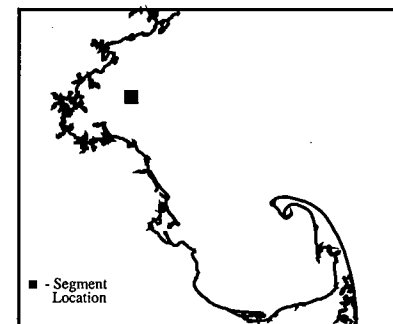
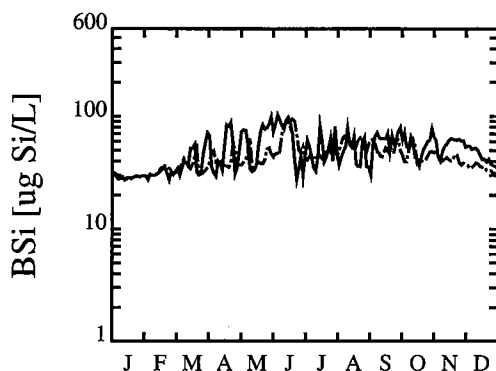
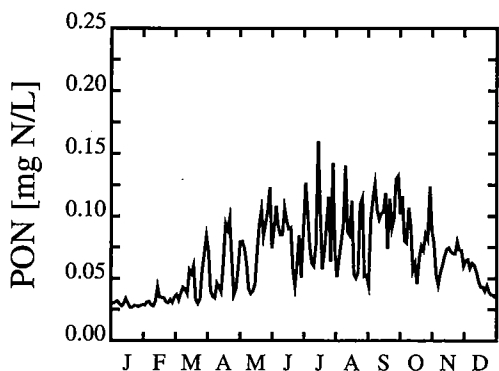
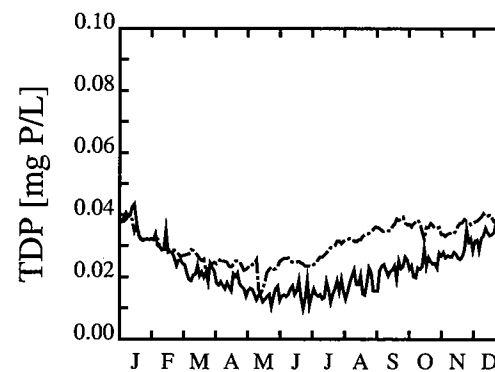
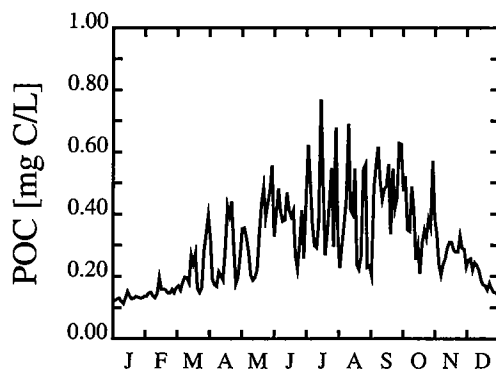
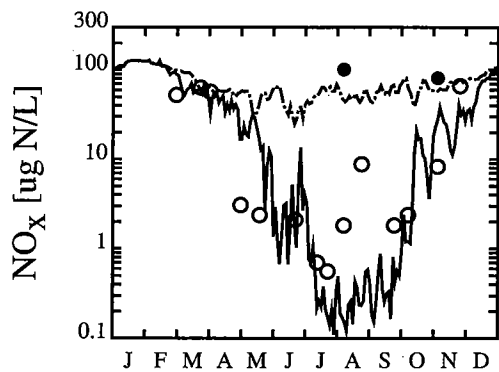
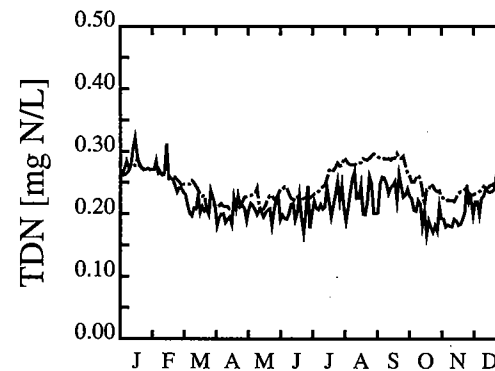
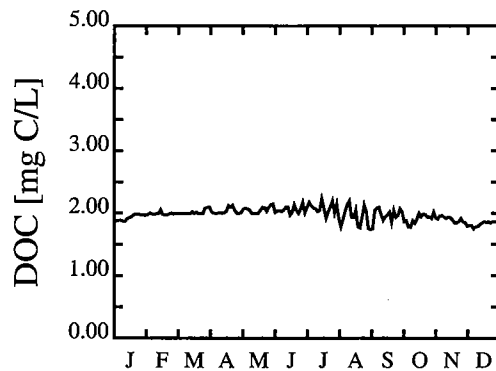
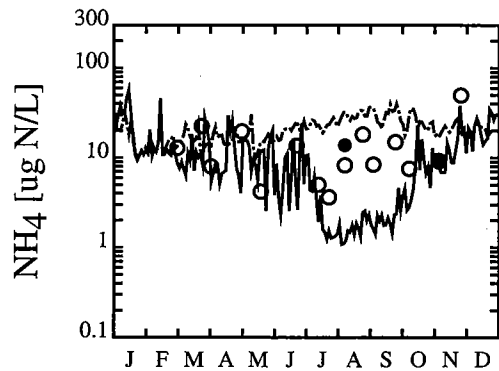
1998 Temporal Calibration Results for Grid Cell (29,49) Vs Data Station N20P



LEGEND

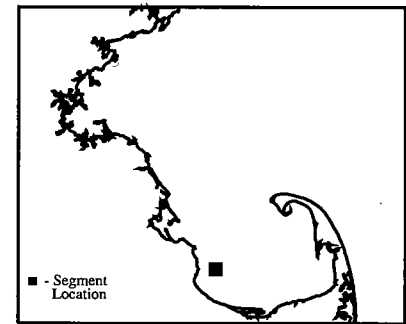
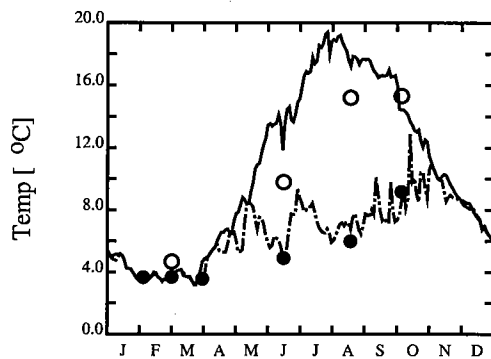
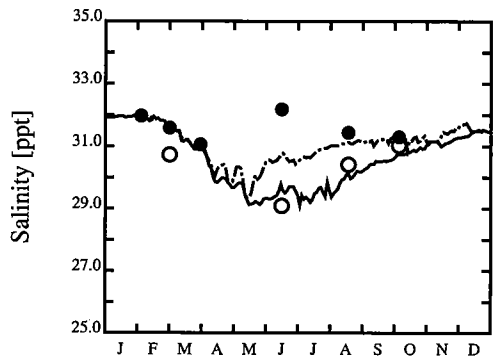
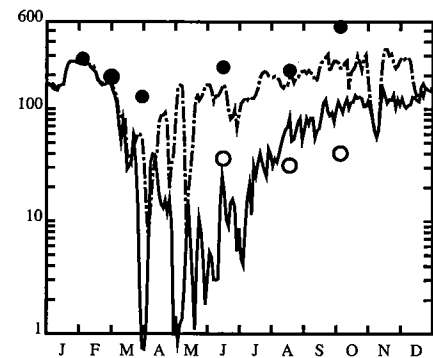
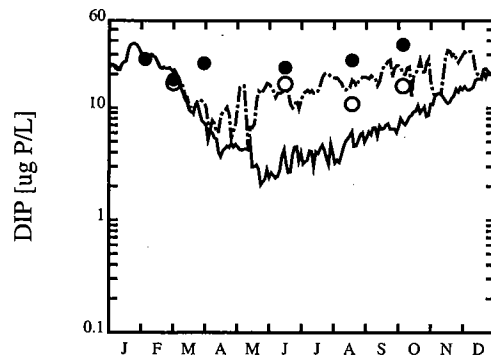
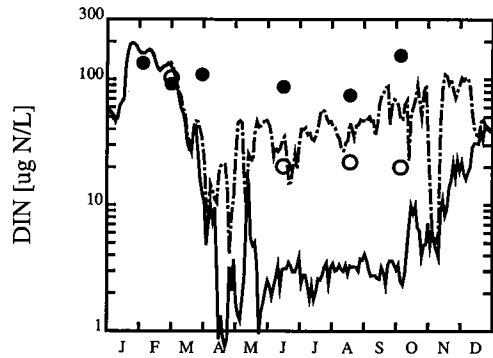
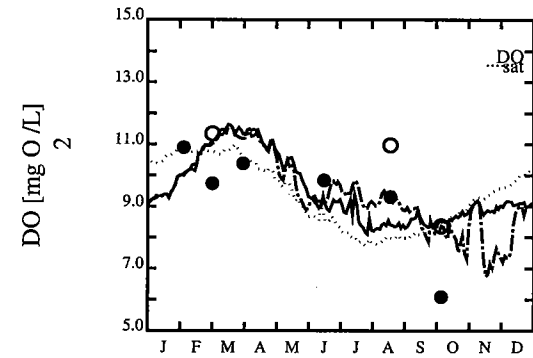
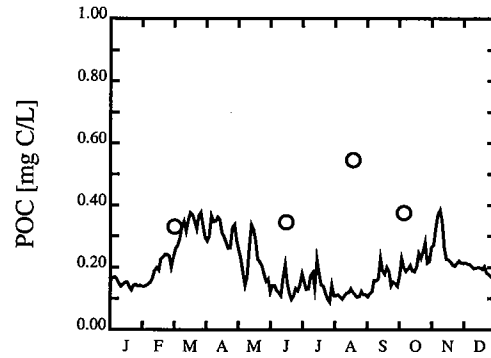
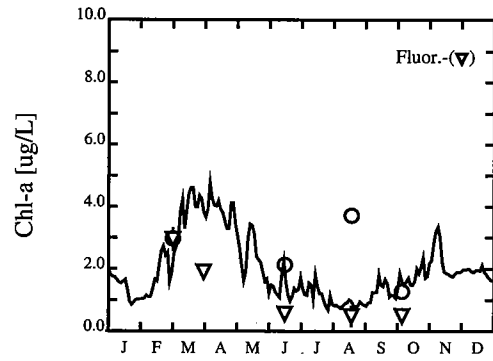
- +/- Surface Data
- Bottom Data
- std.dev. Surface Model
- Bottom Model

1998 Temporal Calibration Results for Grid Cell (31,47) Vs Data Station N21



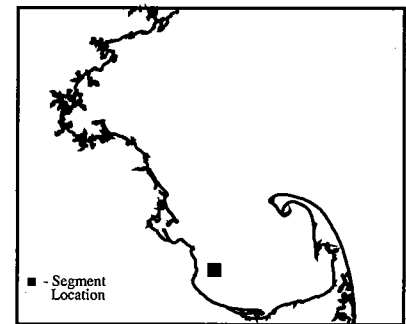
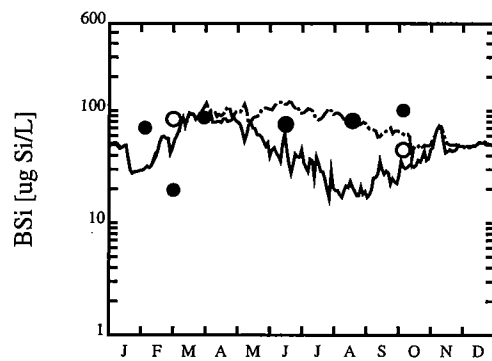
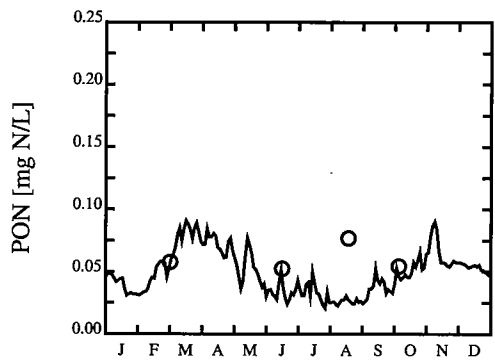
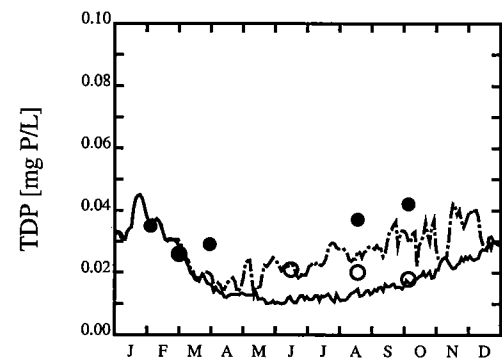
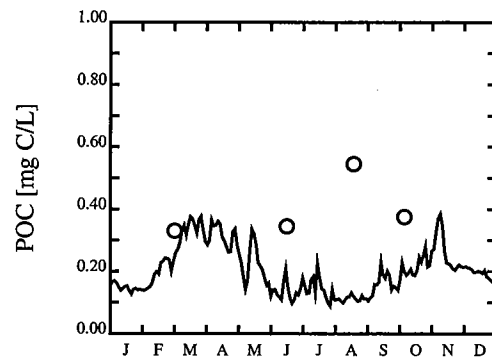
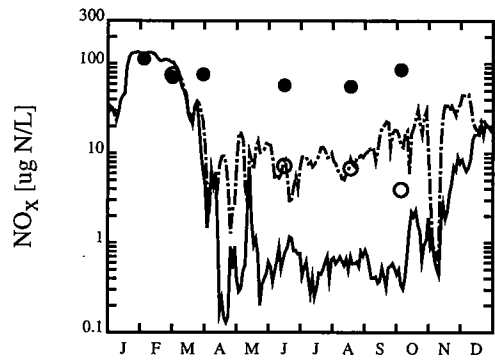
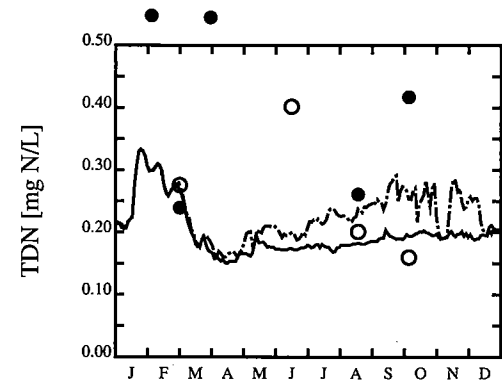
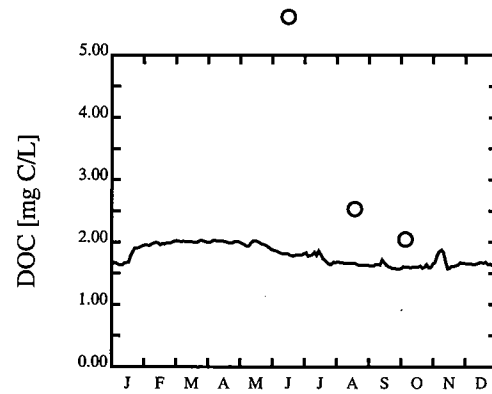
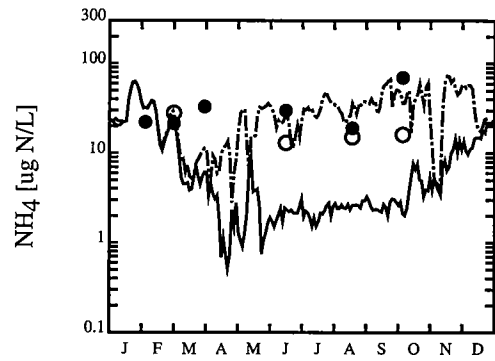
----- LEGEND -----
 ○ +/- Surface Data
 ● +/- Bottom Data
 --- std.dev. Surface Model
 --- Bottom Model

1998 Temporal Calibration Results for Grid Cell (31,47) Vs Data Station N21



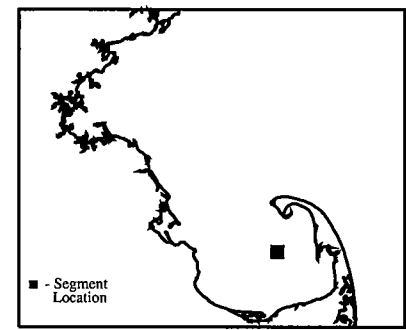
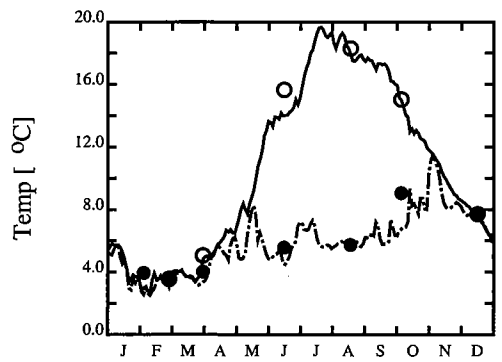
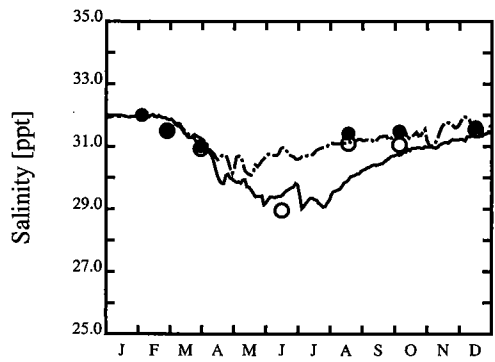
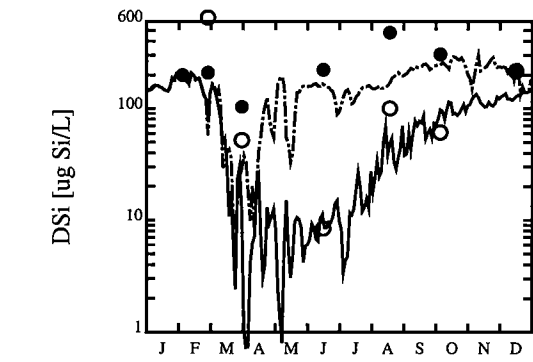
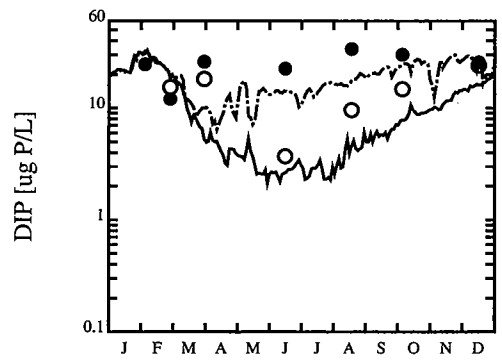
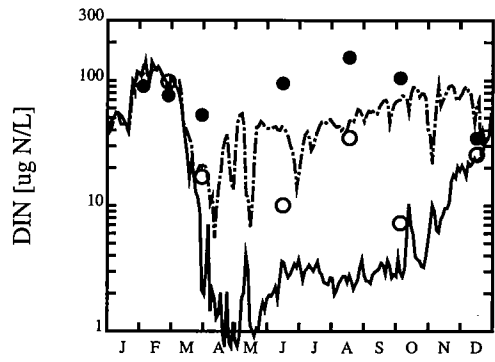
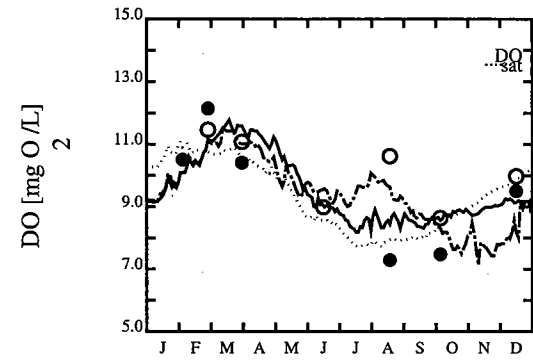
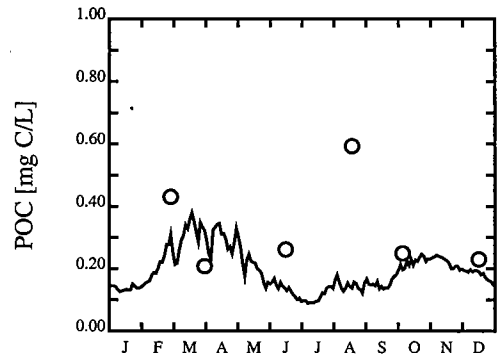
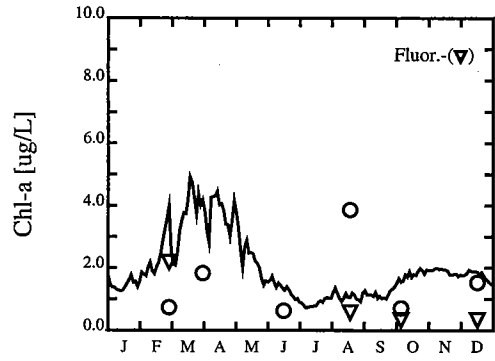
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev- Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (18,11) Vs Data Station F01P



----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 — std dev. Surface Model
 - - - - - Bottom Model

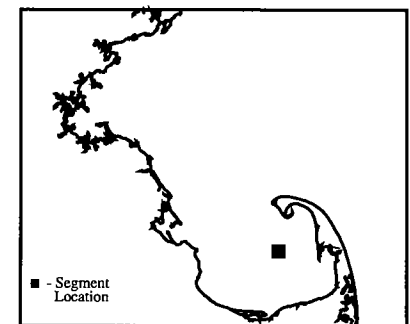
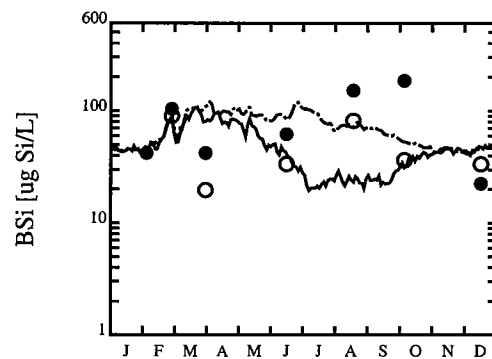
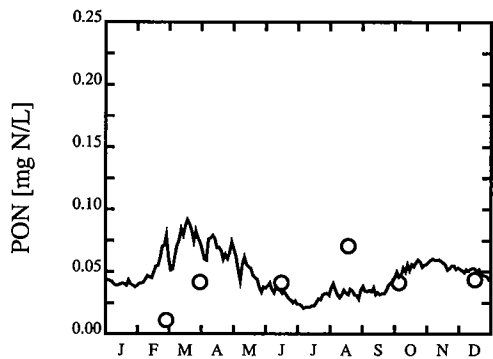
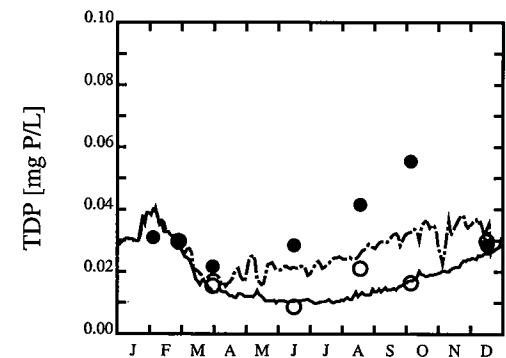
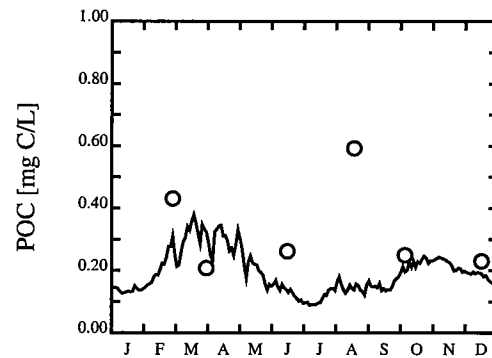
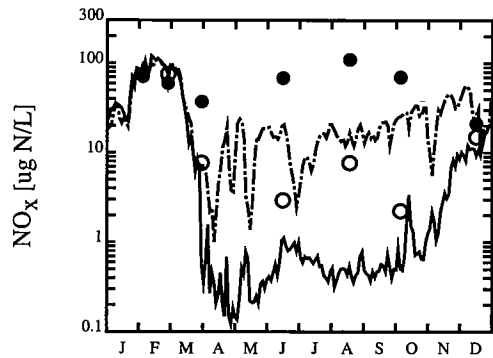
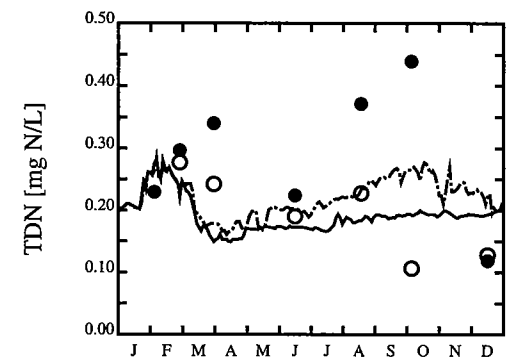
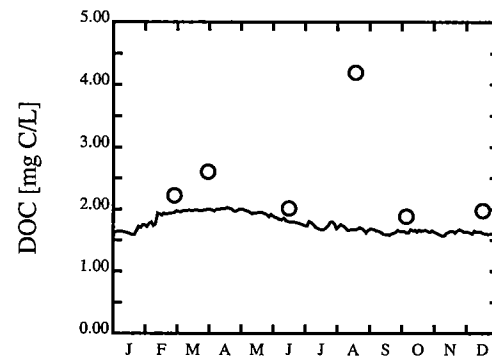
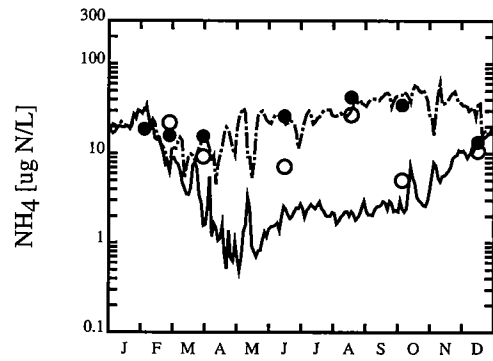
1998 Temporal Calibration Results for
 Grid Cell (18,11) Vs Data Station F01P



LEGEND

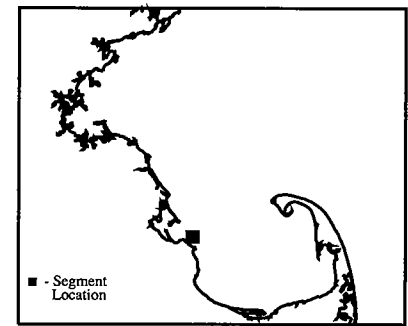
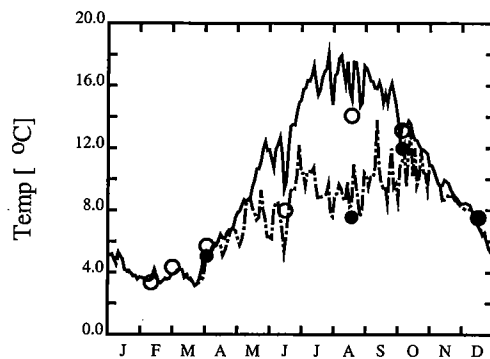
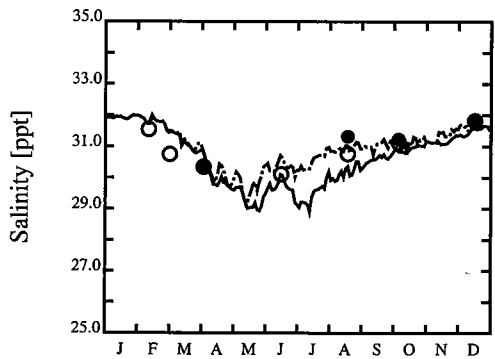
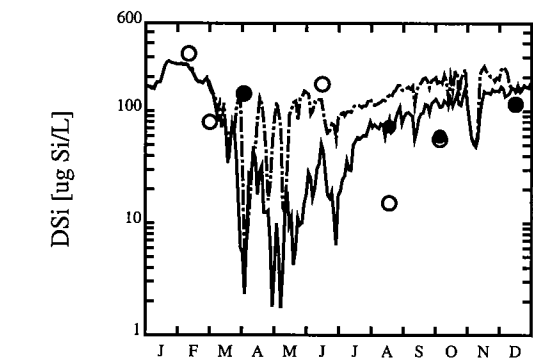
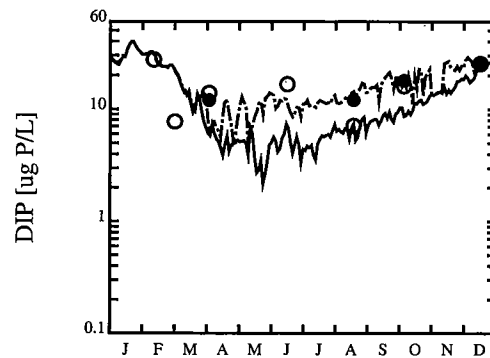
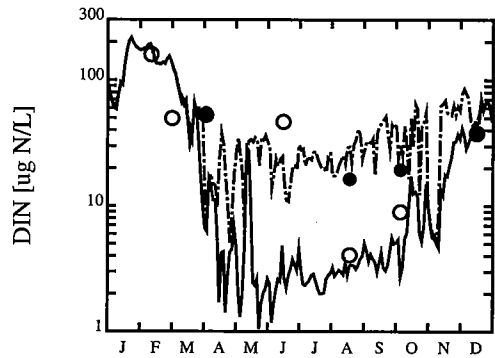
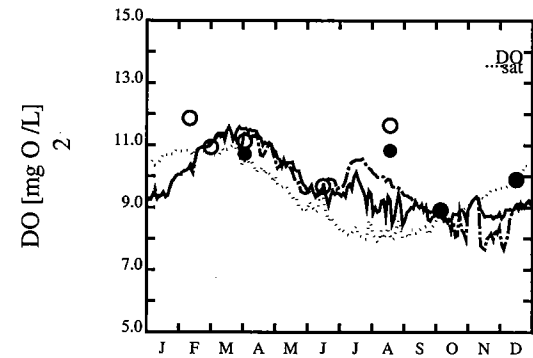
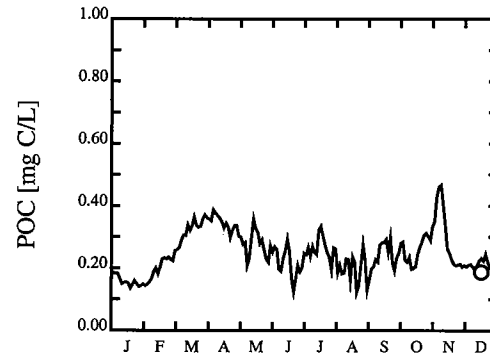
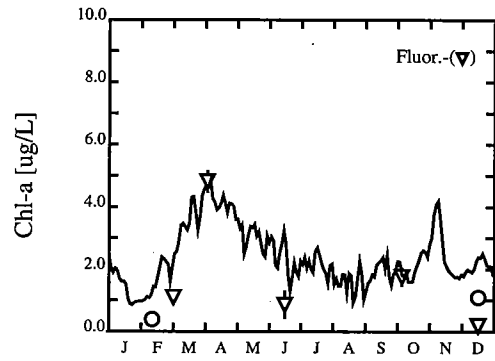
- +/- Surface Data
- Bottom Data
- std.dev Surface Model
- - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (38,11) Vs Data Station F02P



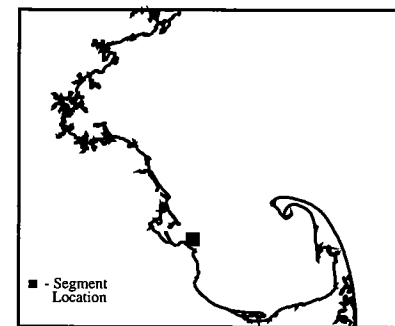
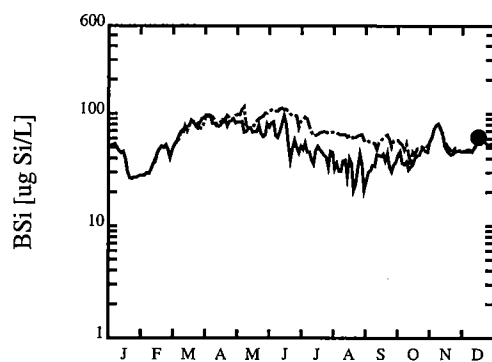
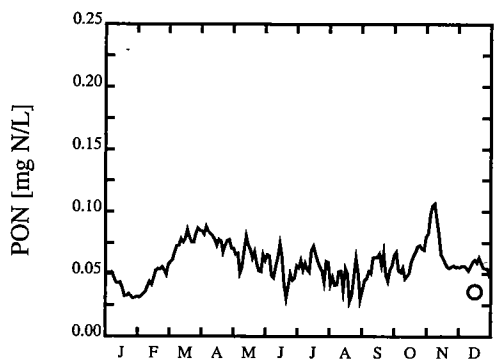
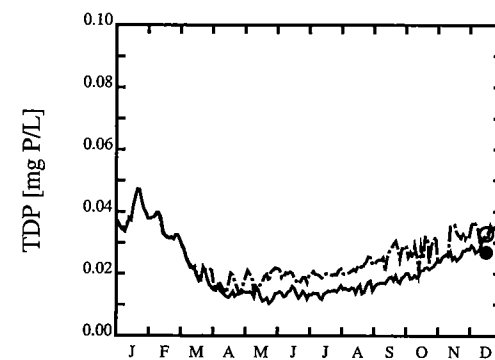
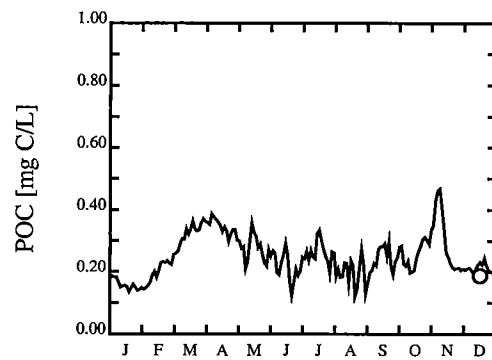
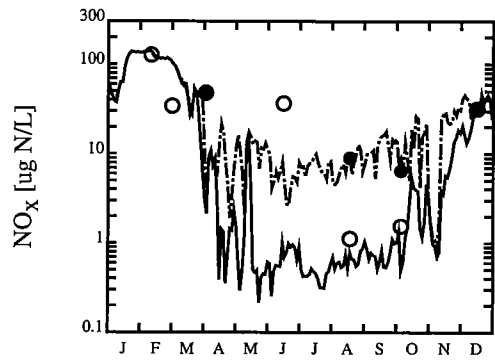
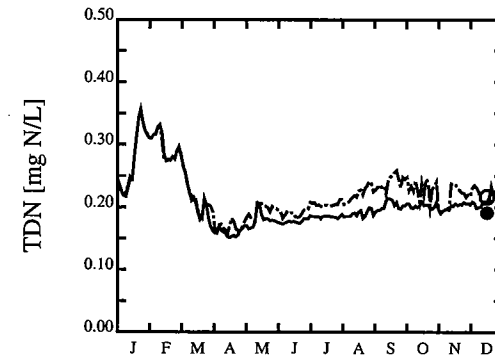
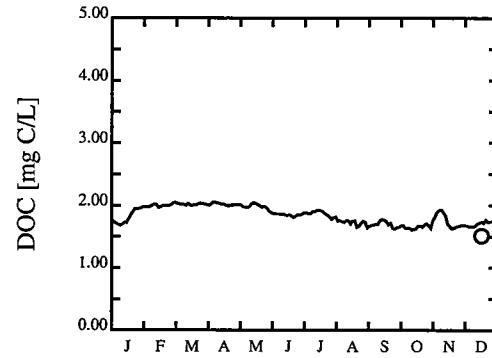
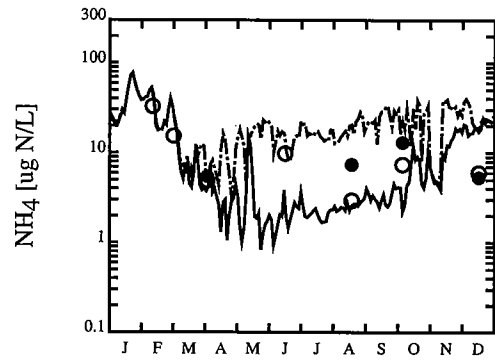
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev. Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (38,11) Vs Data Station F02P



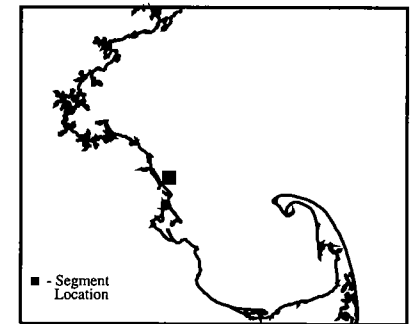
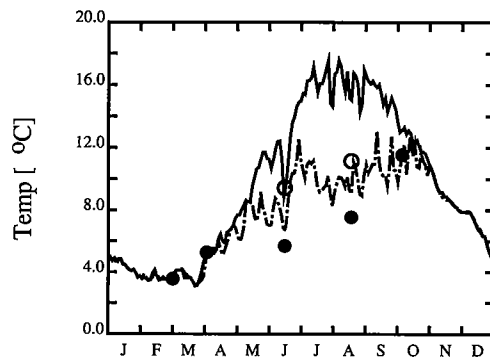
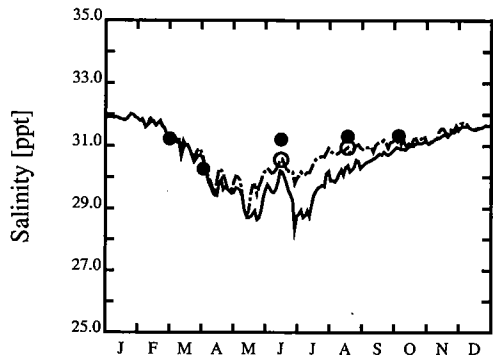
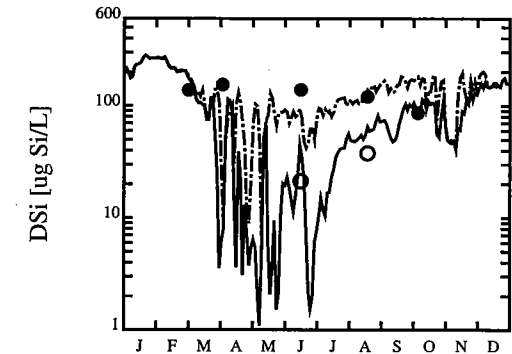
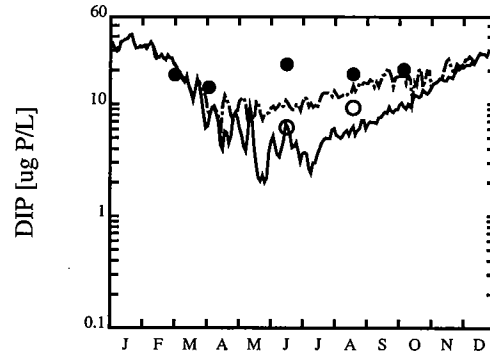
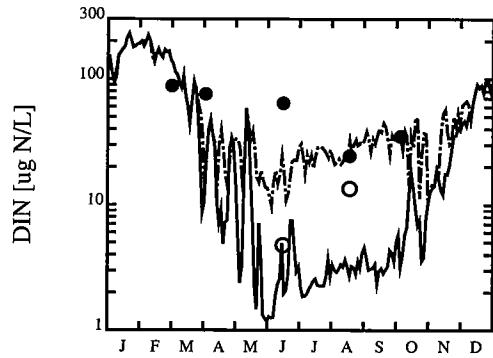
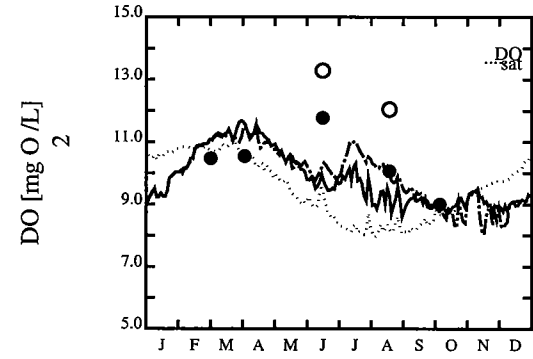
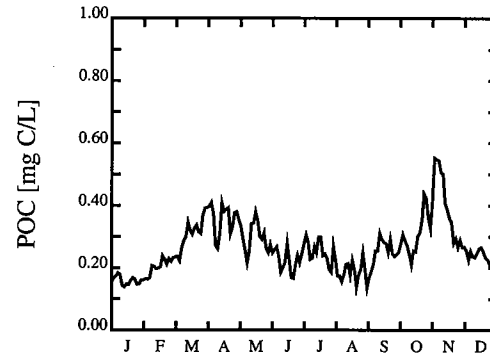
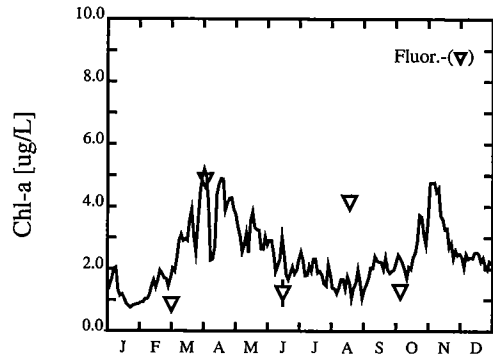
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev. Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (15,18) Vs Data Station F03



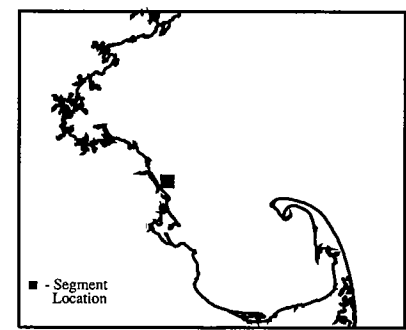
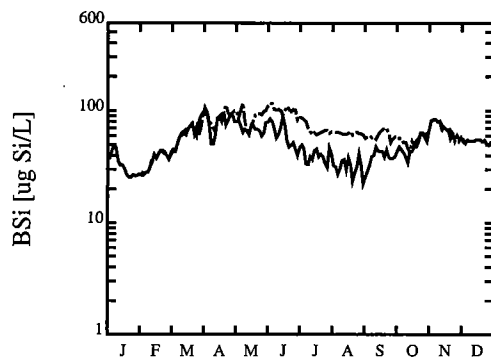
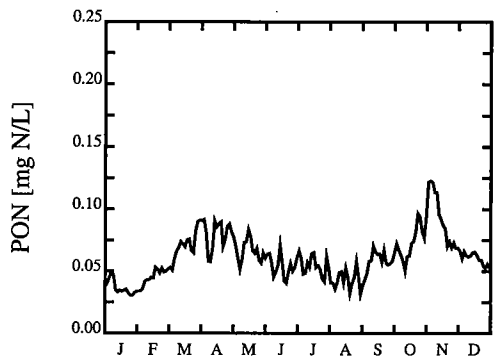
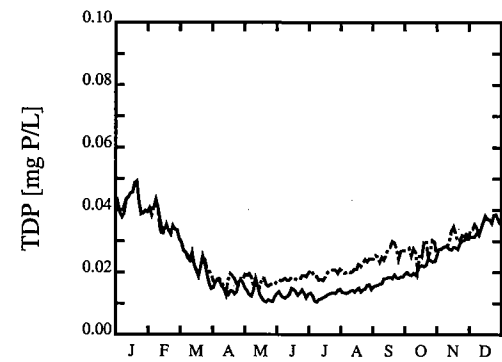
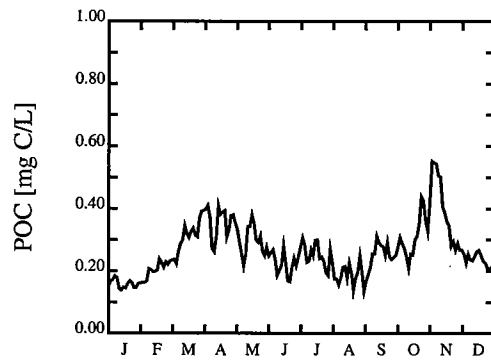
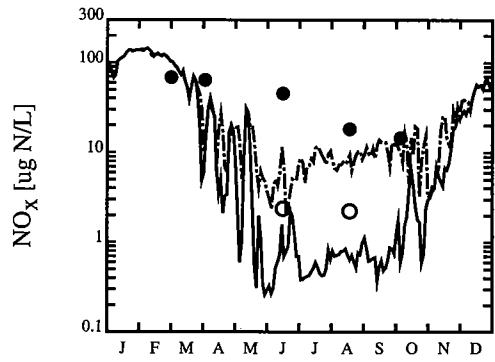
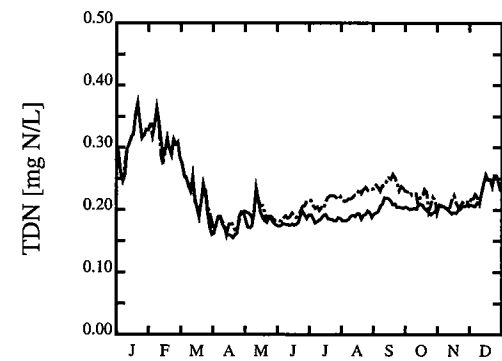
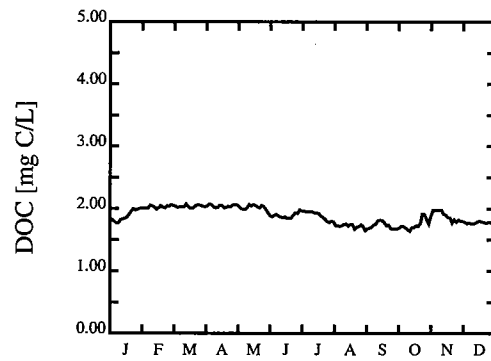
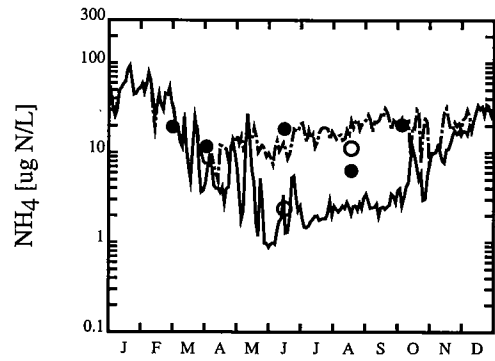
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 . std dev. Surface Model
 — Surface Model
 - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (15,18) Vs Data Station F03



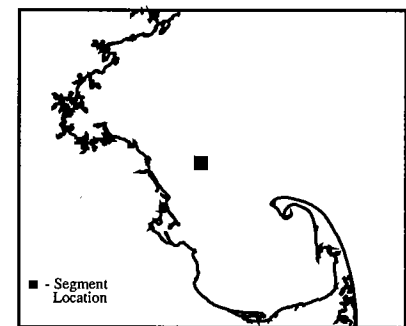
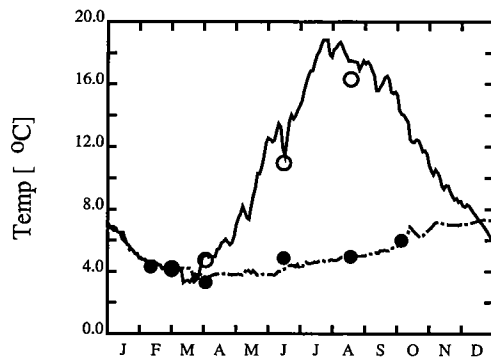
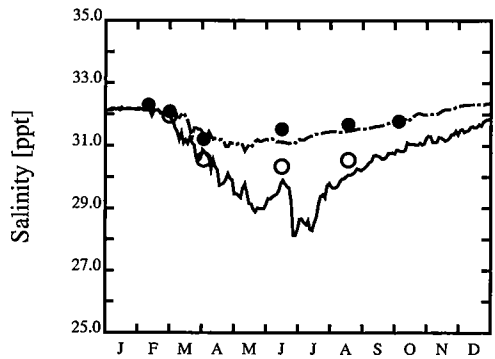
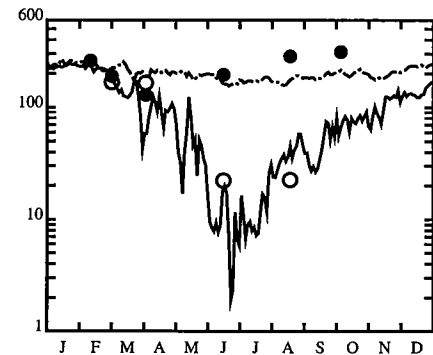
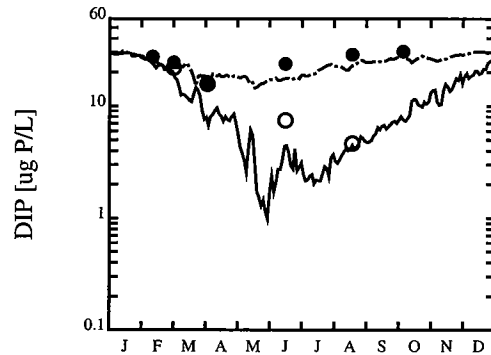
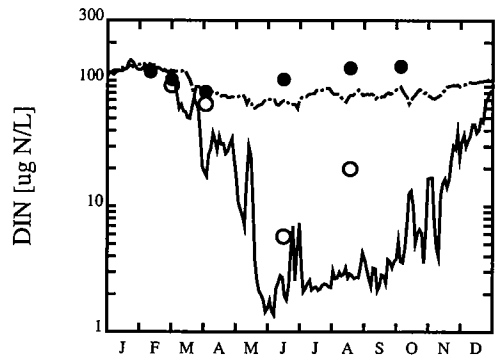
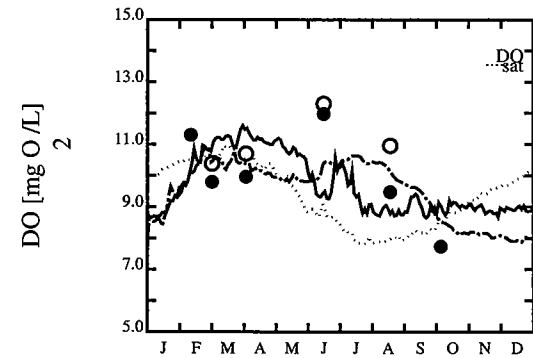
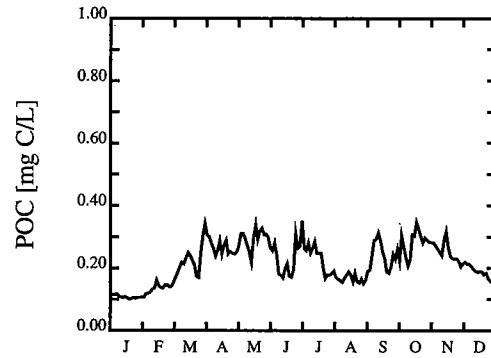
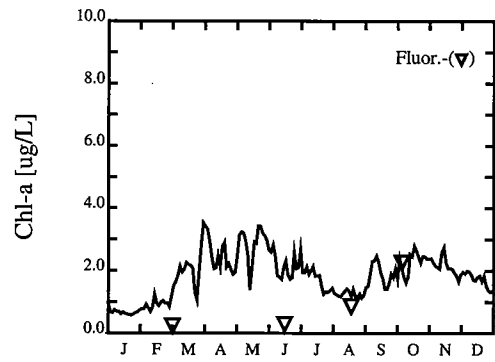
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev- Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (19,30) Vs Data Station F05



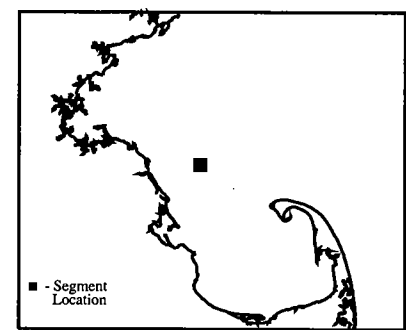
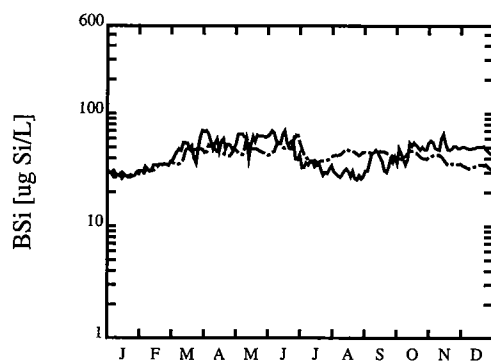
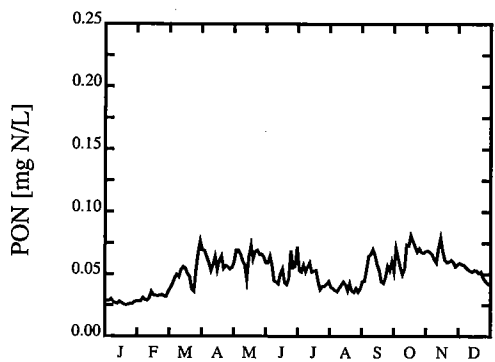
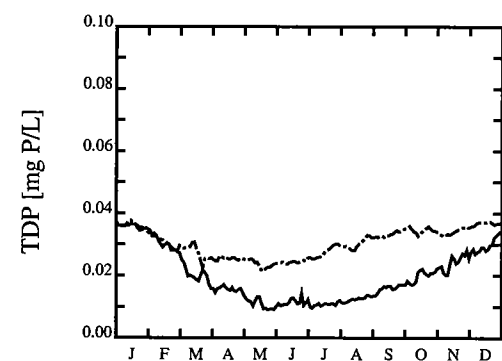
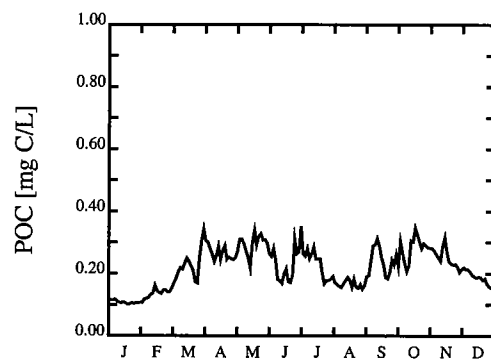
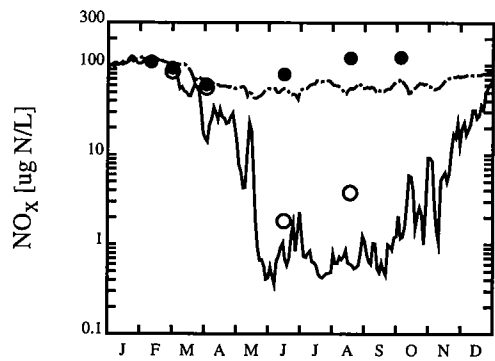
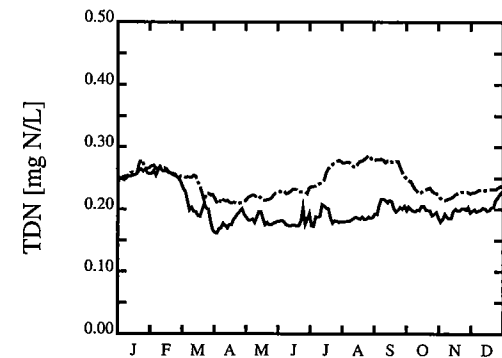
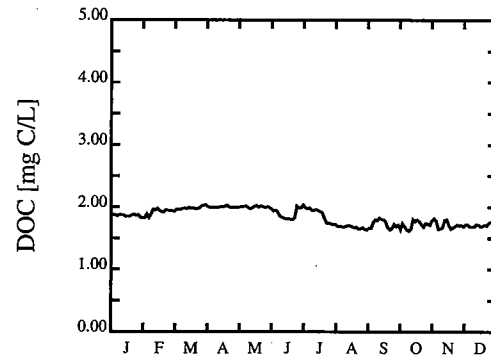
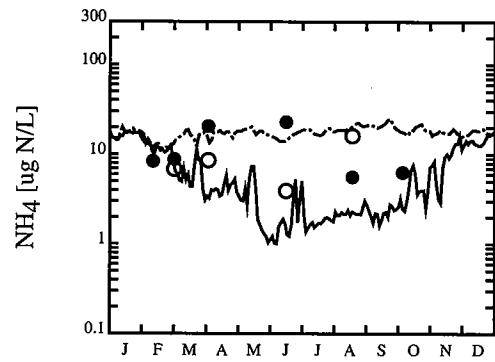
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std dev- Surface Model
 - Bottom Model

1998 Temporal Calibration Results for Grid Cell (19,30) Vs Data Station F05



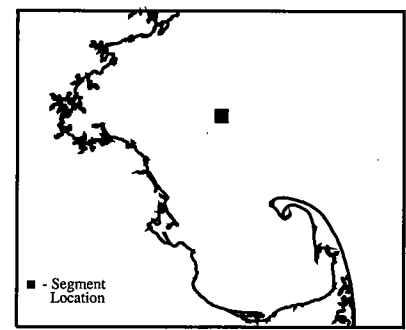
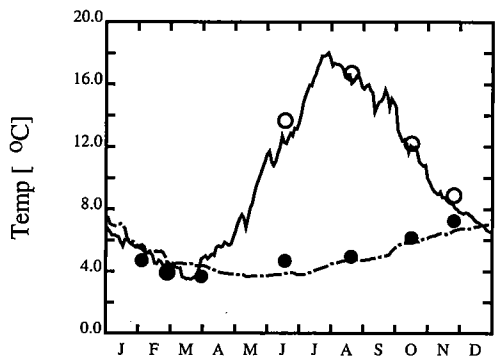
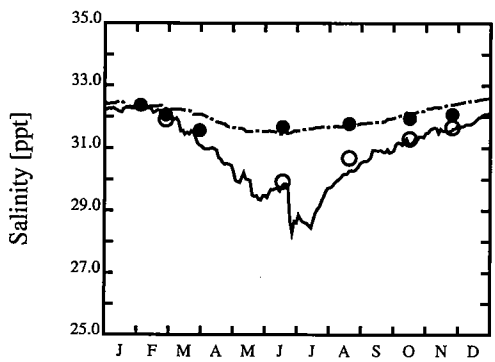
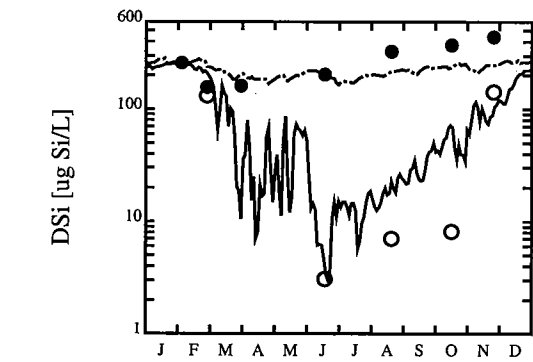
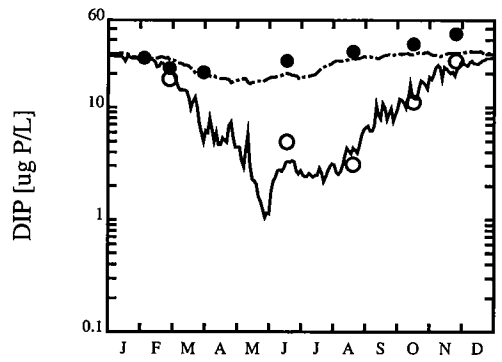
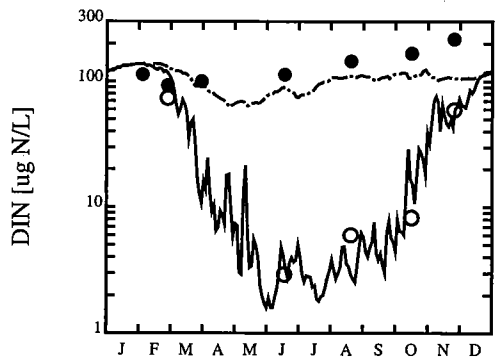
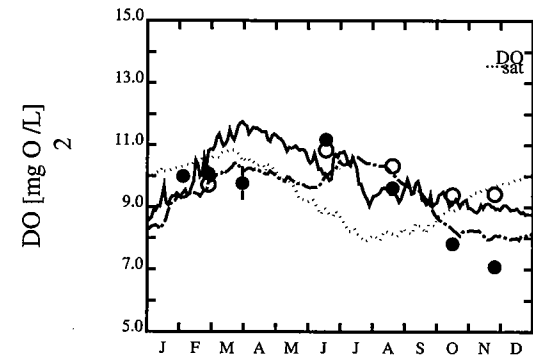
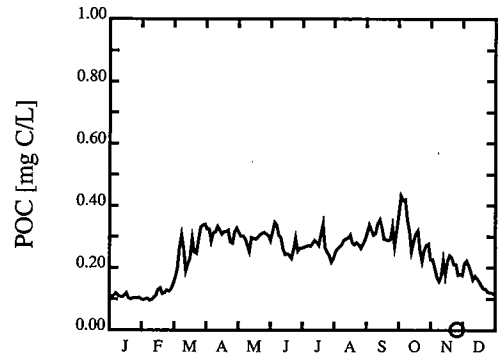
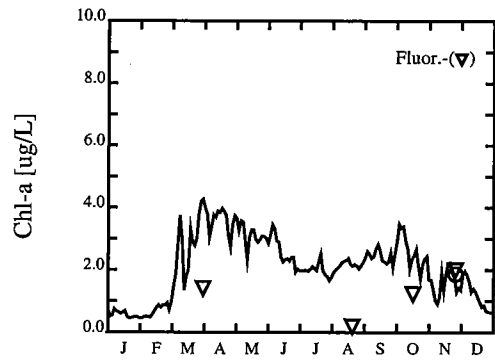
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std dev Surface Model
 - Bottom Model

1998 Temporal Calibration Results for Grid Cell (31,29) Vs Data Station F07



----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev Surface Model
 - - - Bottom Model

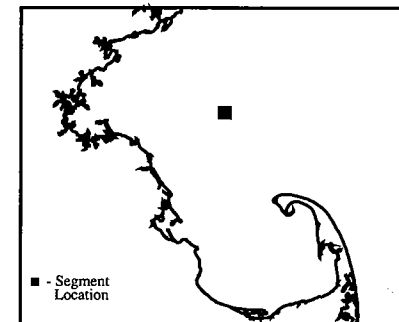
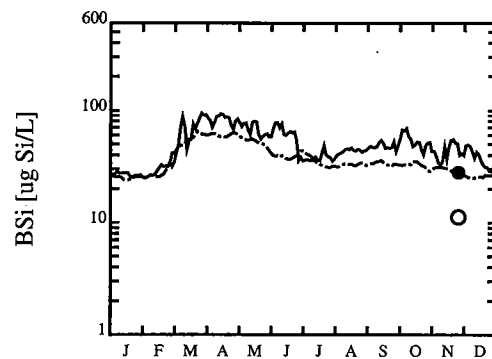
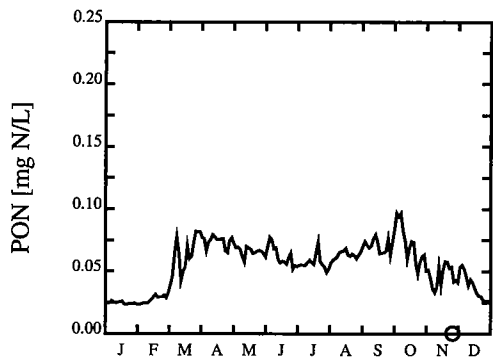
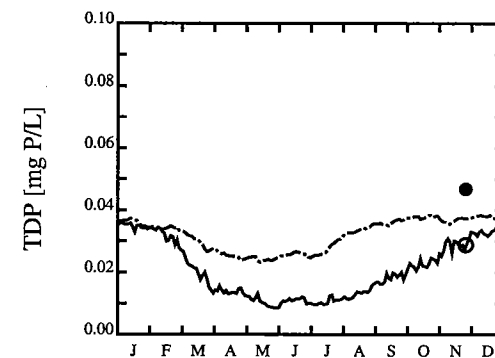
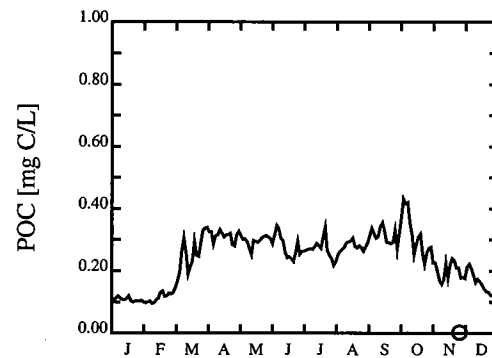
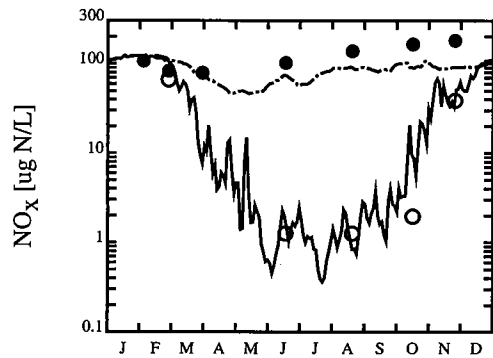
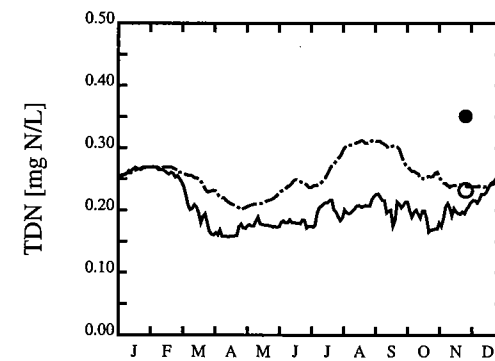
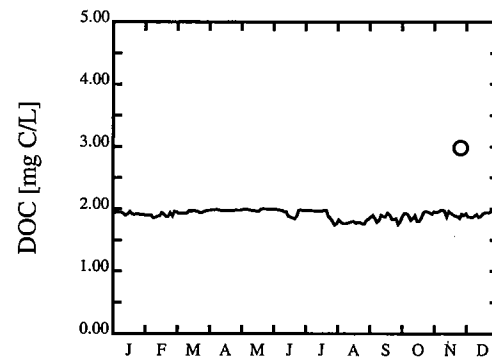
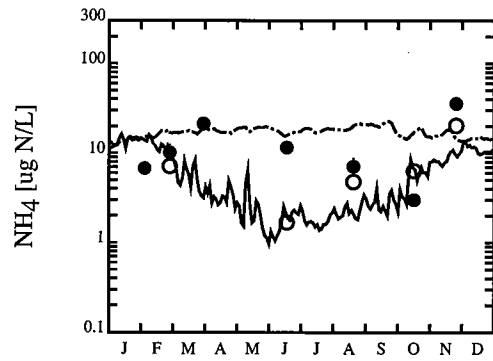
1998 Temporal Calibration Results for Grid Cell (31,29) Vs Data Station F07



LEGEND

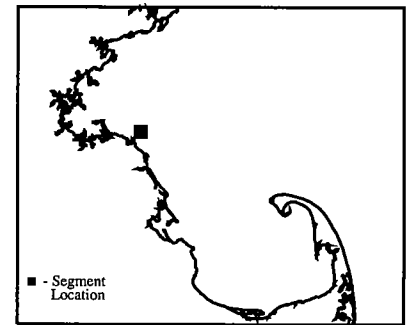
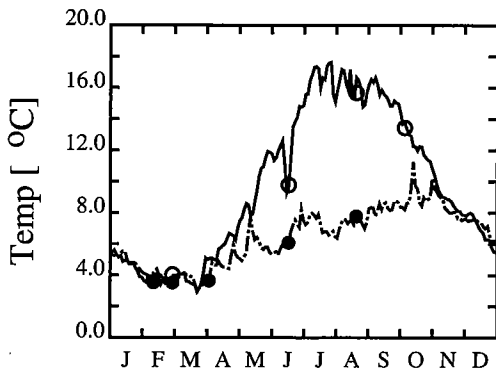
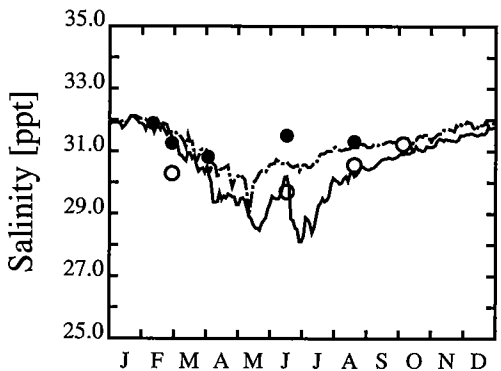
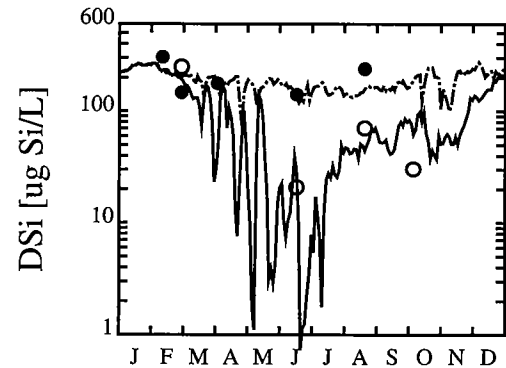
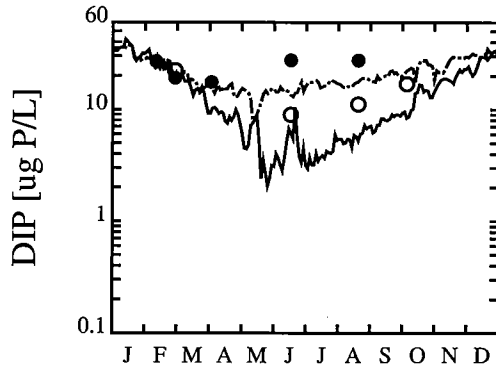
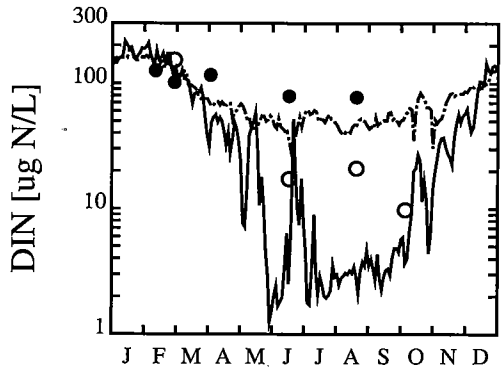
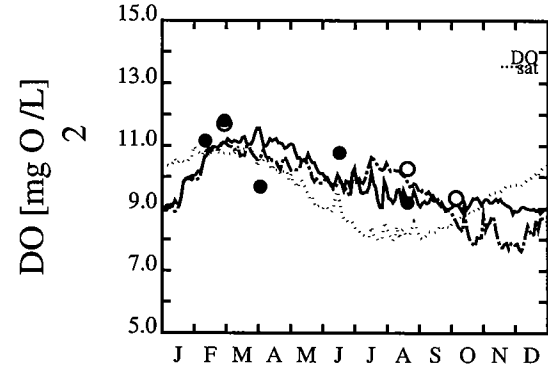
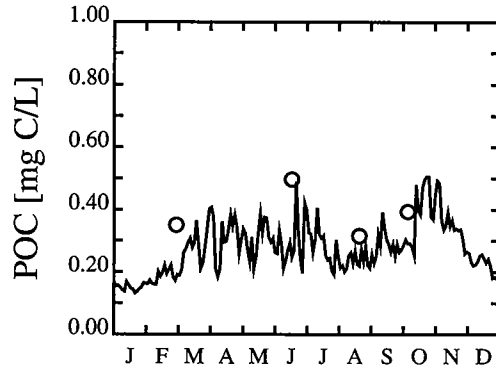
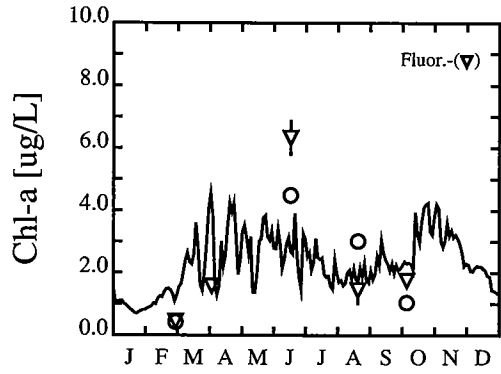
- +/- Surface Data
- Bottom Data
- std.dev Surface Model
- Bottom Model

1998 Temporal Calibration Results for Grid Cell (43,33) Vs Data Station F12



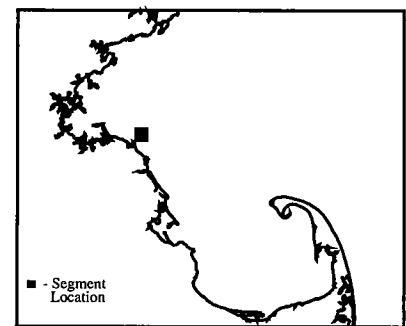
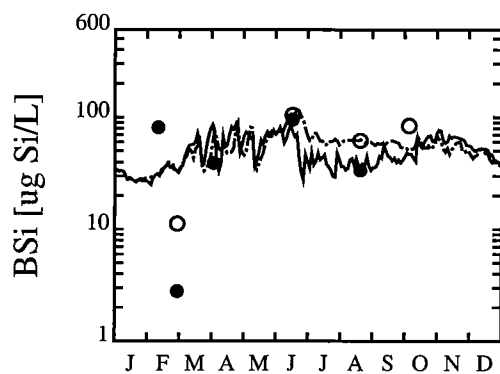
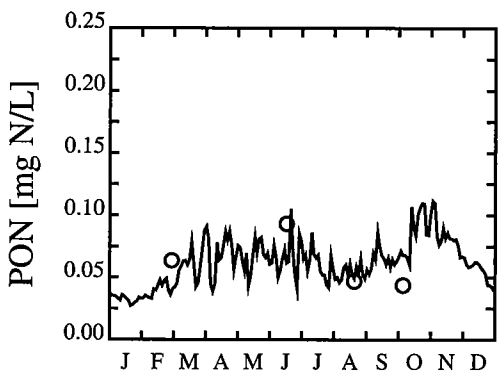
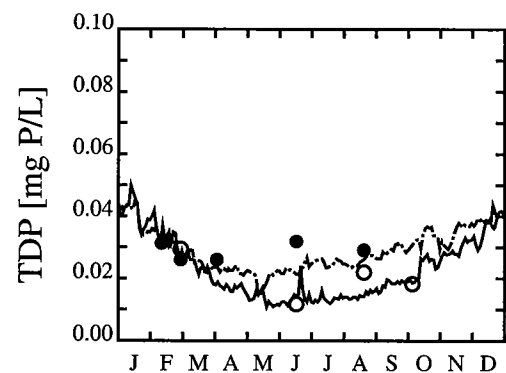
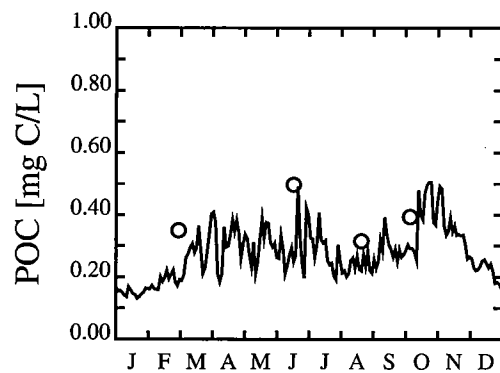
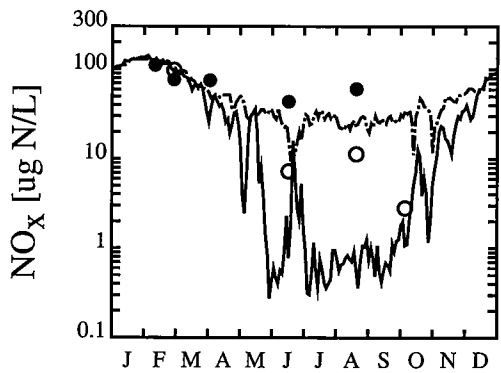
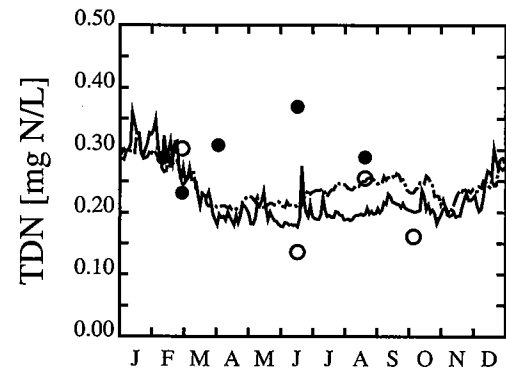
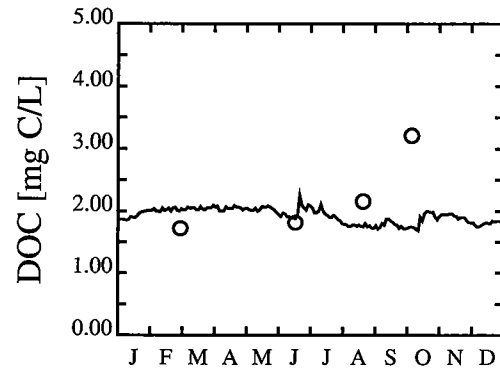
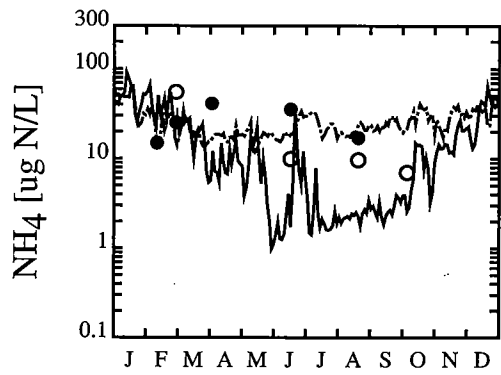
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - std dev Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (43,33) Vs Data Station F12



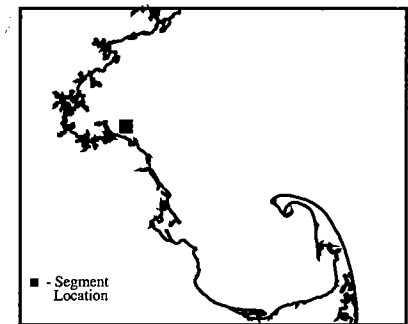
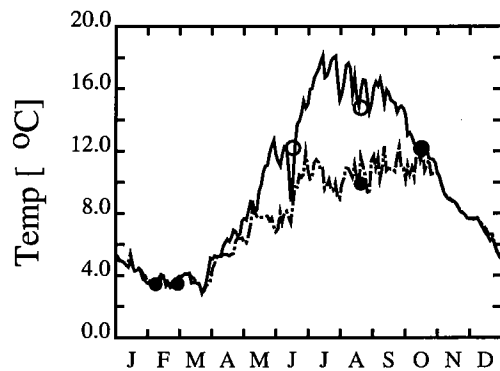
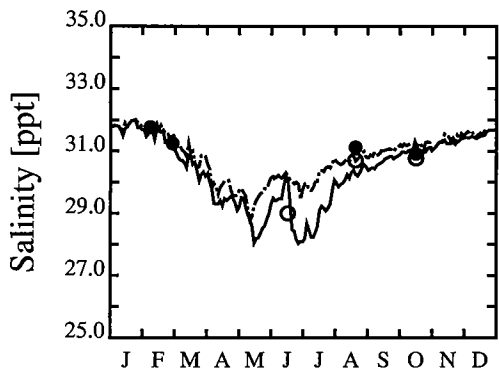
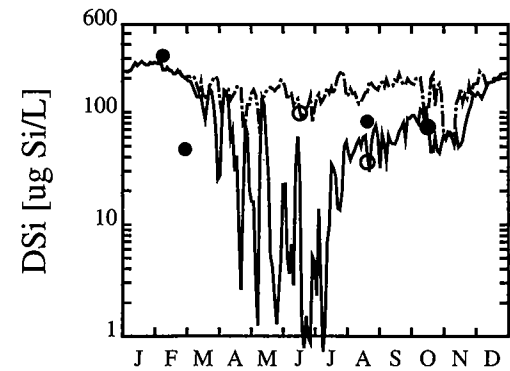
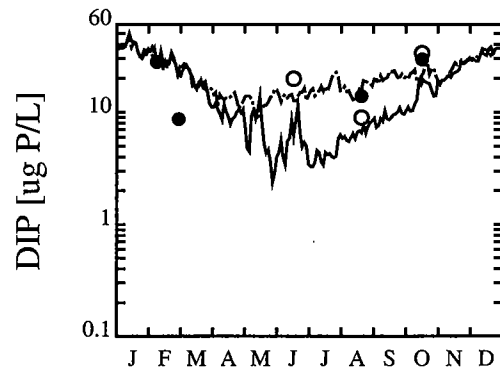
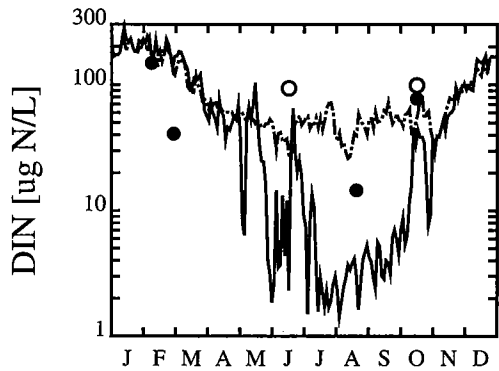
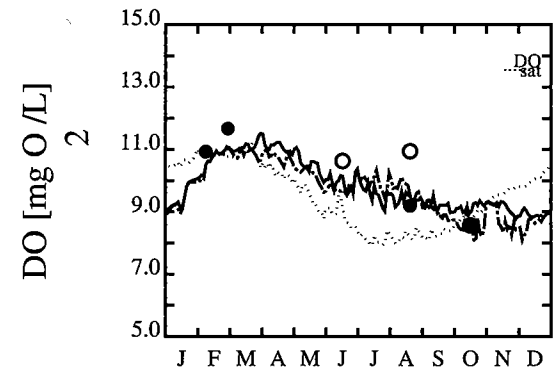
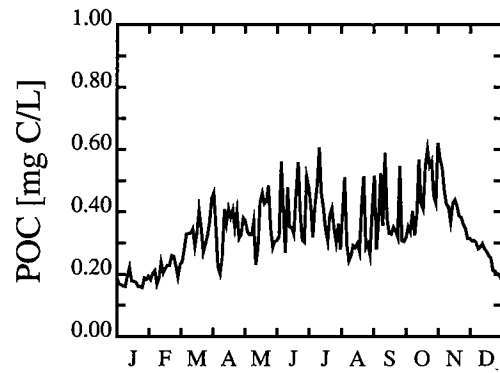
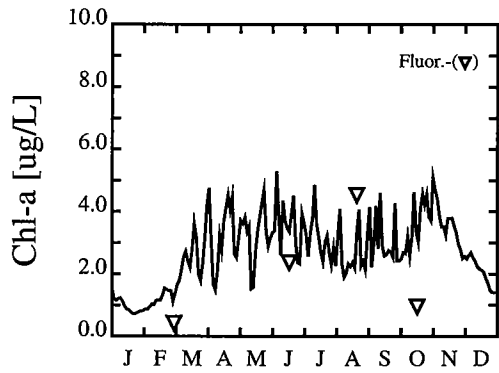
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std dev. Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (24,40) Vs Data Station F13P



LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 — std dev Surface Model
 - - - Bottom Model

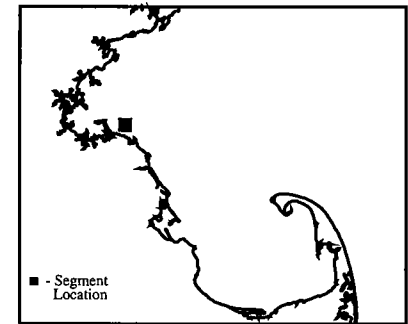
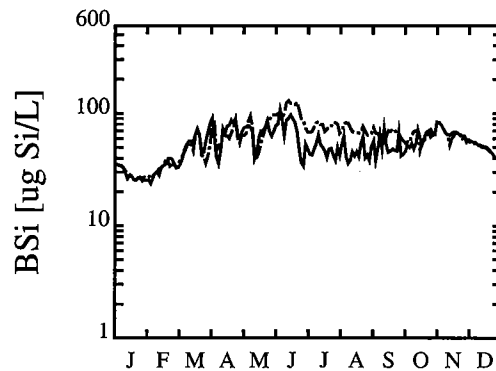
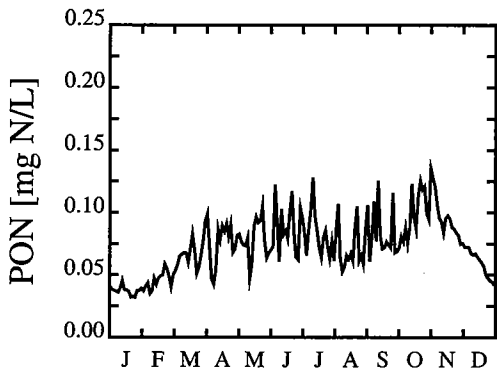
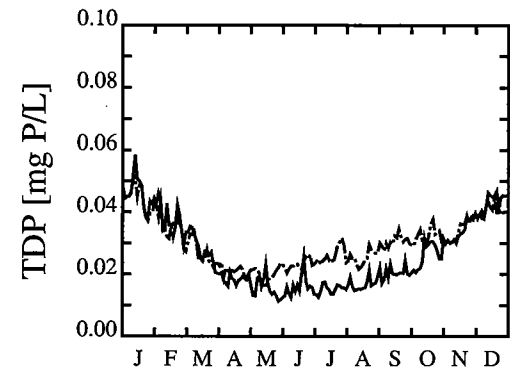
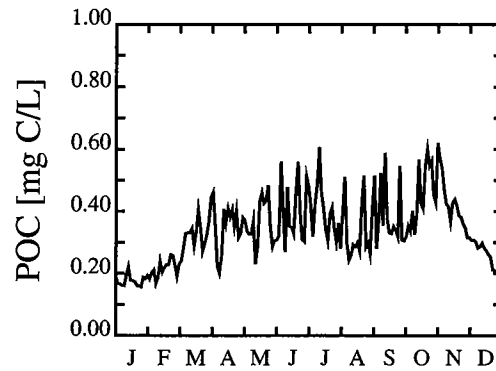
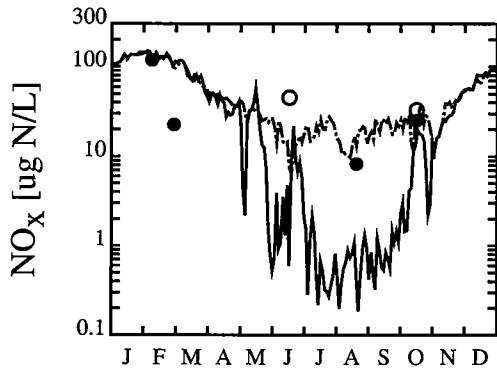
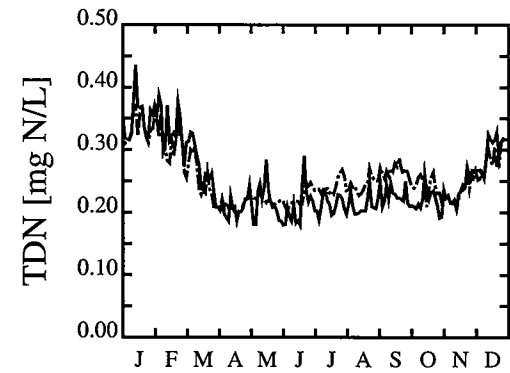
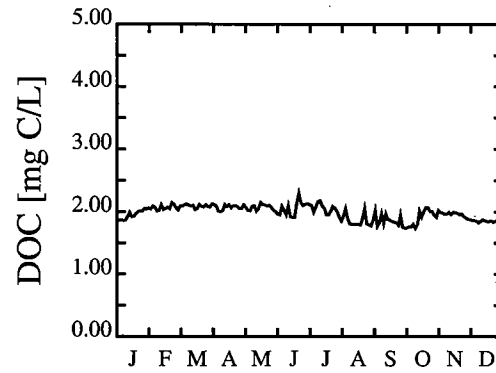
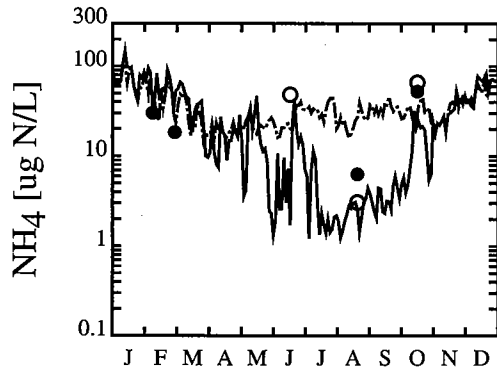
1998 Temporal Calibration Results for Grid Cell (24,40) Vs Data Station F13P



LEGEND

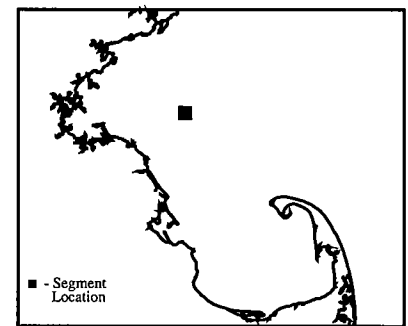
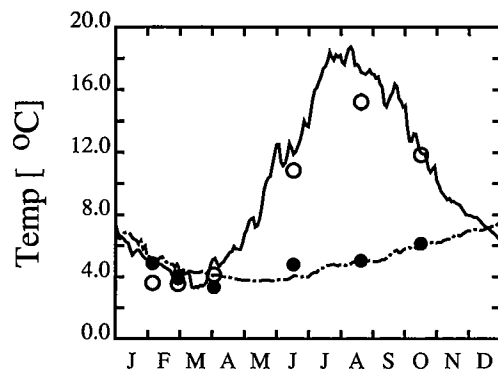
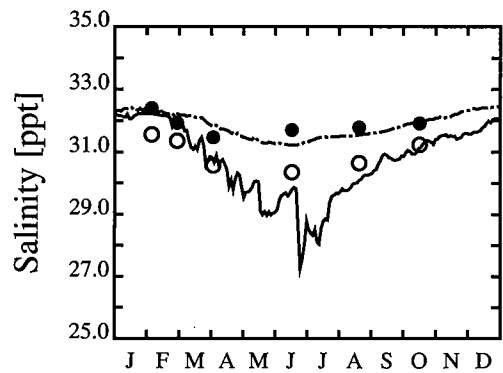
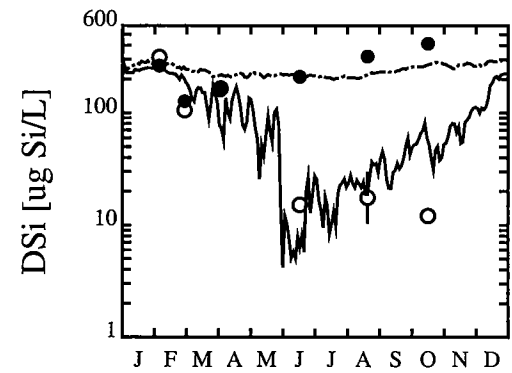
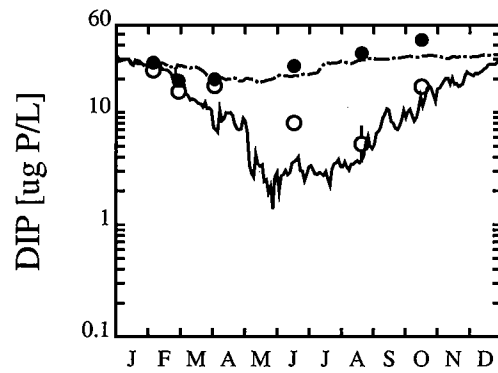
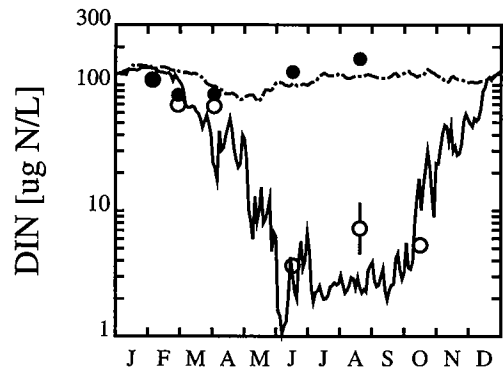
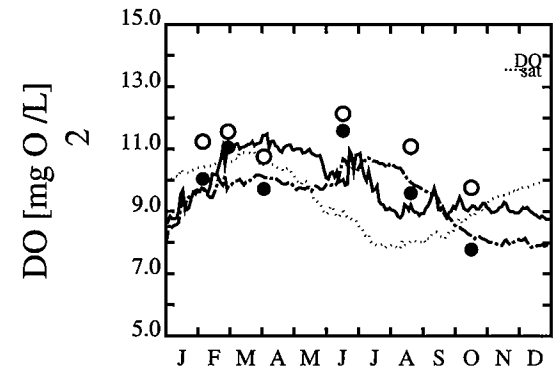
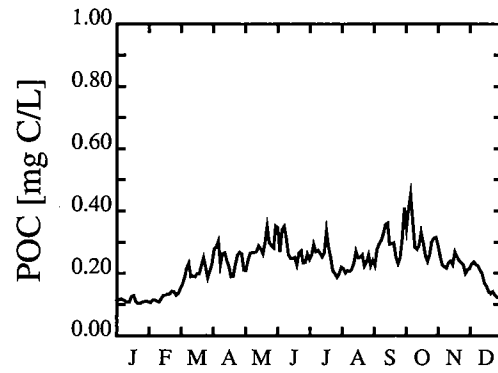
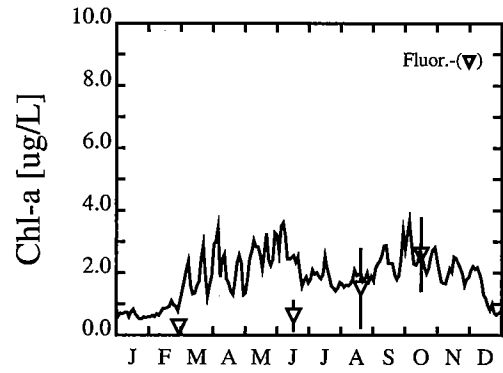
- +/- Surface Data
- Bottom Data
- std.dev. Surface Model
- Bottom Model

1998 Temporal Calibration Results for Grid Cell (22,44) Vs Data Station F14



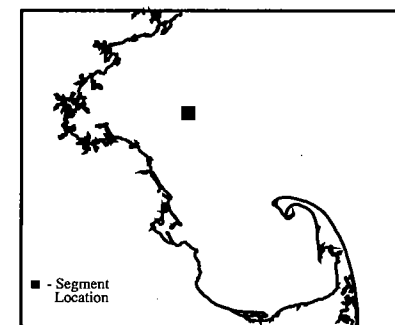
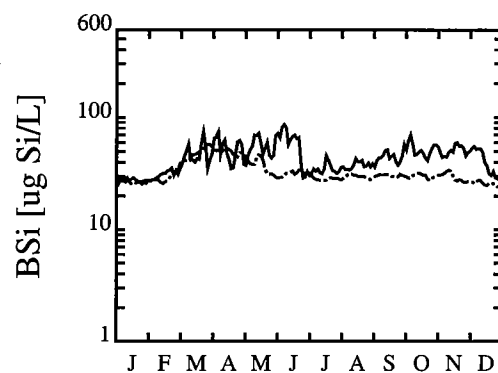
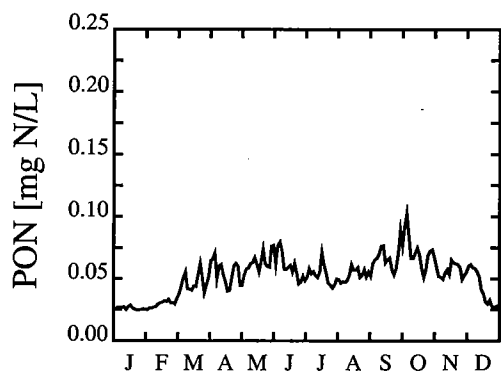
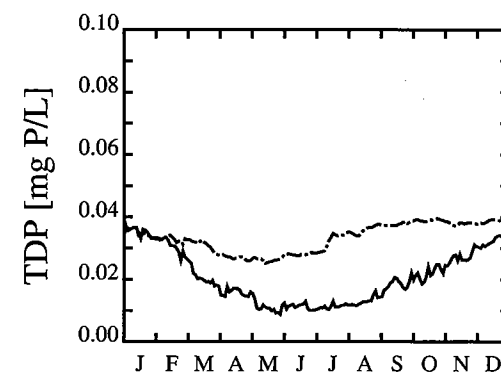
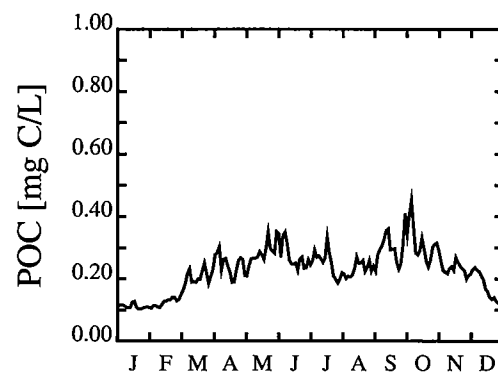
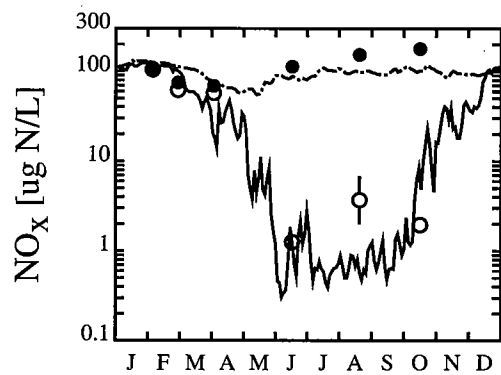
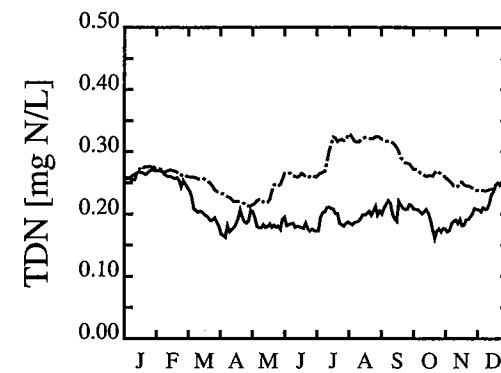
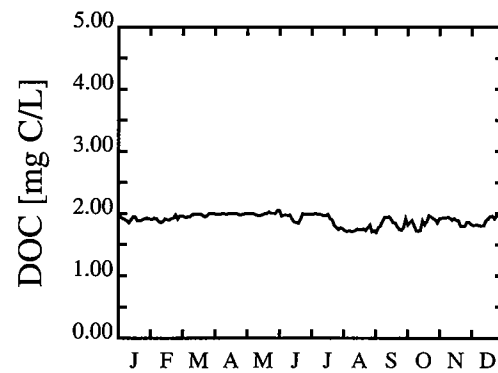
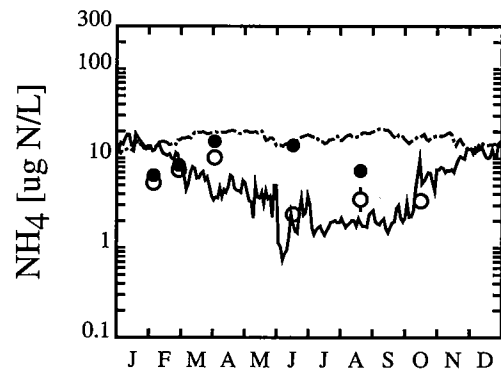
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - std.dev. Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (22,44) Vs Data Station F14



----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - std.dev Surface Model
 - - - - - Bottom Model

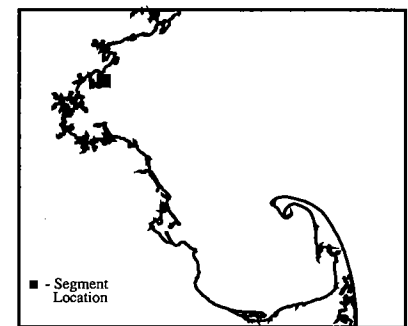
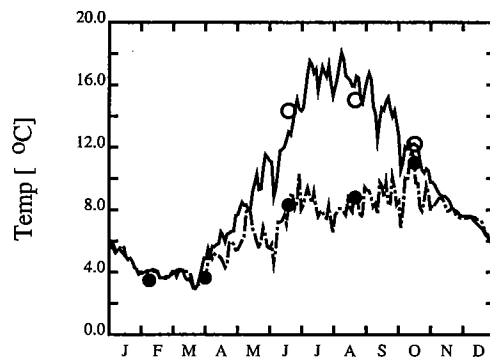
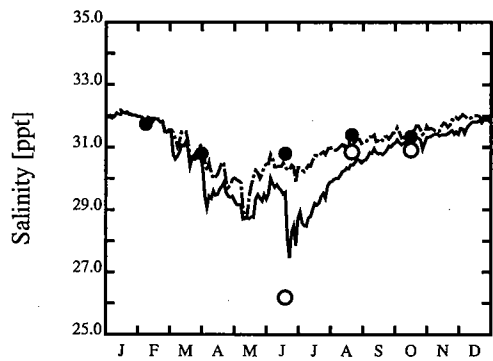
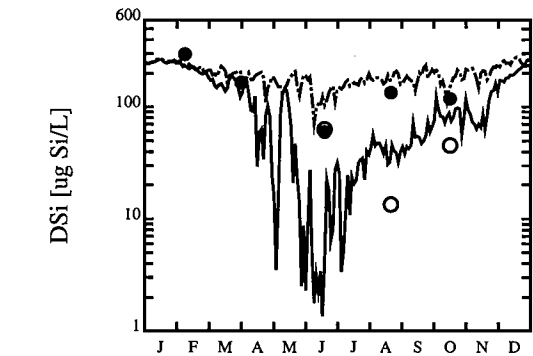
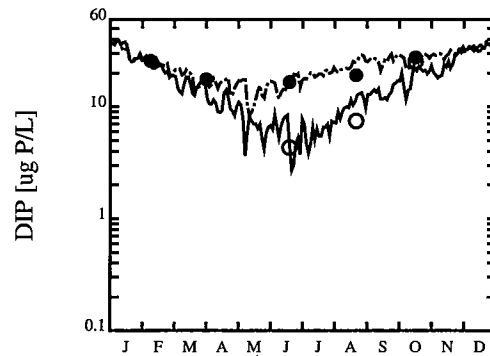
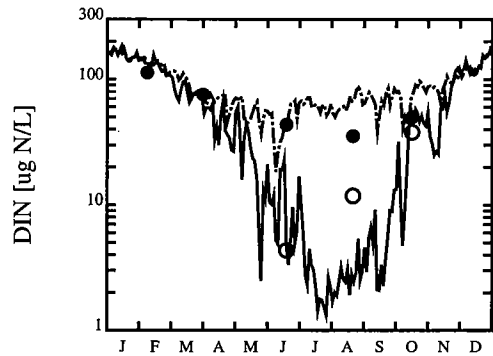
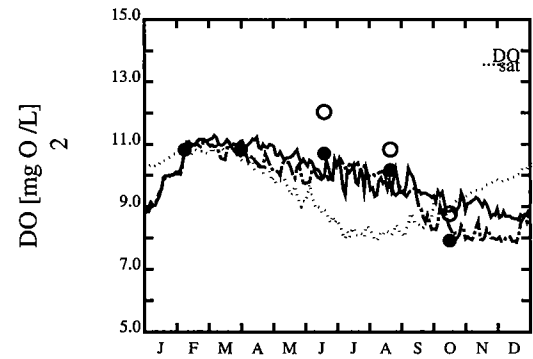
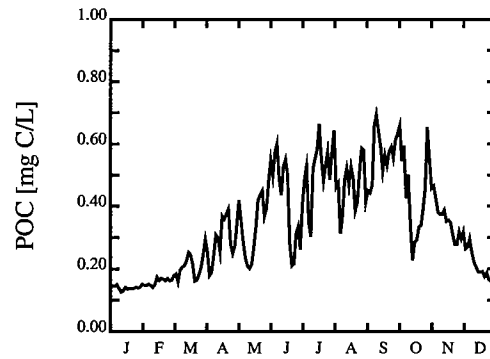
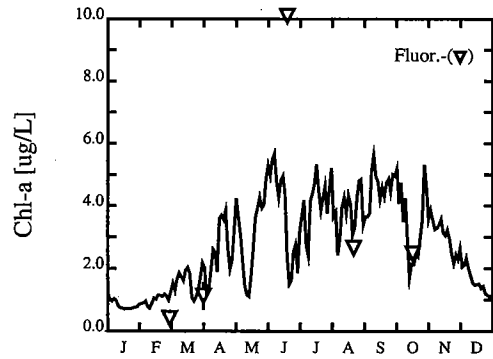
1998 Temporal Calibration Results for Grid Cell (37,37) Vs Data Station F17



LEGEND

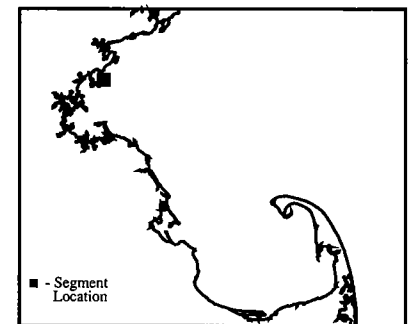
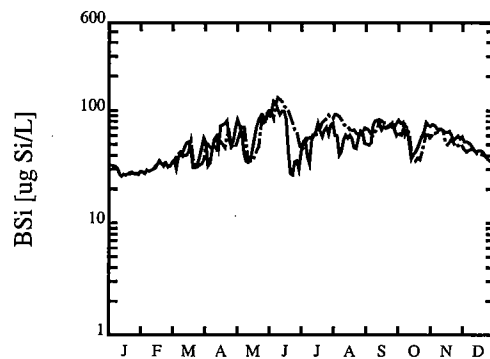
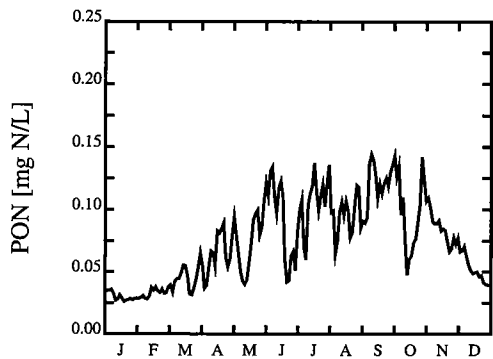
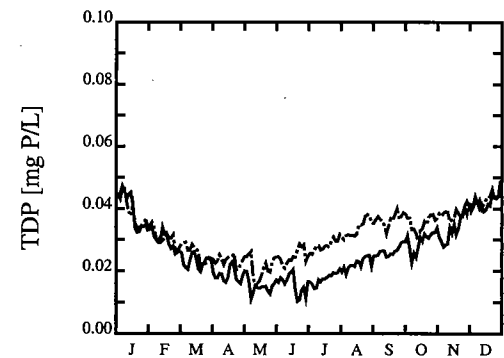
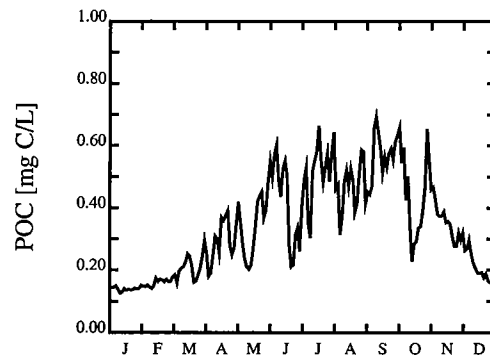
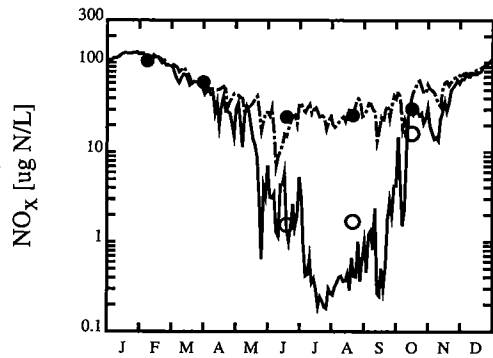
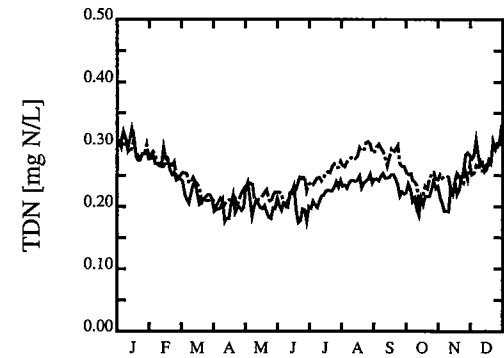
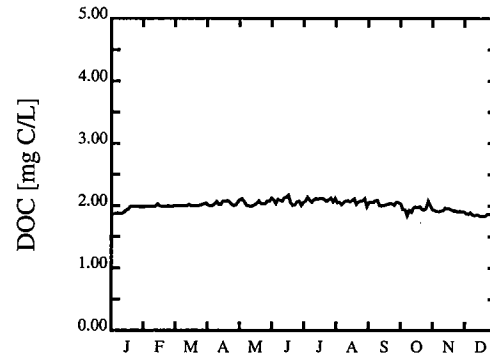
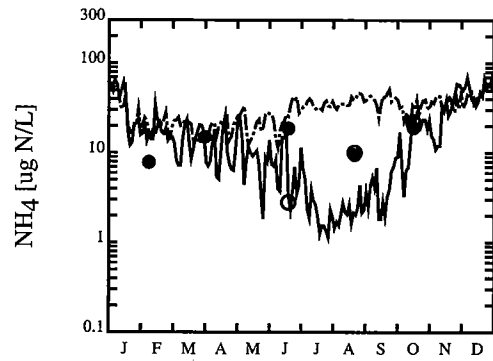
- +/- Surface Data
- Bottom Data
- std dev Surface Model
- - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (37,37) Vs Data Station F17



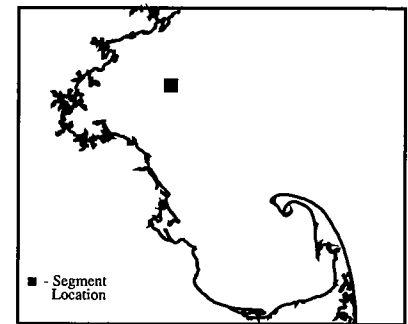
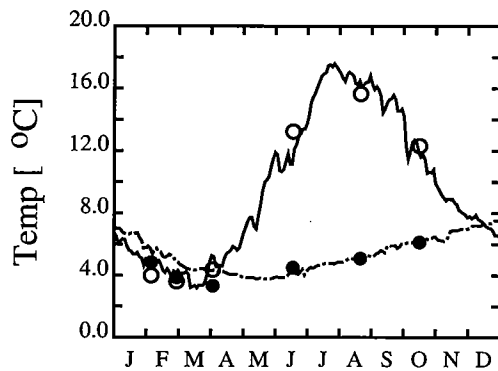
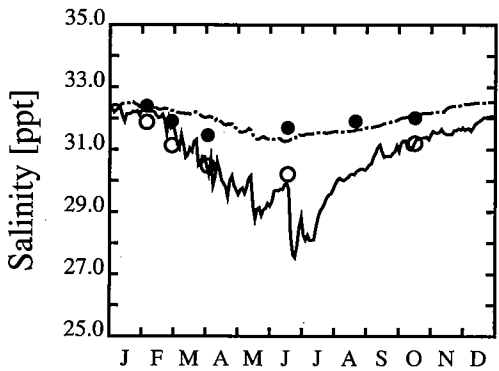
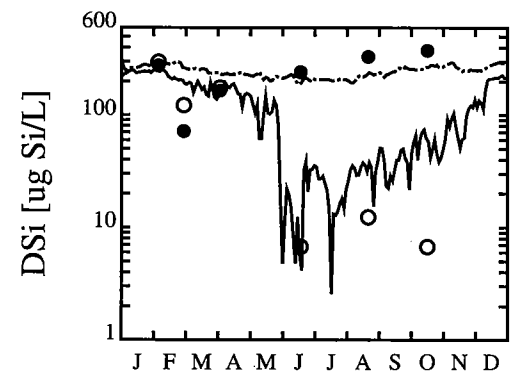
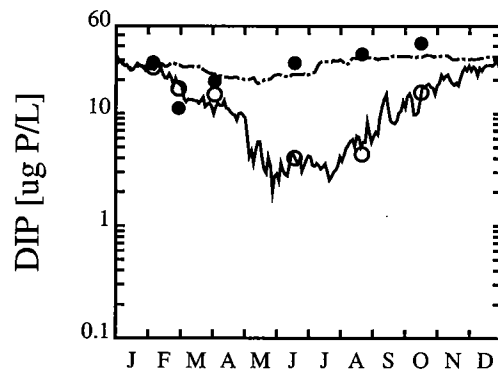
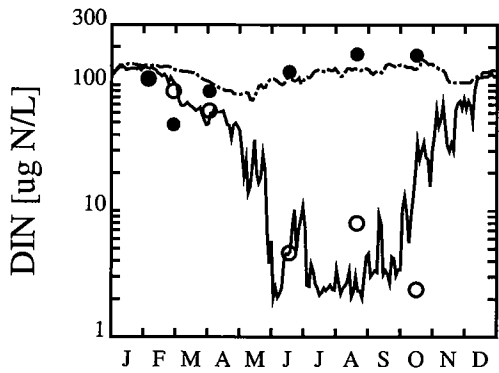
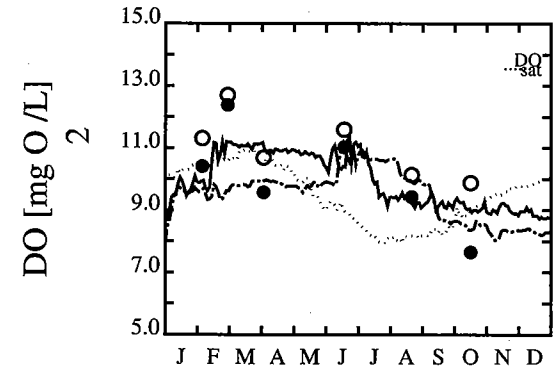
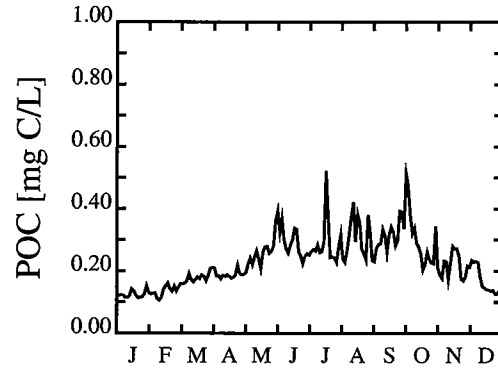
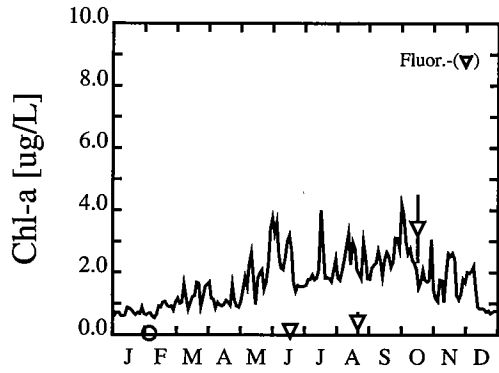
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev- Surface Model
 - Bottom Model

1998 Temporal Calibration Results for Grid Cell (31,55) Vs Data Station F18



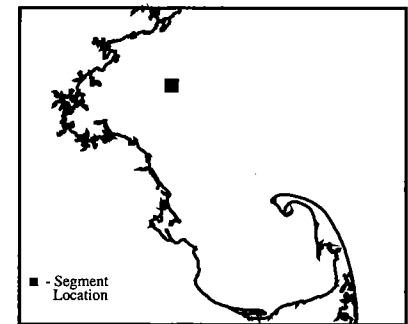
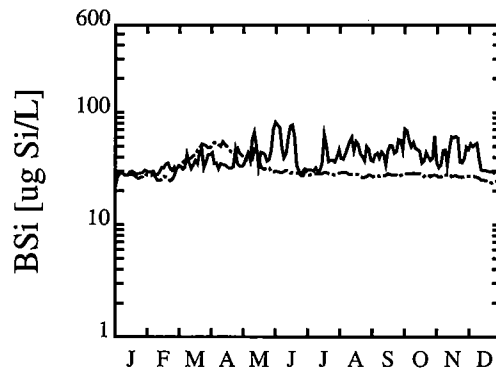
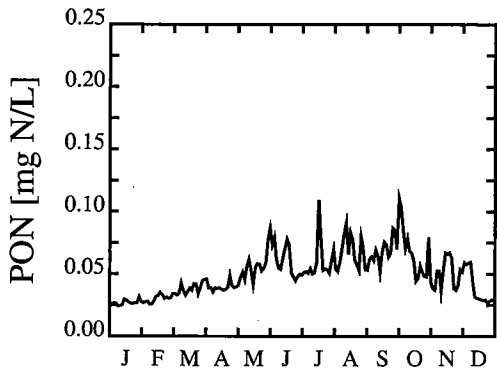
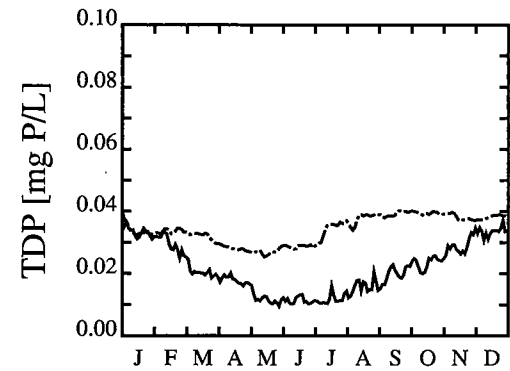
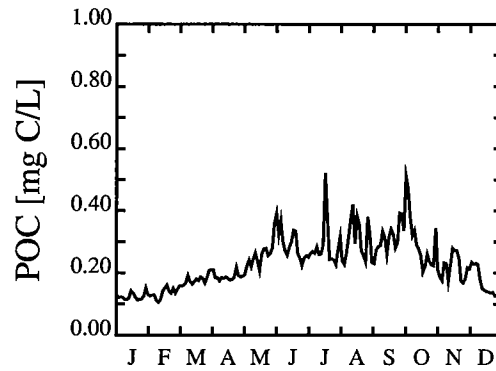
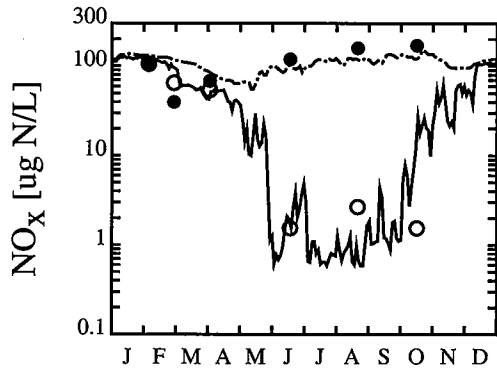
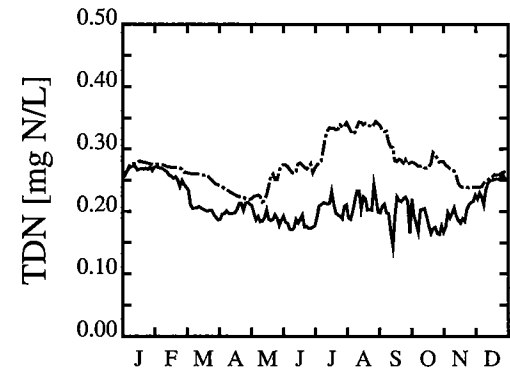
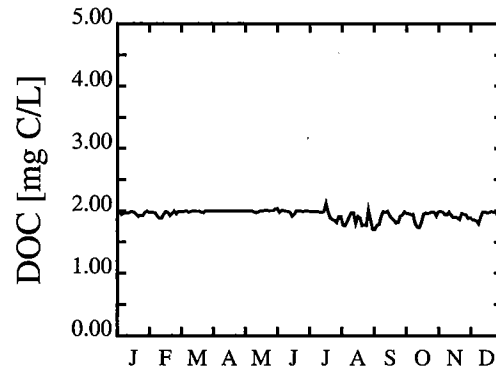
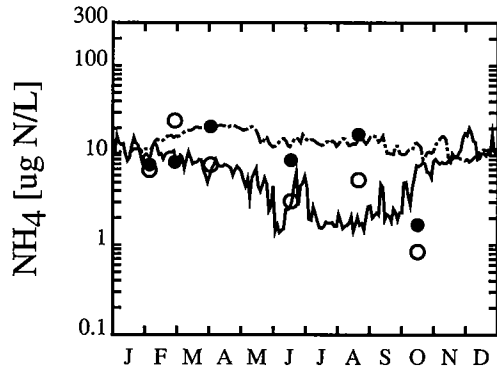
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 — std.dev. Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (31,55) Vs Data Station F18



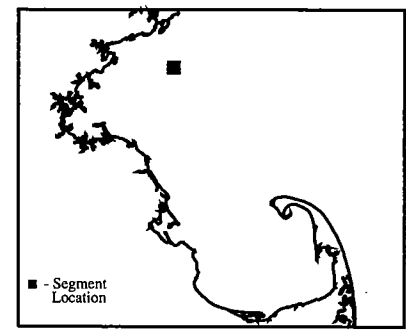
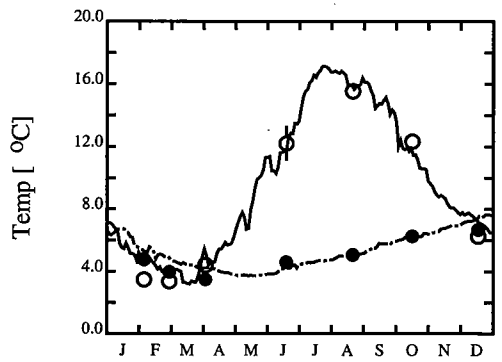
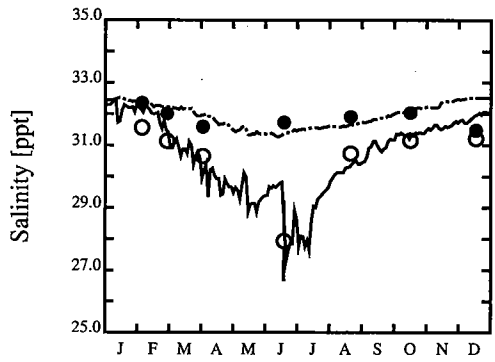
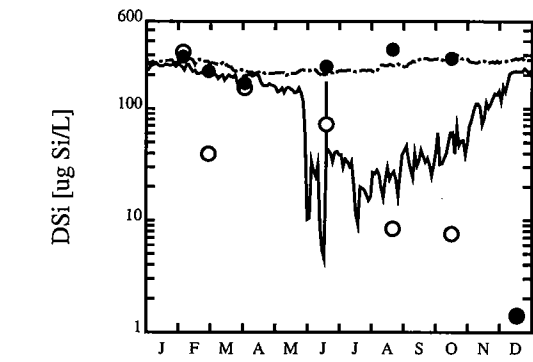
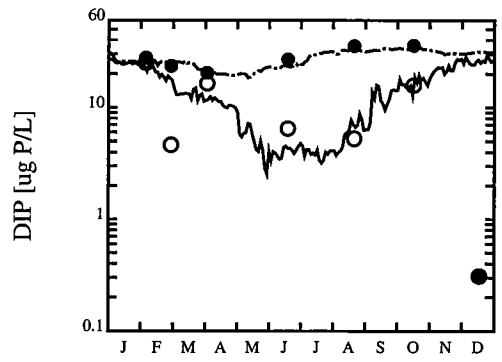
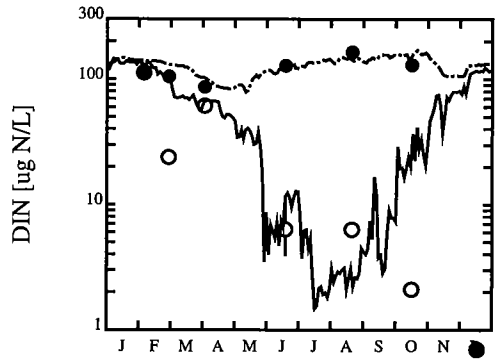
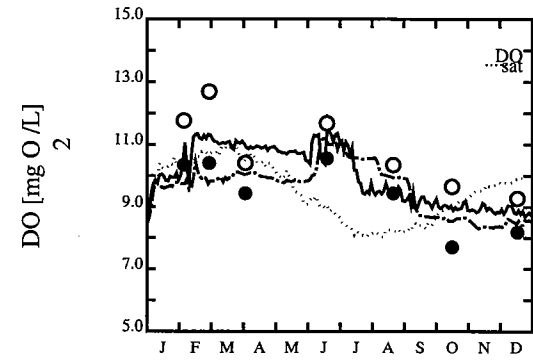
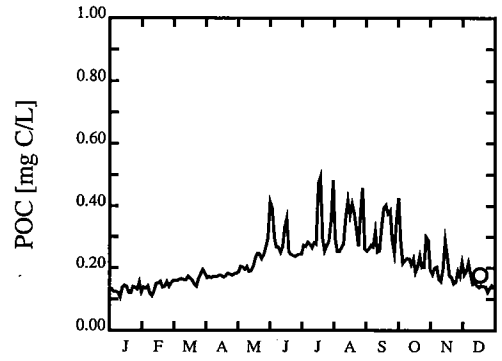
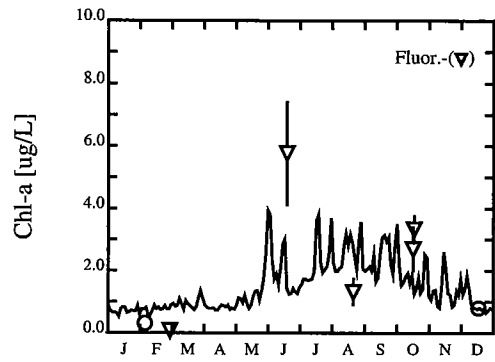
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev. Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (39,42) Vs Data Station F19



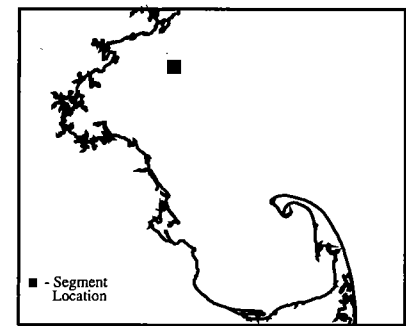
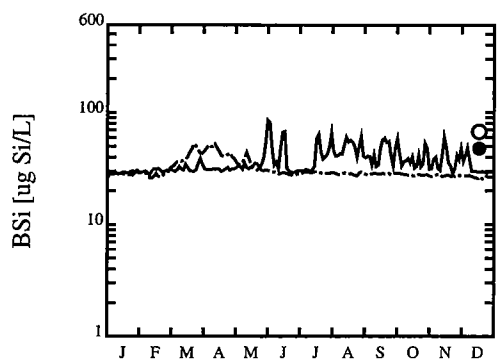
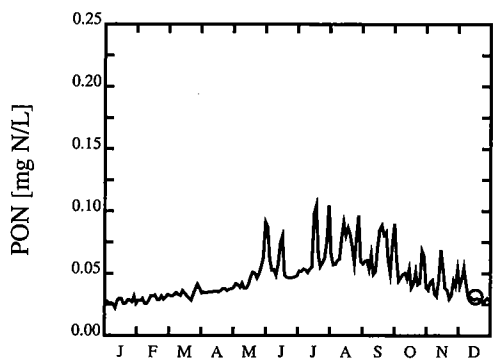
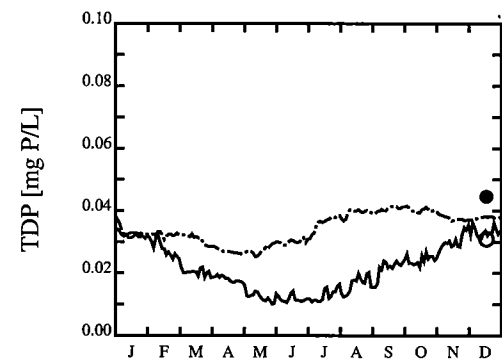
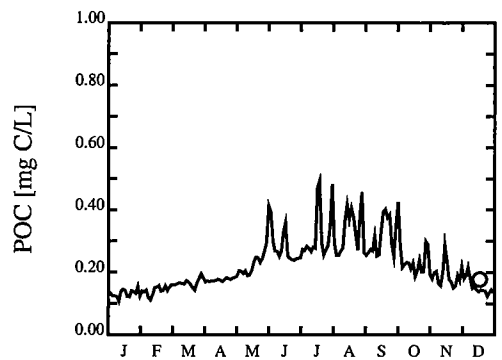
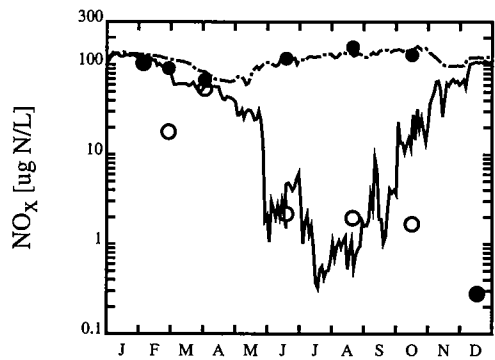
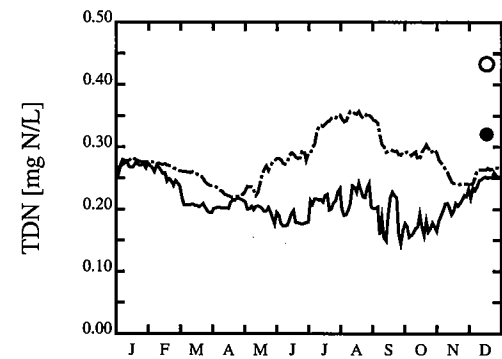
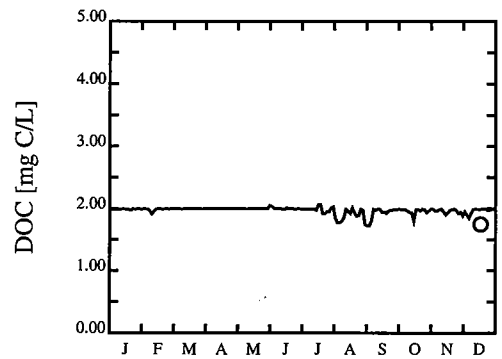
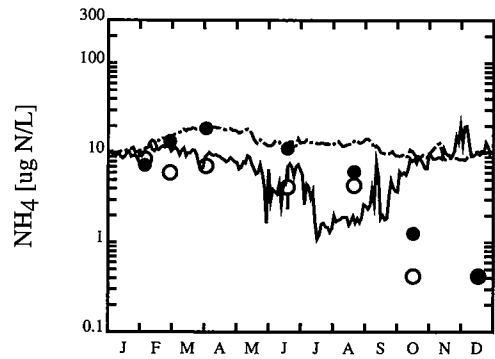
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev Surface Model
 - Bottom Model

1998 Temporal Calibration Results for Grid Cell (39,42) Vs Data Station F19



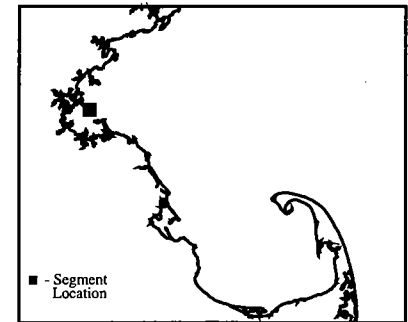
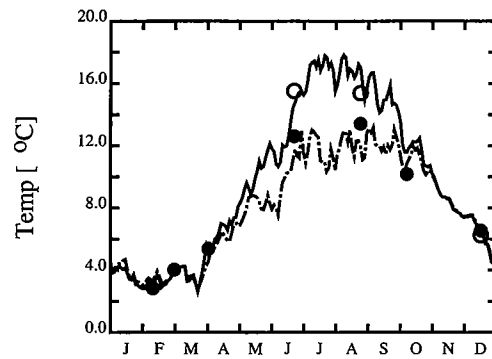
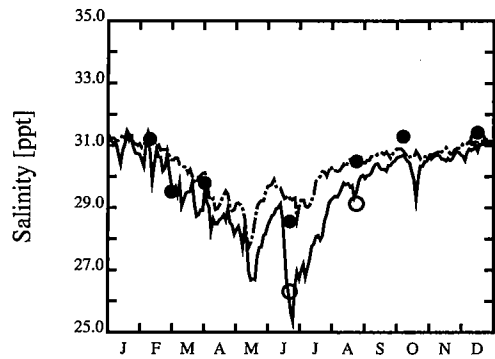
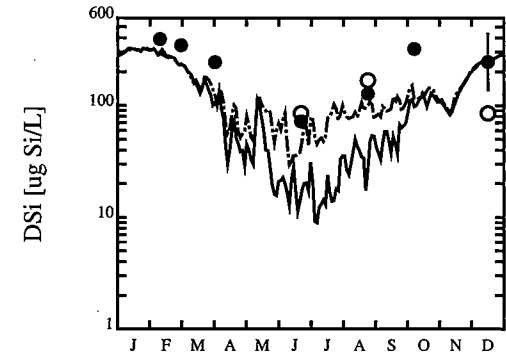
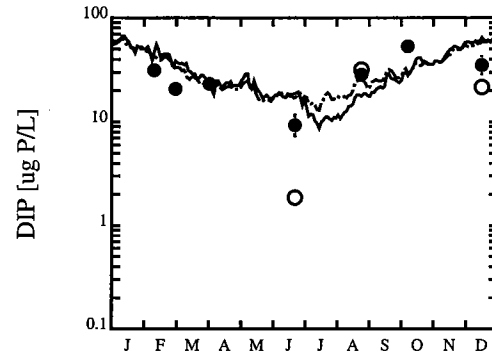
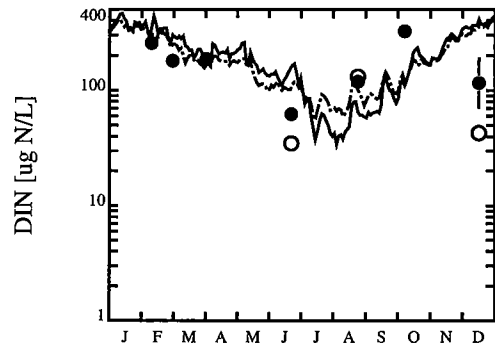
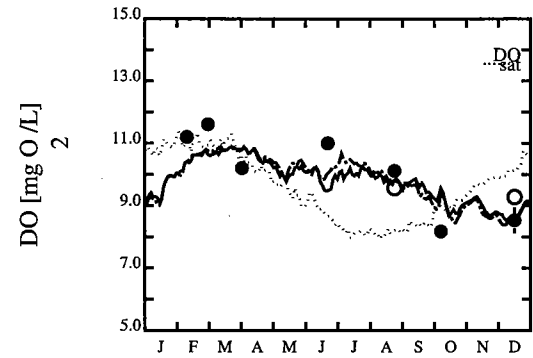
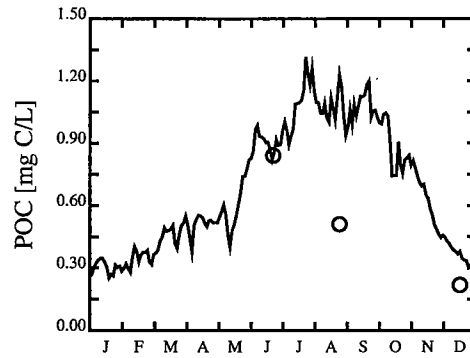
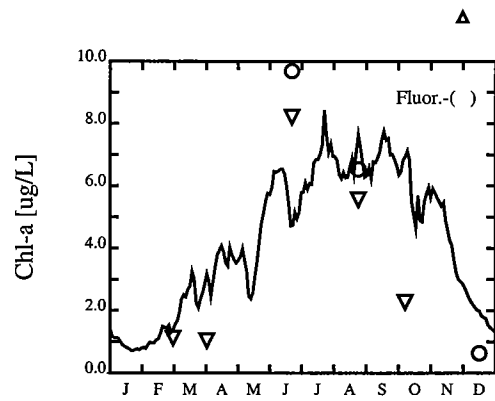
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std dev- Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (43,44) Vs Data Station F22



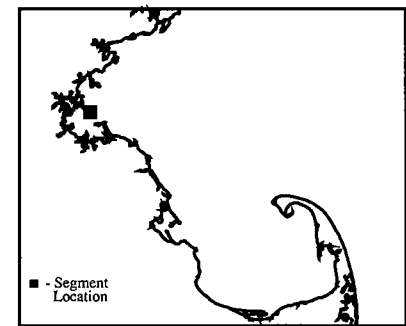
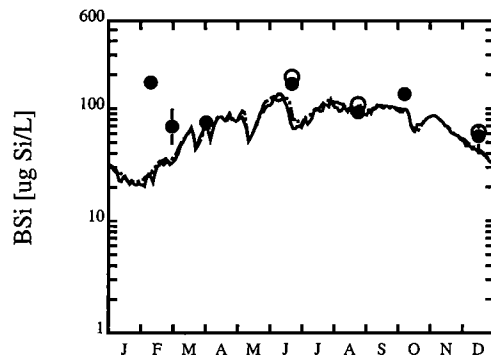
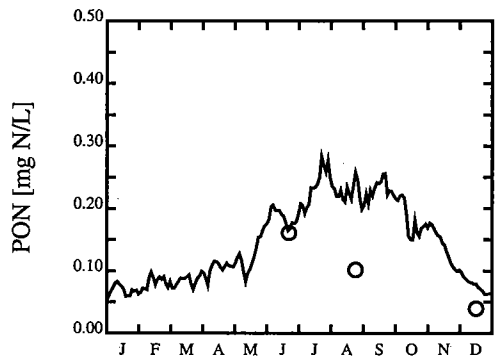
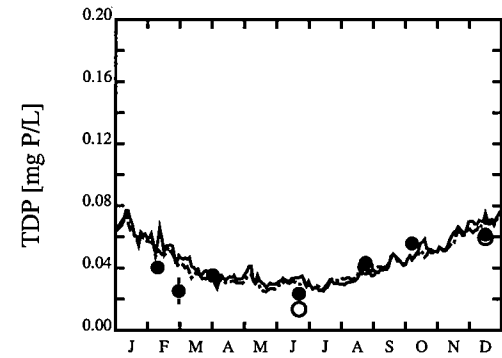
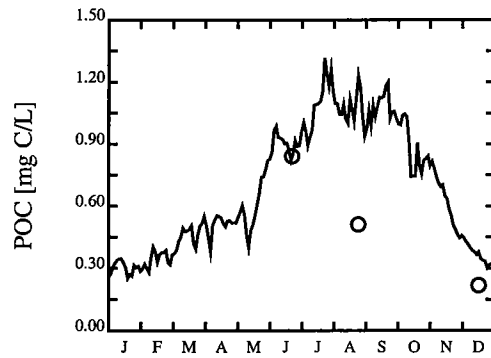
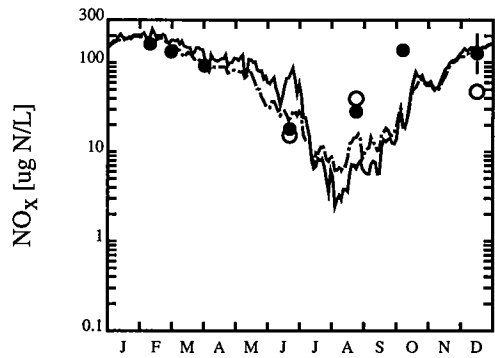
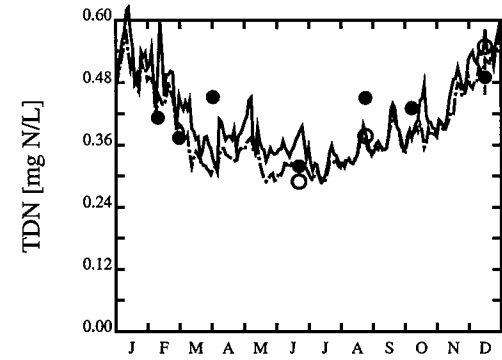
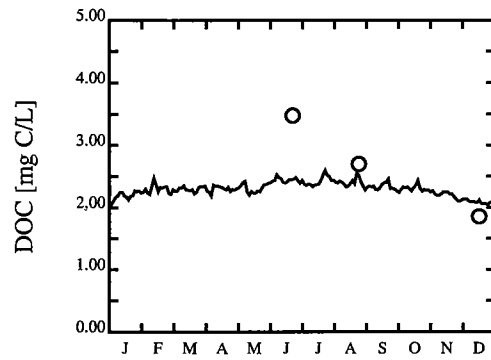
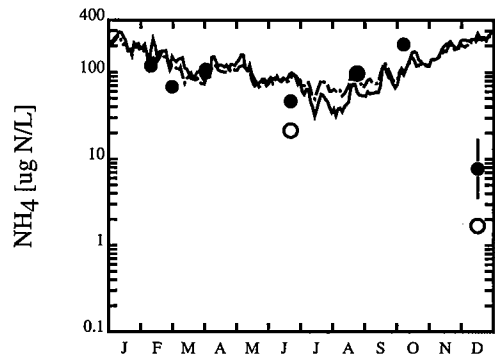
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev- Surface Model
 - Bottom Model

1998 Temporal Calibration Results for Grid Cell (43,44) Vs Data Station F22



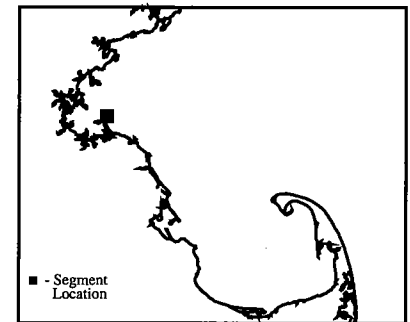
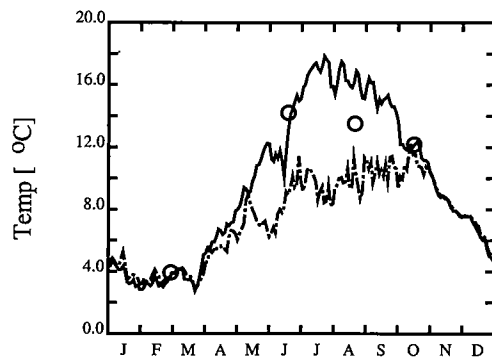
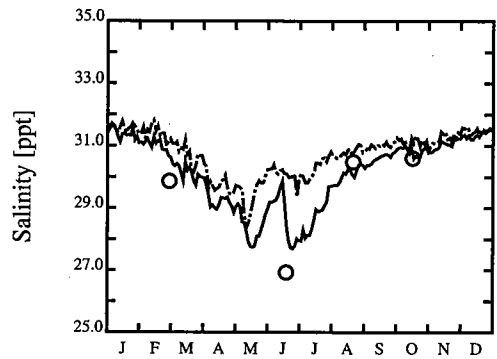
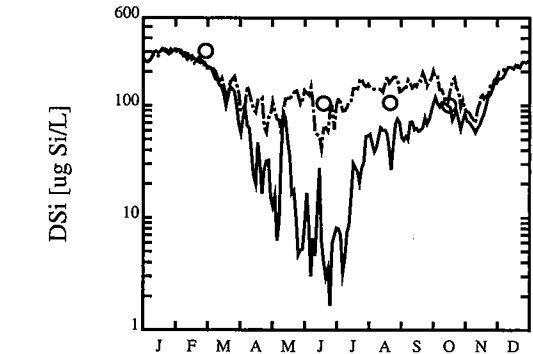
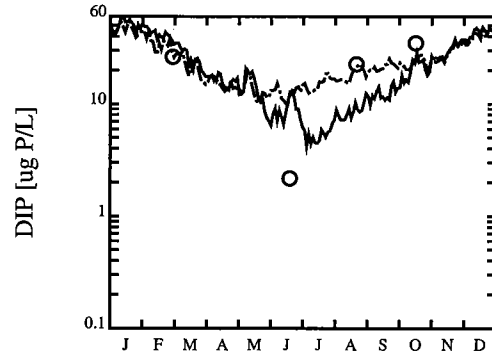
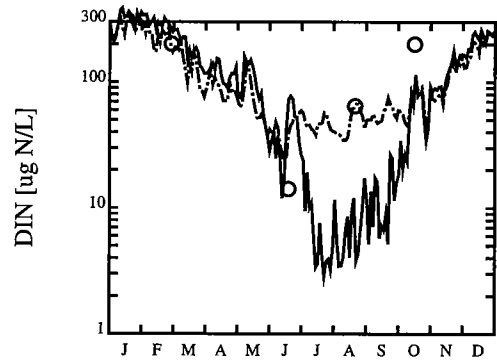
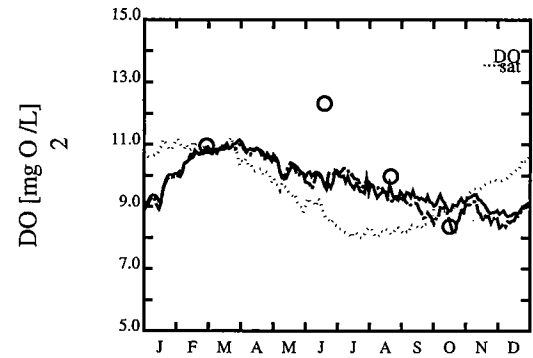
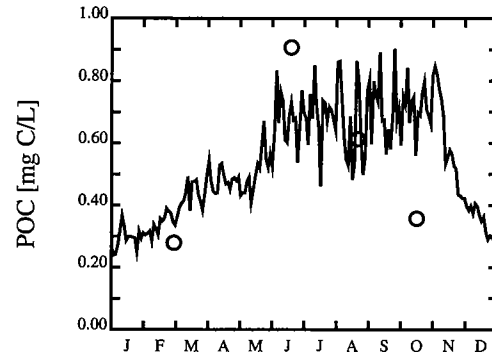
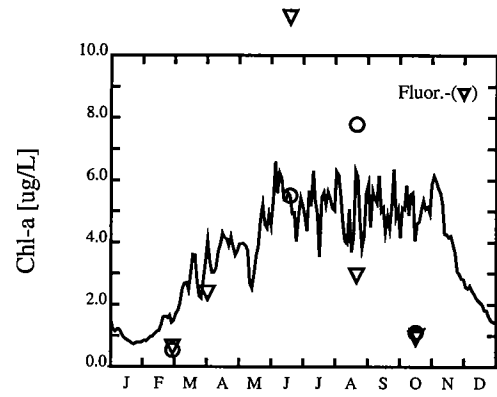
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 — std.dev Surface Model
 - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (20,54) Vs Data Station F23P



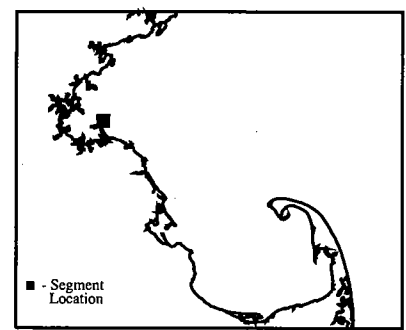
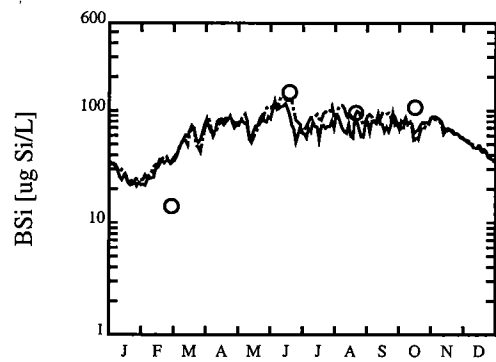
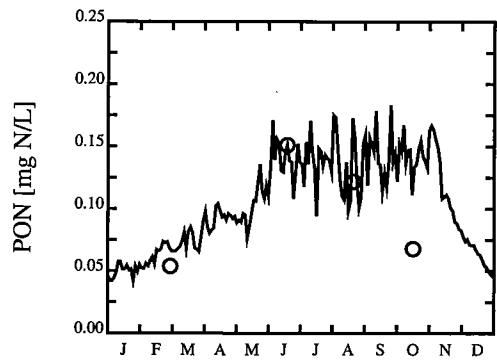
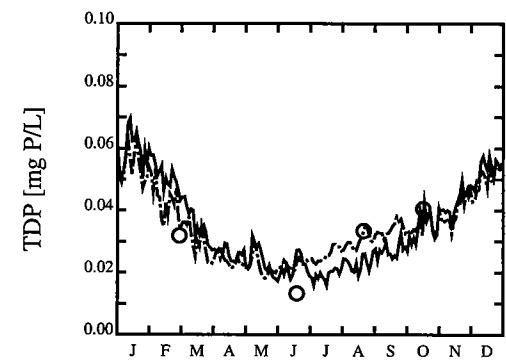
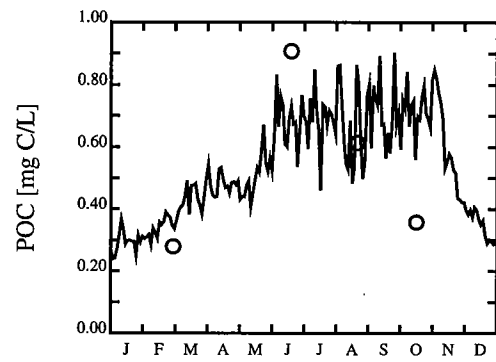
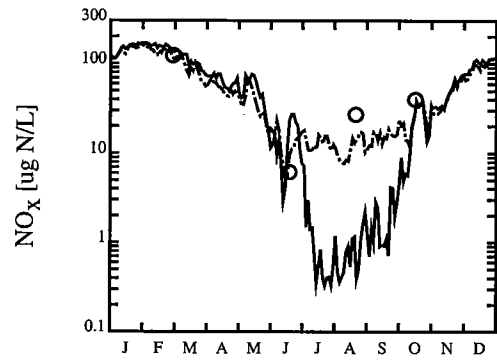
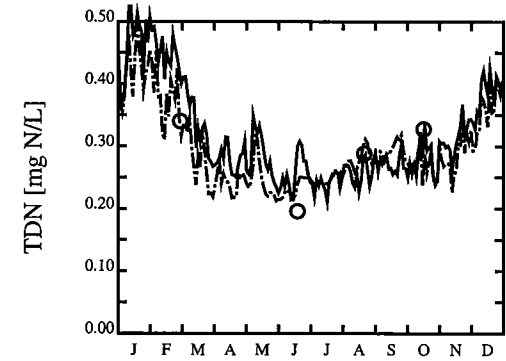
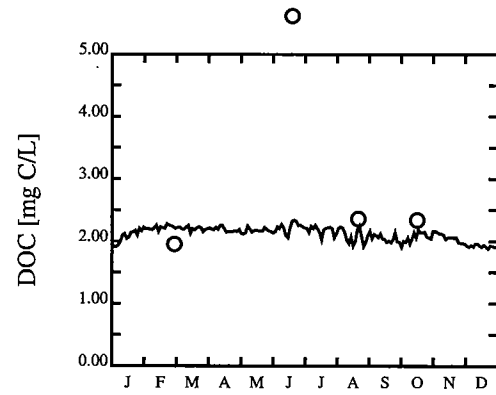
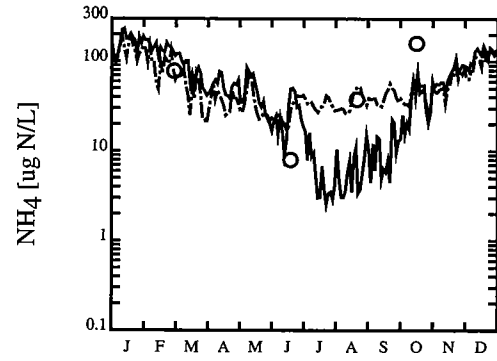
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev- Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for
 Grid Cell (20,54) Vs Data Station F23P



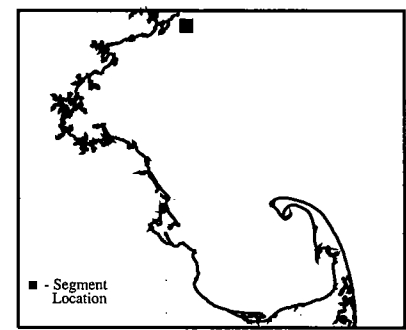
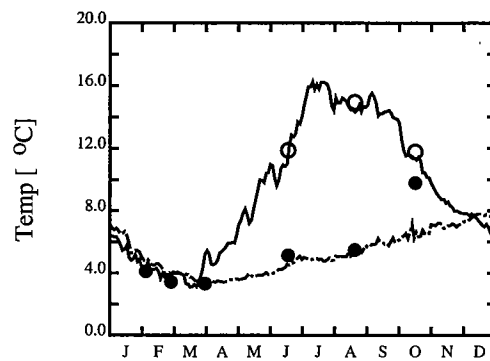
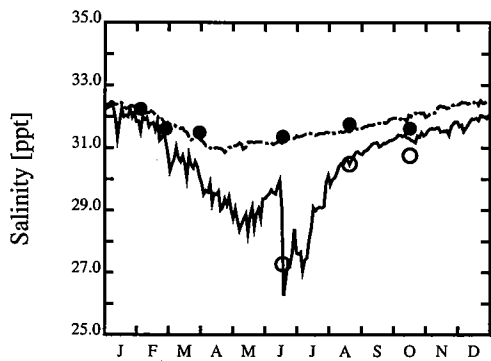
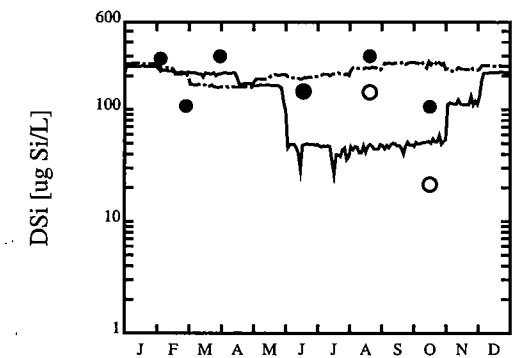
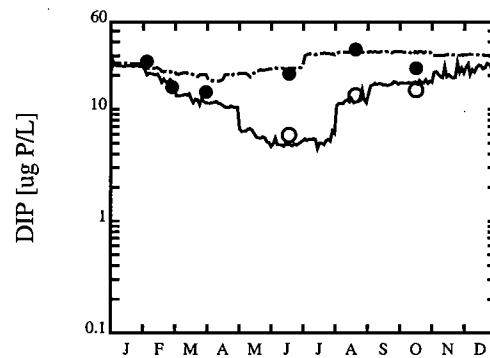
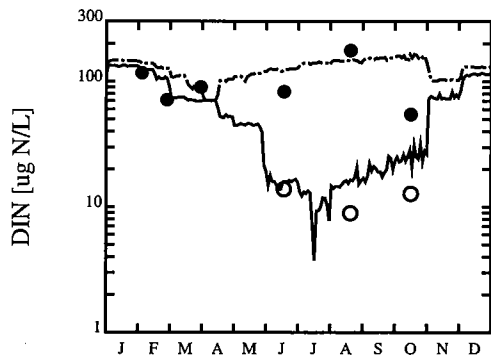
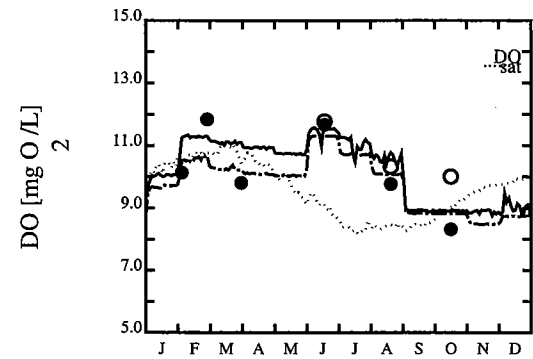
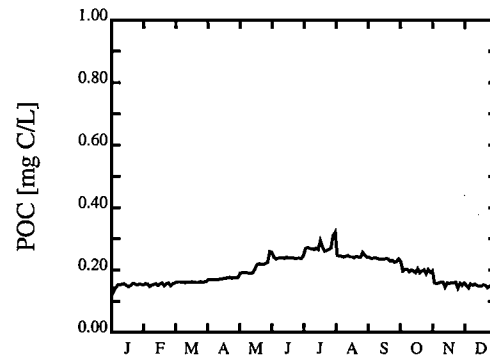
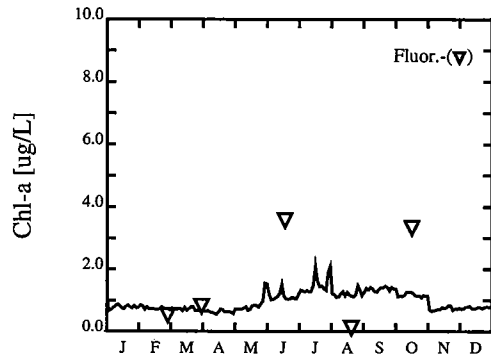
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 — std dev Surface Model
 - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (21,49) Vs Data Station F25



----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std dev- Surface Model
 - - - - - Bottom Model

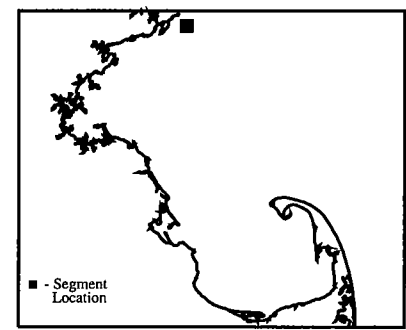
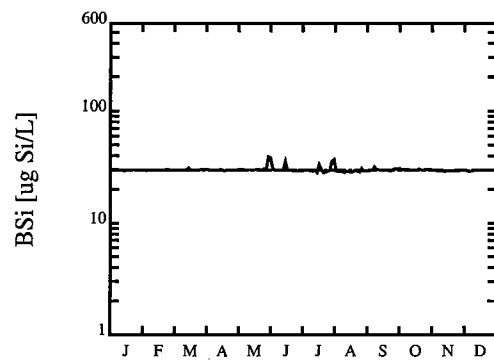
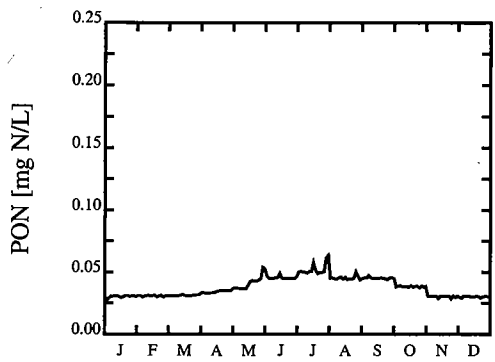
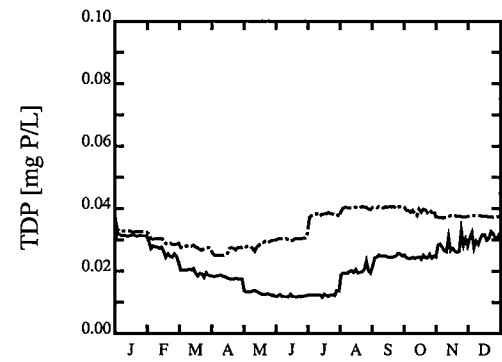
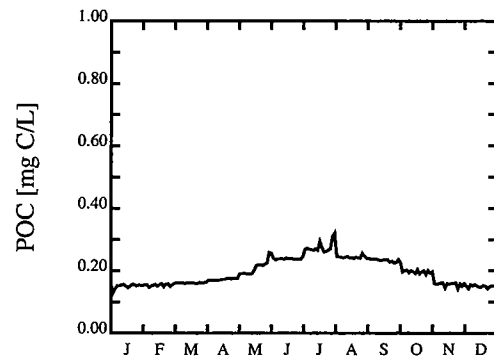
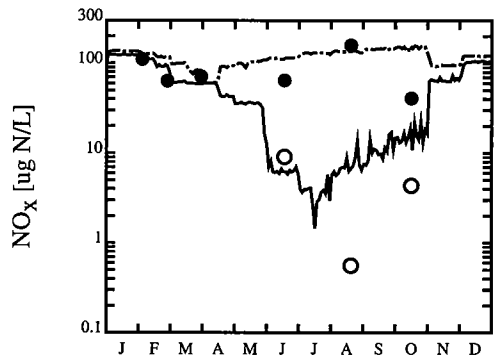
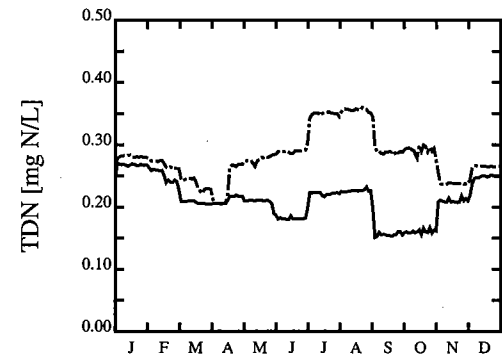
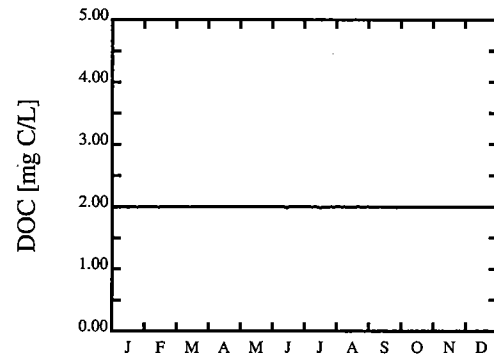
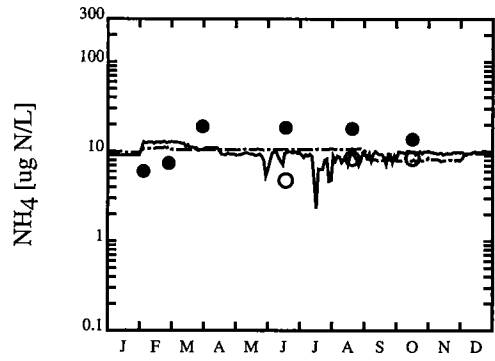
1998 Temporal Calibration Results for Grid Cell (21,49) Vs Data Station F25



LEGEND

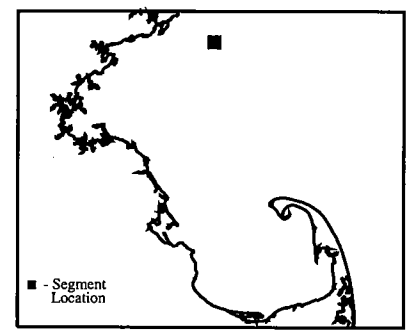
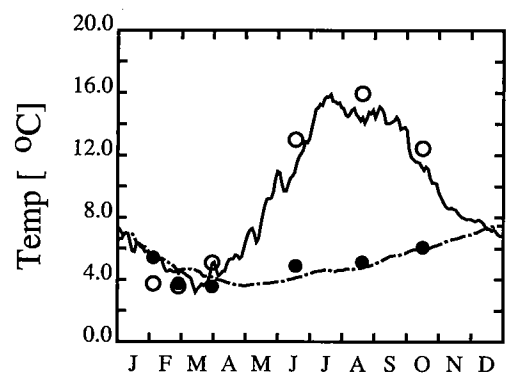
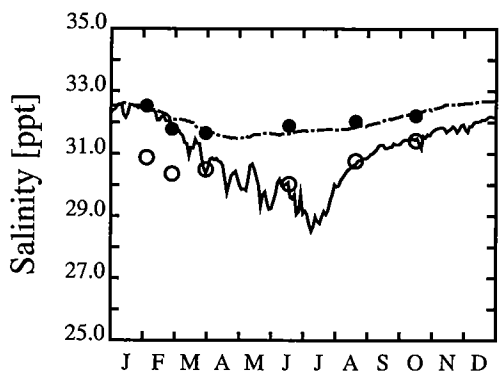
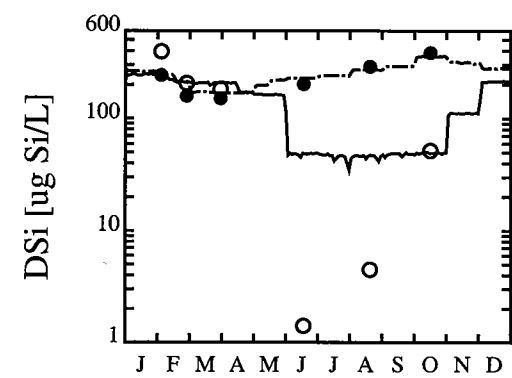
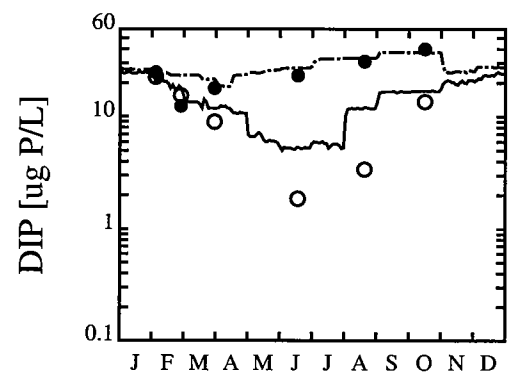
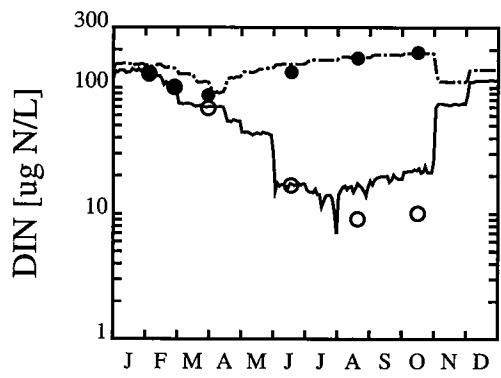
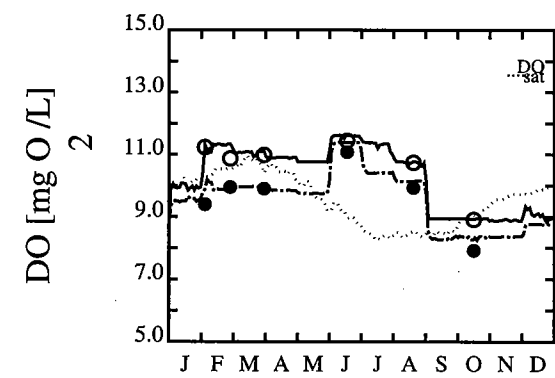
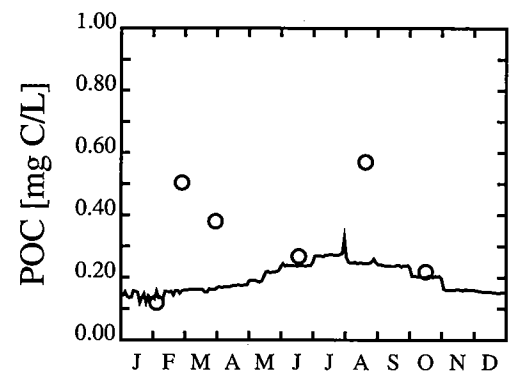
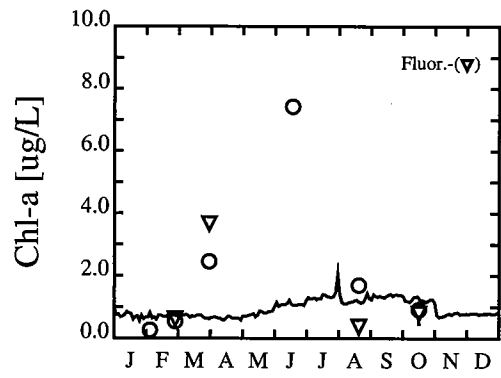
- +/- Surface Data
- Bottom Data
- std.dev. Surface Model
- Bottom Model

1998 Temporal Calibration Results for Grid Cell (51,47) Vs Data Station F26



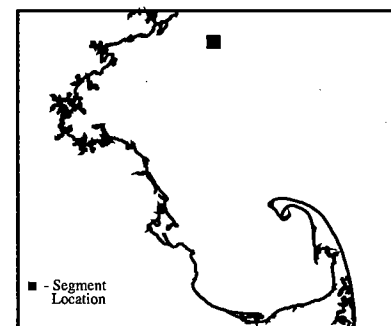
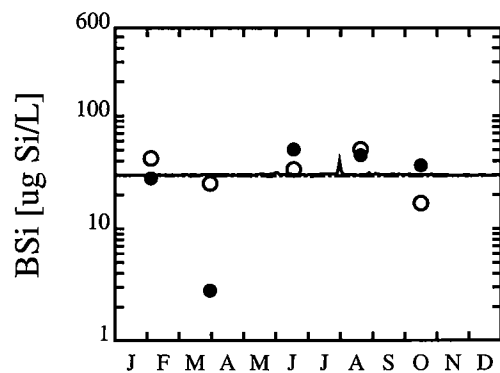
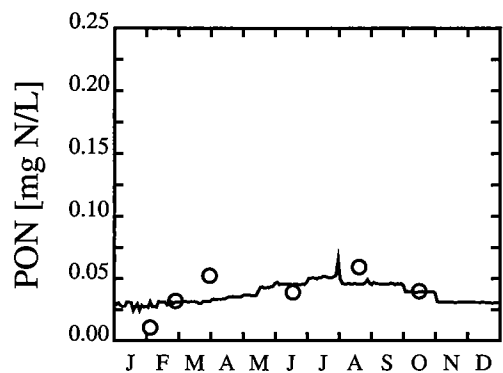
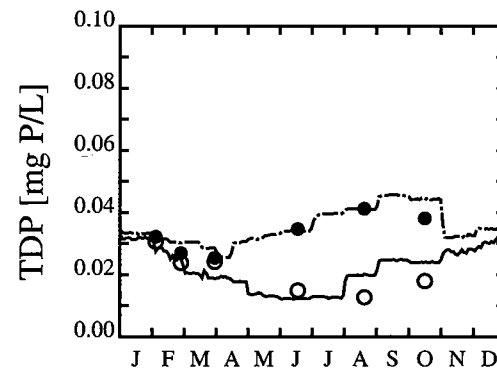
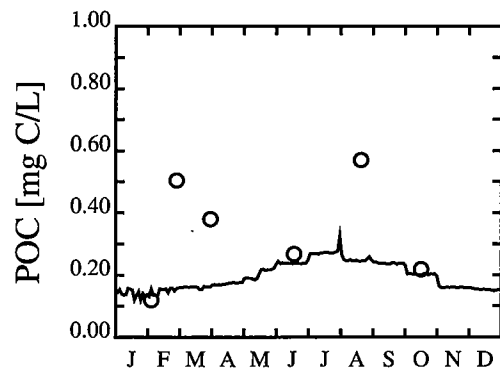
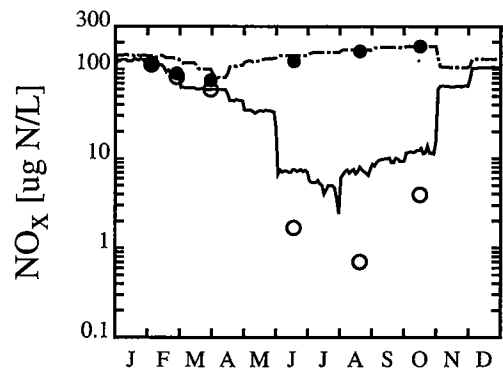
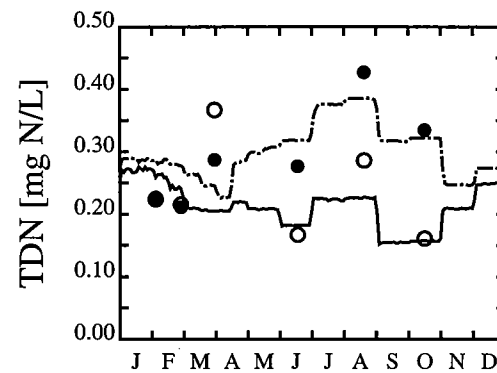
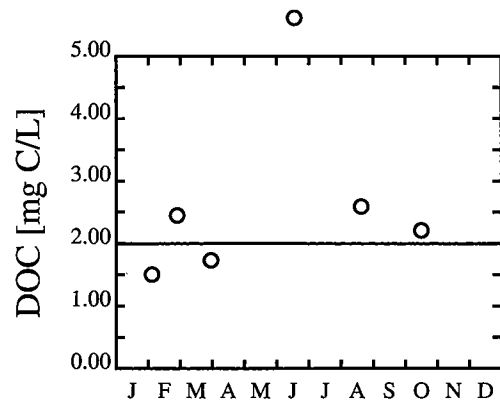
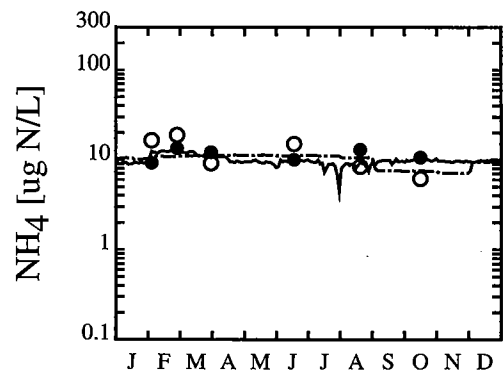
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 -std dev Surface Model
 - Bottom Model

1998 Temporal Calibration Results for Grid Cell (51,47) Vs Data Station F26



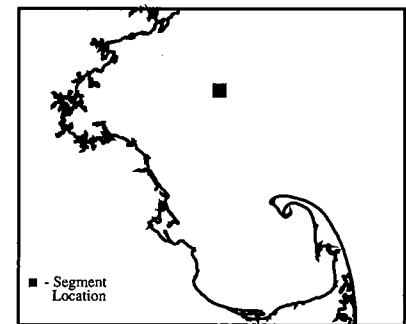
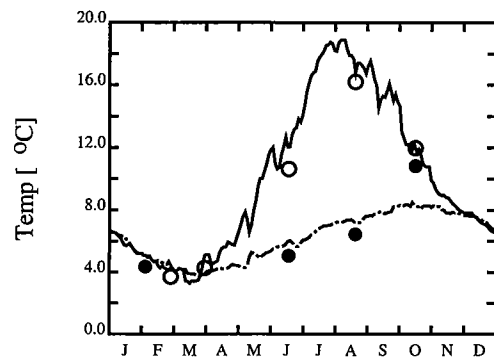
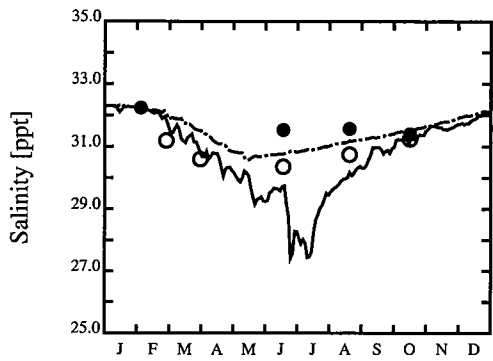
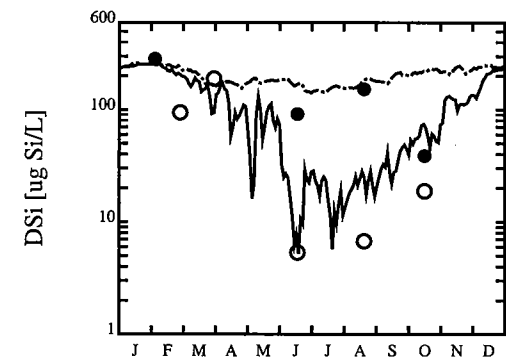
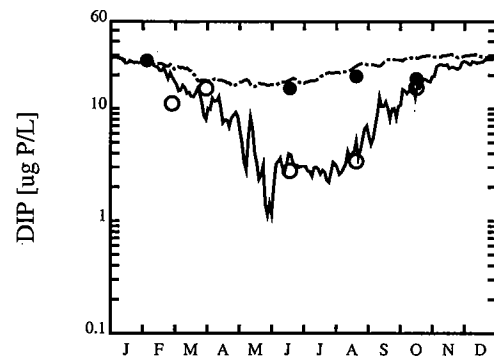
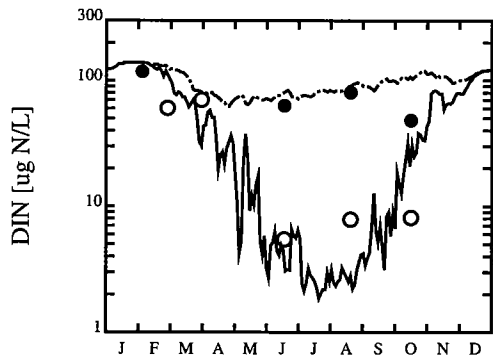
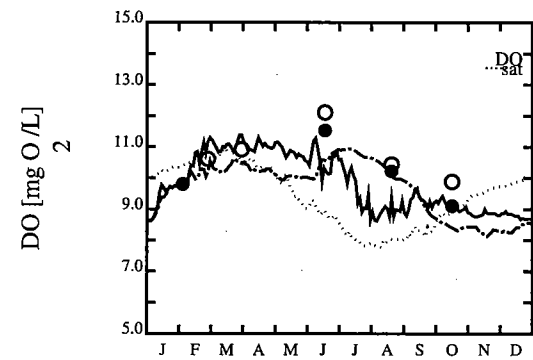
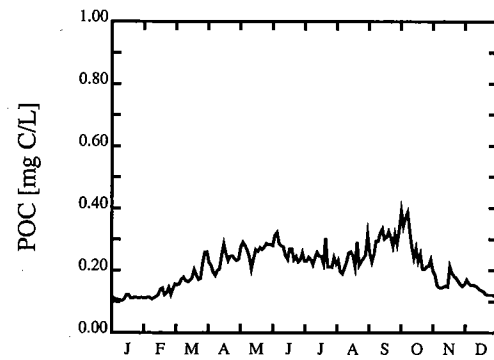
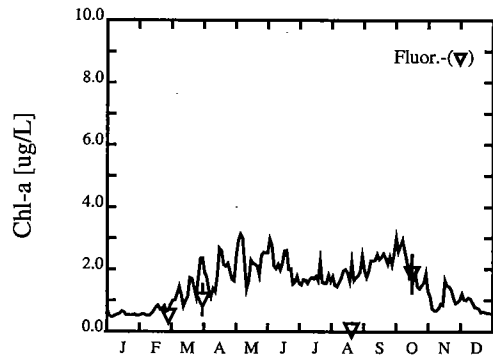
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev. Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (52,42) Vs Data Station F27



LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 —std dev Surface Model
 - - - Bottom Model

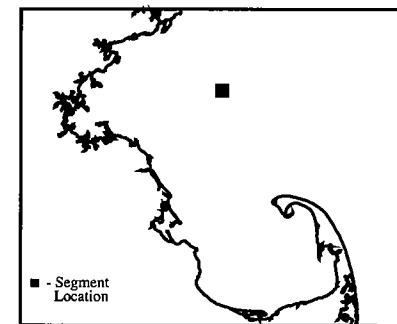
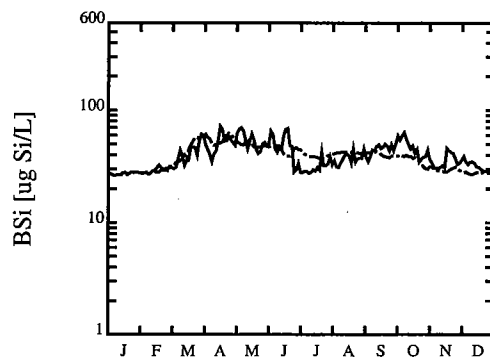
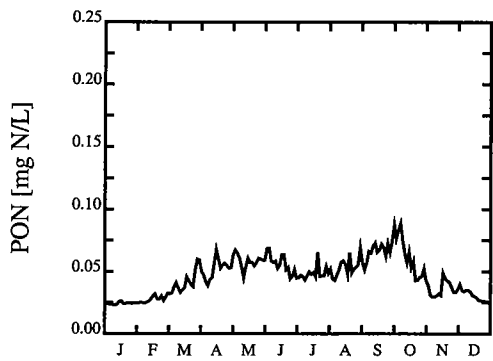
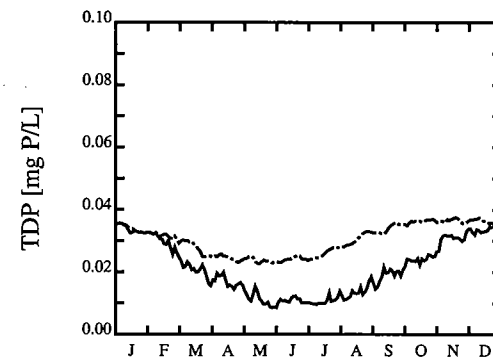
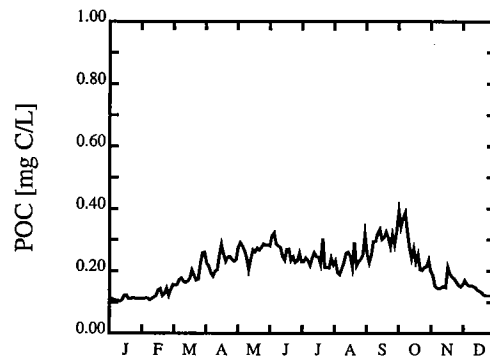
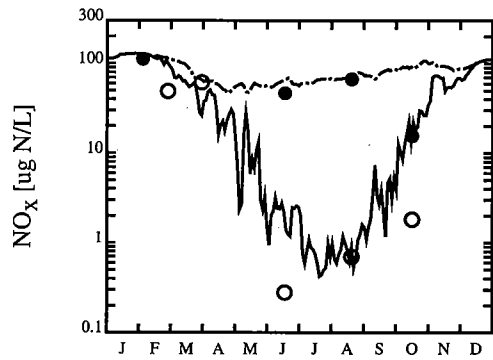
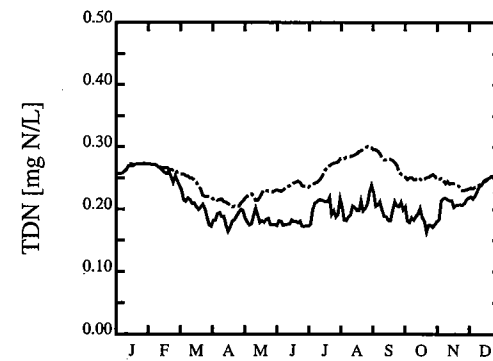
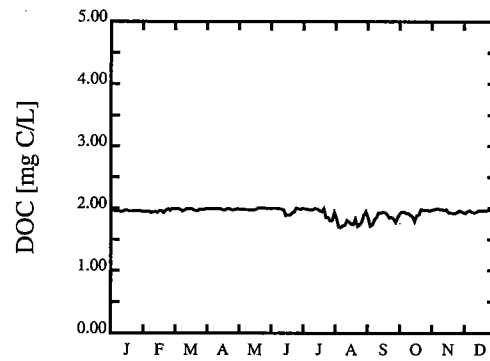
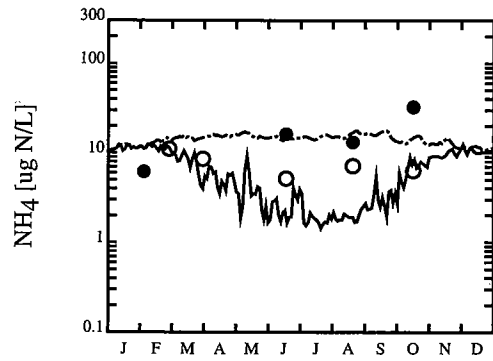
1998 Temporal Calibration Results for Grid Cell (52,42) Vs Data Station F27



LEGEND

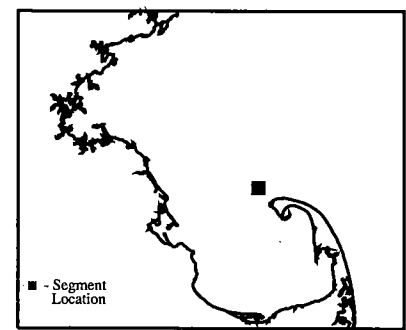
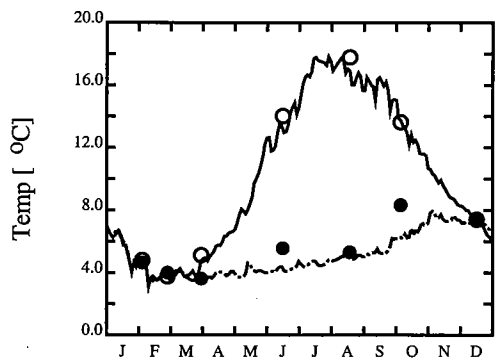
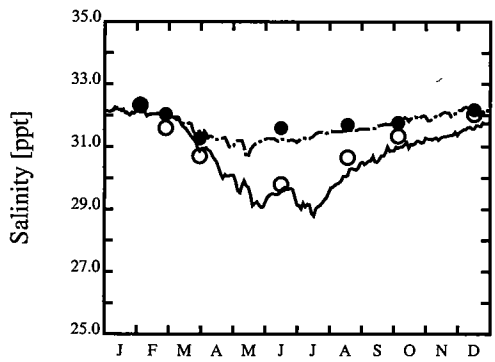
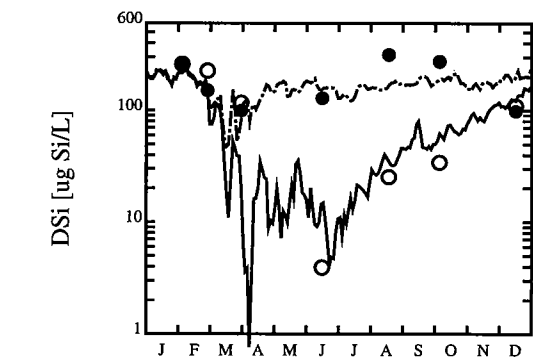
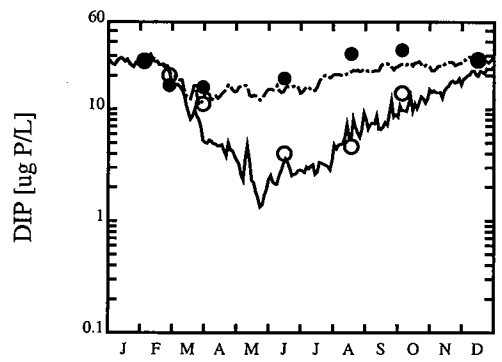
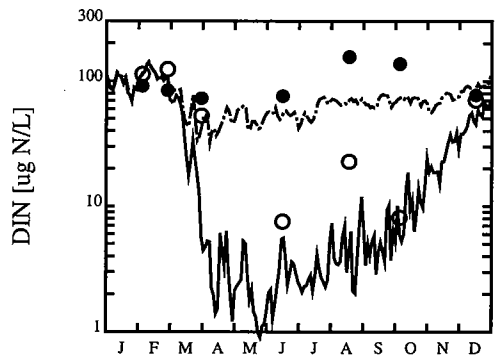
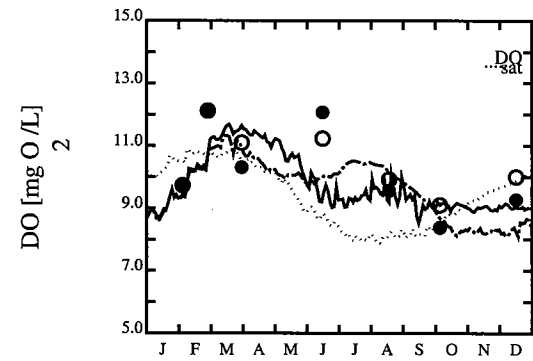
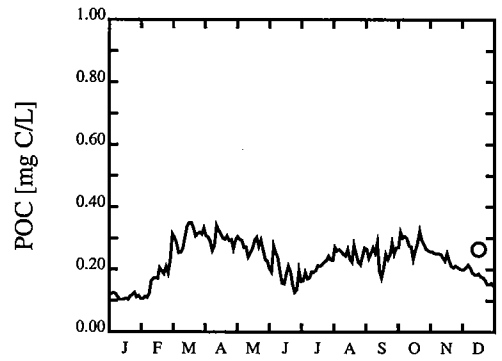
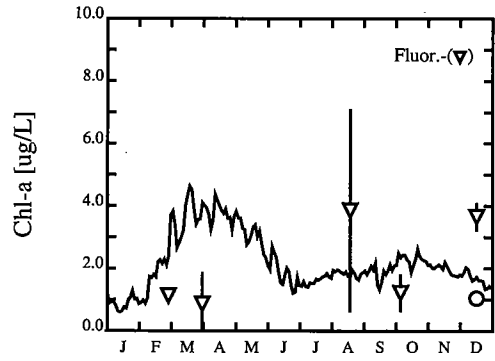
- +/- Surface Data
- Bottom Data
- std.dev Surface Model
- Bottom Model

1998 Temporal Calibration Results for Grid Cell (46,36) Vs Data Station F28



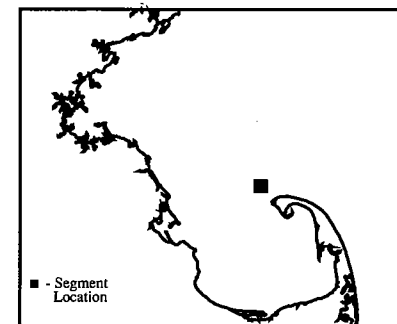
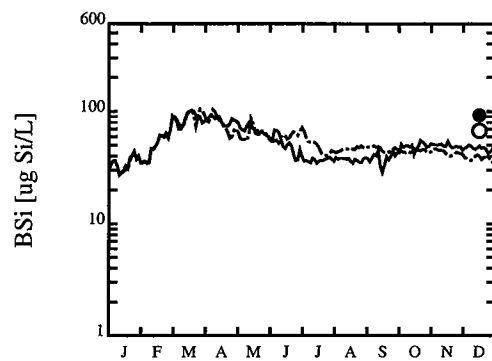
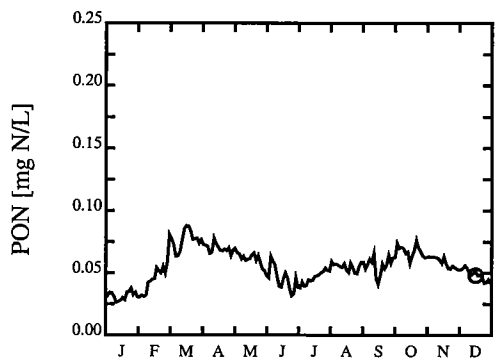
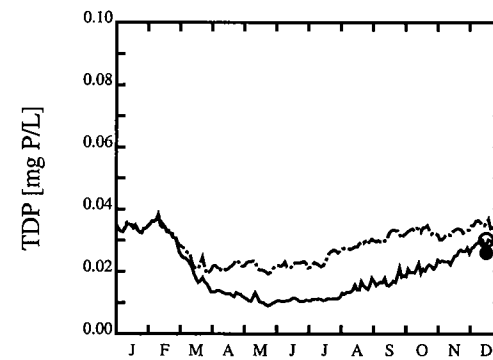
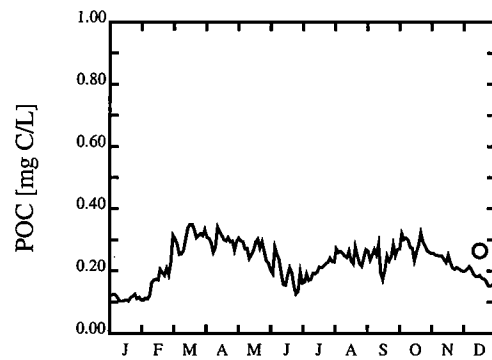
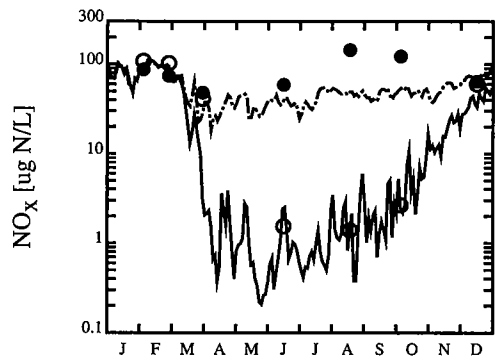
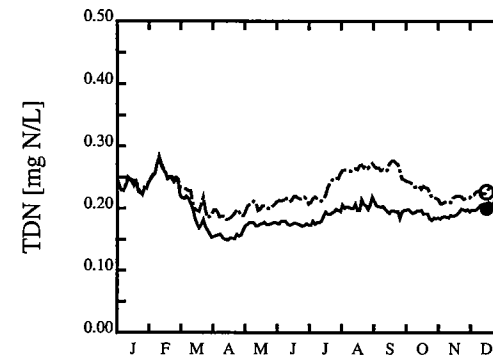
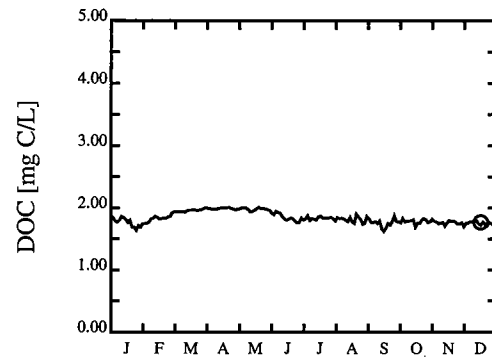
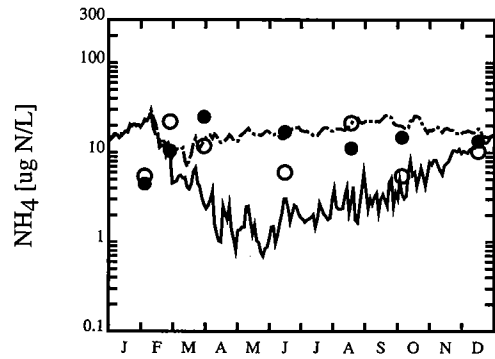
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 — std.dev. Surface Model
 - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (46,36) Vs Data Station F28



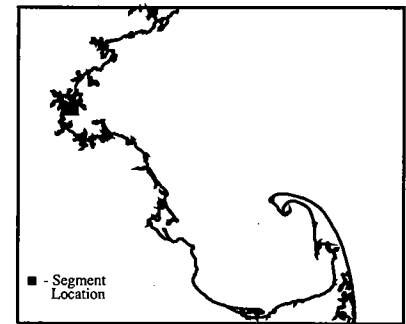
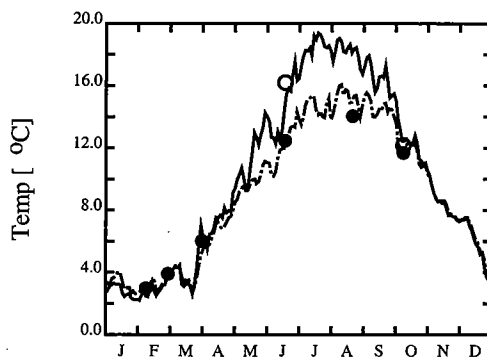
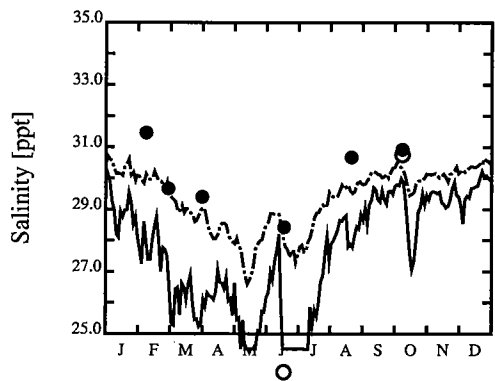
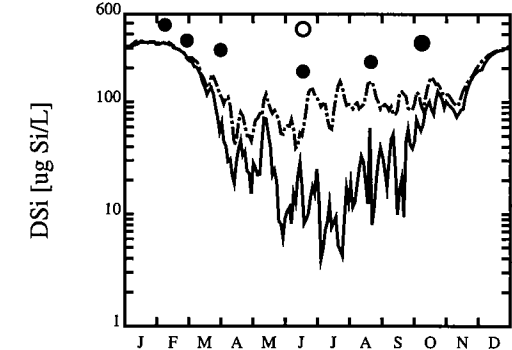
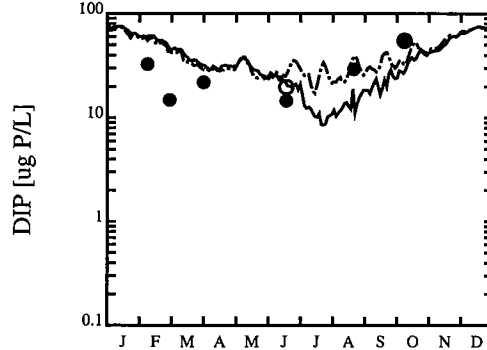
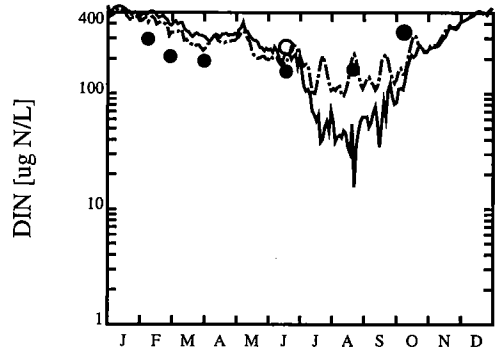
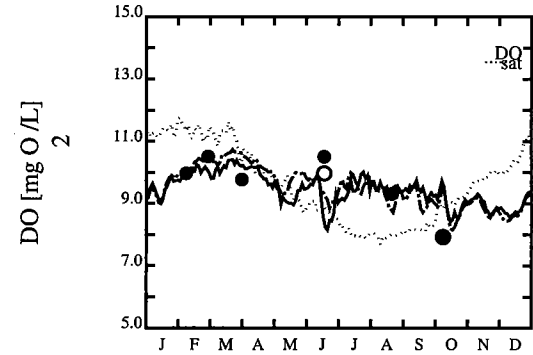
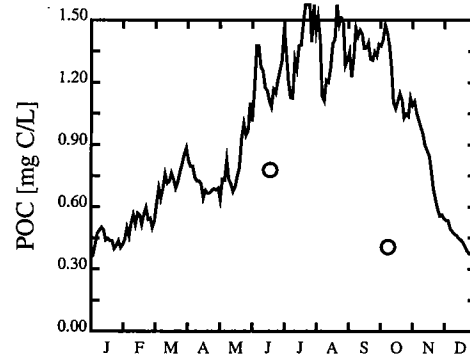
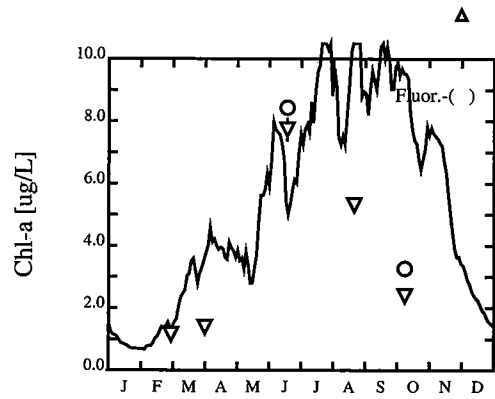
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev. Surface Model
 - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (41,21) Vs Data Station F29



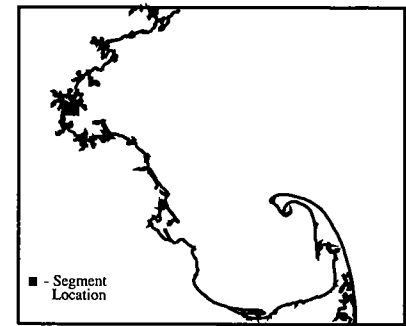
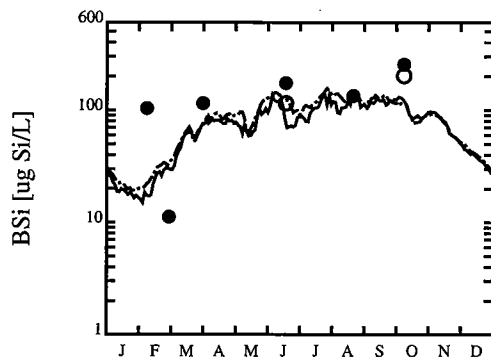
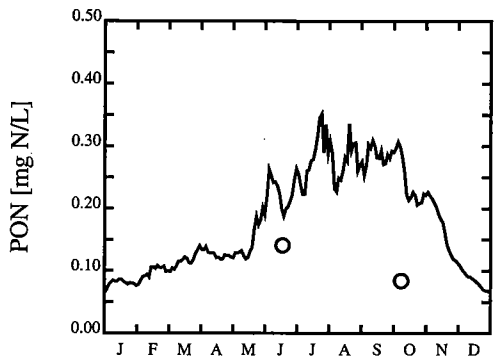
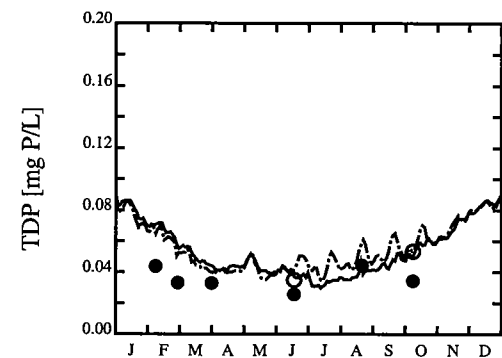
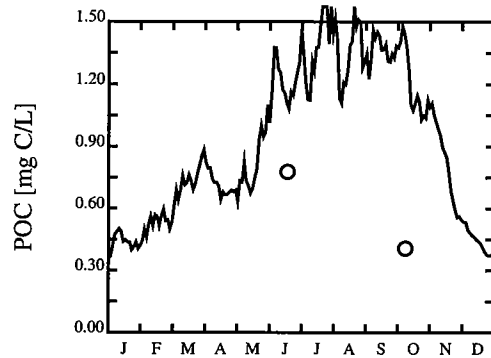
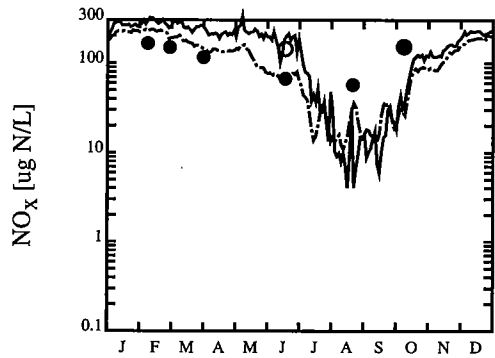
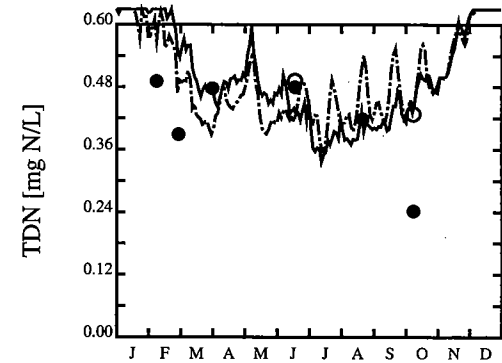
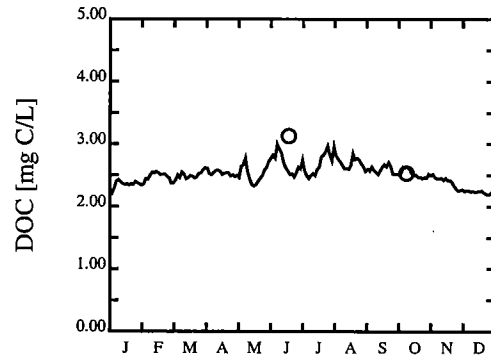
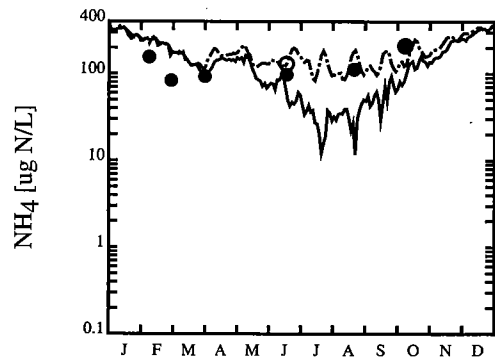
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - std.dev. Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (41,21) Vs Data Station F29



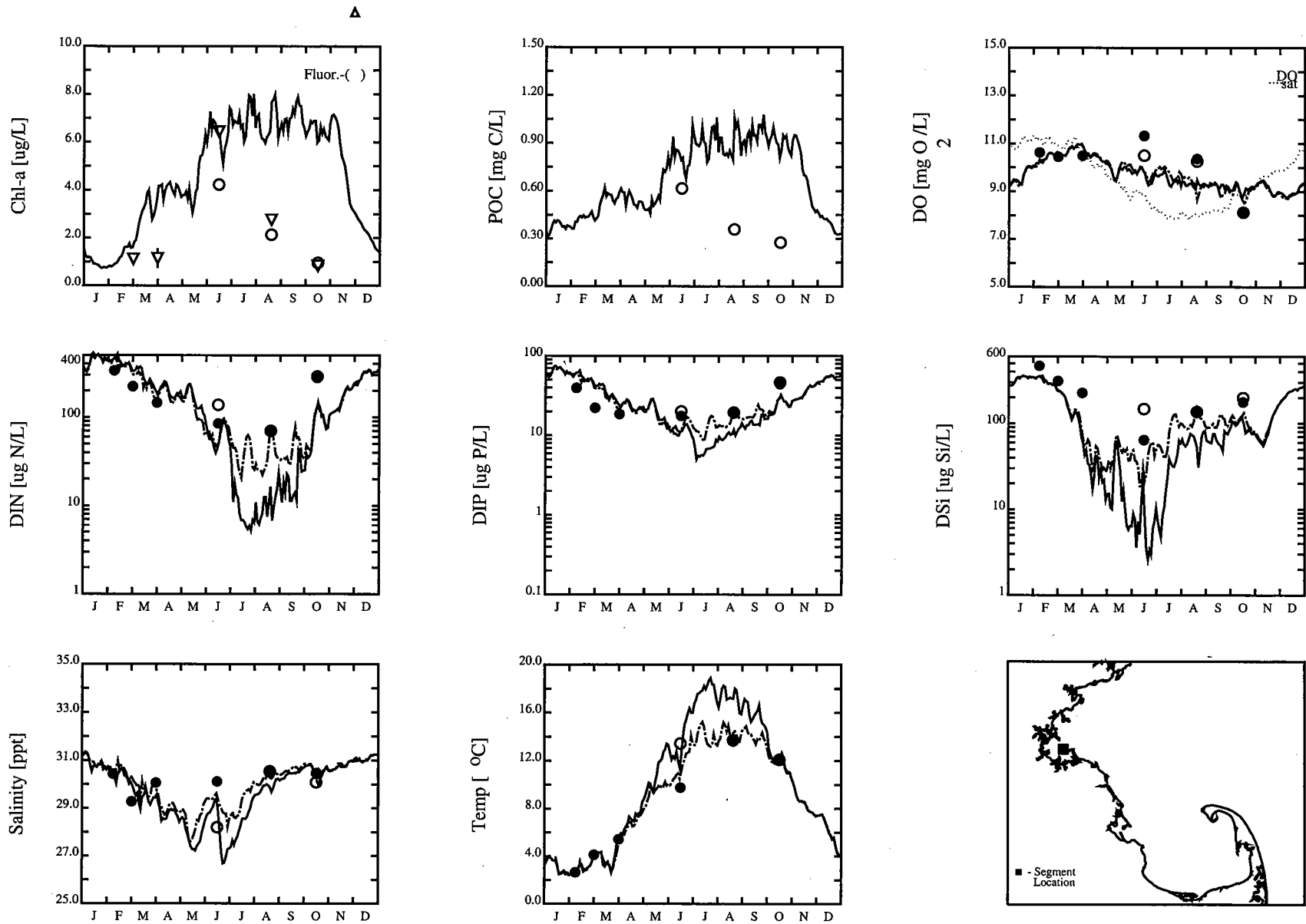
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 ● Bottom Data
 — std.dev Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (18,59) Vs Data Station F30

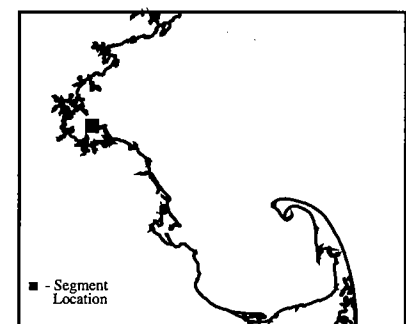
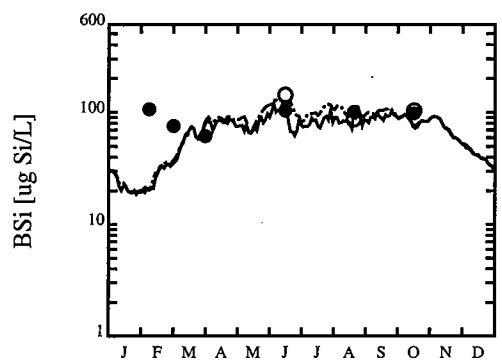
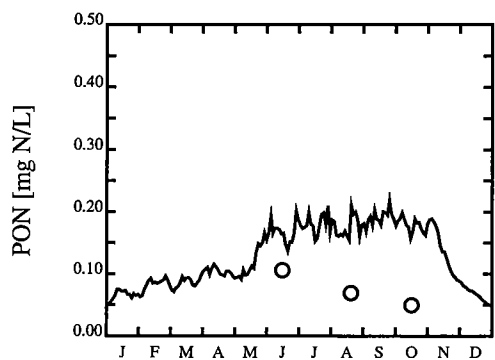
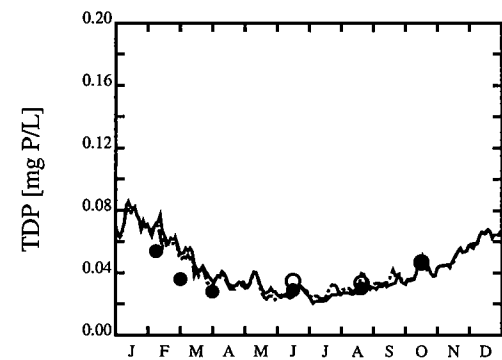
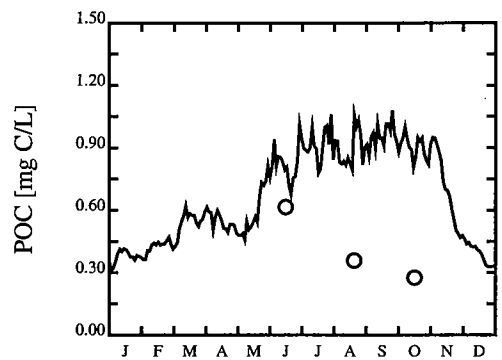
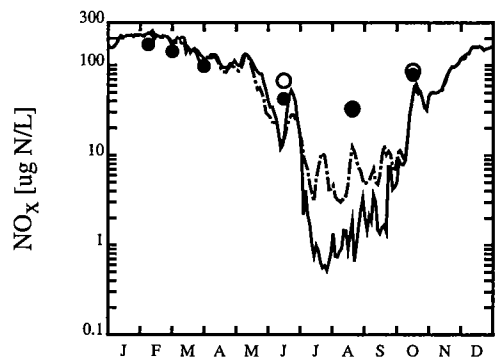
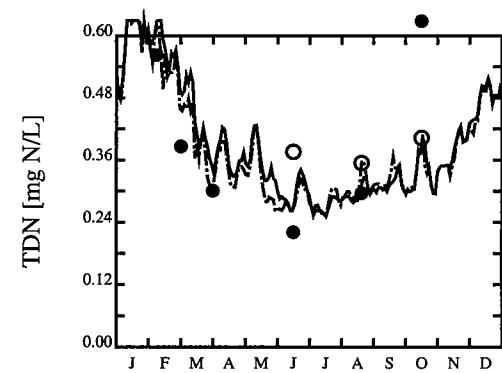
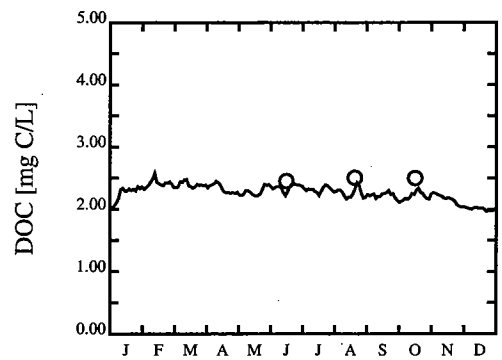
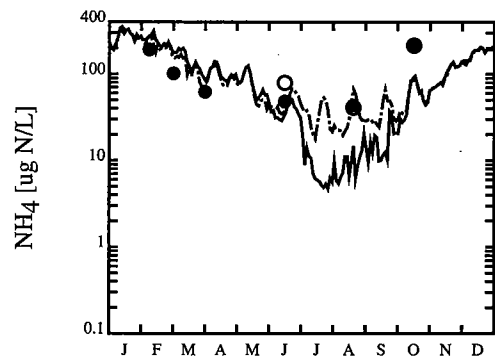


----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std dev- Surface Model
 - - - - - Bottom Model

1998 Temporal Calibration Results for Grid Cell (18,59) Vs Data Station F30



1998 Temporal Calibration Results for Grid Cell (17,52) Vs Data Station F31



----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev- Surface Model
 - - - - Bottom Model

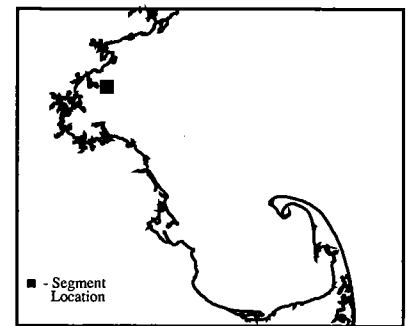
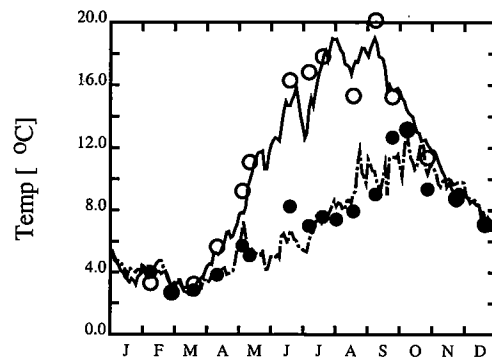
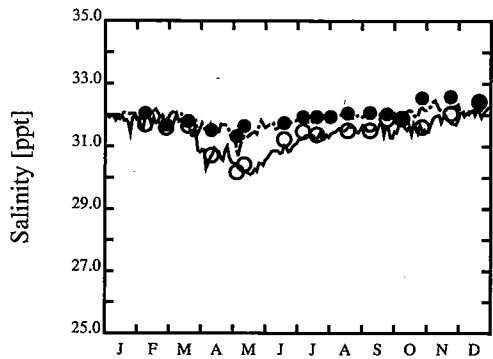
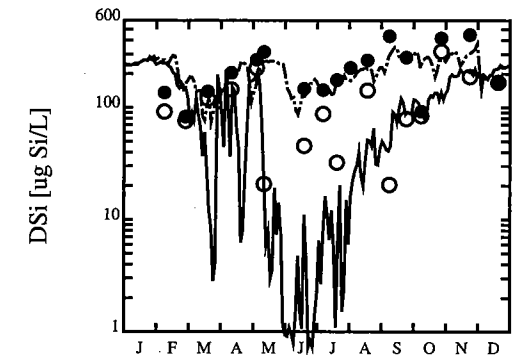
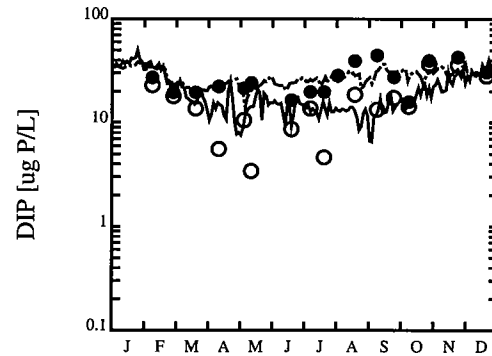
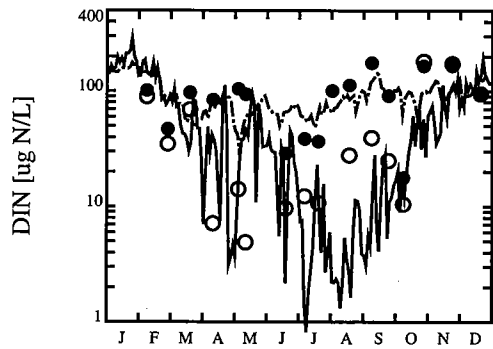
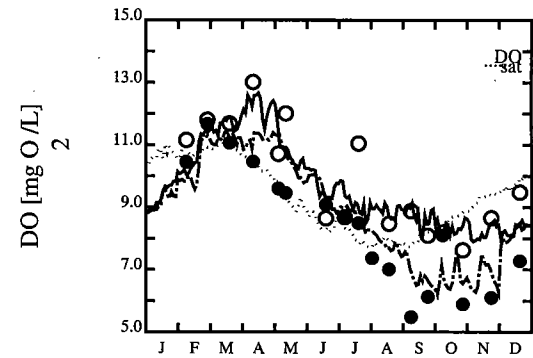
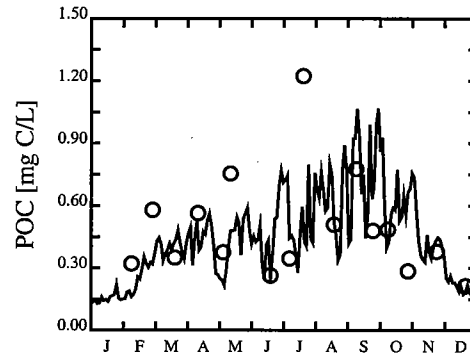
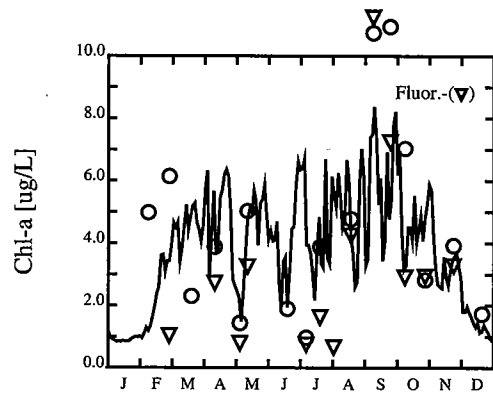
1998 Temporal Calibration Results for
 Grid Cell (17,52) Vs Data Station F31

APPENDIX B

1999 RESULTS

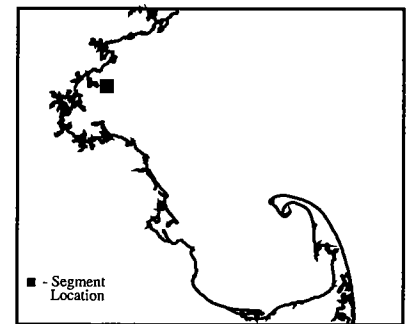
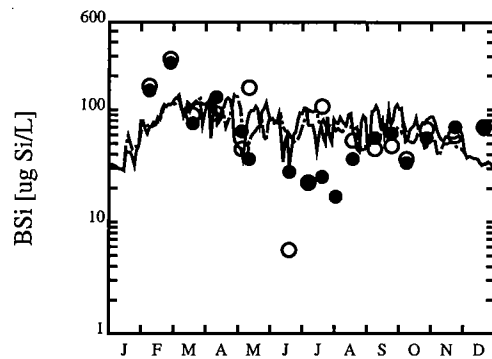
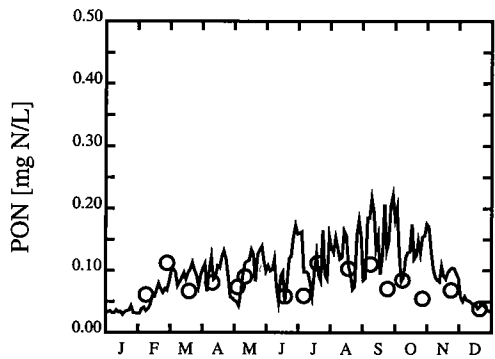
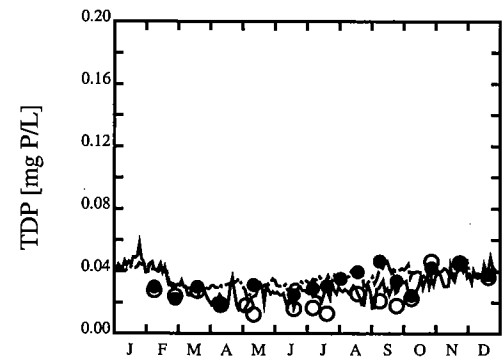
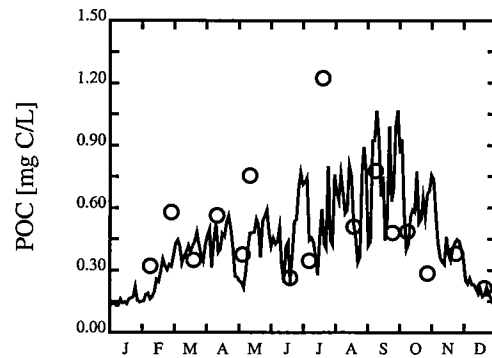
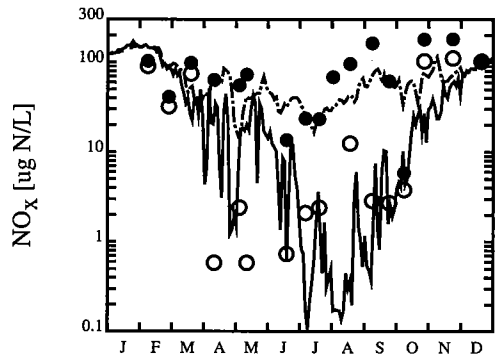
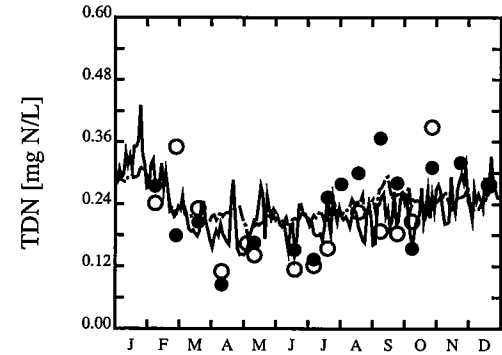
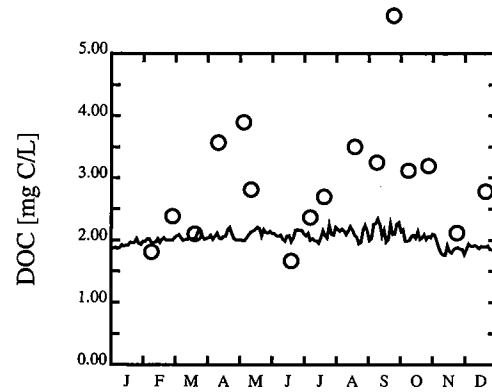
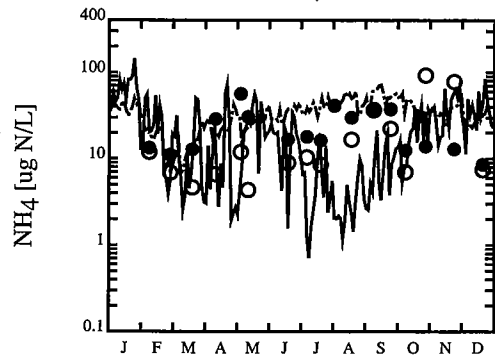


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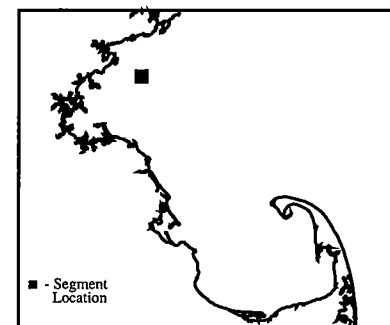
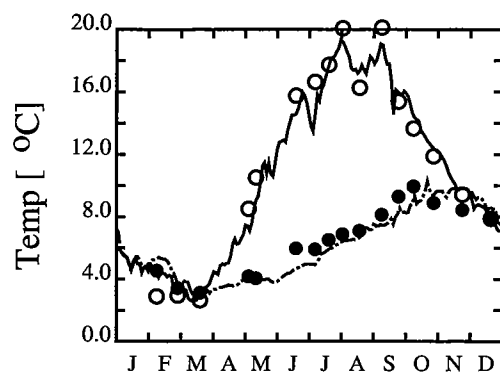
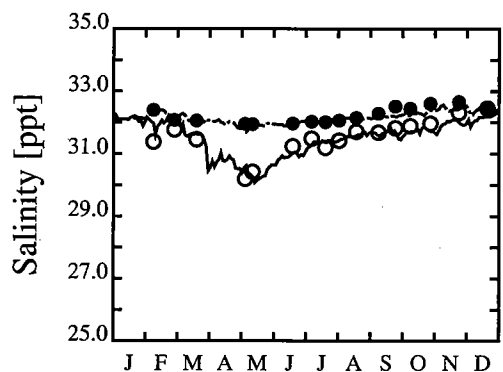
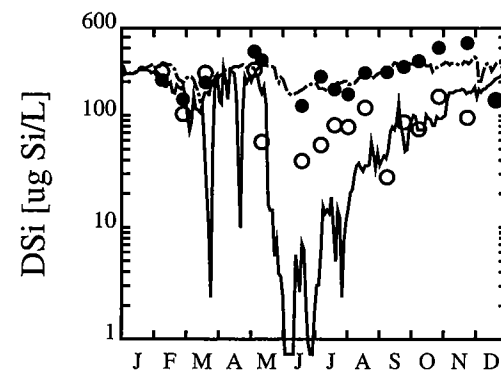
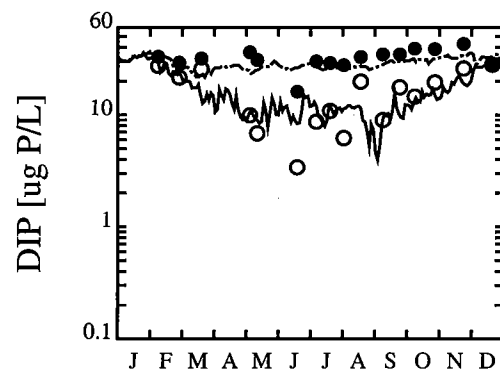
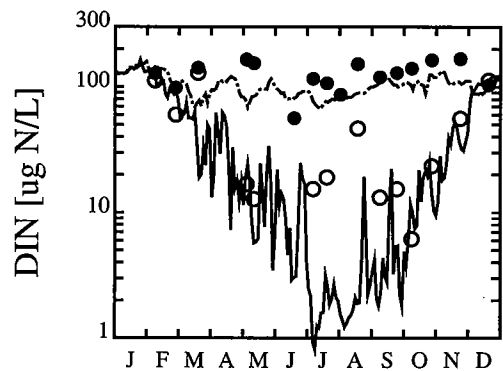
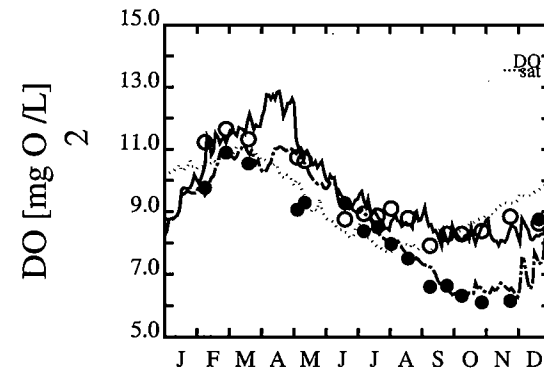
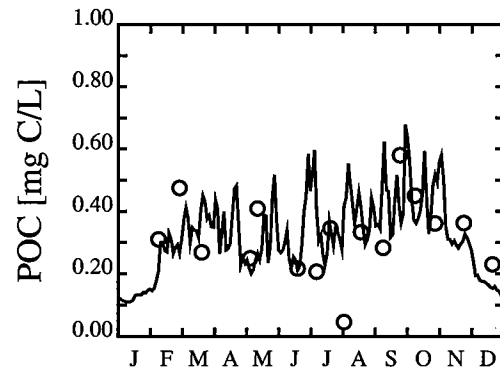
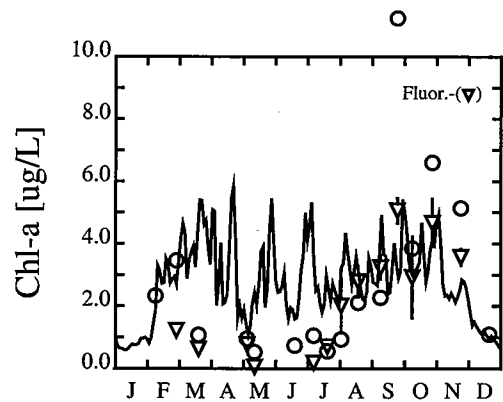
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 ---std.dev. Surface Model
 --- Bottom Model

1999 Temporal Calibration Results for Grid Cell (30,53) Vs Data Station N01P



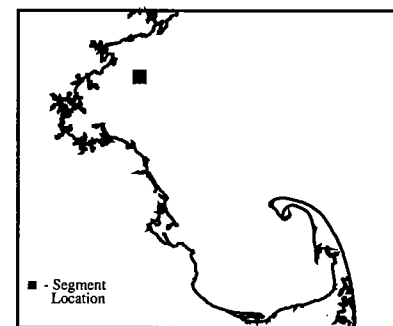
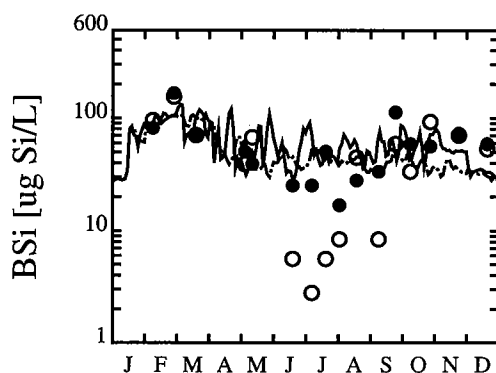
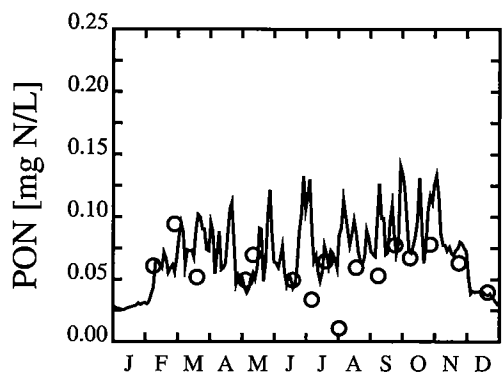
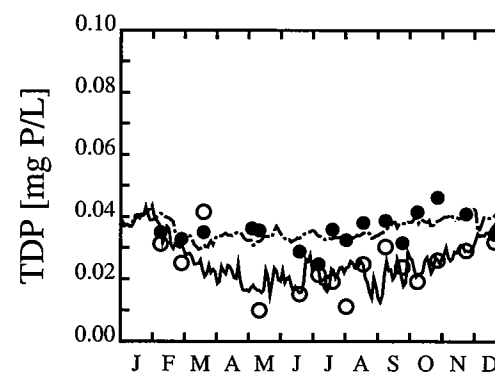
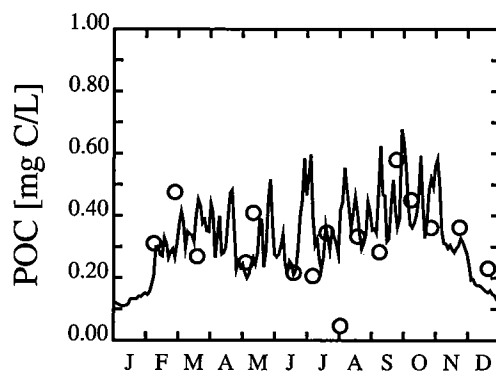
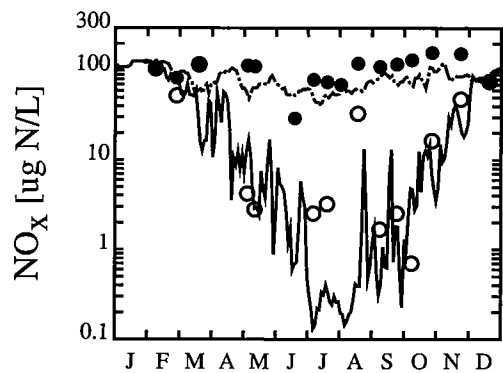
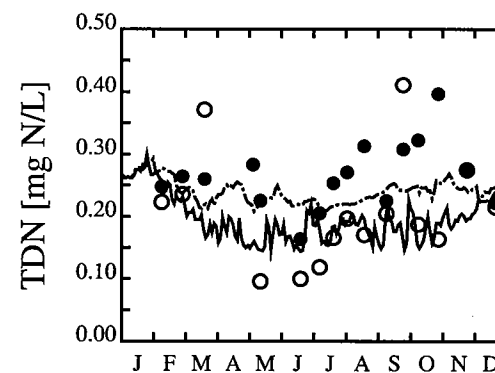
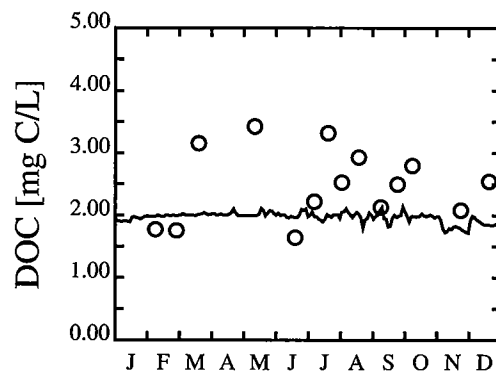
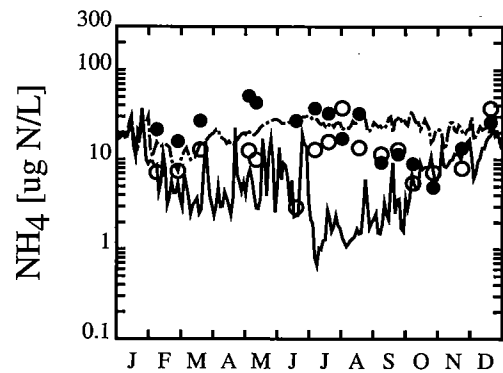
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 ● Bottom Data
 — std dev Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (30,53) Vs Data Station N01P



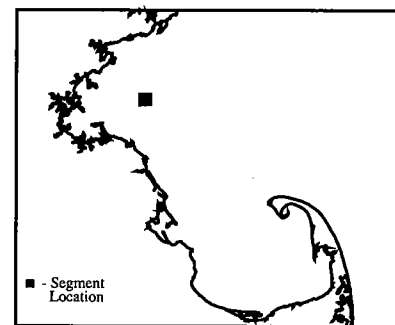
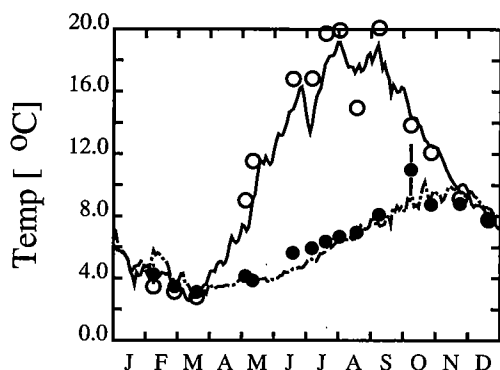
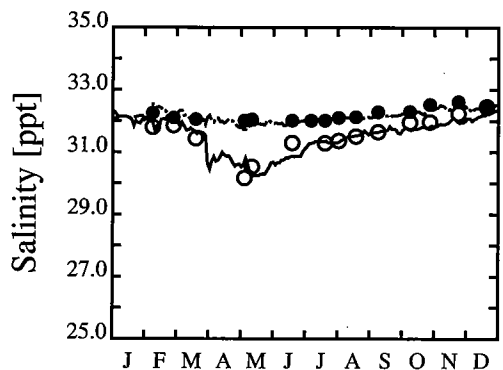
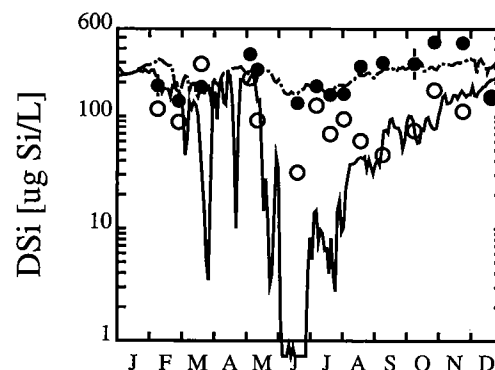
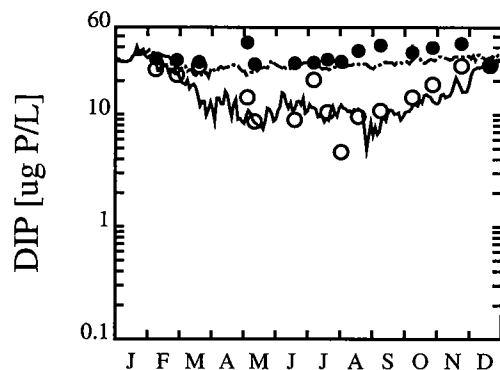
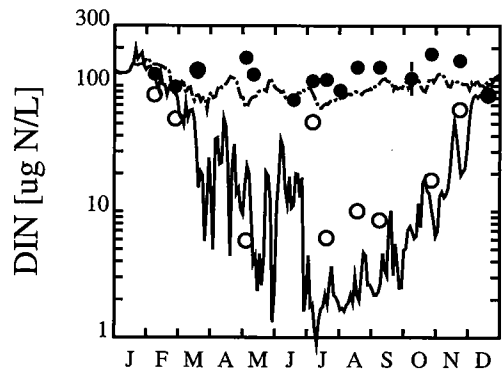
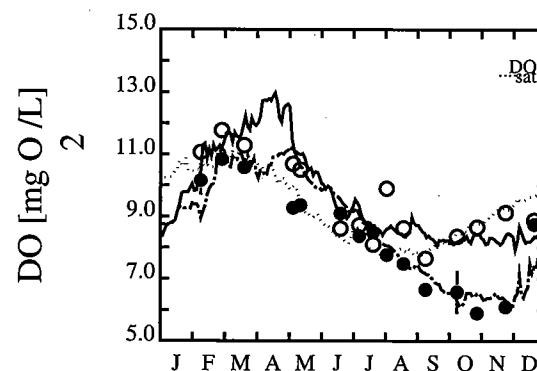
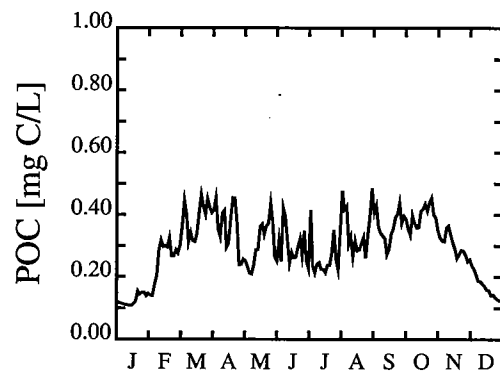
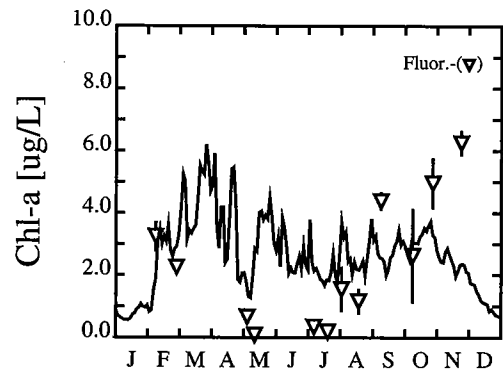
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 ● std.dev. Surface Model
 ----- Bottom Model

1999 Temporal Calibration Results for Grid Cell (37,48) Vs Data Station N04P



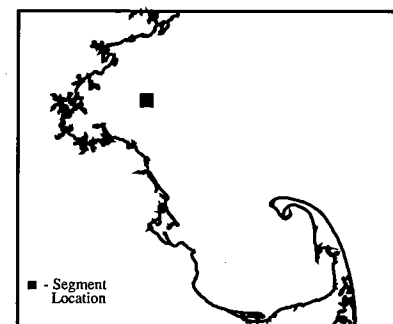
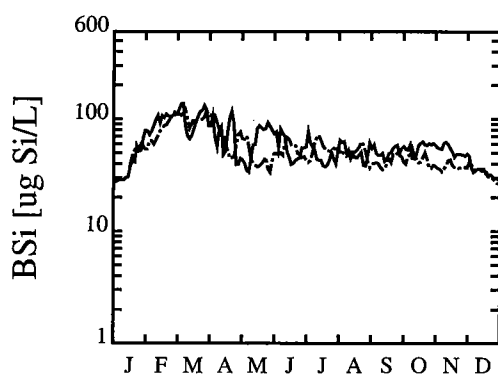
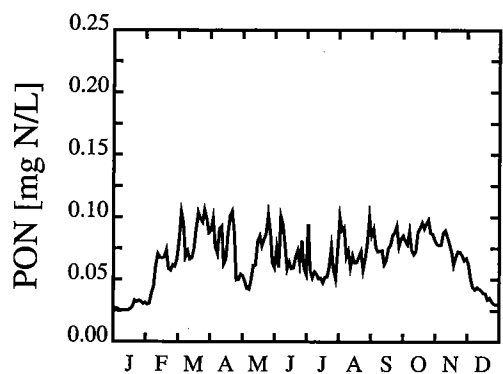
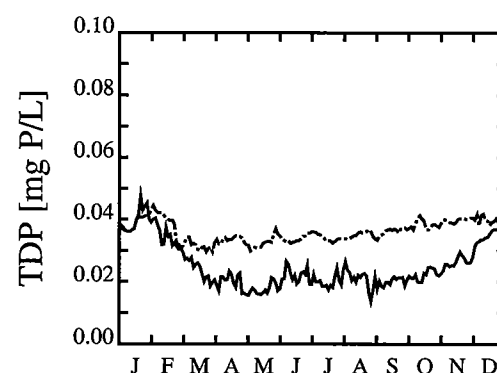
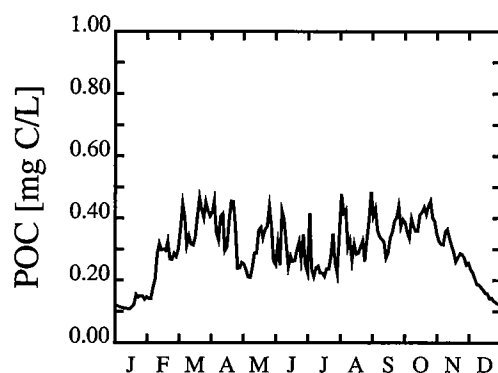
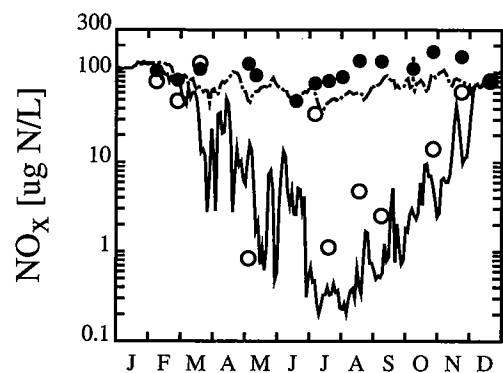
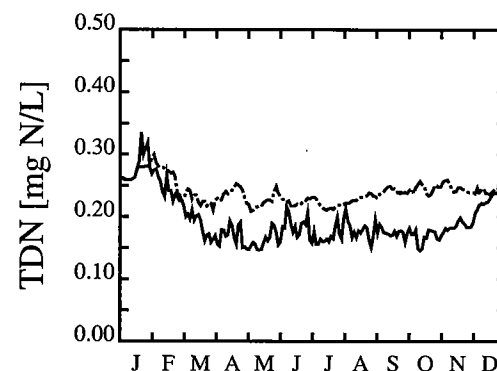
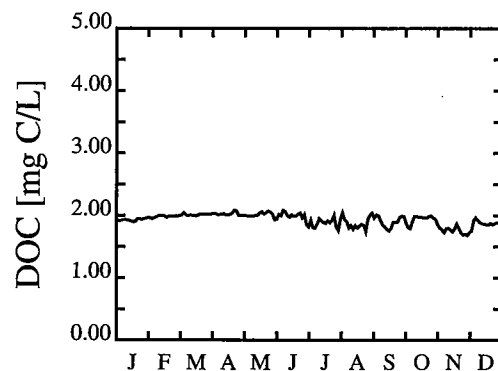
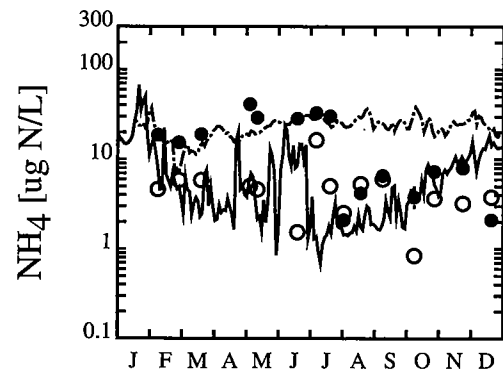
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - std.dev. Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (37,48) Vs Data Station N04P



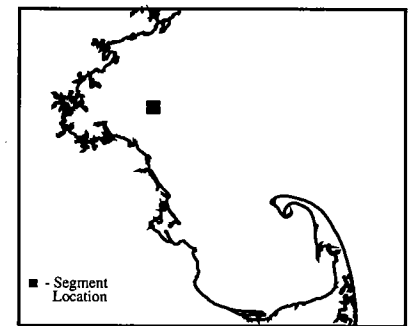
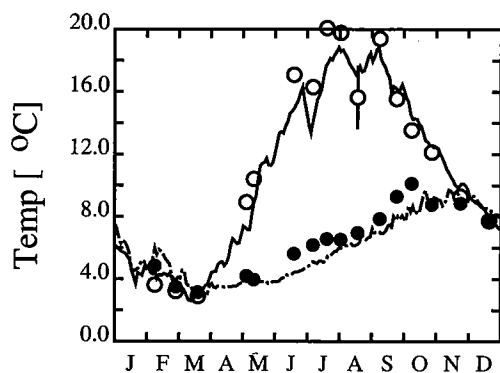
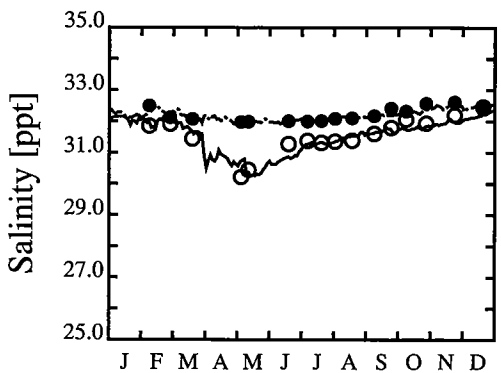
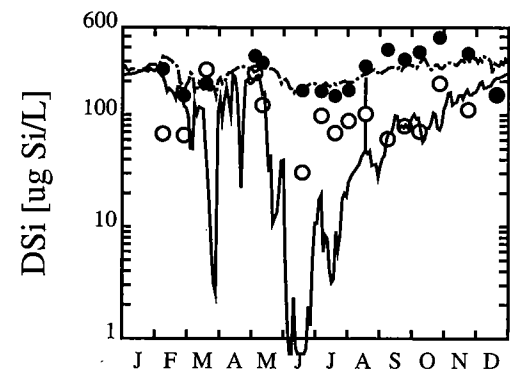
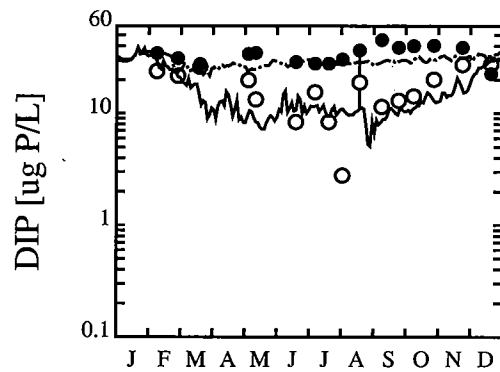
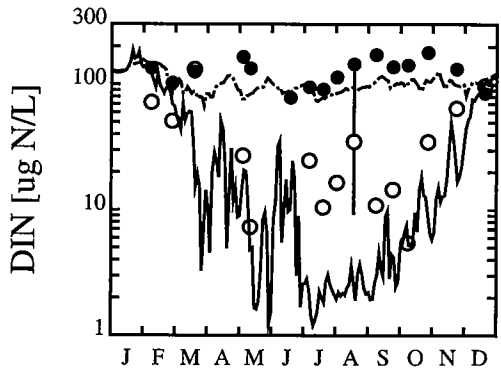
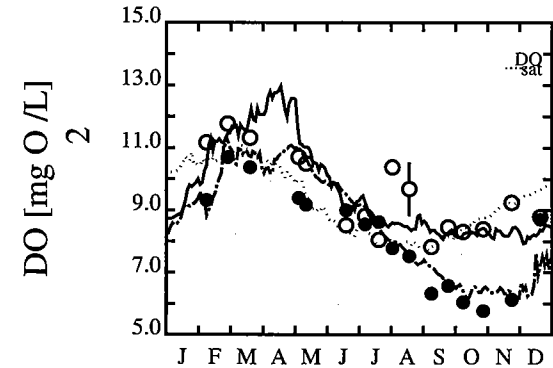
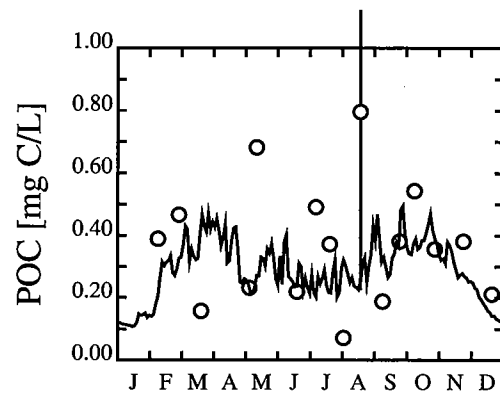
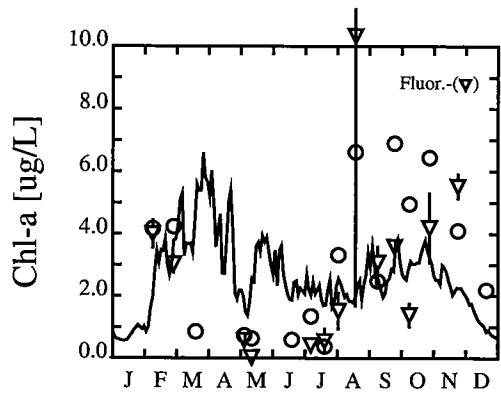
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - std dev Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (33,44) Vs Data Station N06



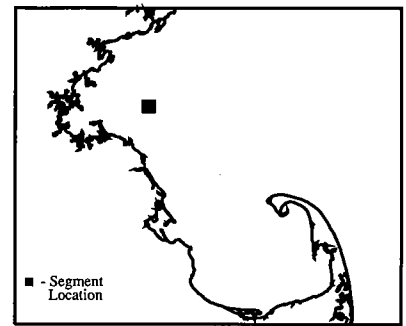
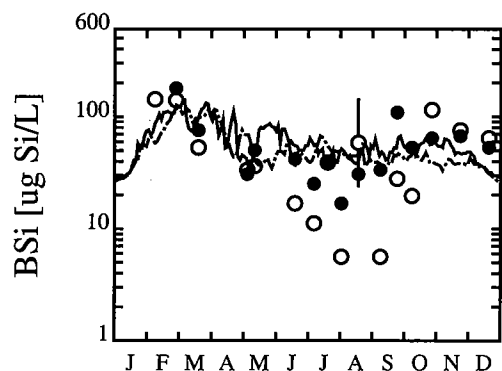
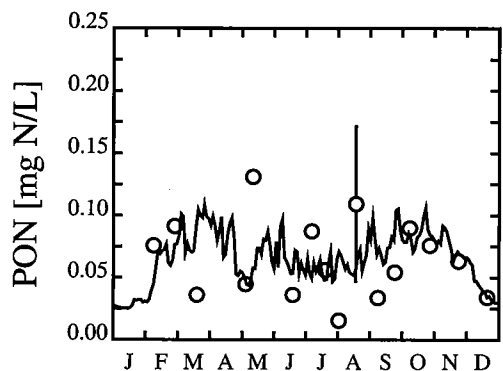
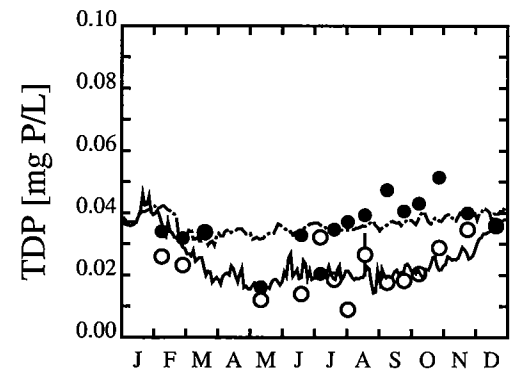
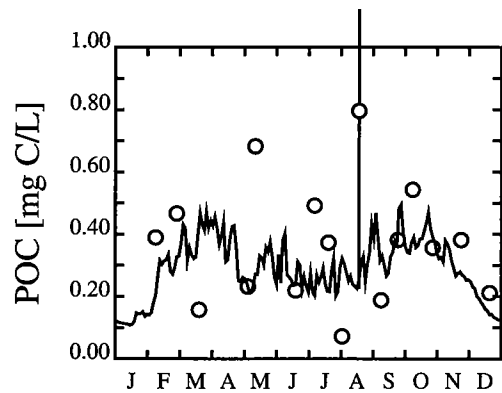
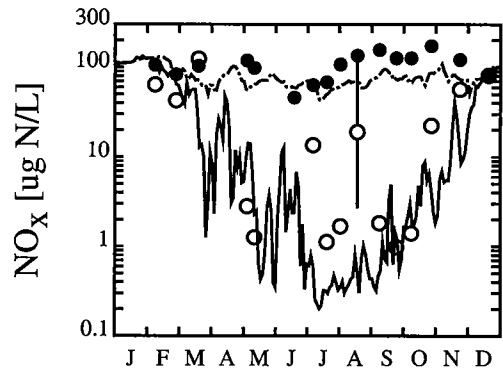
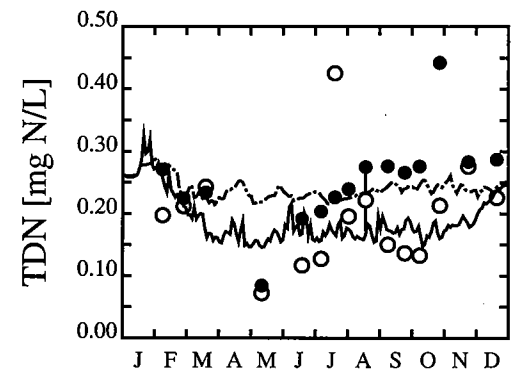
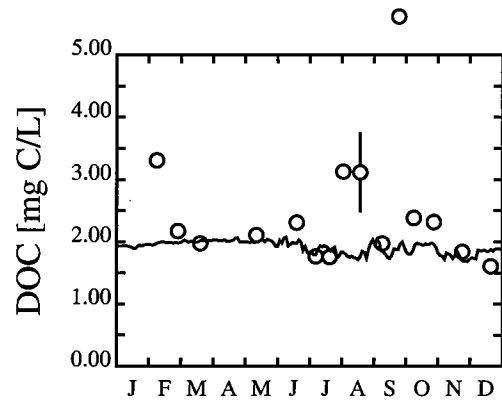
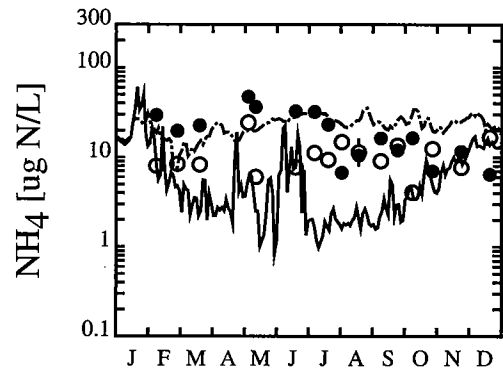
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 — sid.dev Surface Model
 - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (33,44) Vs Data Station N06



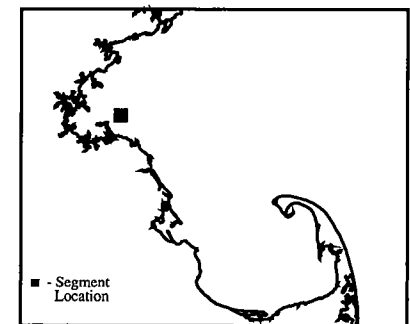
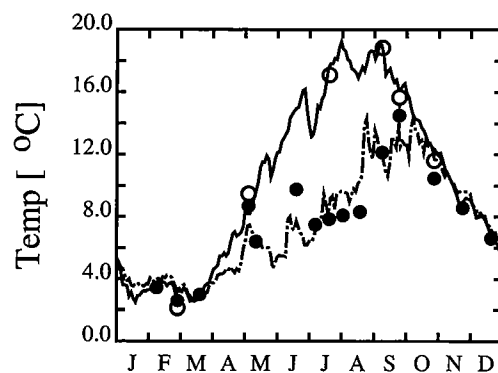
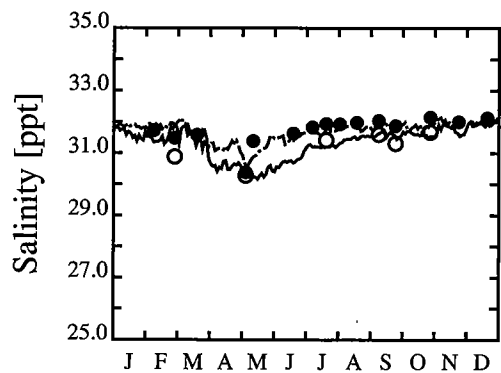
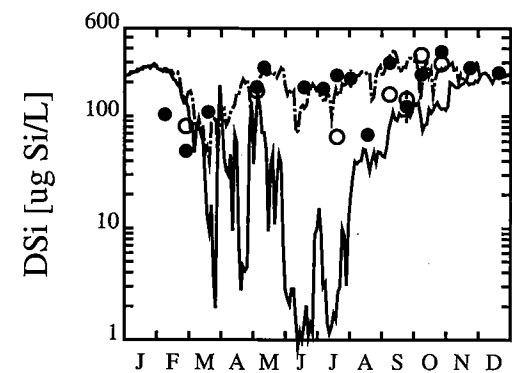
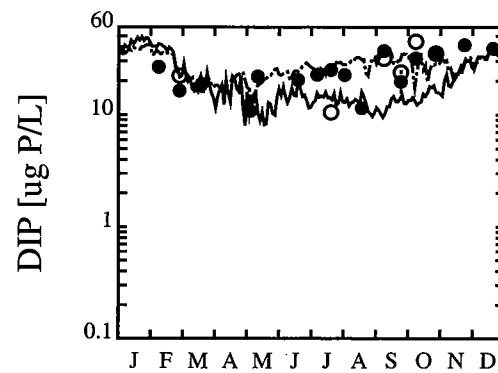
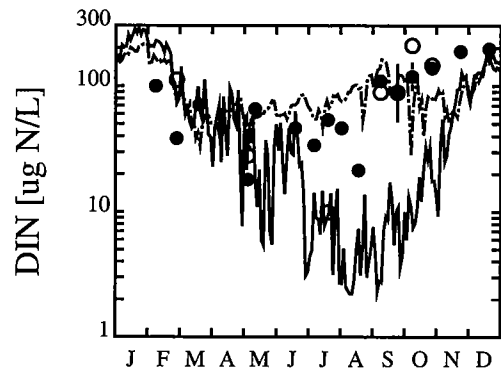
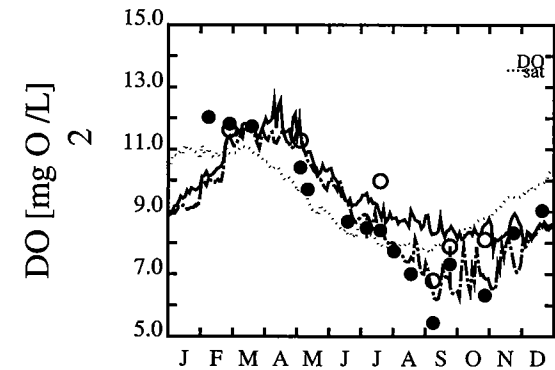
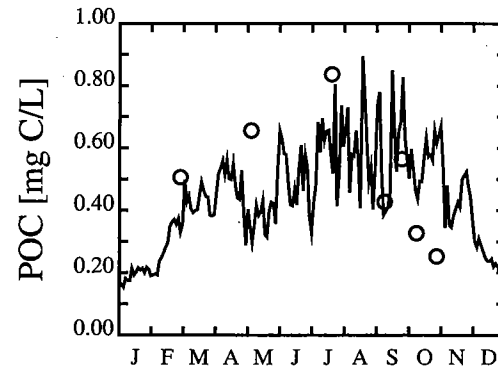
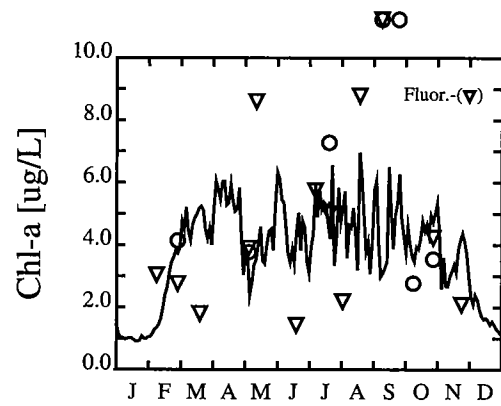
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 ---std.dev. Surface Model
 --- Bottom Model

1999 Temporal Calibration Results for Grid Cell (32,42) Vs Data Station N07P



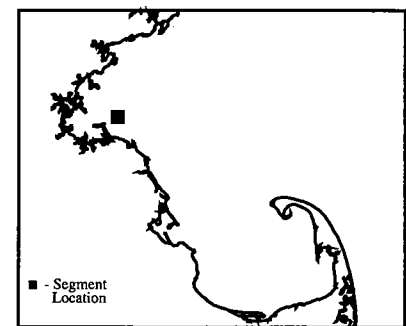
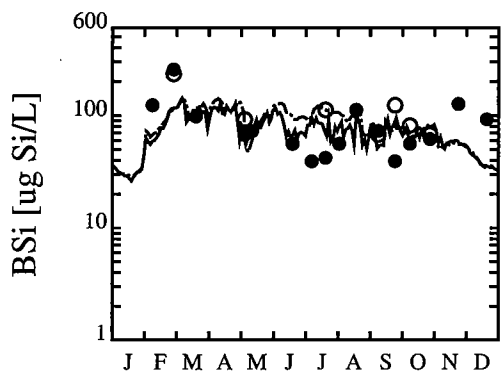
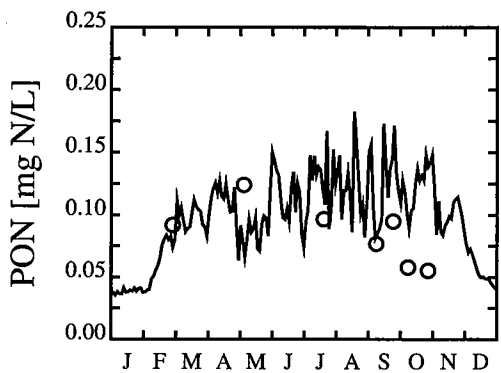
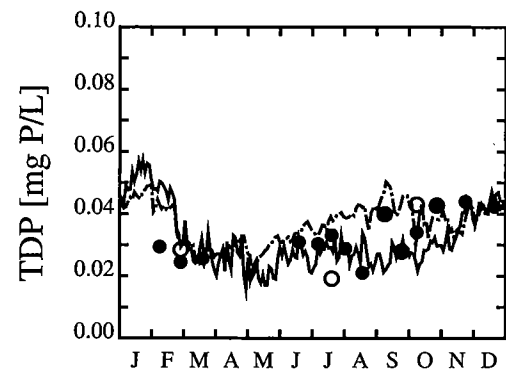
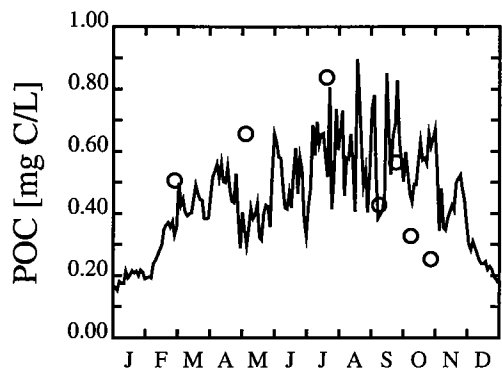
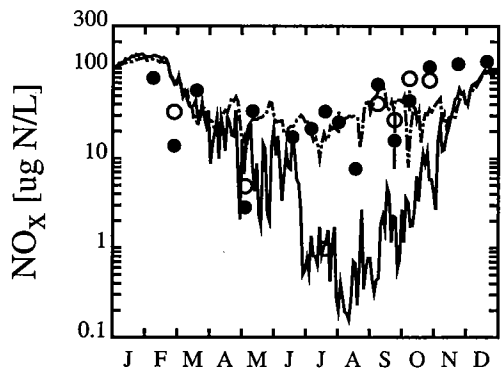
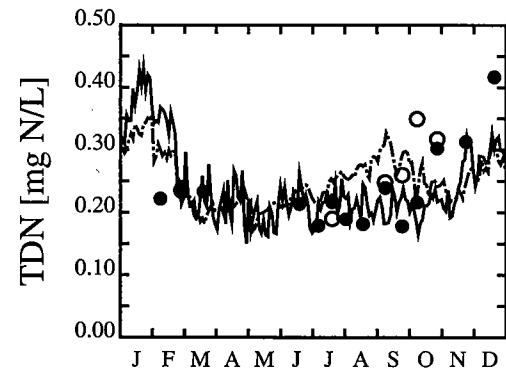
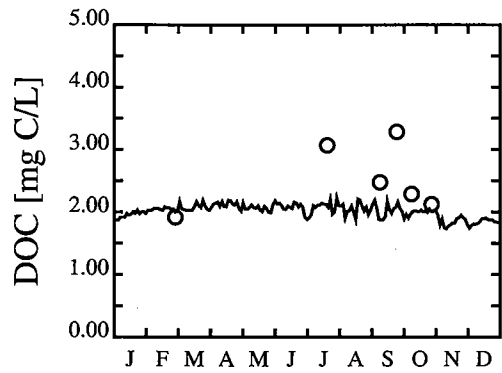
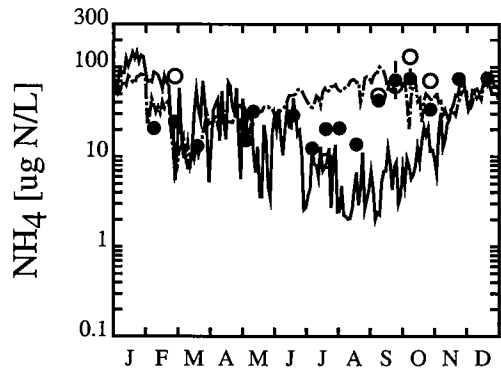
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std dev- Surface Model
 - Bottom Model

1999 Temporal Calibration Results for Grid Cell (32,42) Vs Data Station N07P



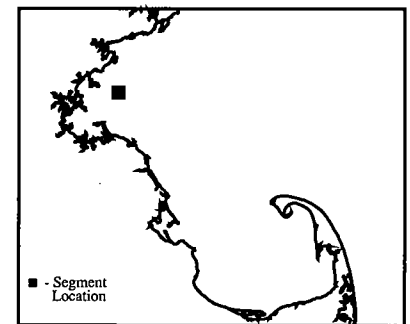
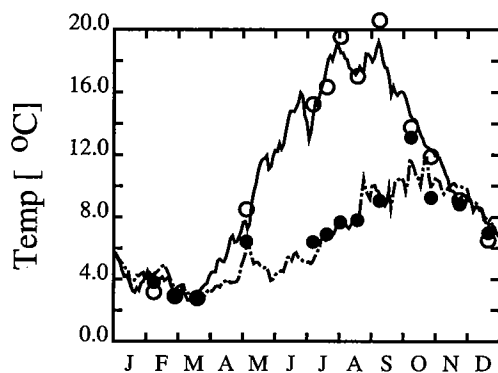
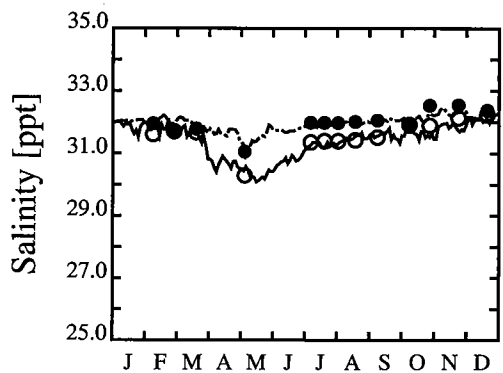
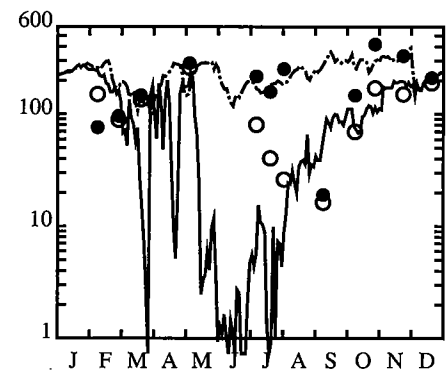
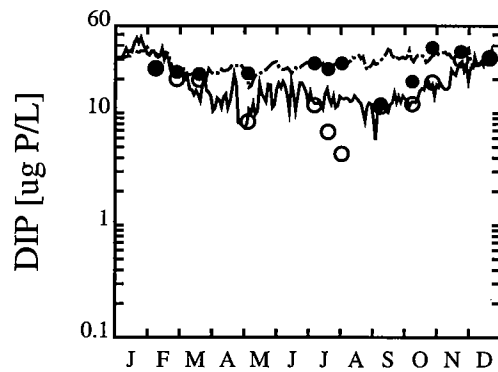
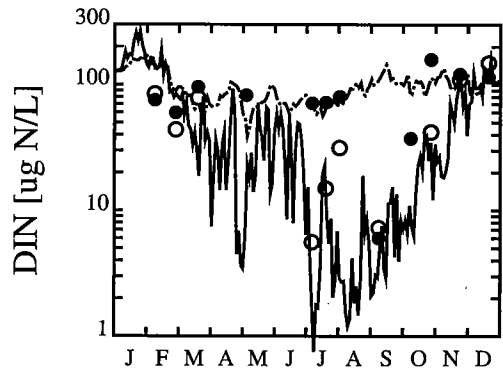
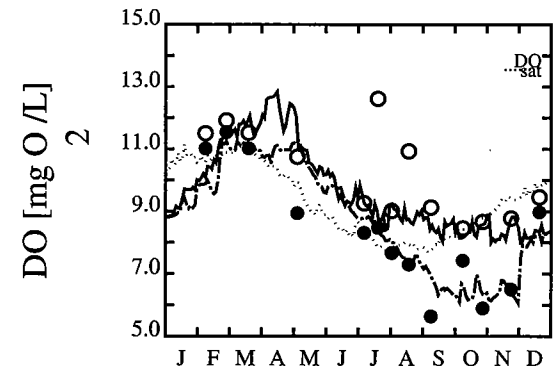
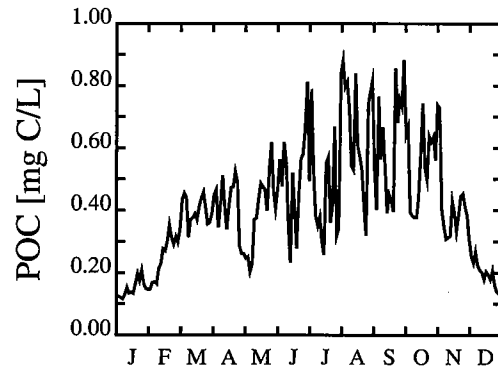
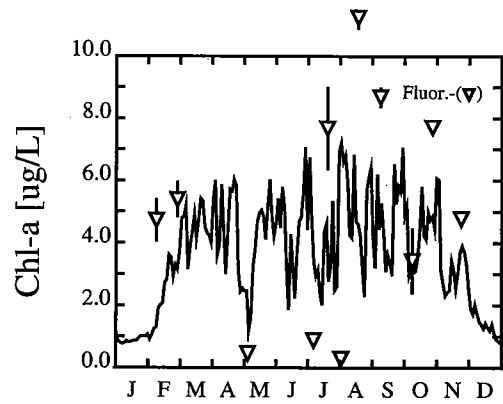
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std dev- Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (24,47) Vs Data Station N10P



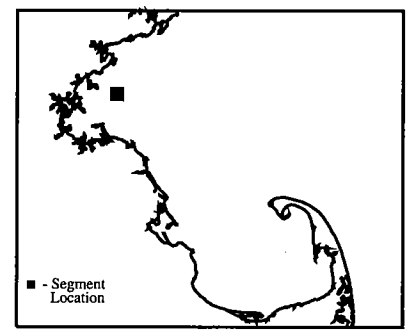
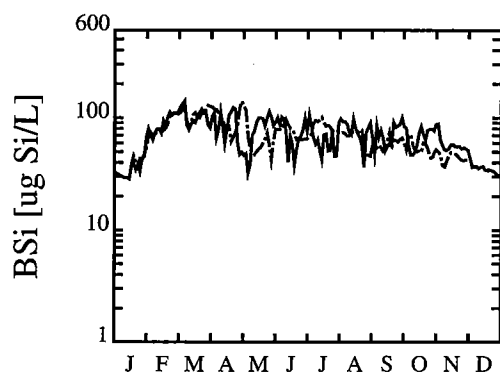
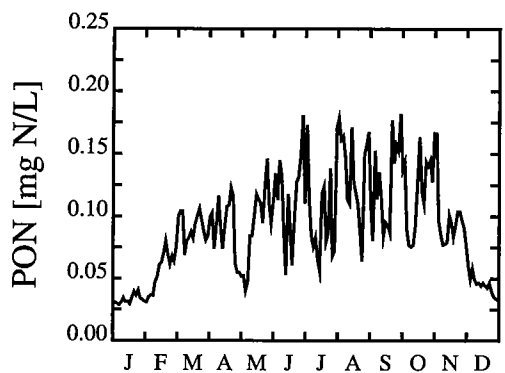
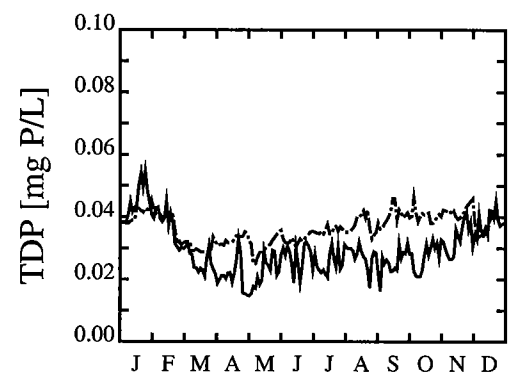
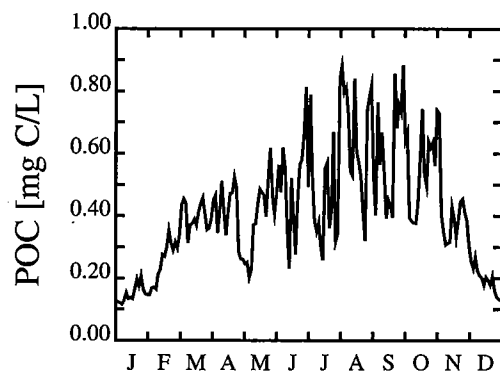
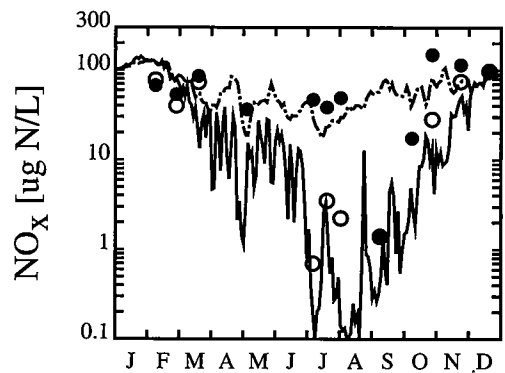
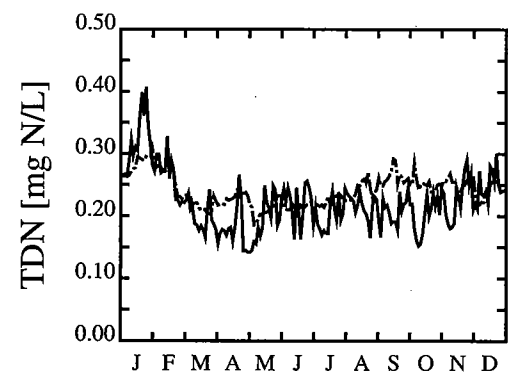
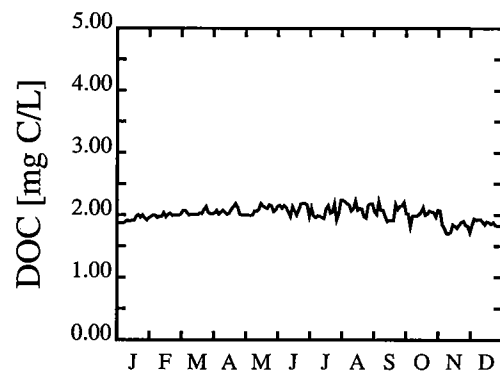
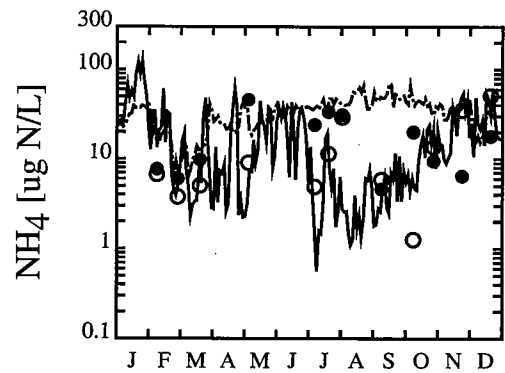
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev- Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (24,47) Vs Data Station N10P



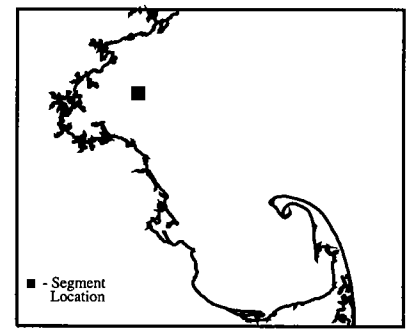
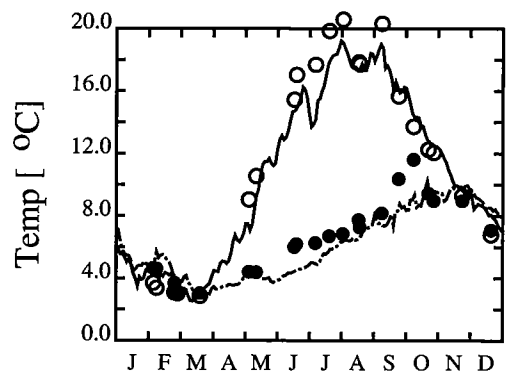
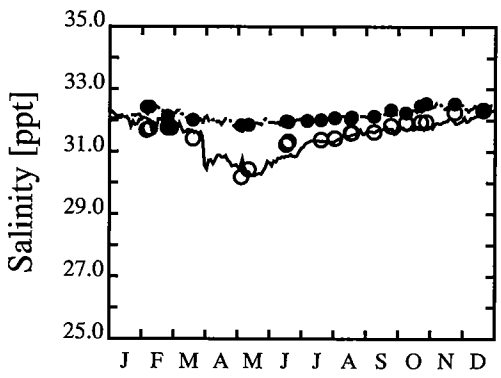
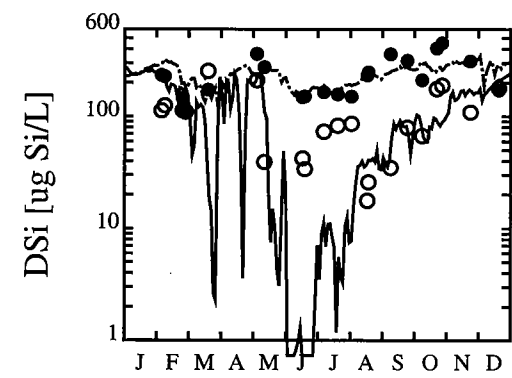
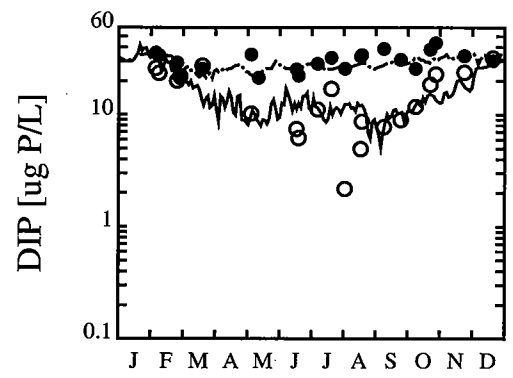
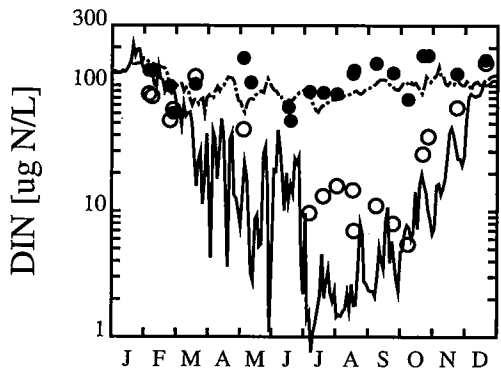
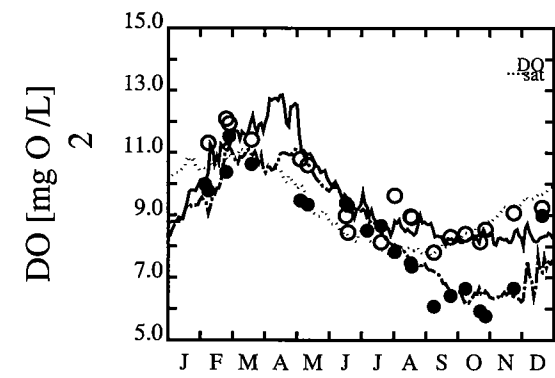
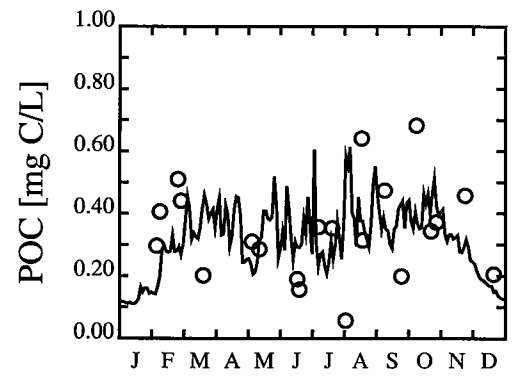
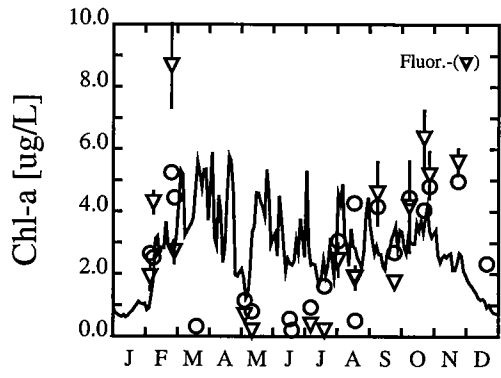
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 ● std.dev. Surface Model
 --- Bottom Model

1999 Temporal Calibration Results for Grid Cell (30,50) Vs Data Station N13



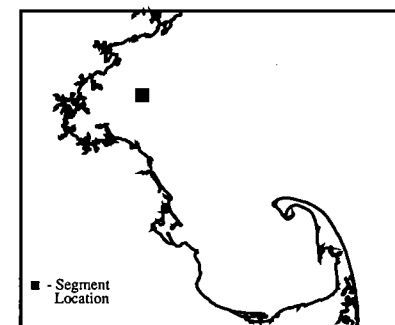
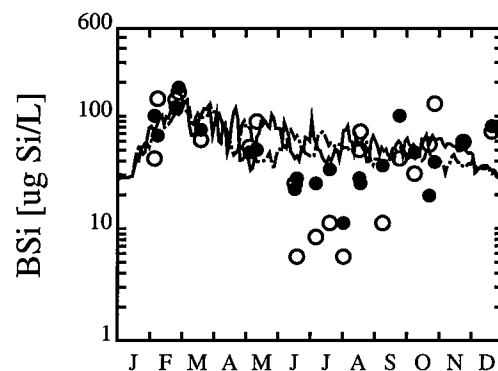
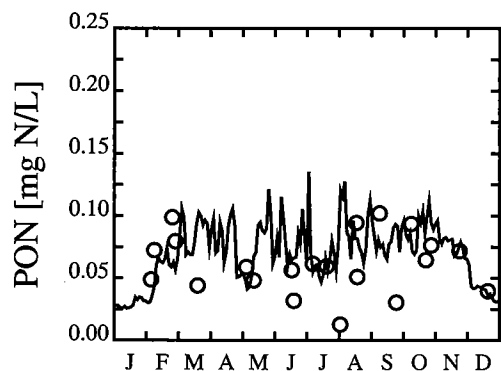
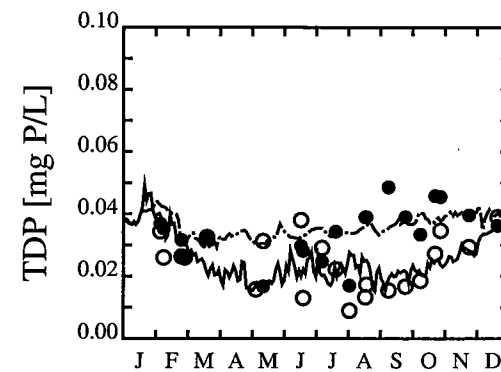
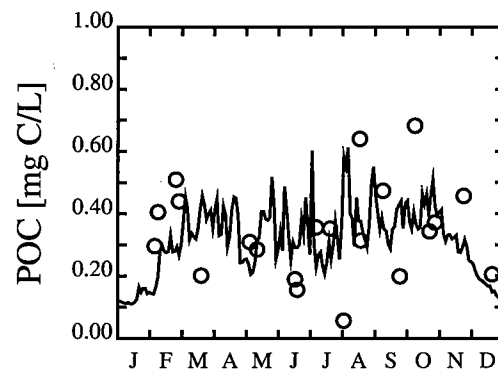
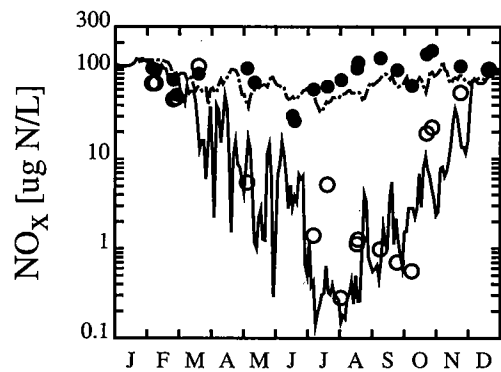
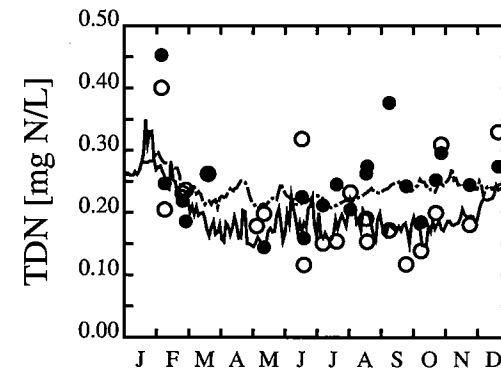
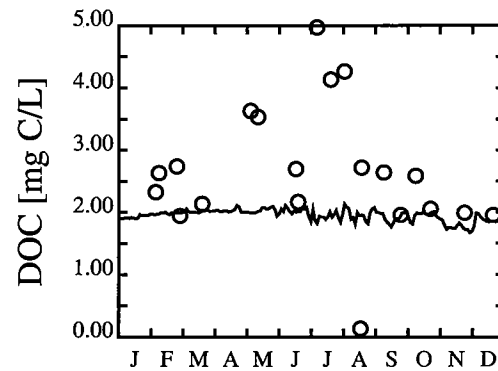
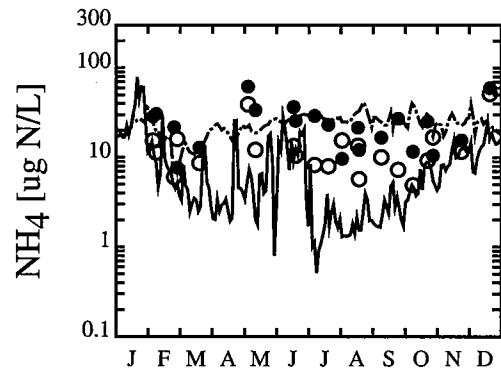
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 — std dev Surface Model
 - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (30,50) Vs Data Station N13



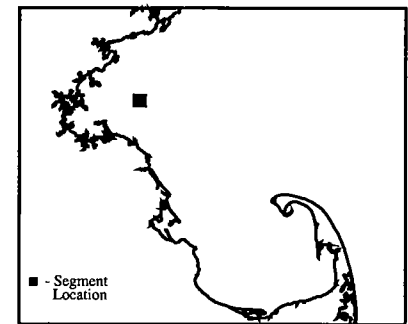
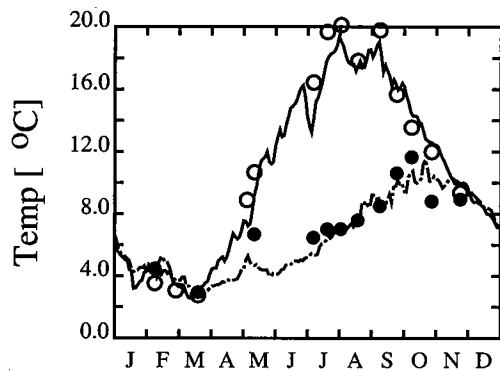
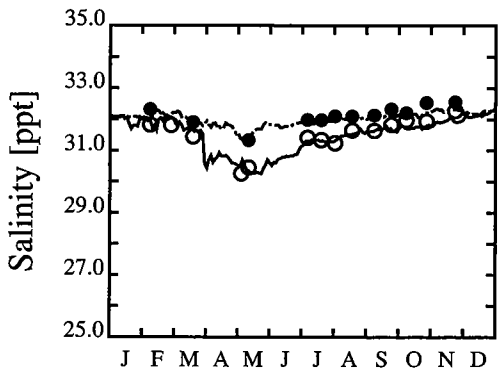
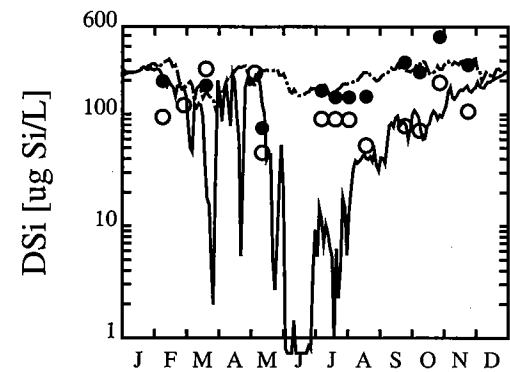
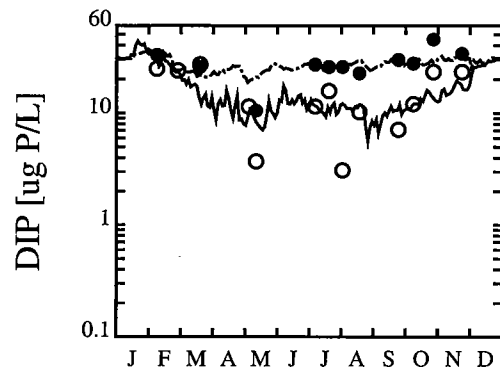
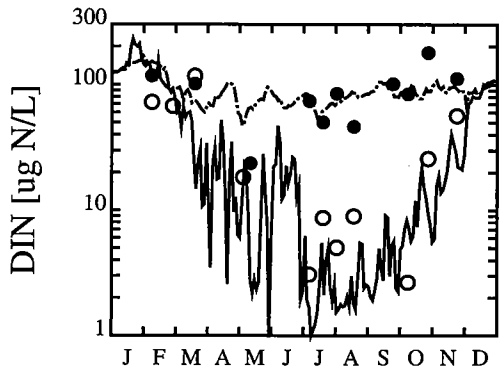
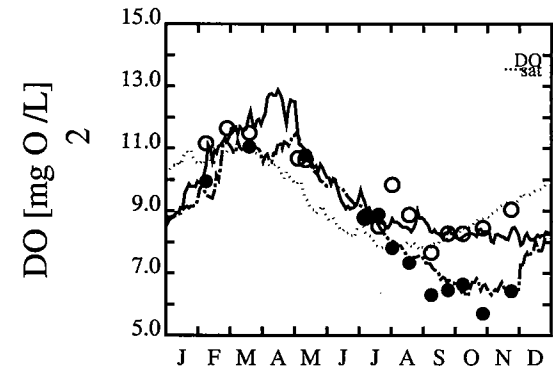
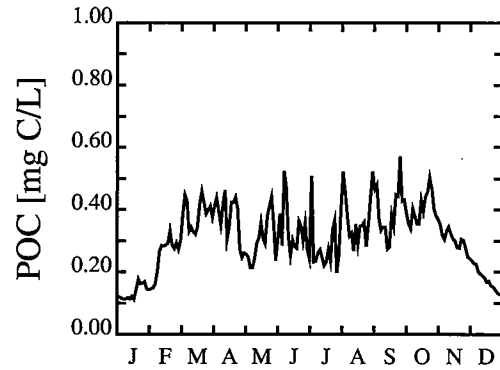
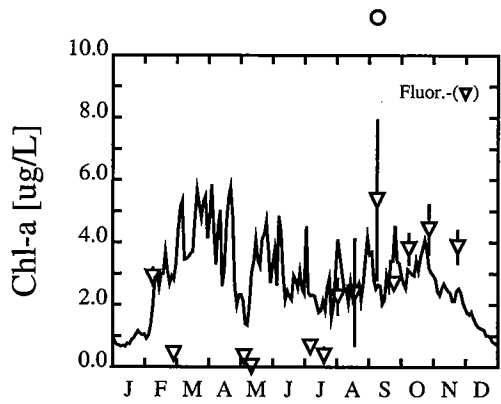
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (33,46) Vs Data Station N16P



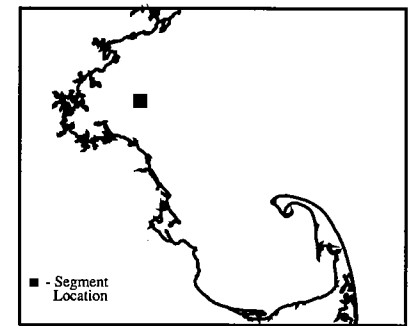
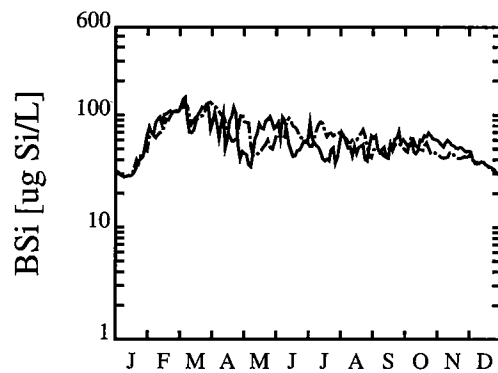
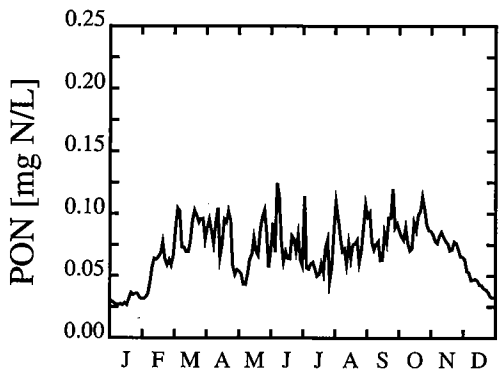
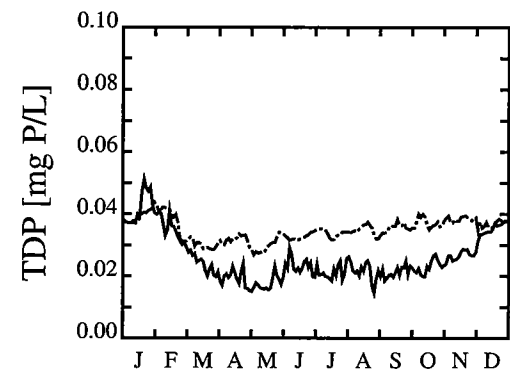
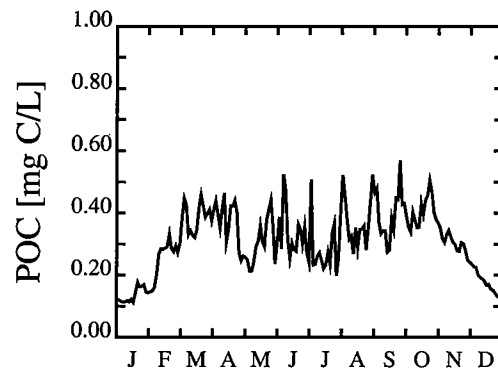
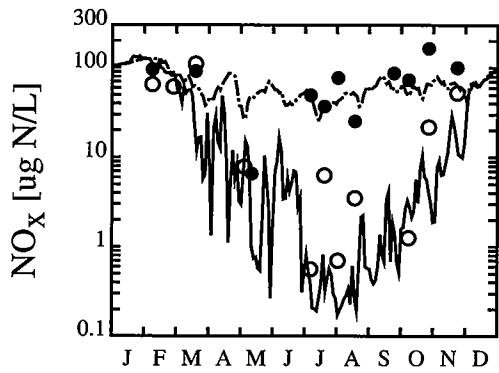
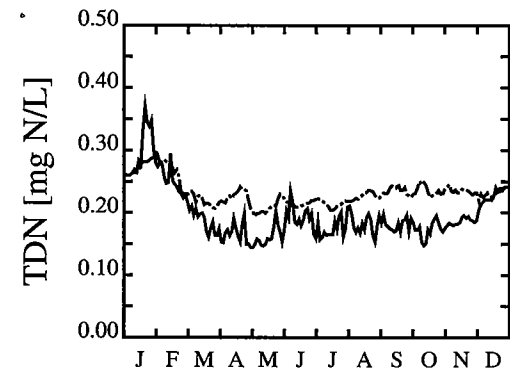
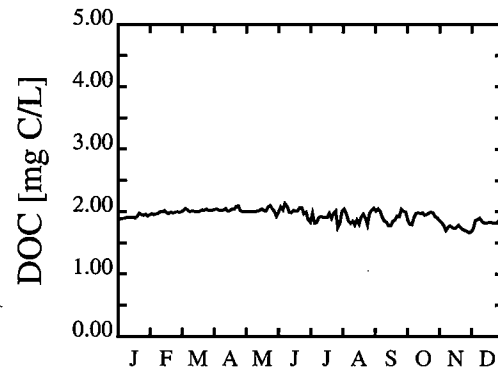
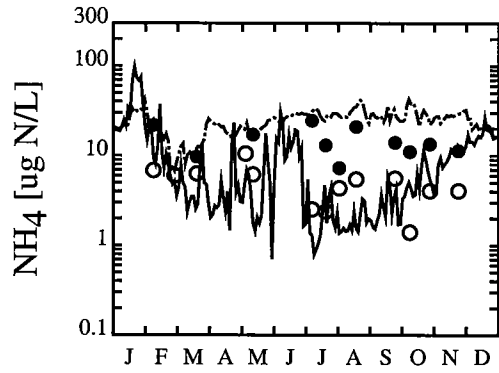
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev. Surface Model
 - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (33,46) Vs Data Station N16P



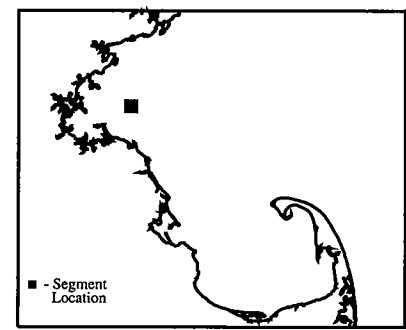
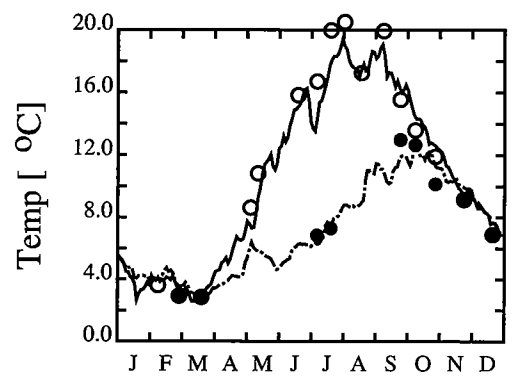
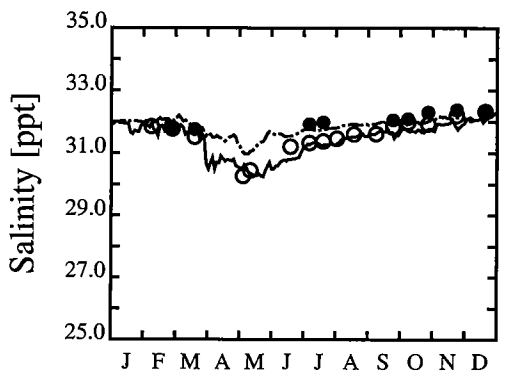
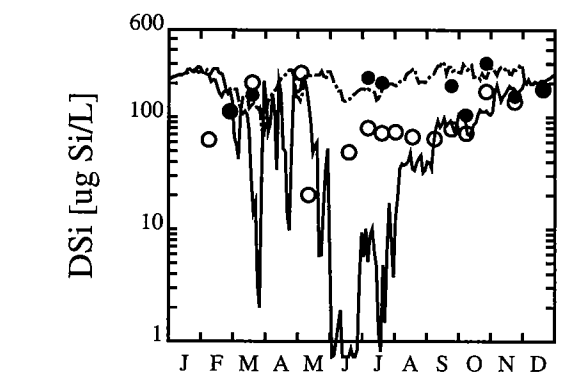
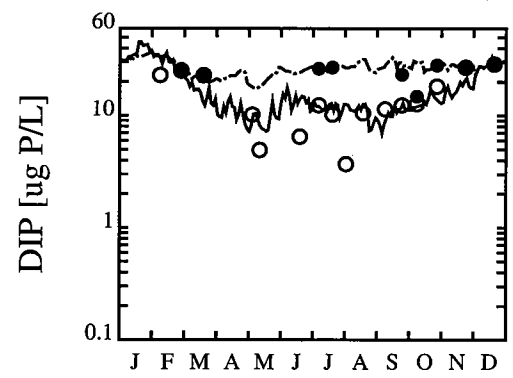
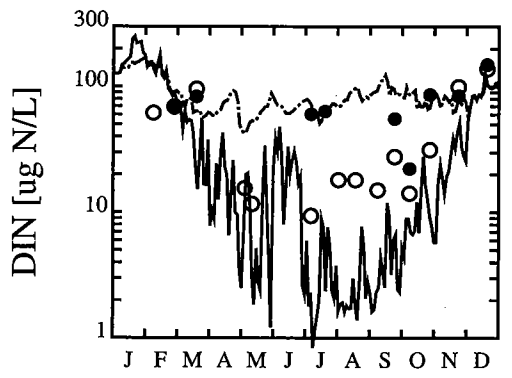
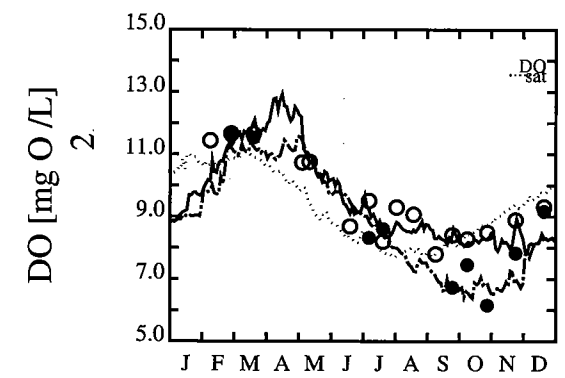
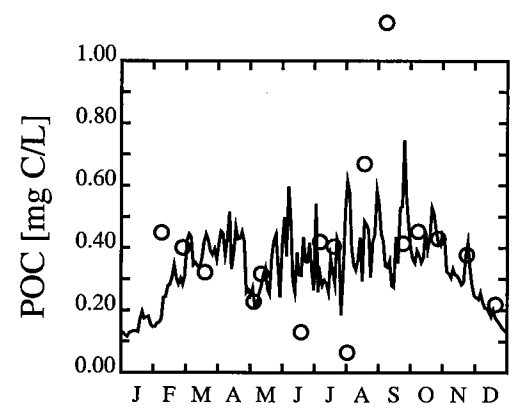
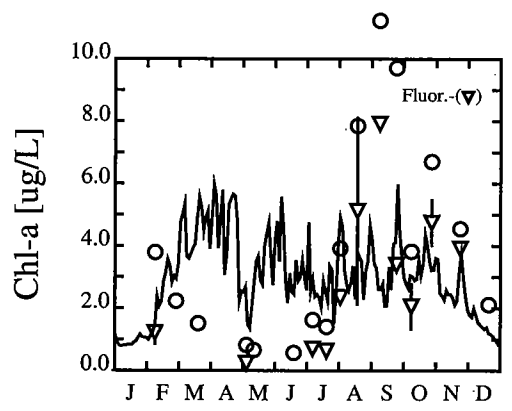
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (31,45) Vs Data Station N17



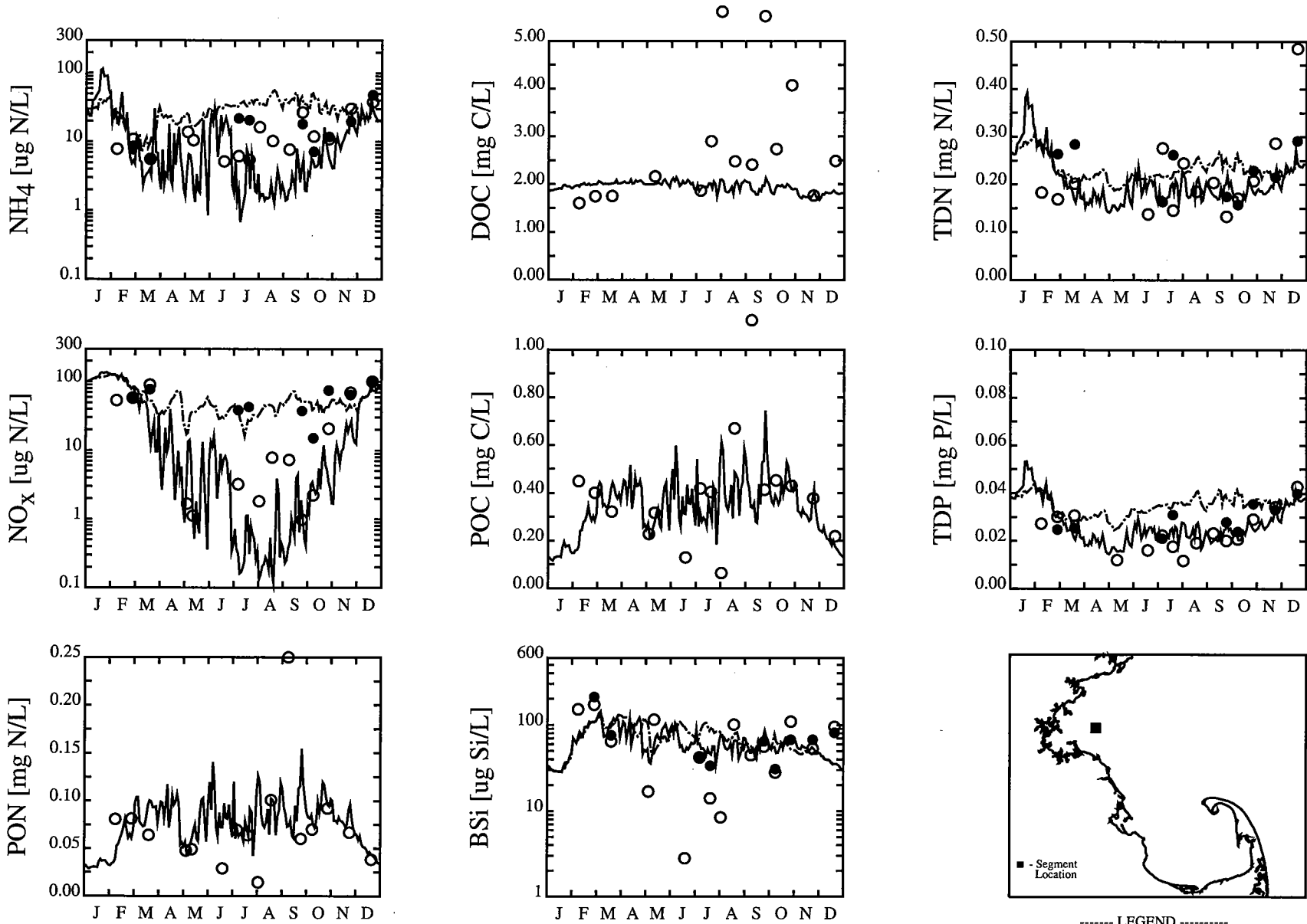
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 — std dev Surface Model
 - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (31,45) Vs Data Station N17

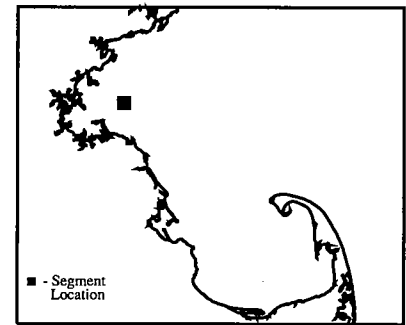
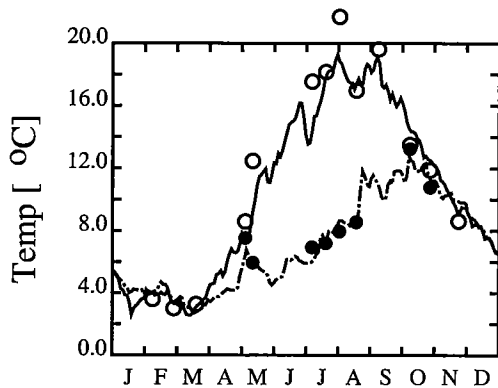
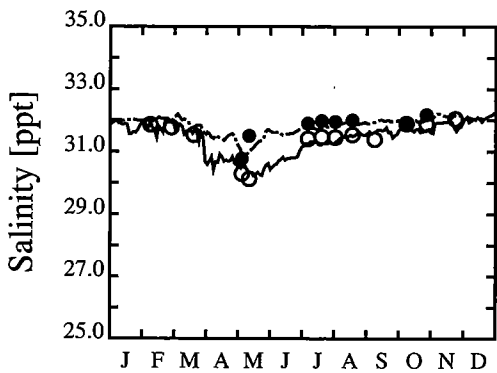
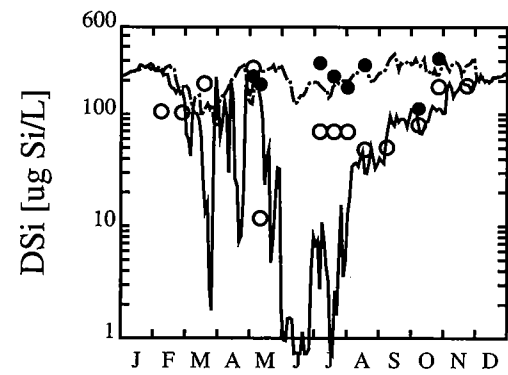
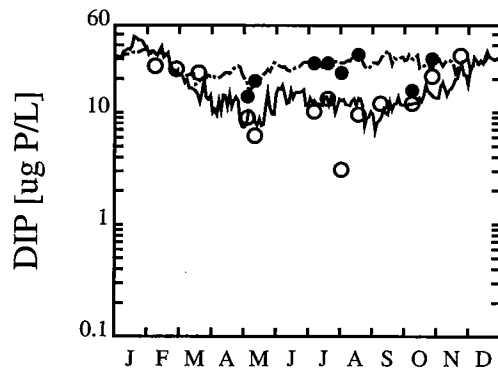
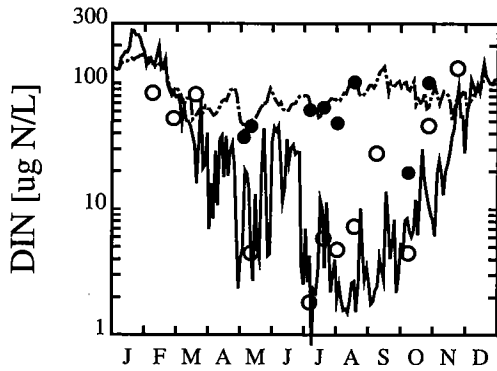
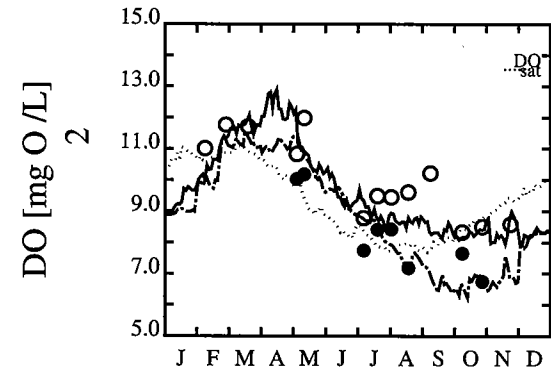
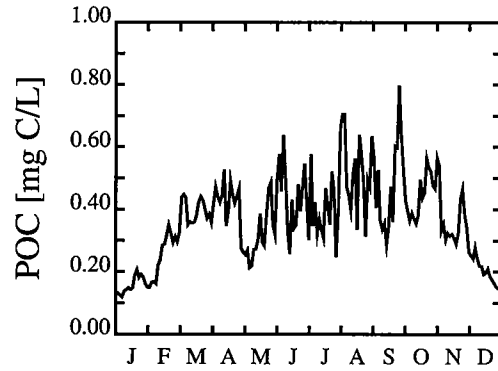
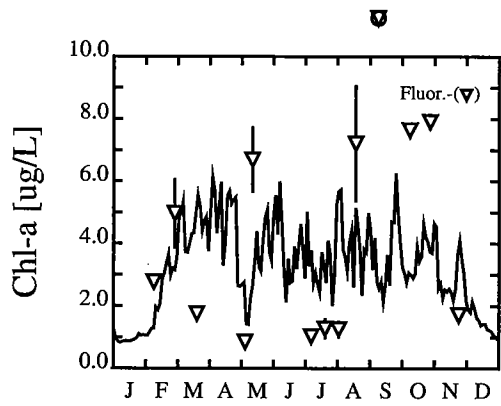


LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev- Surface Model
 — Bottom Model

1999 Temporal Calibration Results for Grid Cell (29,46) Vs Data Station N18

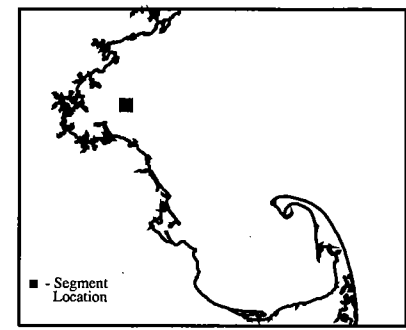
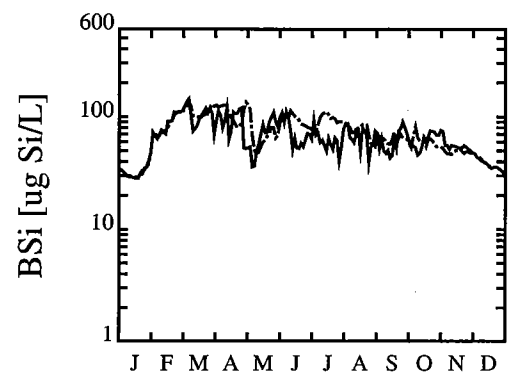
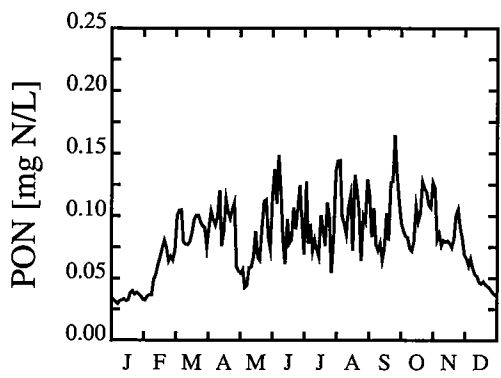
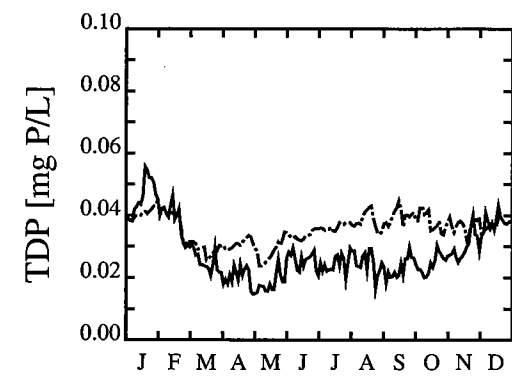
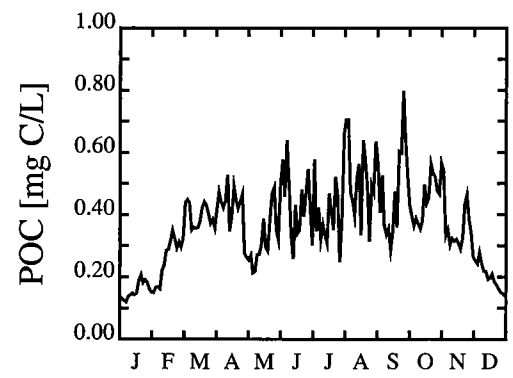
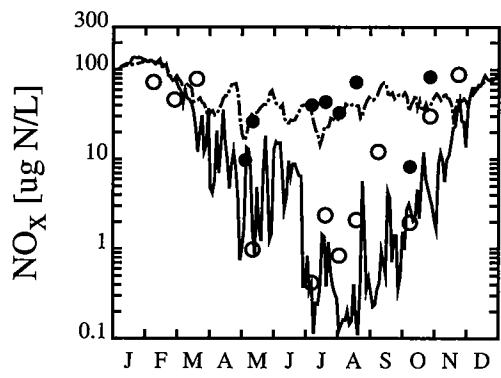
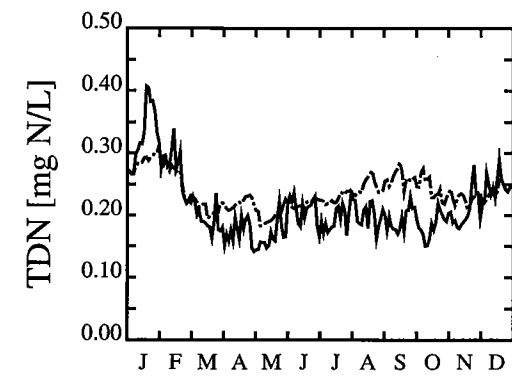
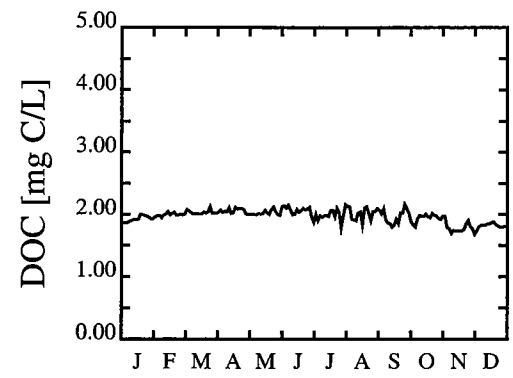
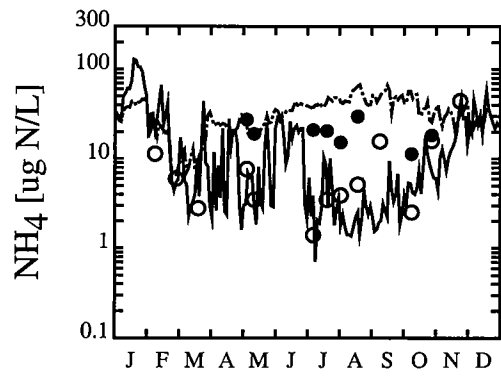


1999 Temporal Calibration Results for Grid Cell (29,46) Vs Data Station N18



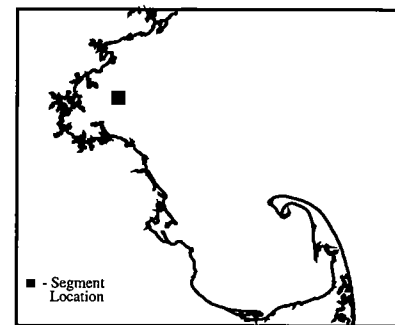
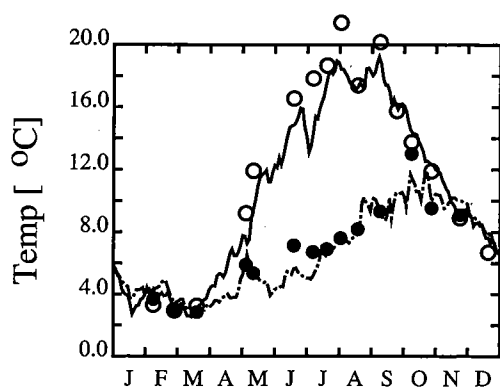
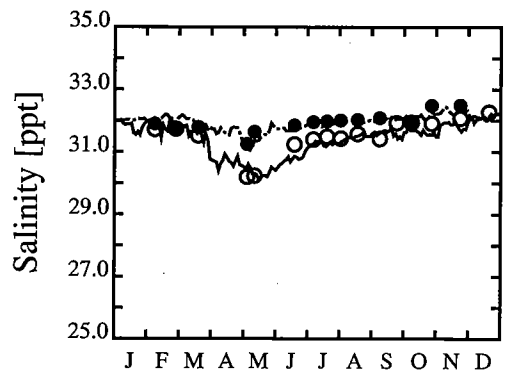
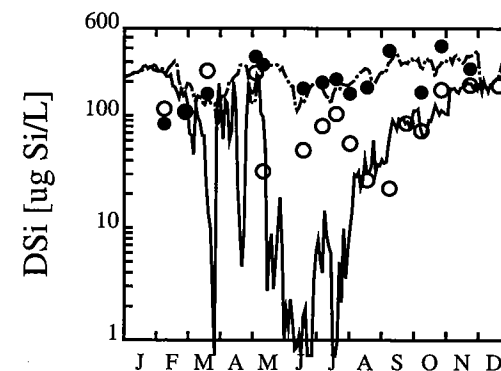
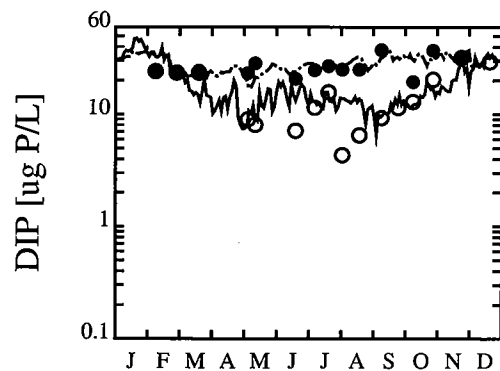
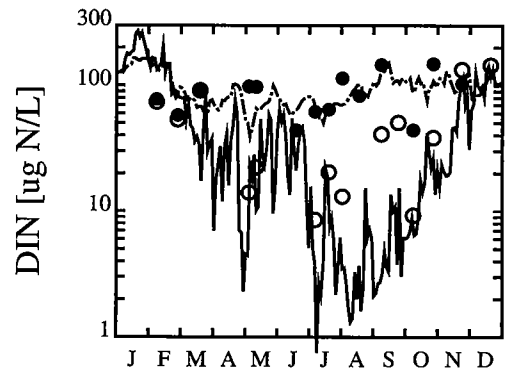
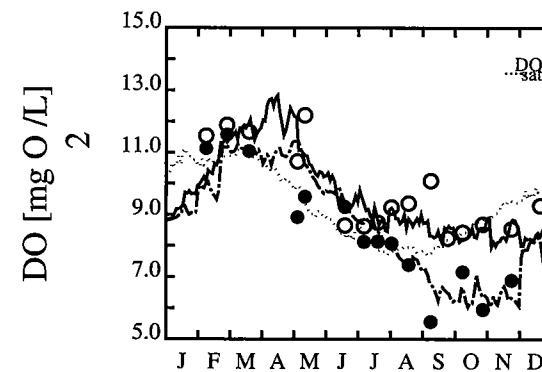
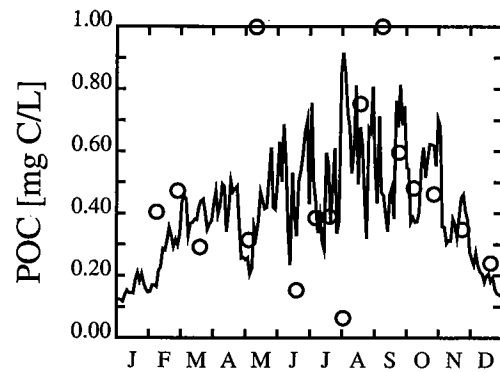
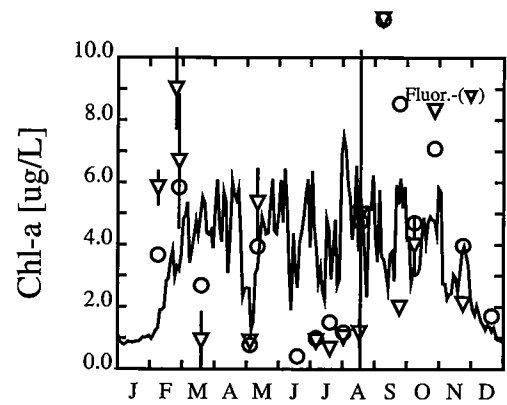
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 ---std.dev. Surface Model
 --- Bottom Model

1999 Temporal Calibration Results for Grid Cell (28,47) Vs Data Station N19



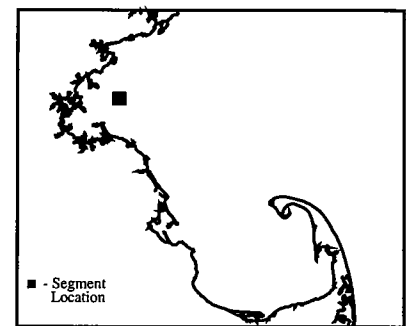
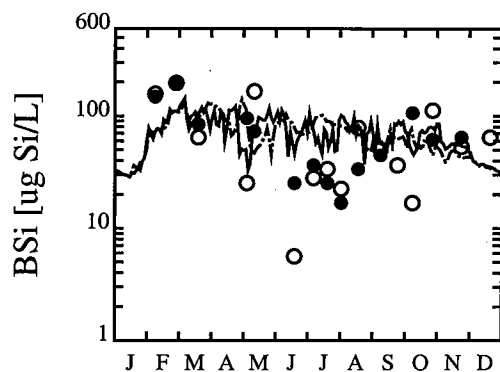
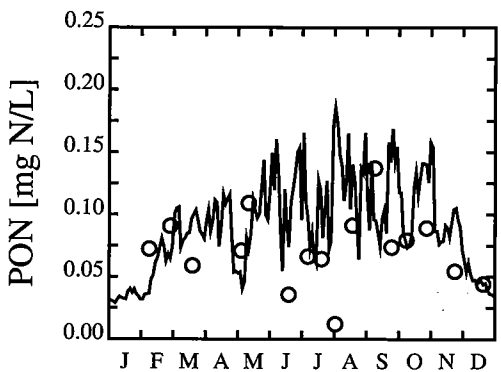
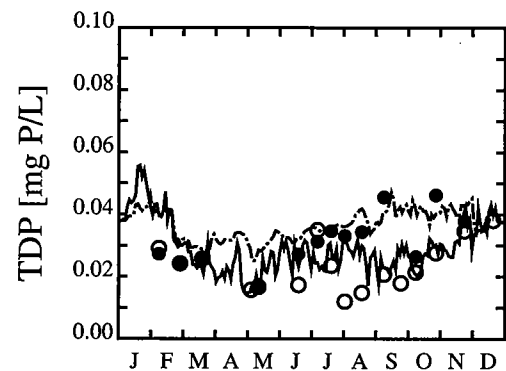
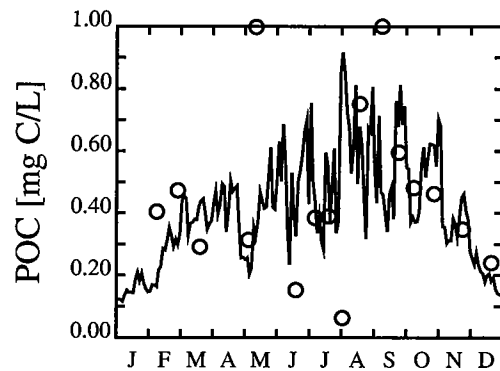
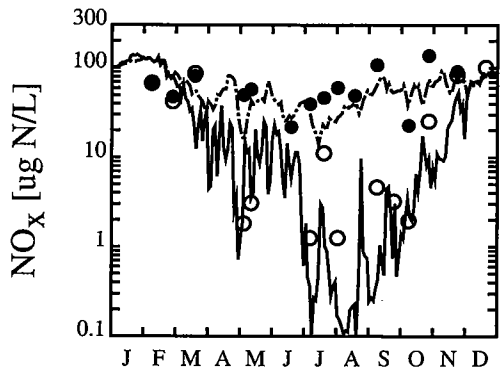
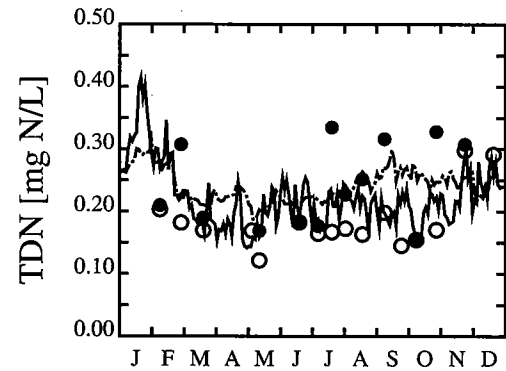
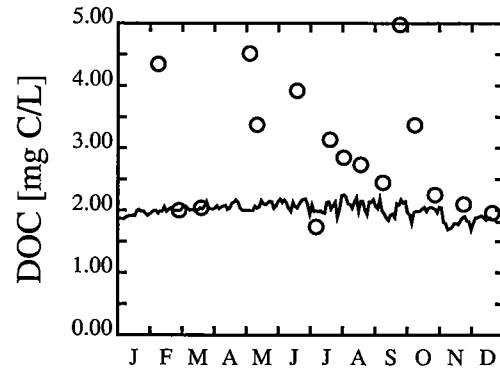
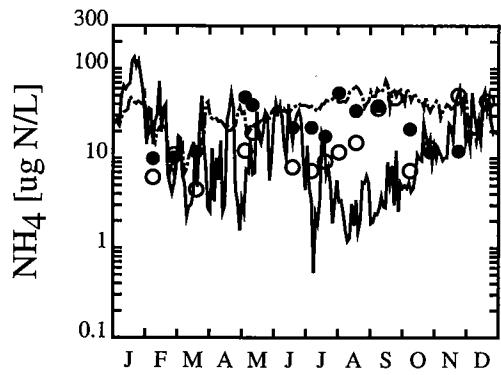
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev- Surface Model
 — Bottom Model

1999 Temporal Calibration Results for Grid Cell (28,47) Vs Data Station N19



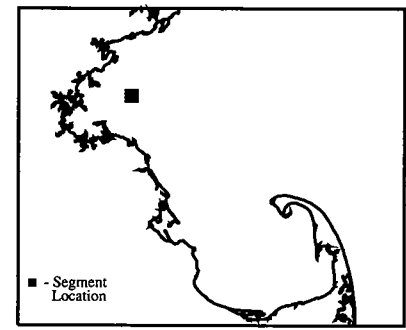
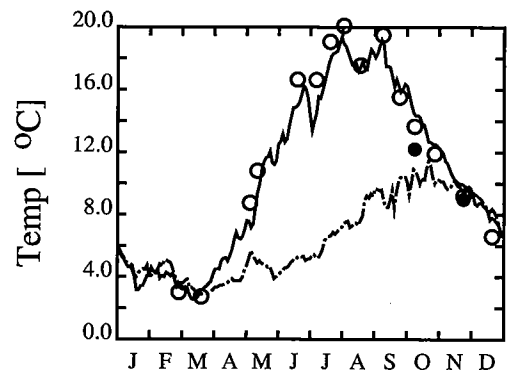
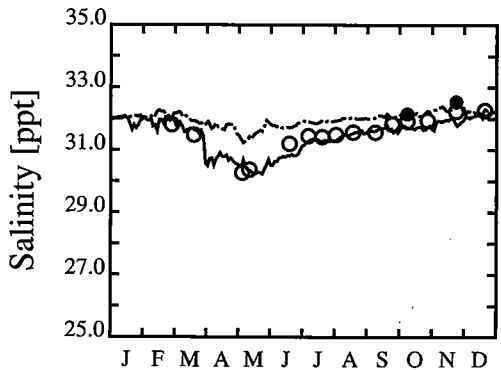
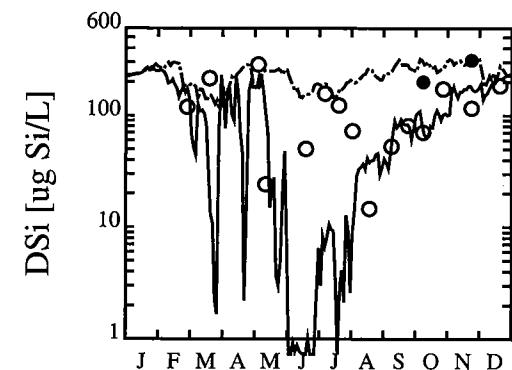
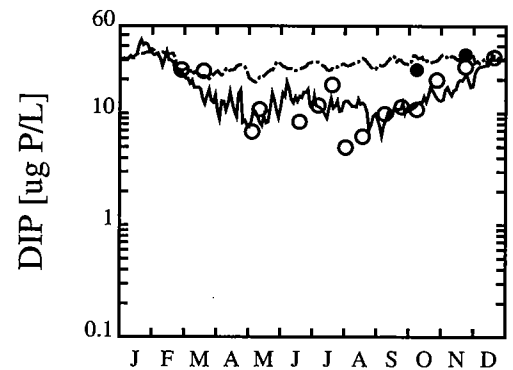
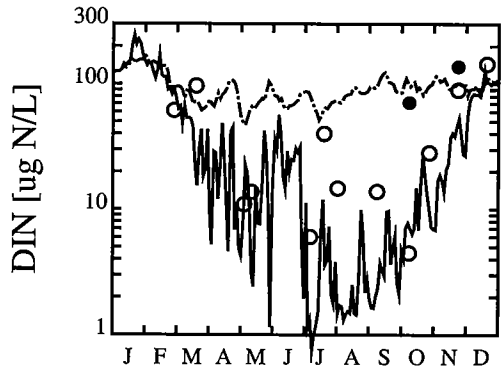
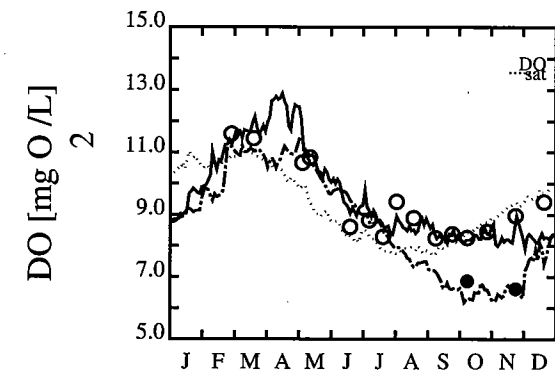
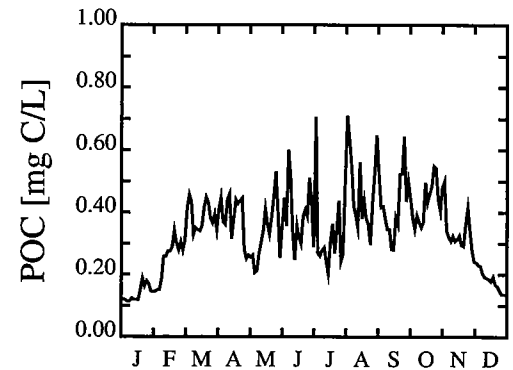
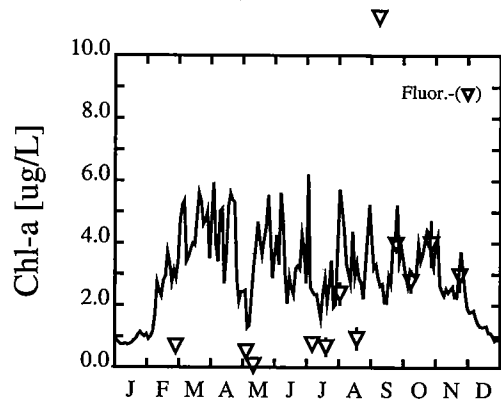
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - sid.dev. Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (29,49) Vs Data Station N20P



LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 -std dev- Surface Model
 - - - Bottom Model

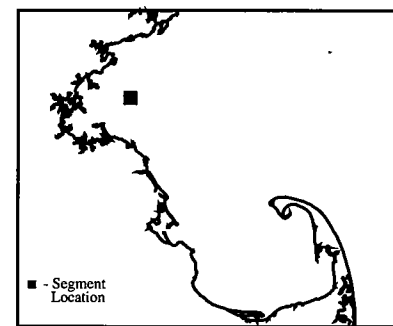
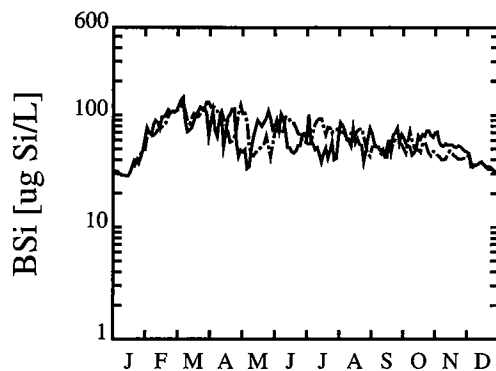
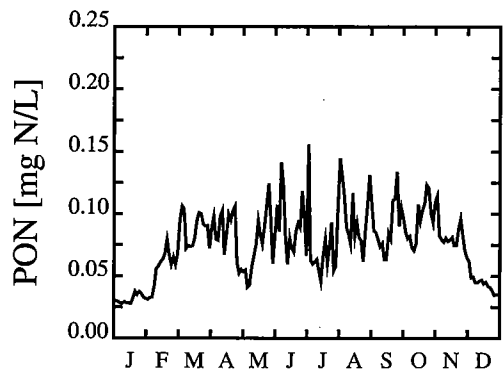
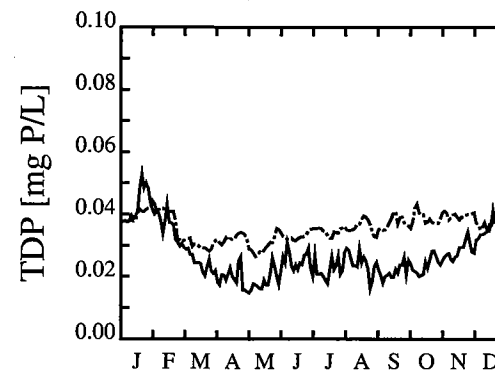
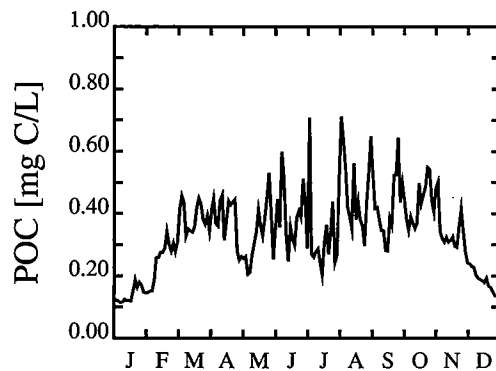
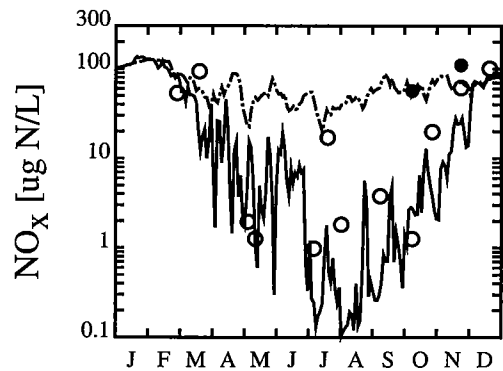
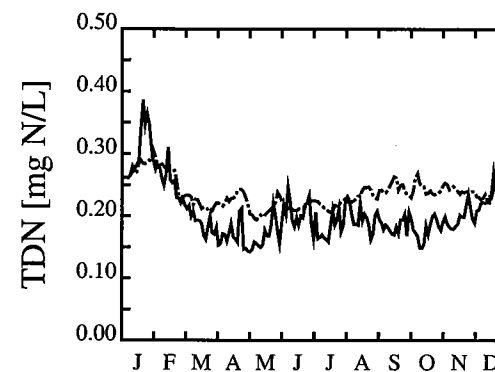
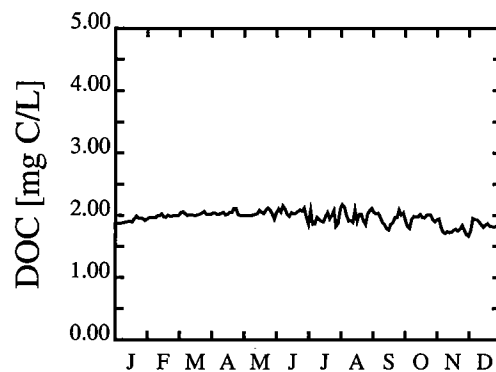
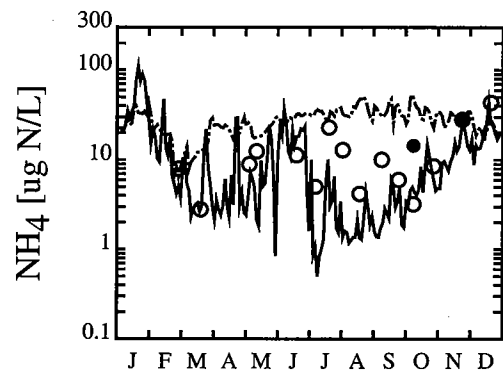
1999 Temporal Calibration Results for Grid Cell (29,49) Vs Data Station N20P



LEGEND

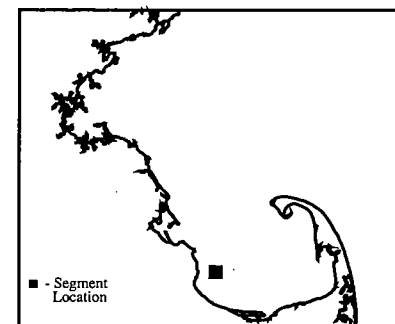
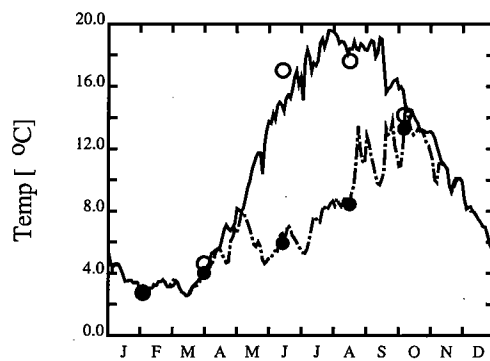
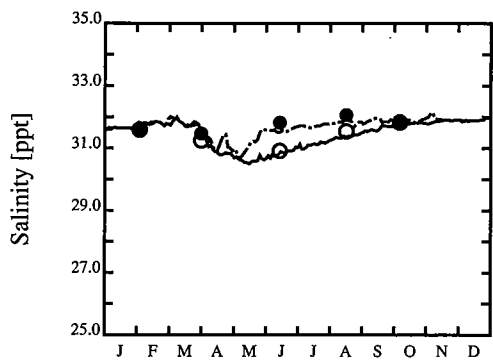
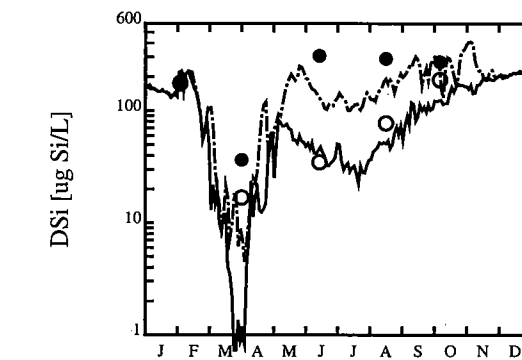
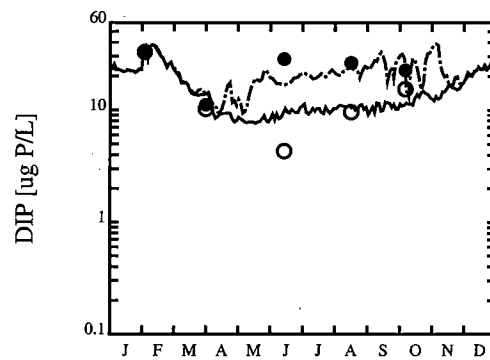
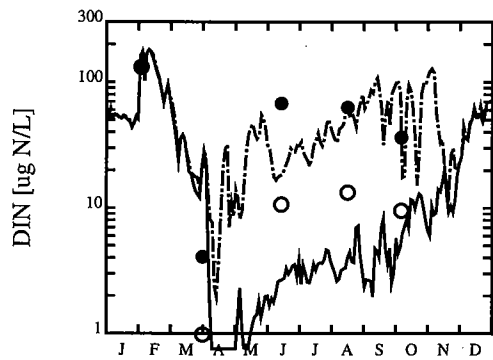
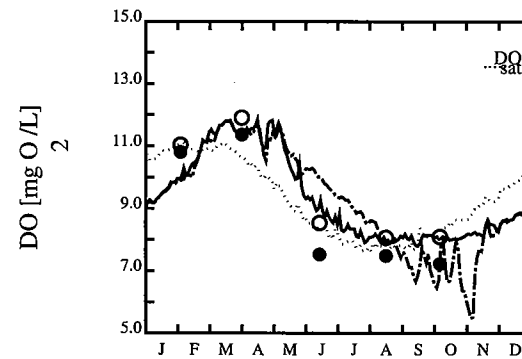
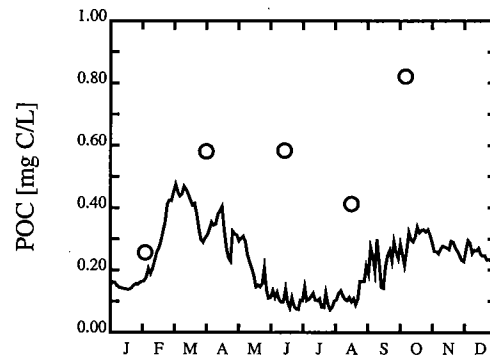
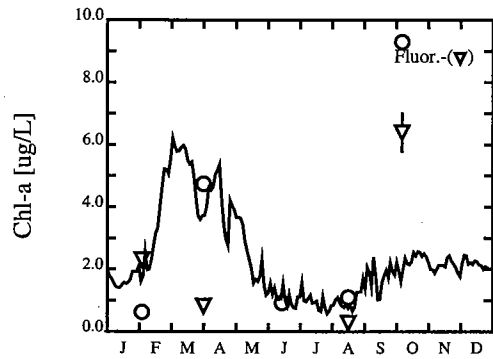
- +/- Surface Data
- Bottom Data
- std dev Surface Model
- Bottom Model

1999 Temporal Calibration Results for Grid Cell (31,47) Vs Data Station N21



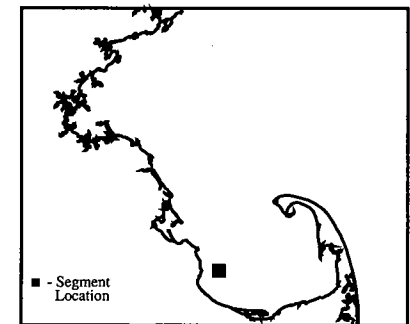
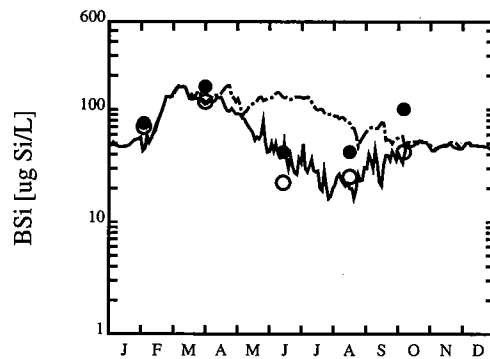
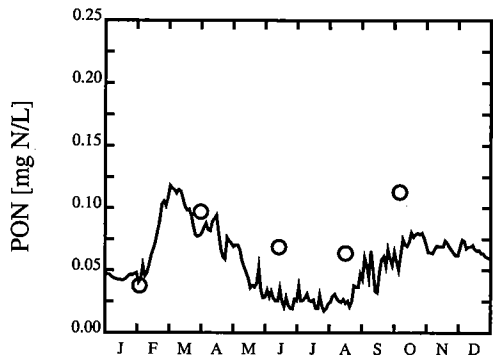
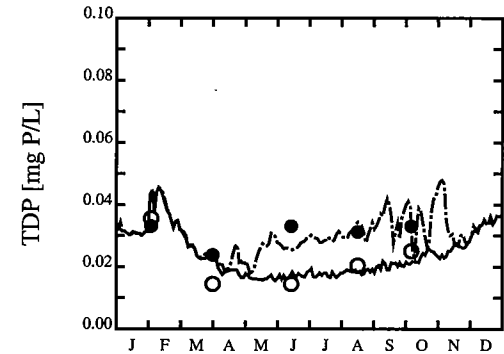
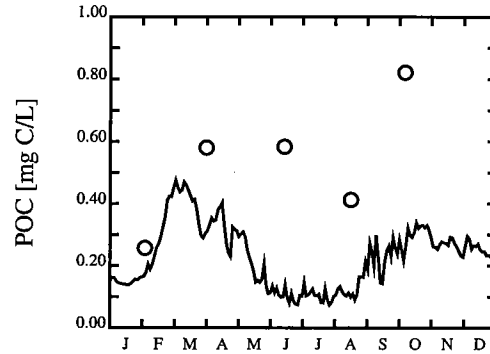
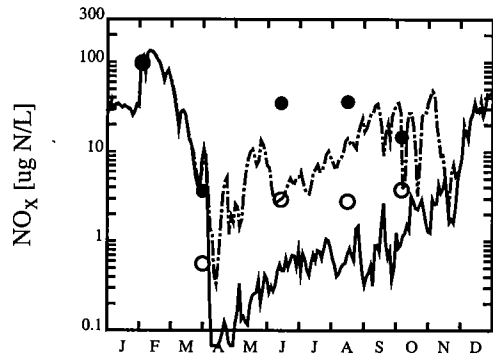
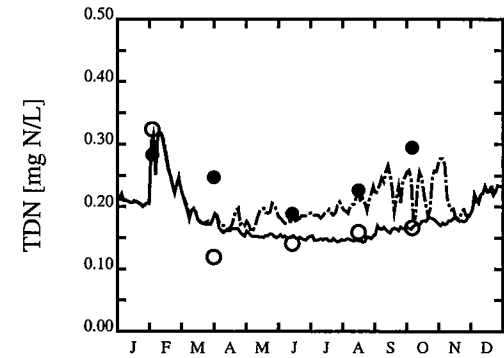
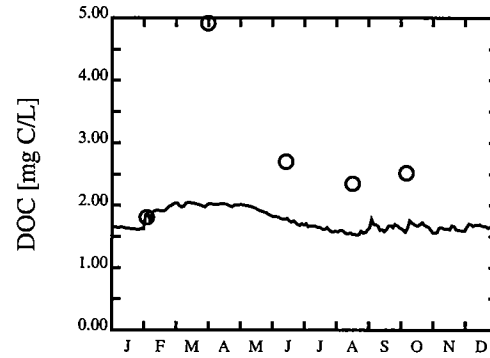
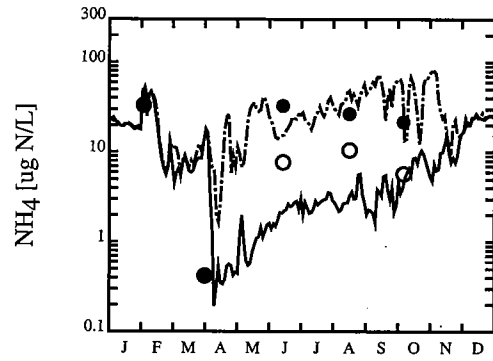
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 — std dev Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (31,47) Vs Data Station N21



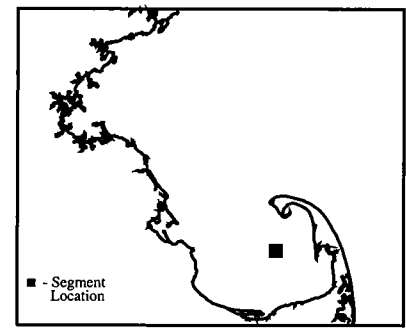
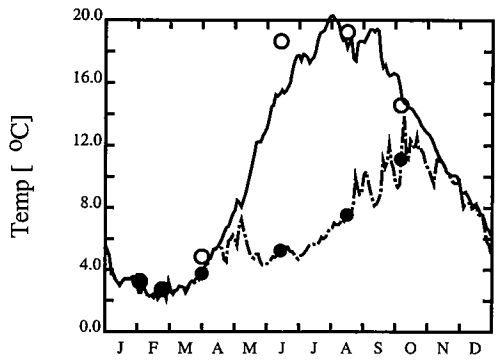
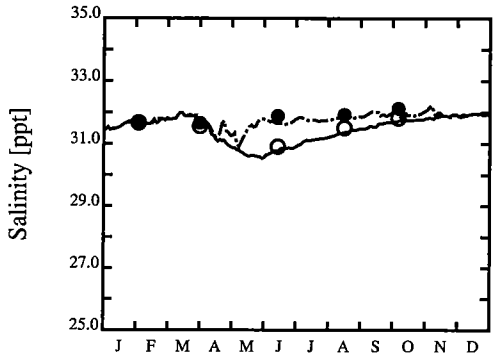
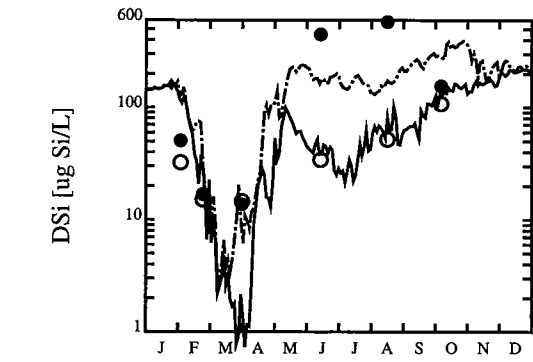
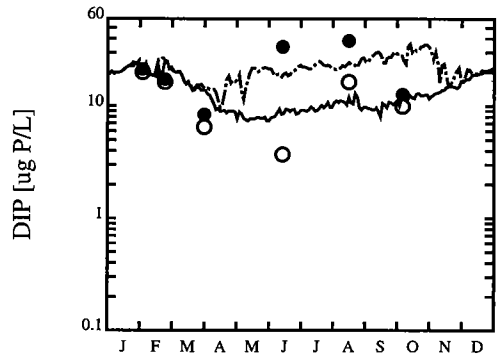
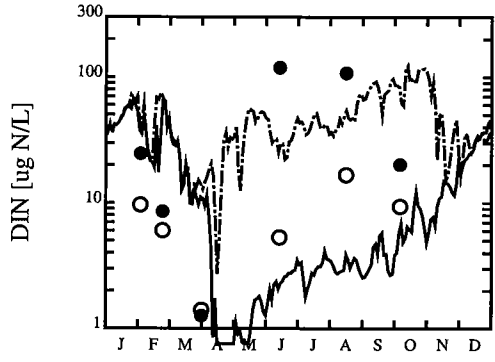
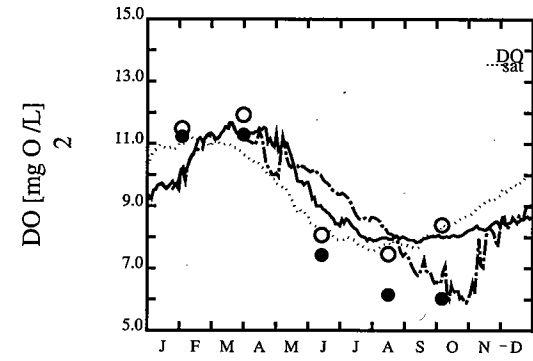
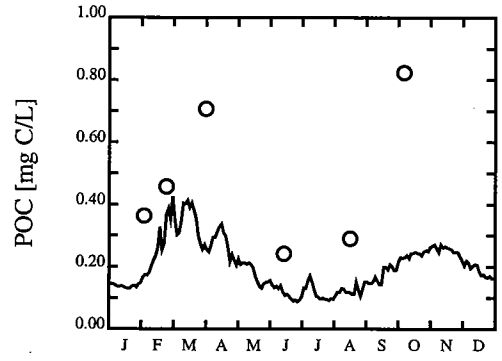
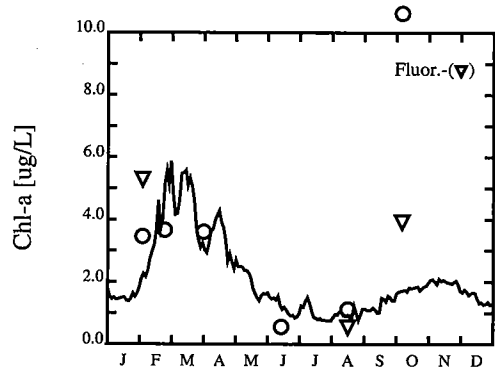
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std dev. Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (18,11) Vs Data Station F01P



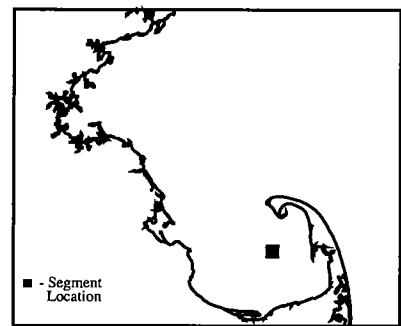
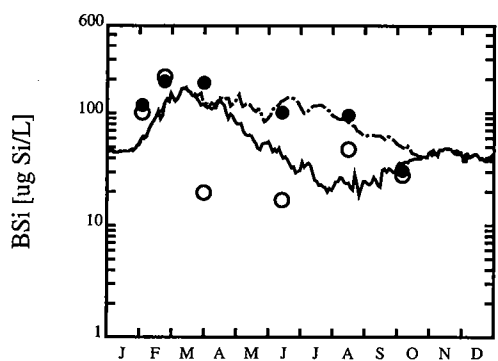
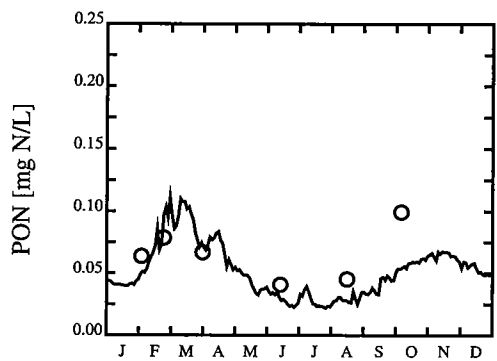
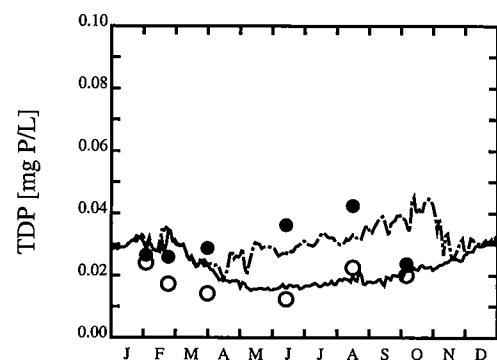
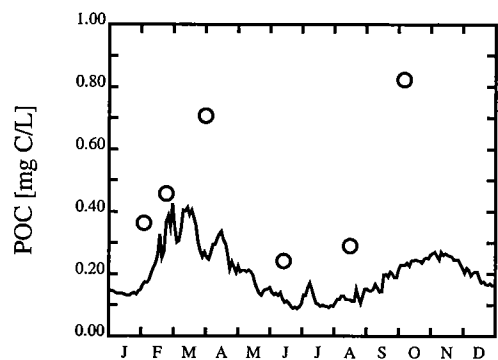
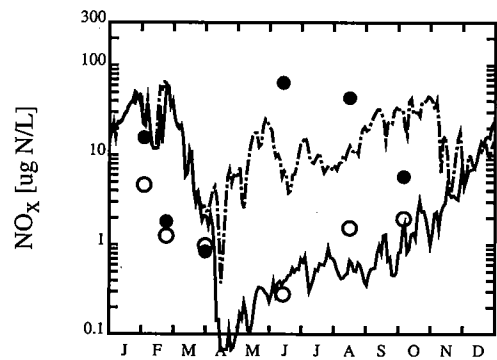
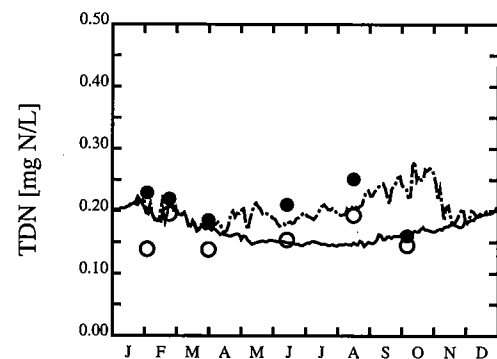
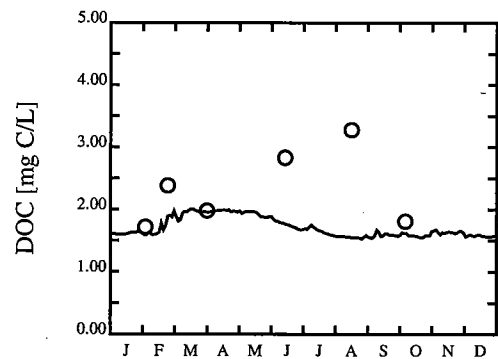
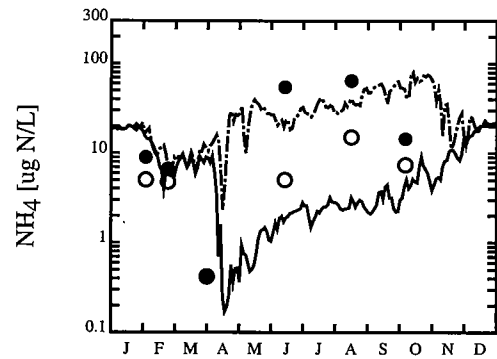
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - std dev Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (18,11) Vs Data Station F01P



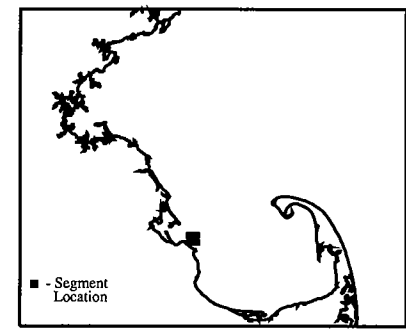
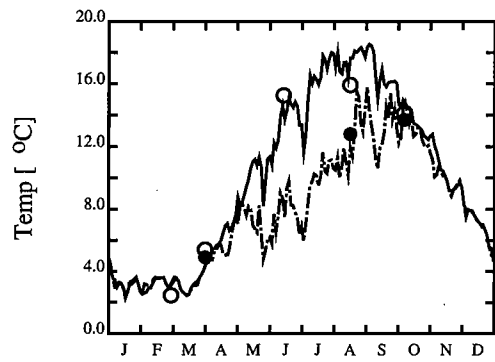
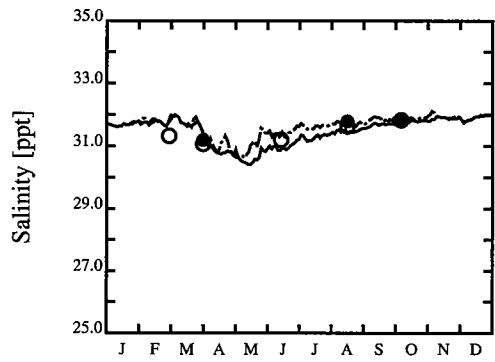
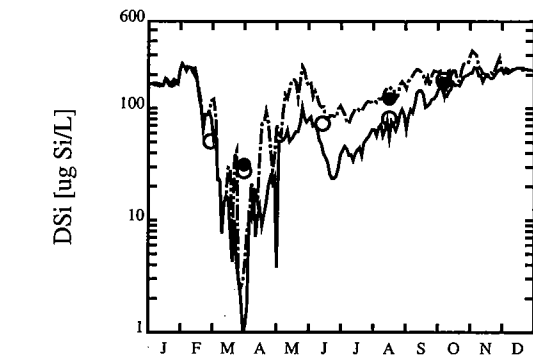
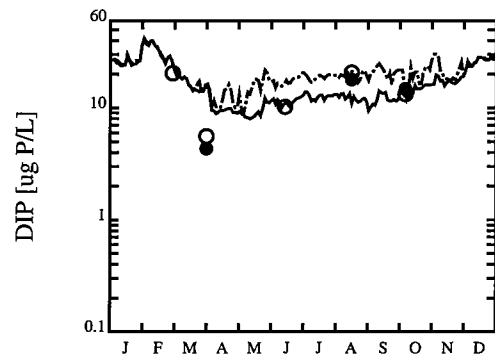
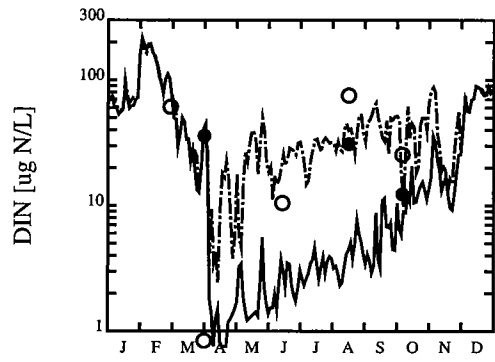
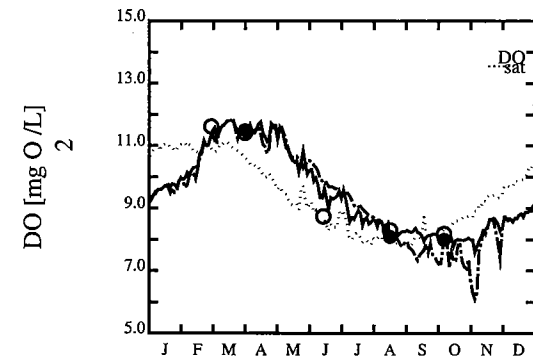
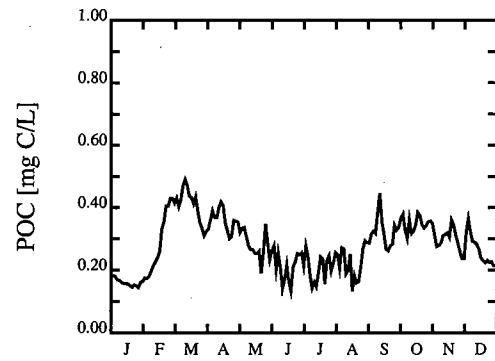
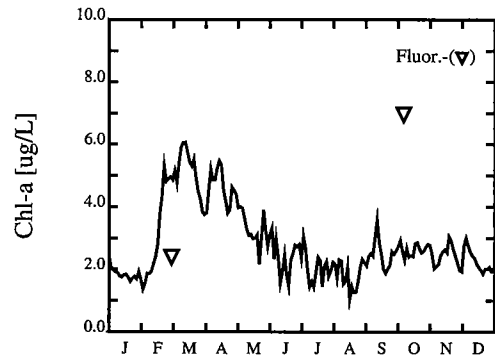
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - sid.dev Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (38,11) Vs Data Station F02P



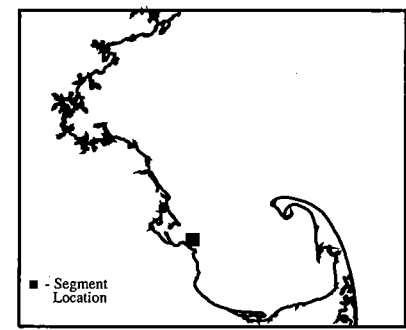
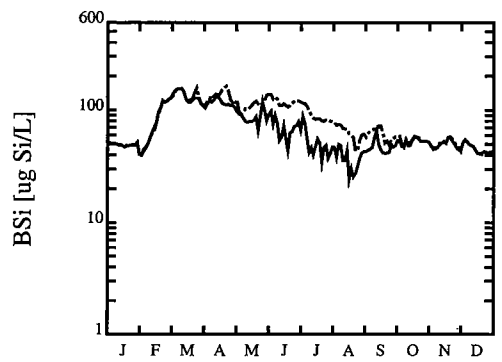
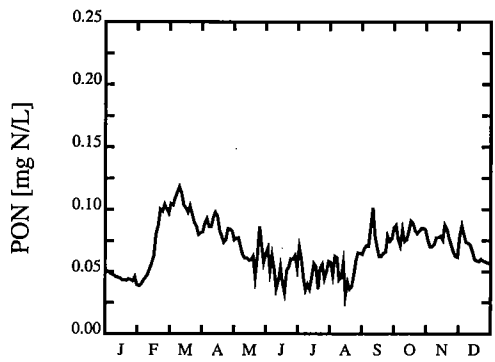
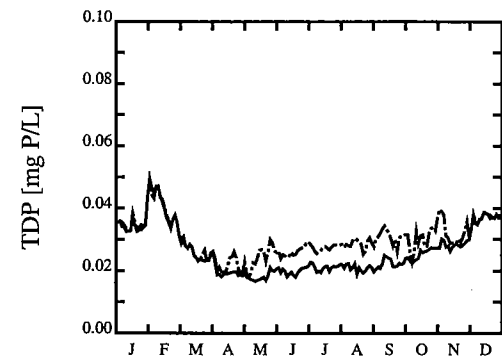
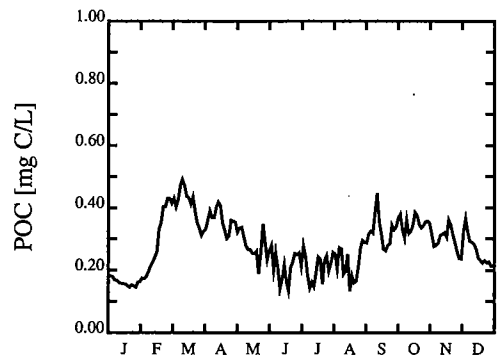
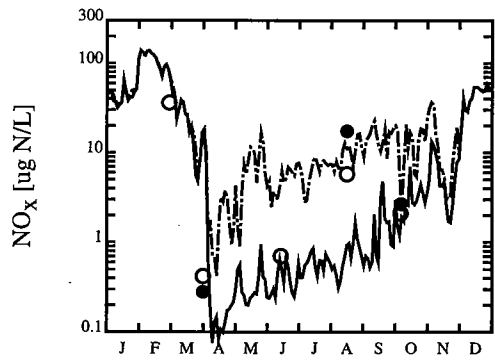
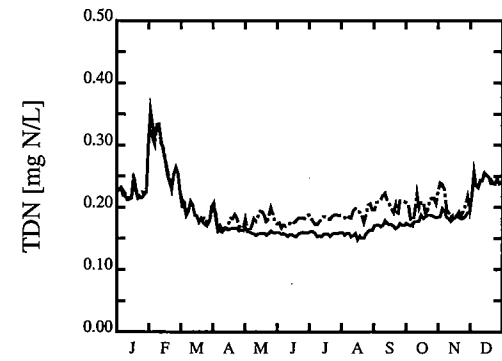
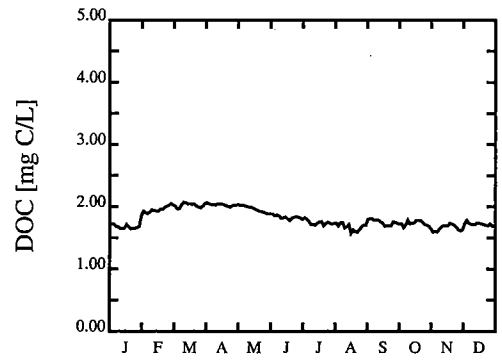
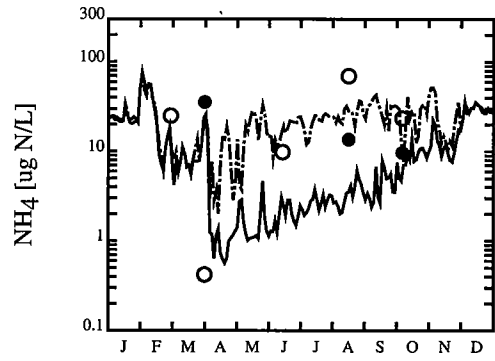
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - std.dev Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (38,11) Vs Data Station F02P



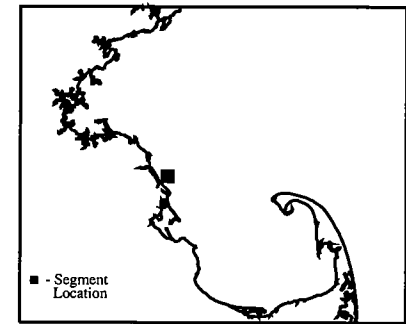
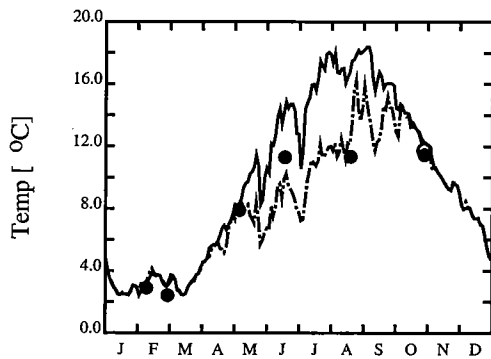
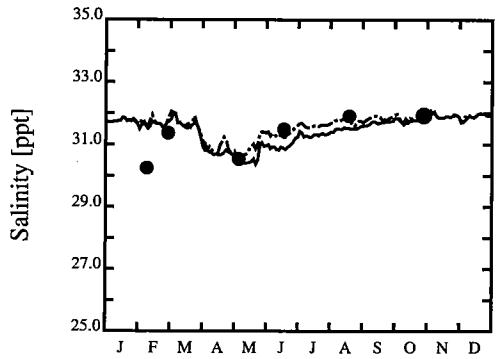
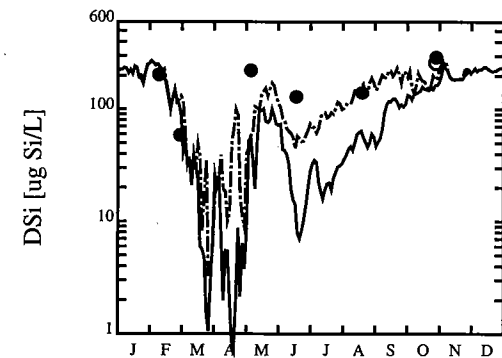
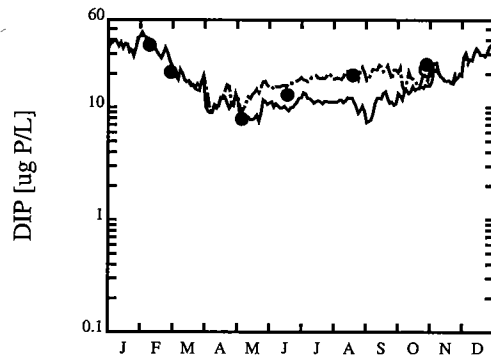
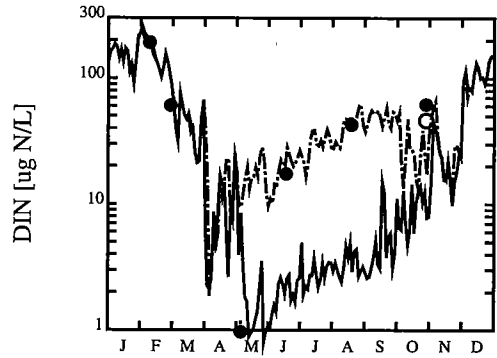
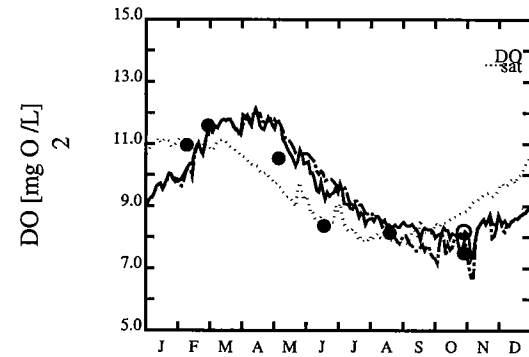
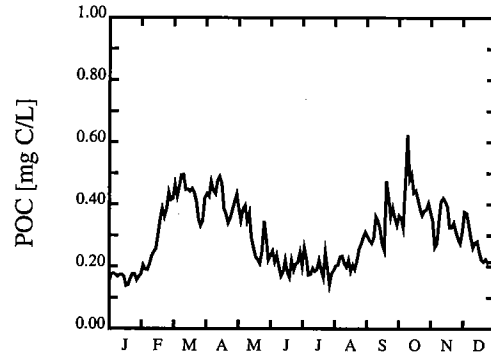
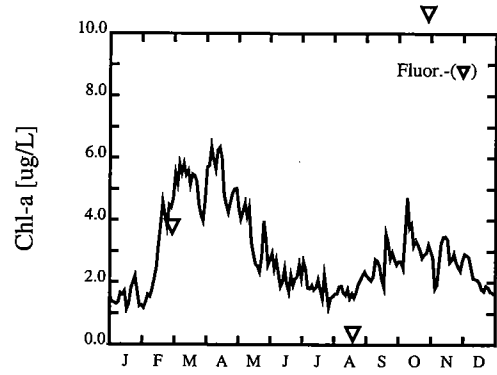
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 ---std.dev Surface Model
 --- Bottom Model

1999 Temporal Calibration Results for Grid Cell (15,18) Vs Data Station F03



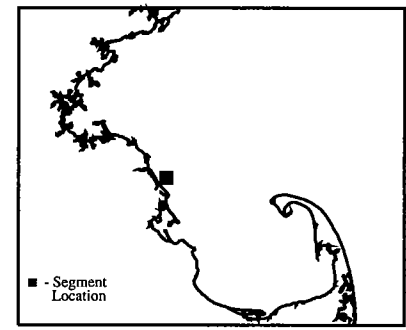
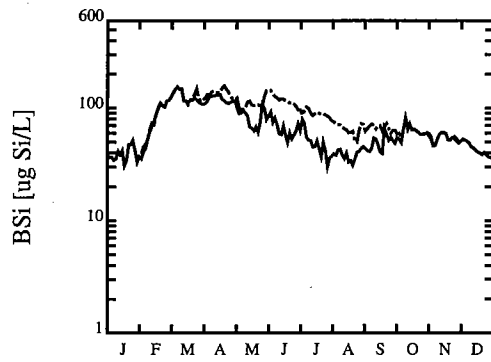
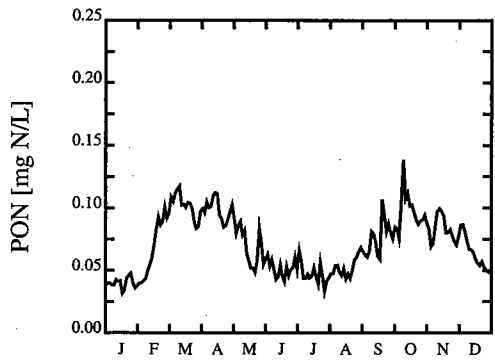
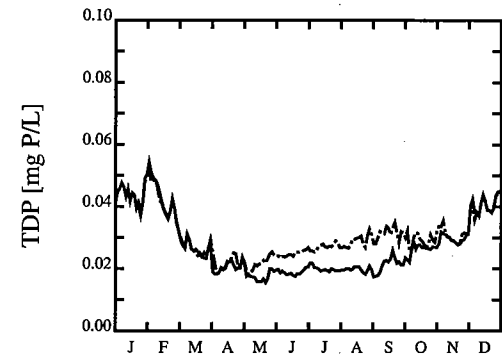
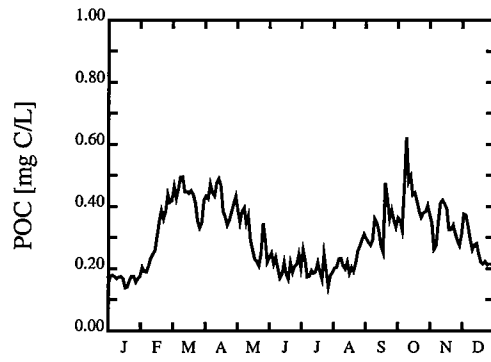
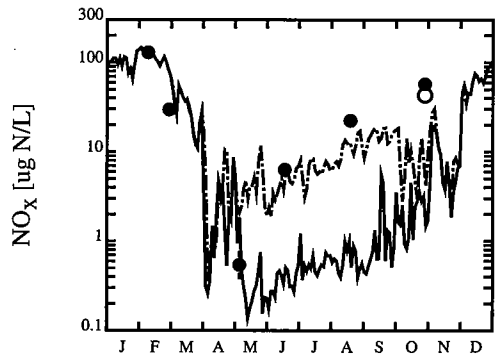
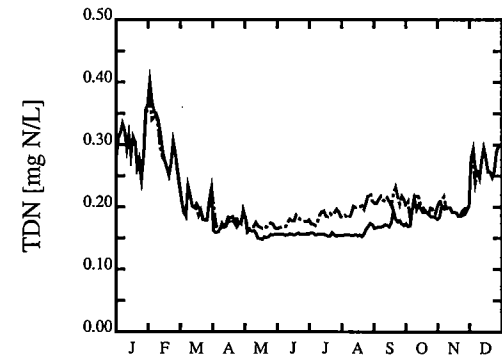
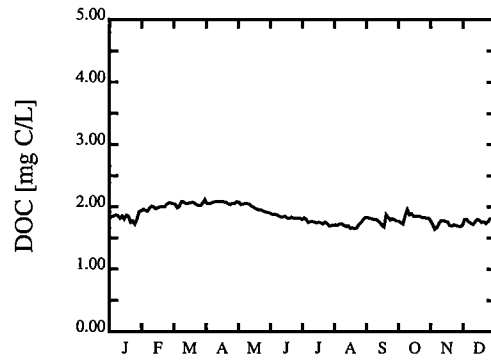
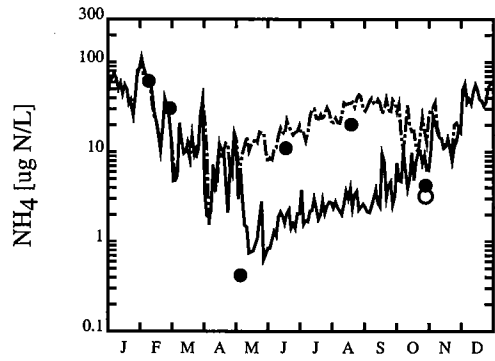
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std dev- Surface Model
 - Bottom Model

1999 Temporal Calibration Results for Grid Cell (15,18) Vs Data Station F03



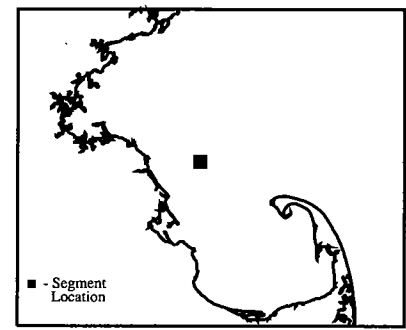
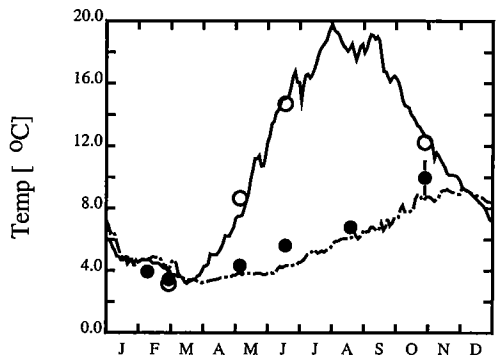
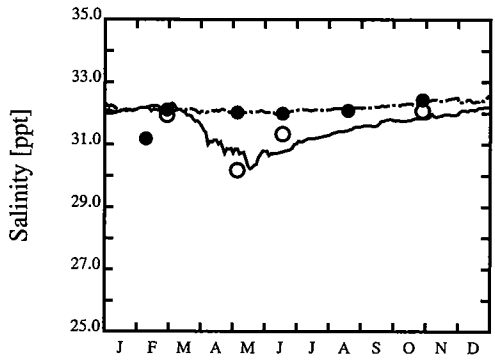
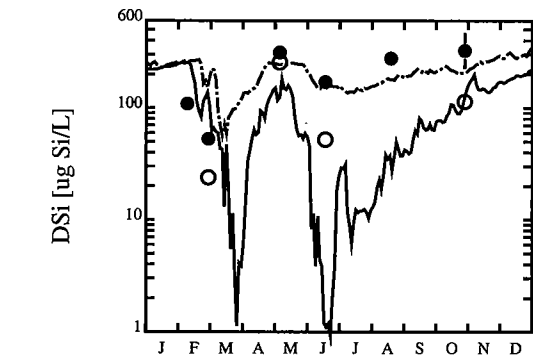
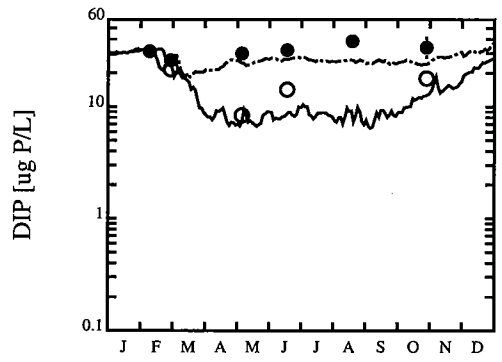
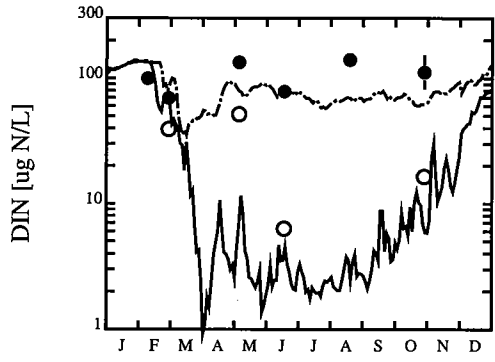
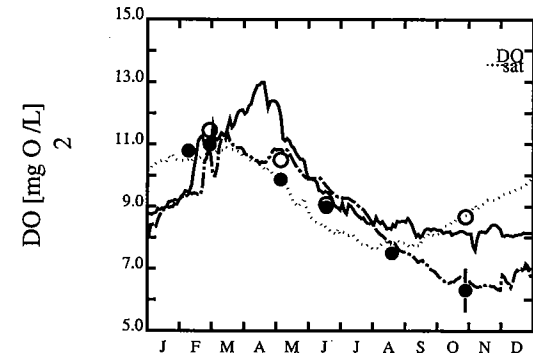
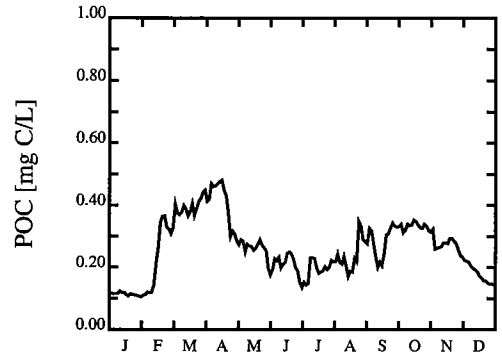
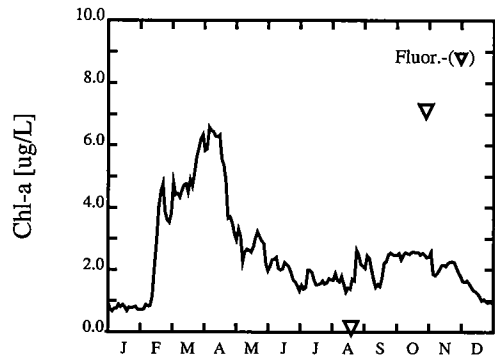
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std dev- Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (19,30) Vs Data Station F05



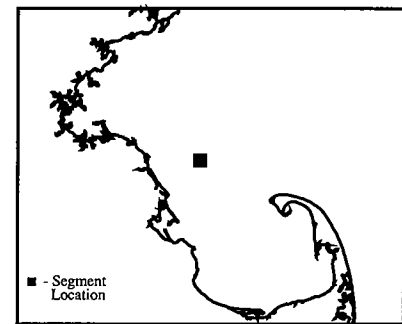
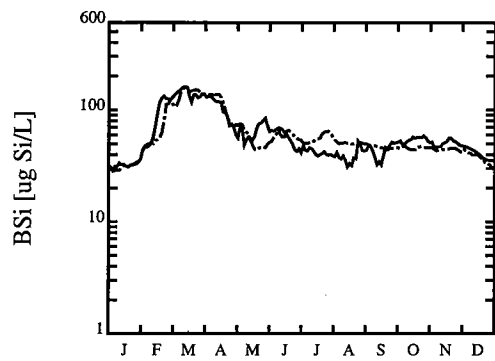
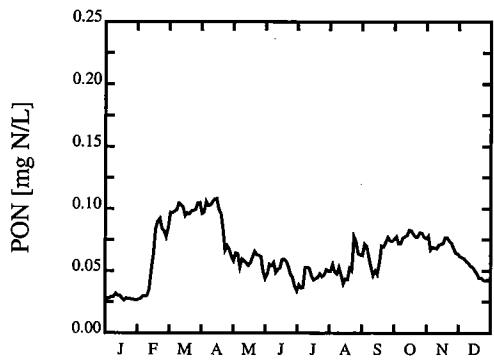
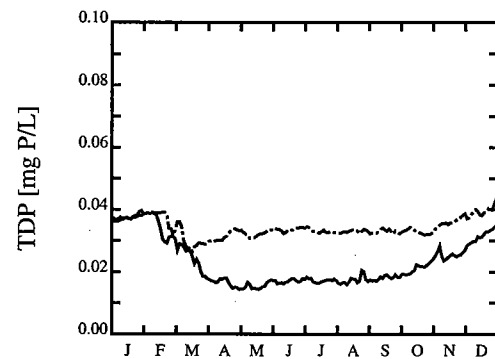
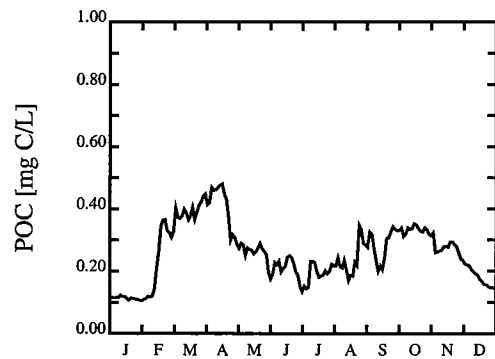
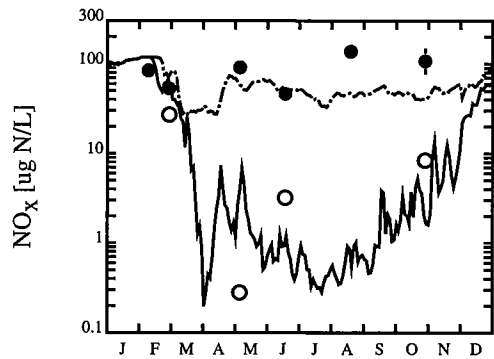
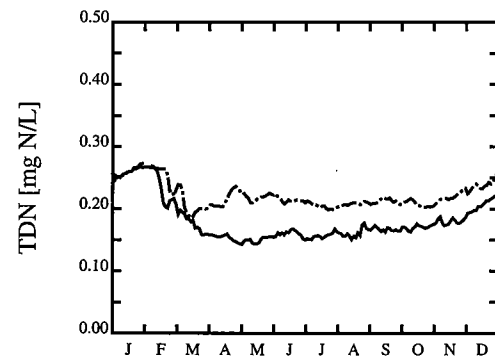
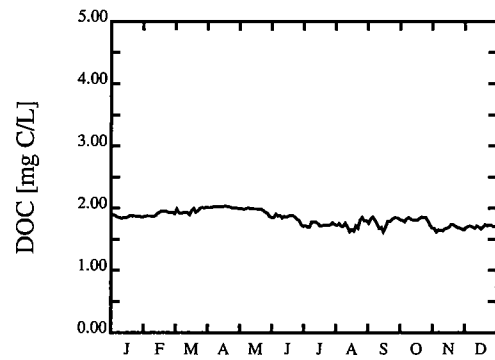
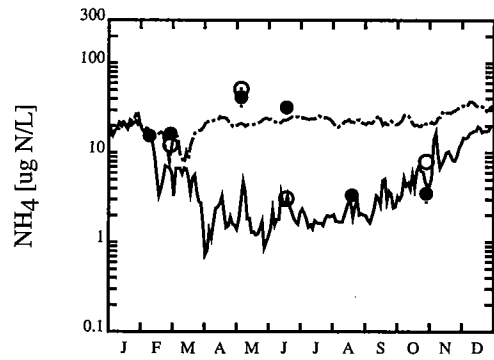
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std dev Surface Model
 - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (19,30) Vs Data Station F05



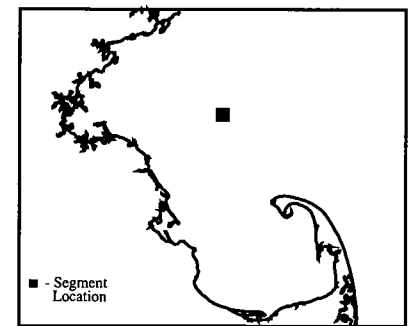
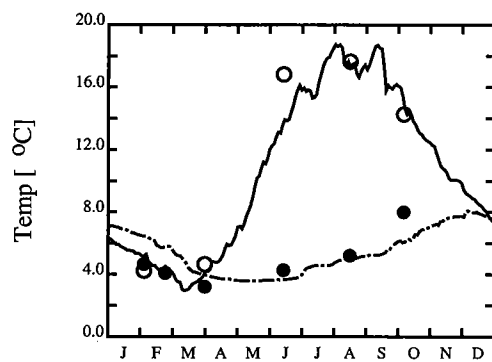
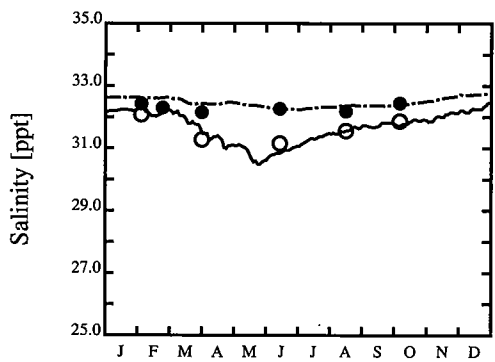
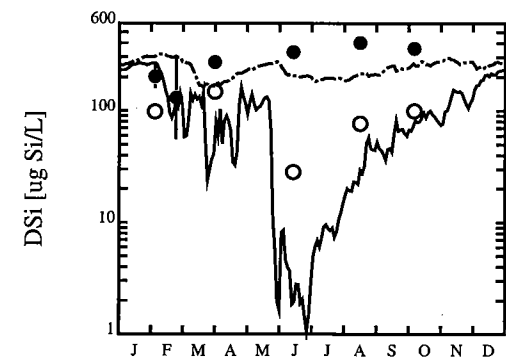
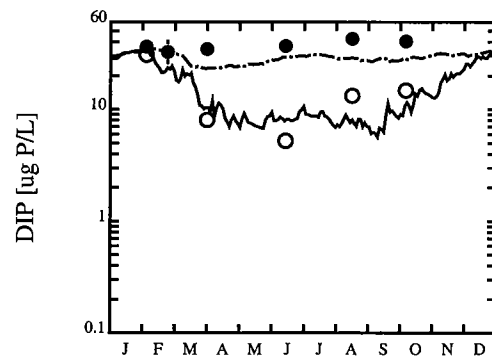
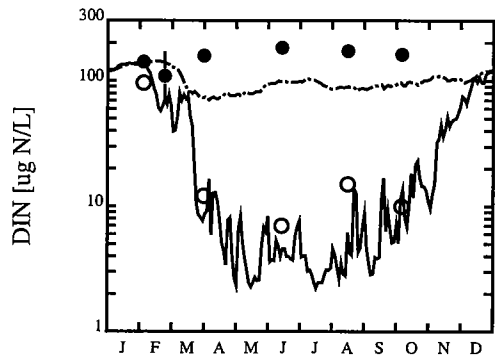
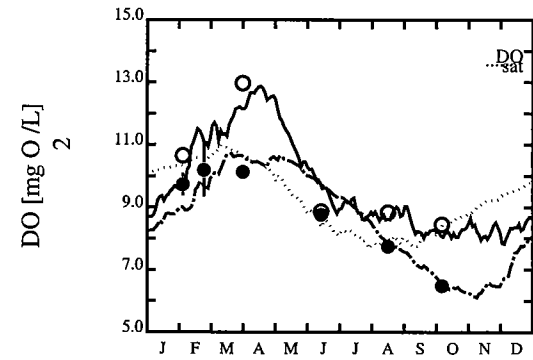
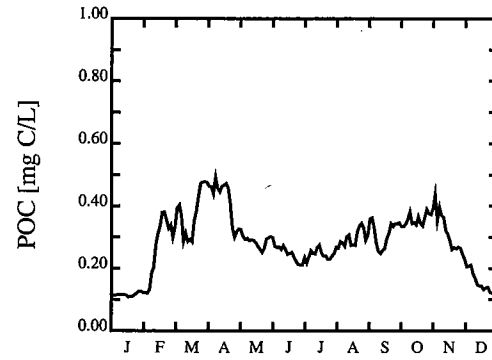
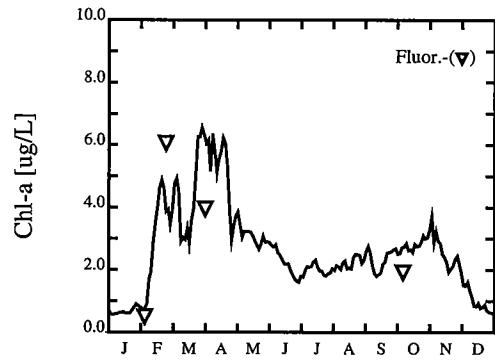
- LEGEND
- +/- Surface Data
 - Bottom Data
 - sid dev Surface Model
 - Bottom Model

1999 Temporal Calibration Results for Grid Cell (31,29) Vs Data Station F07



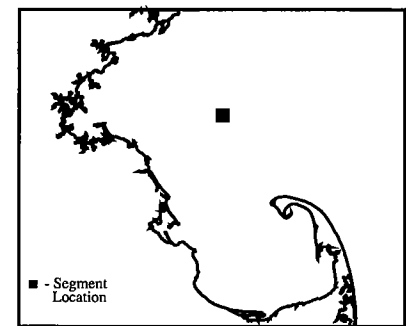
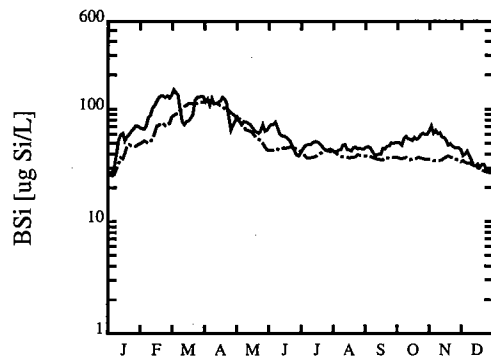
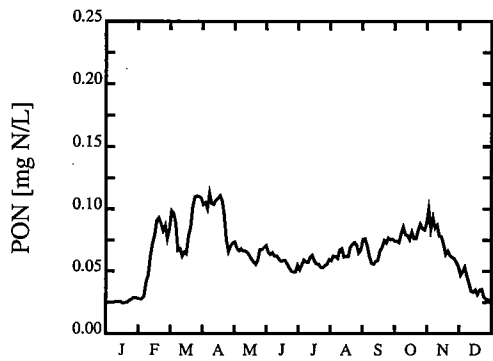
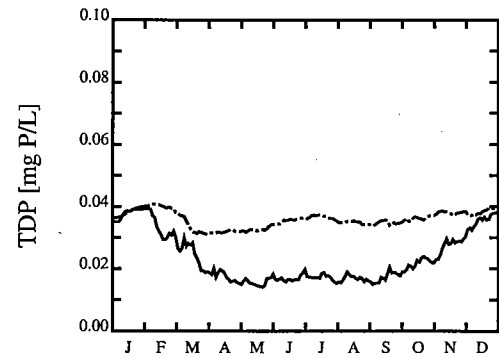
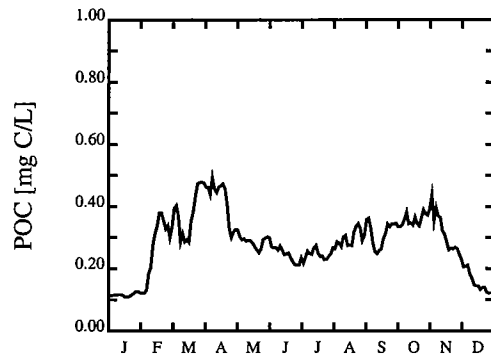
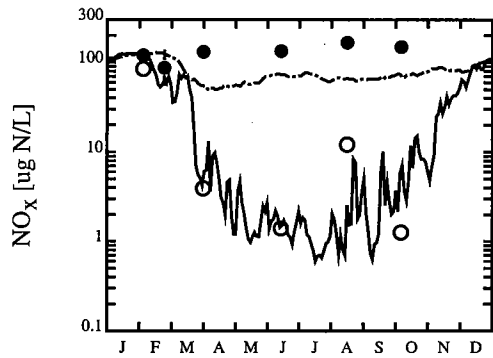
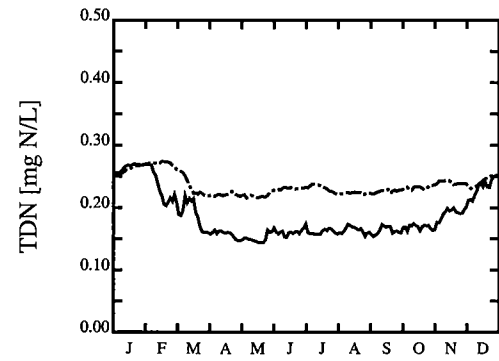
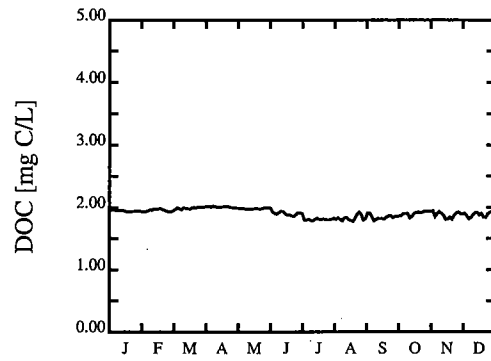
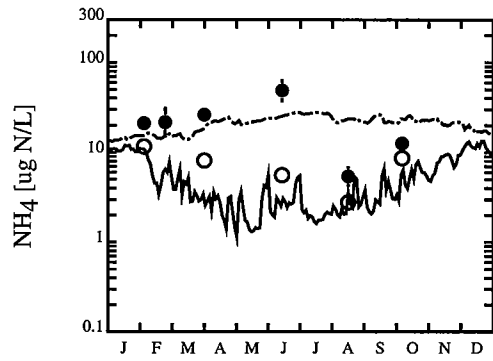
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - std.dev Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for
 Grid Cell (31,29) Vs Data Station F07



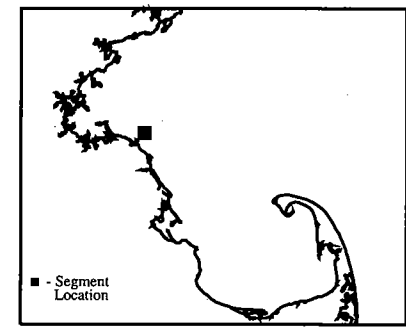
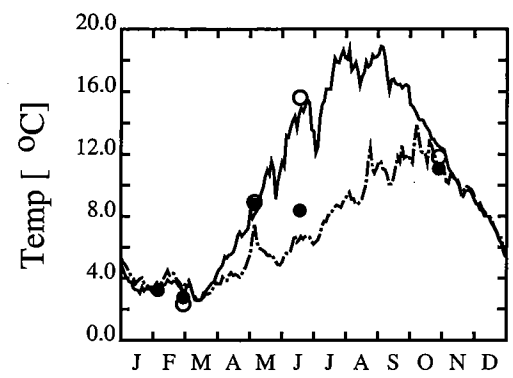
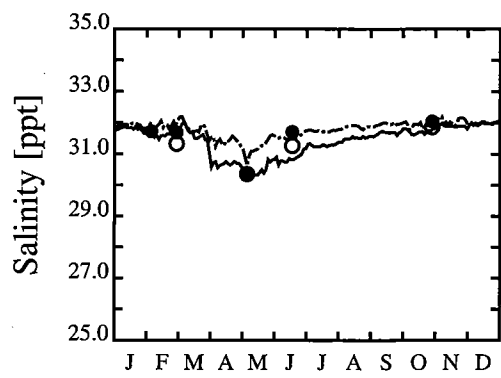
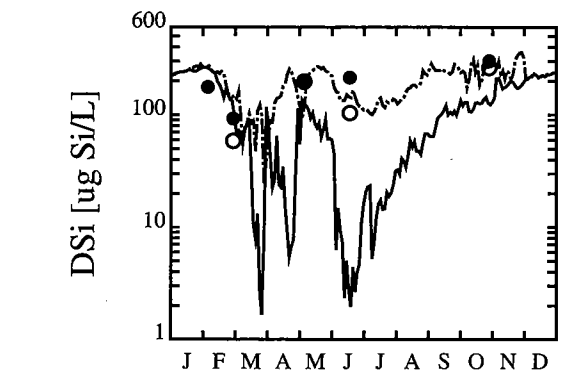
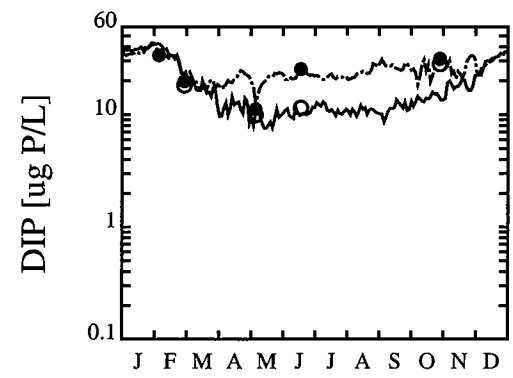
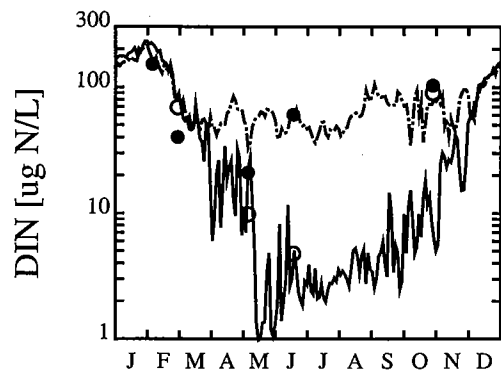
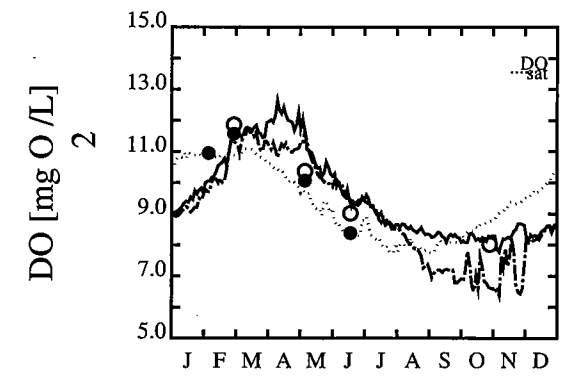
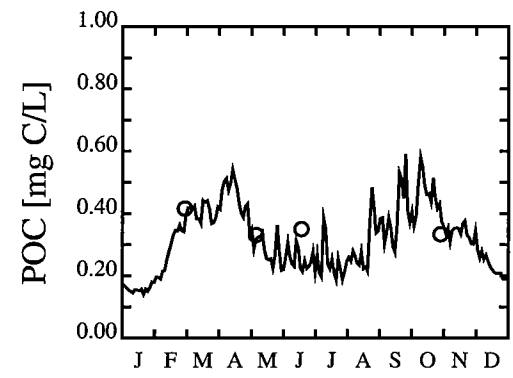
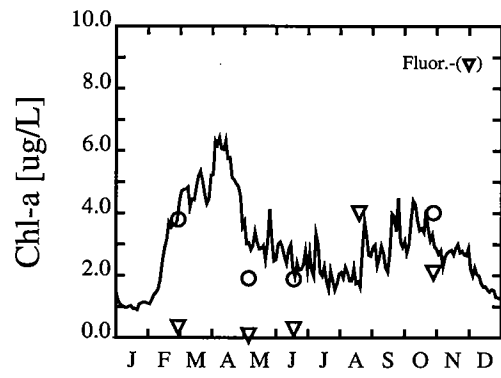
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -sid.dev Surface Model
 - Bottom Model

1999 Temporal Calibration Results for Grid Cell (43,33) Vs Data Station F12



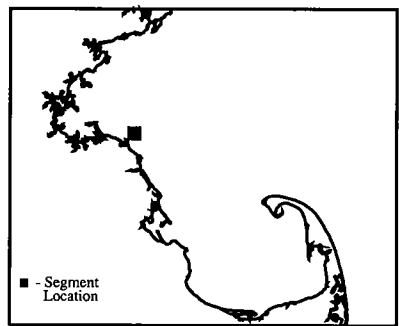
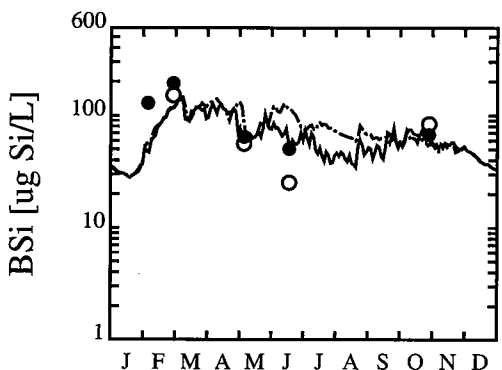
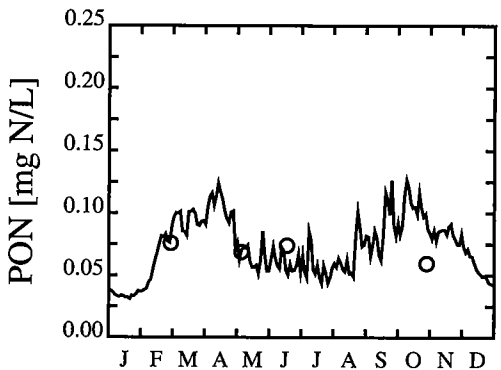
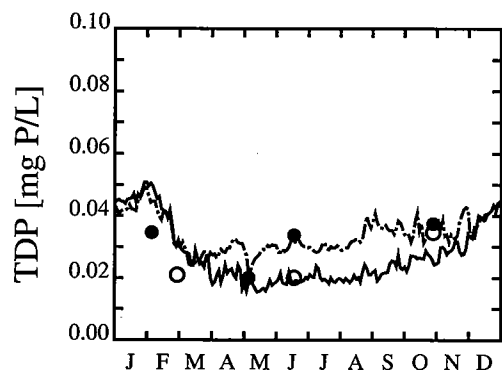
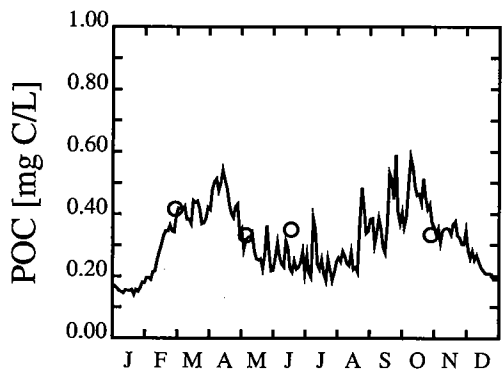
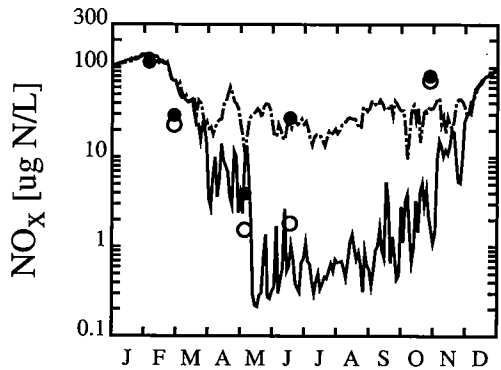
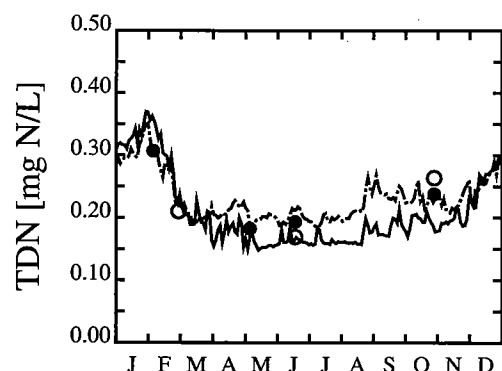
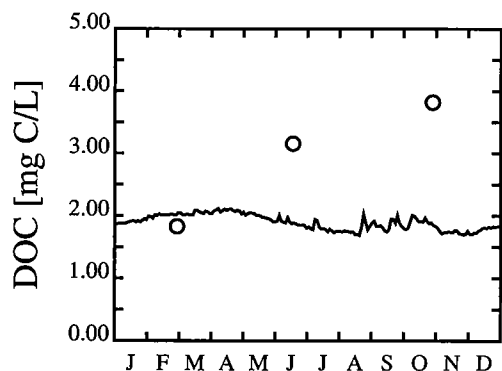
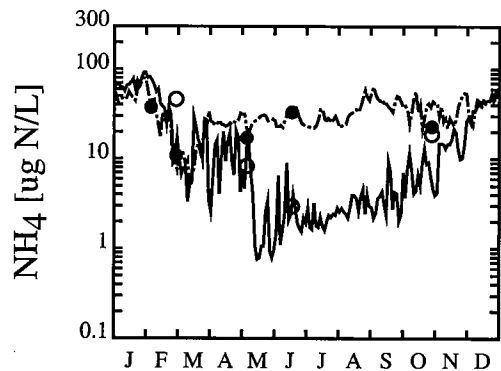
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 — std dev Surface Model
 - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (43,33) Vs Data Station F12



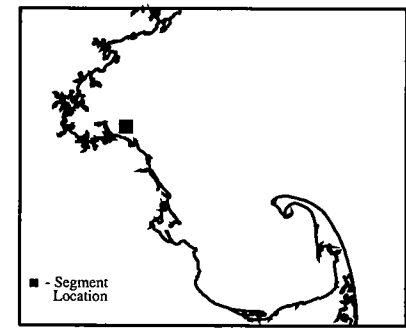
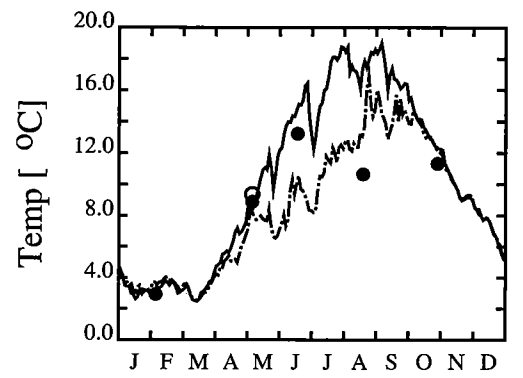
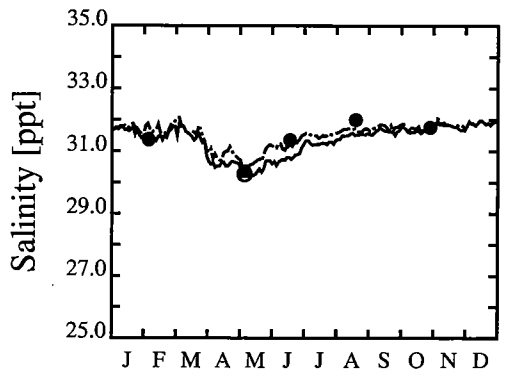
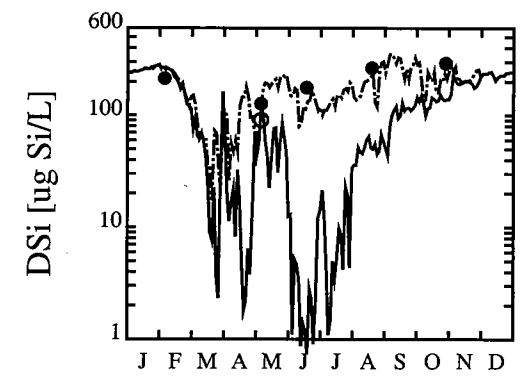
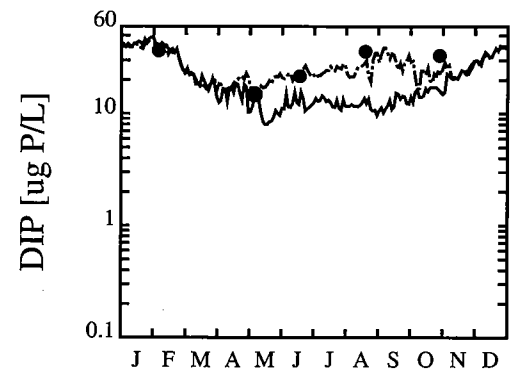
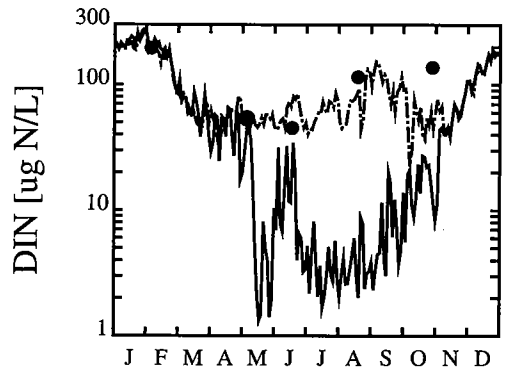
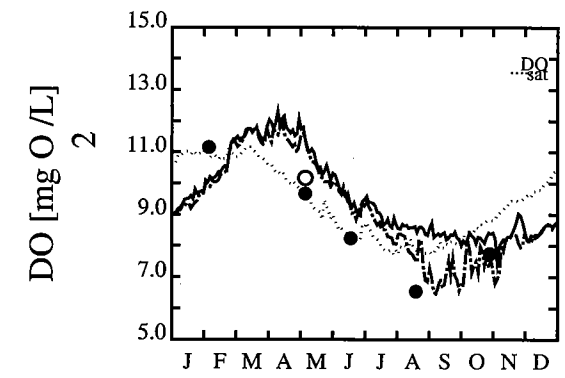
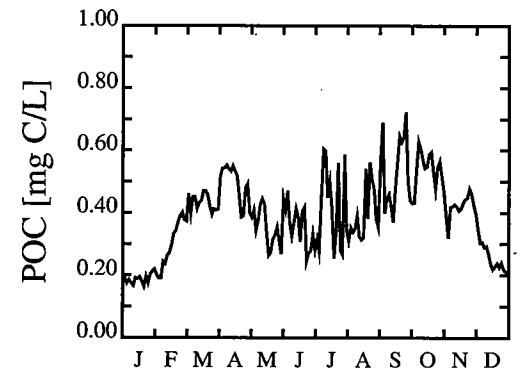
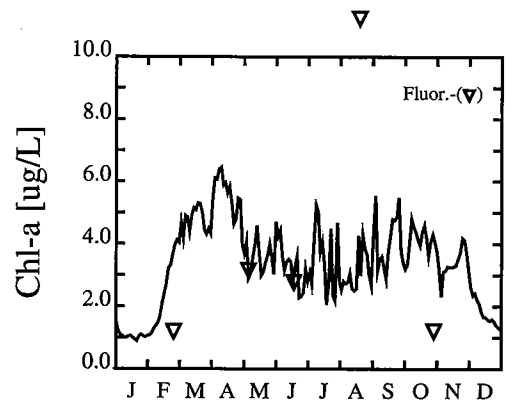
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 --- std.dev Surface Model
 - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (24,40) Vs Data Station F13P



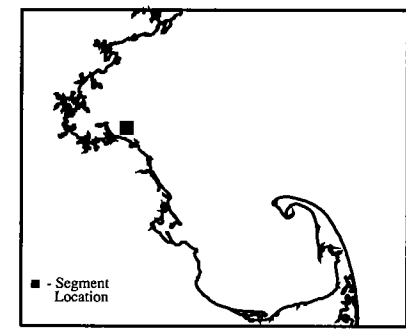
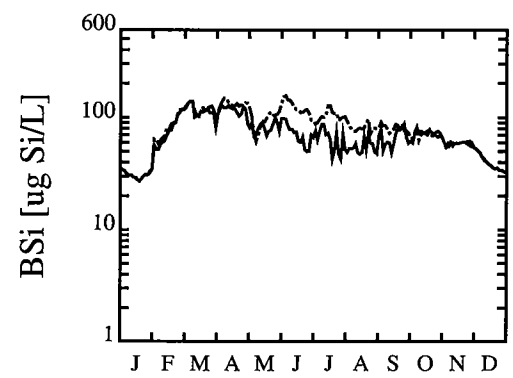
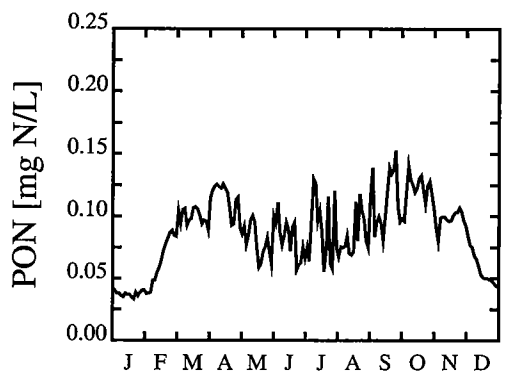
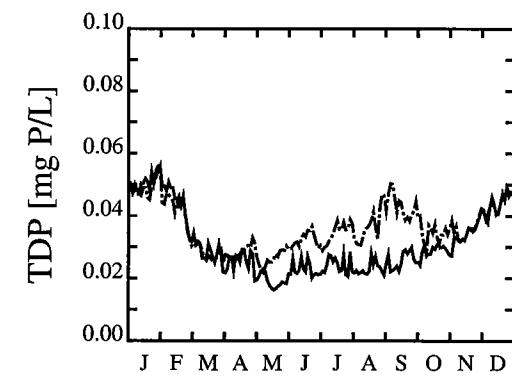
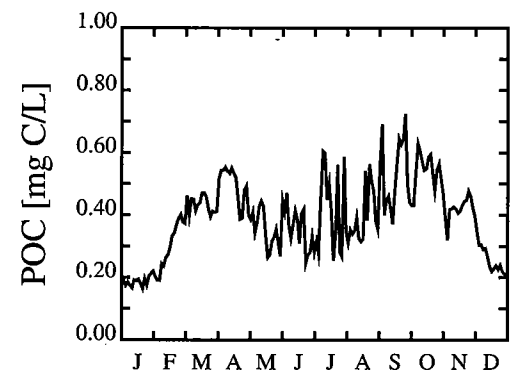
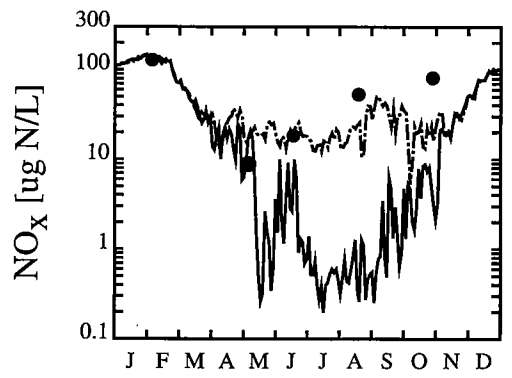
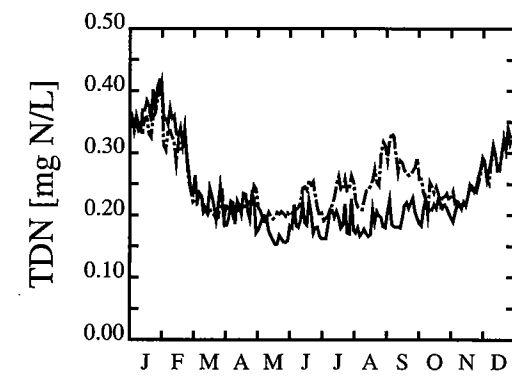
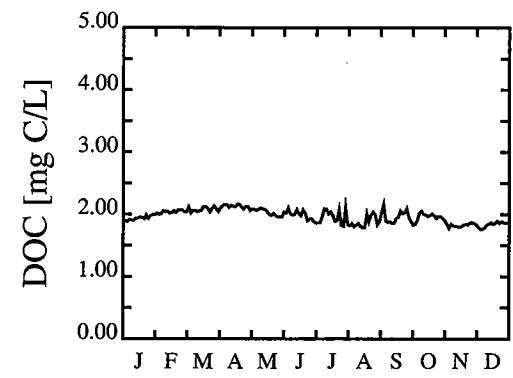
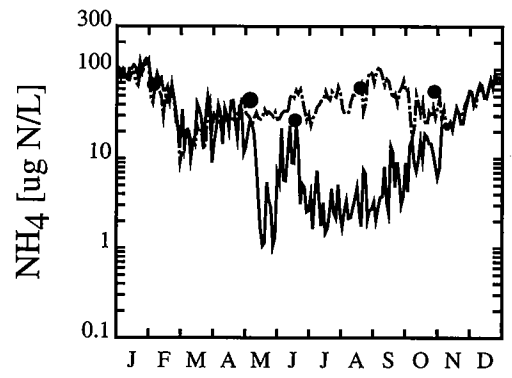
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 ———— std.dev Surface Model
 - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (24,40) Vs Data Station F13P



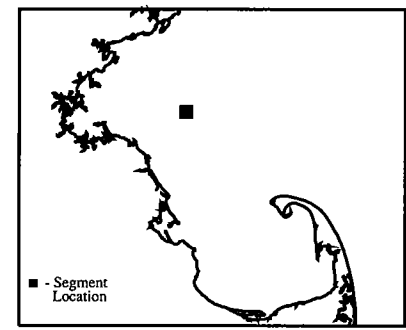
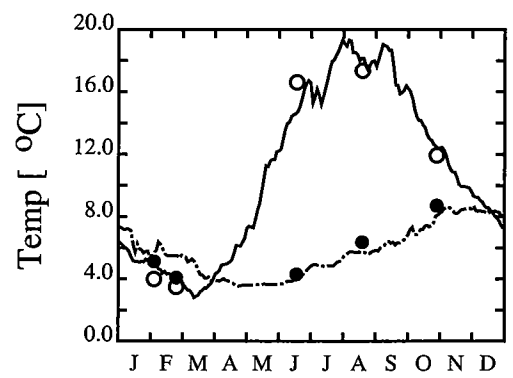
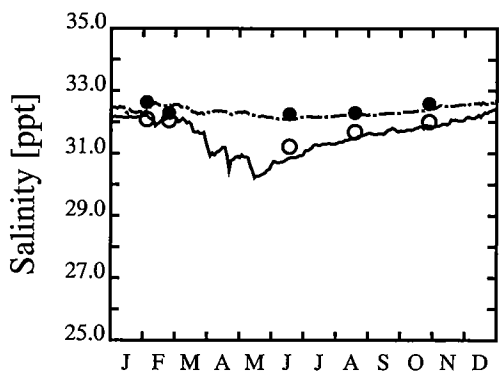
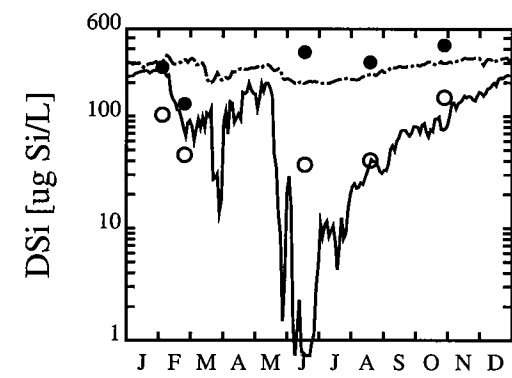
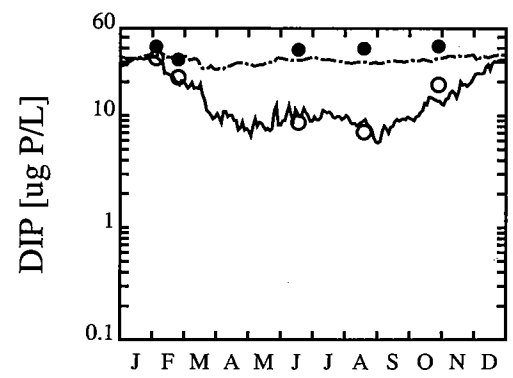
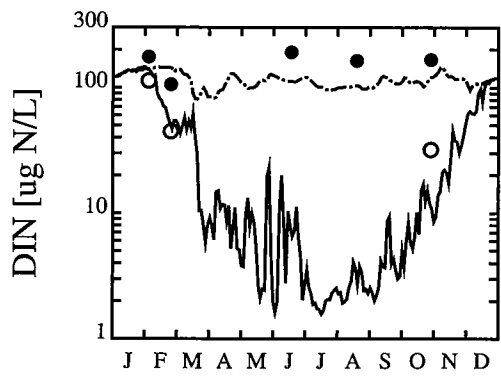
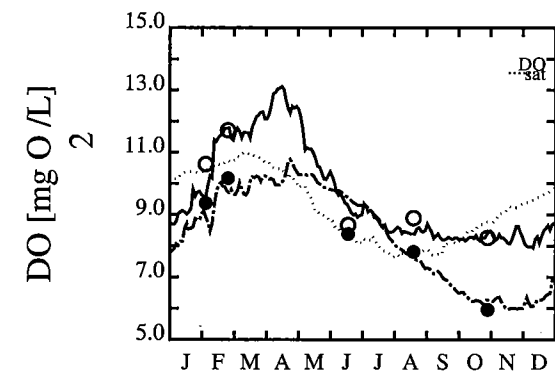
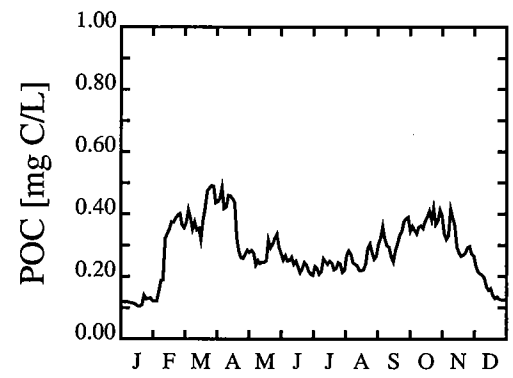
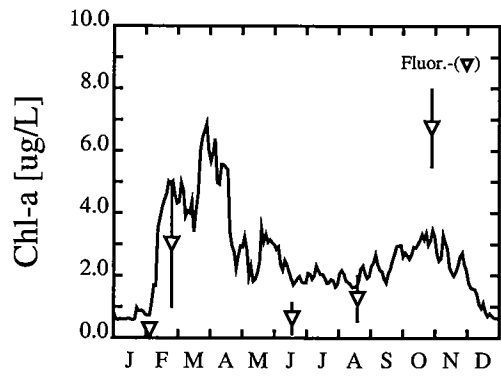
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - std.dev Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (22,44) Vs Data Station F14



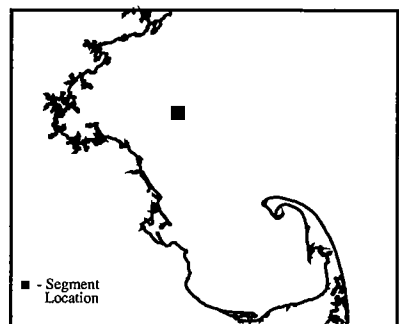
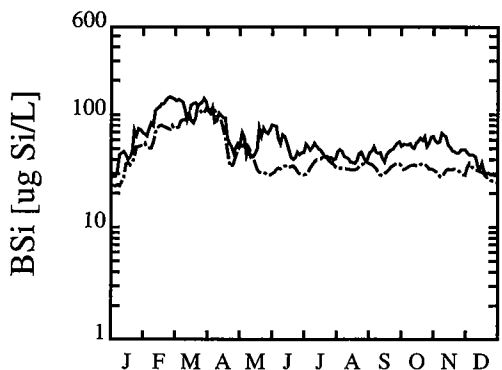
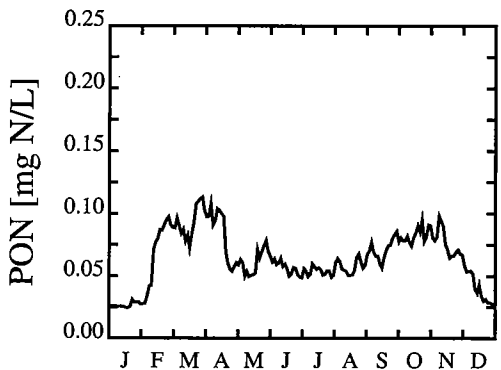
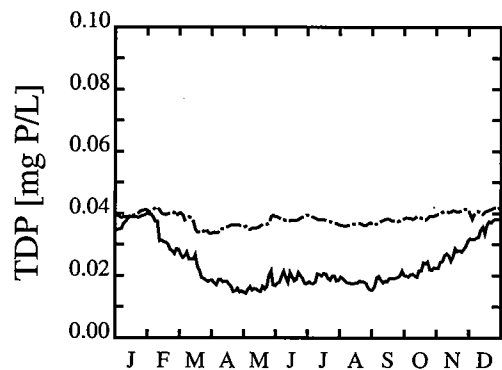
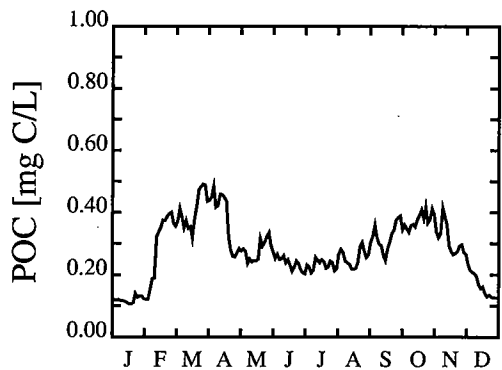
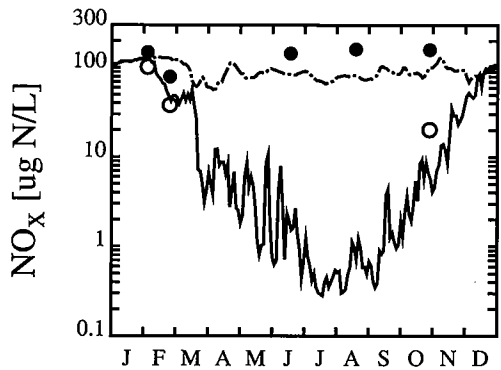
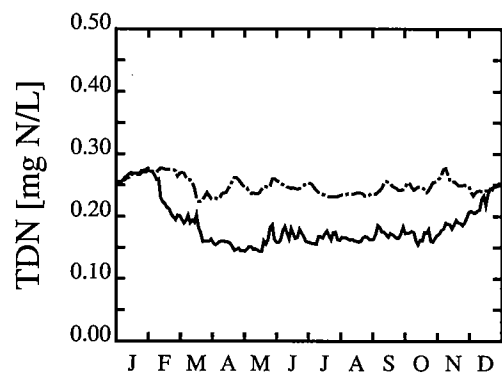
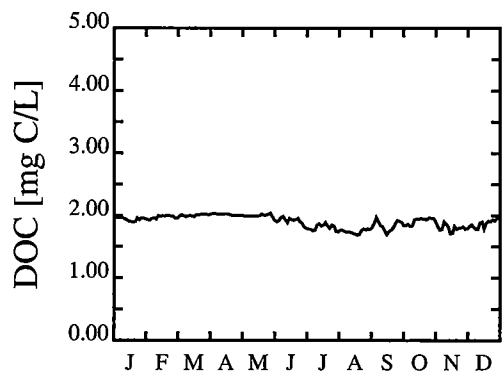
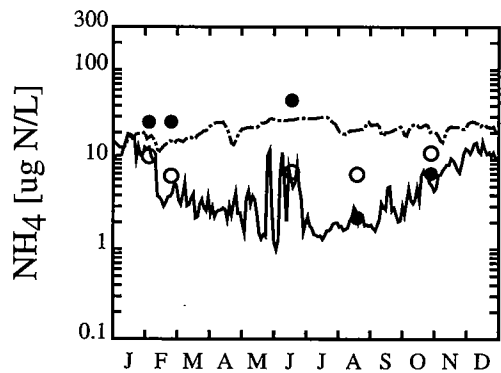
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev Surface Model
 - Bottom Model

1999 Temporal Calibration Results for Grid Cell (22,44) Vs Data Station F14



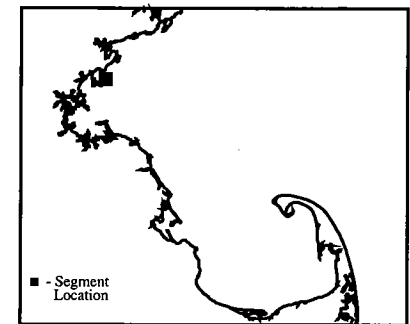
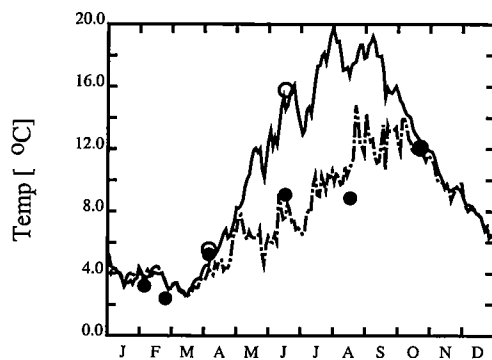
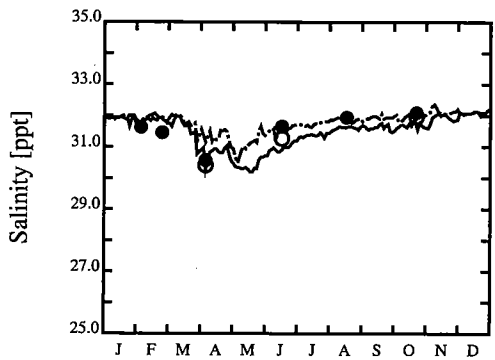
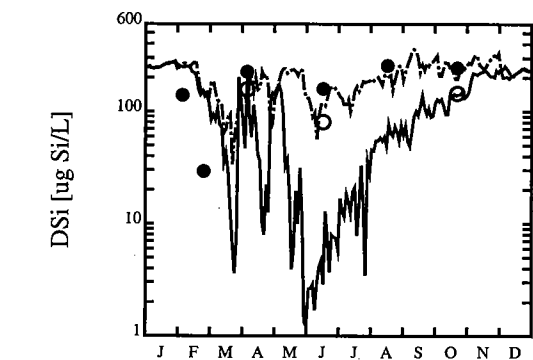
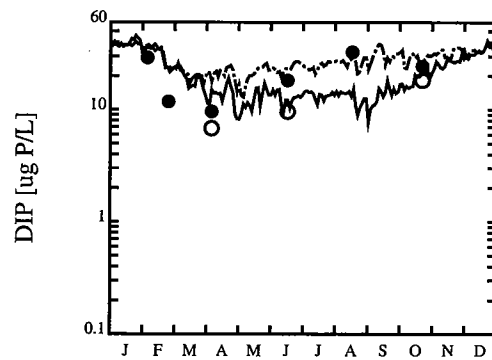
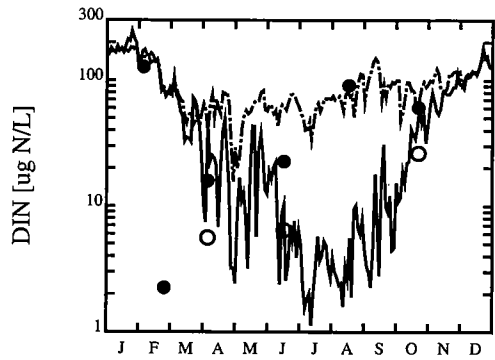
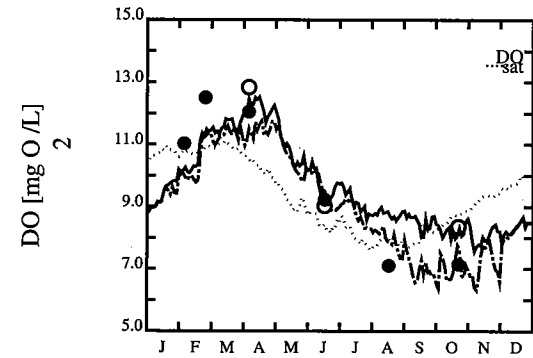
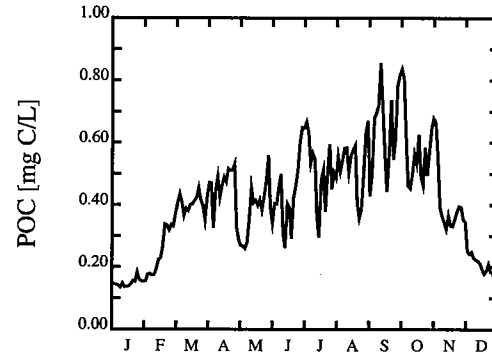
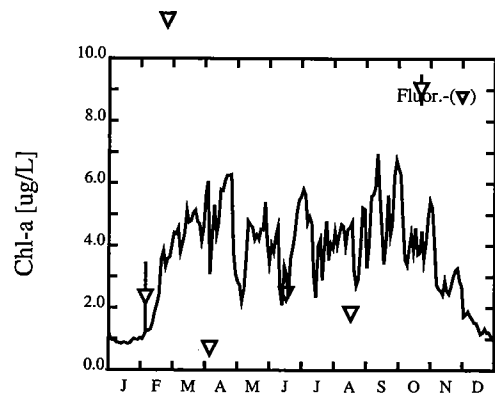
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev- Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (37,37) Vs Data Station F17



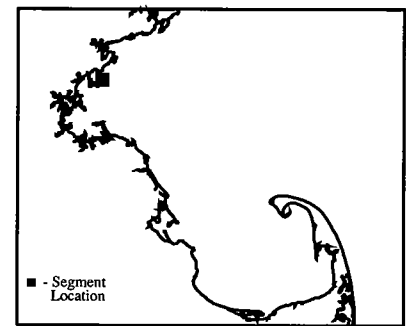
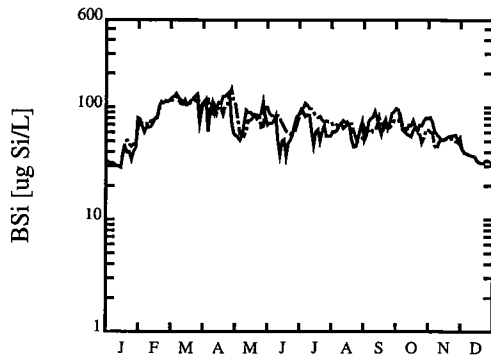
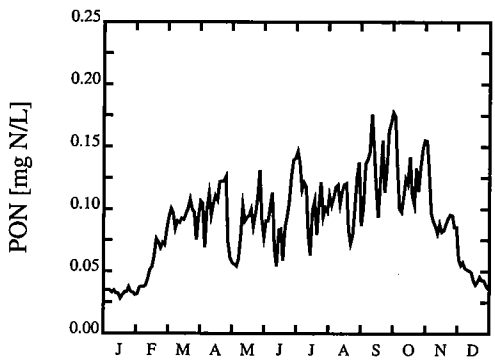
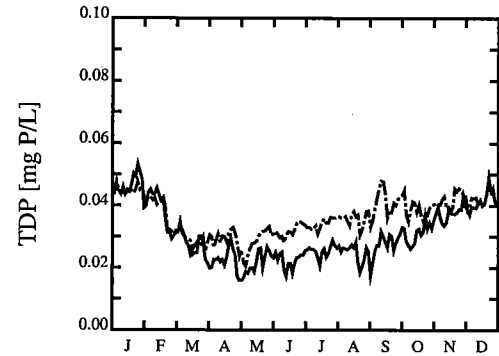
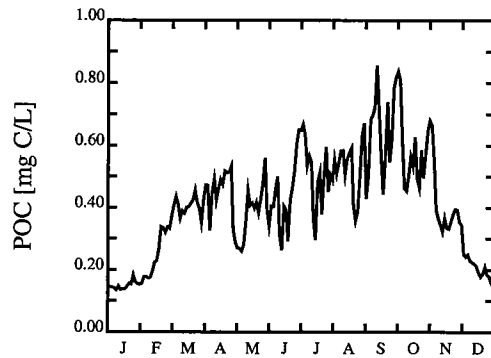
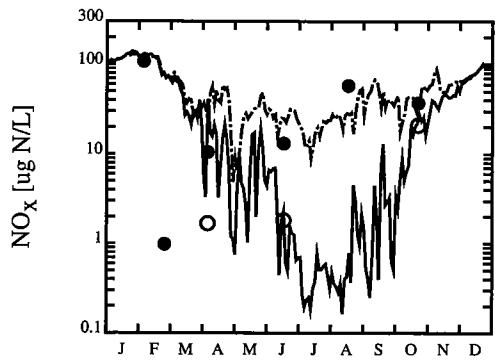
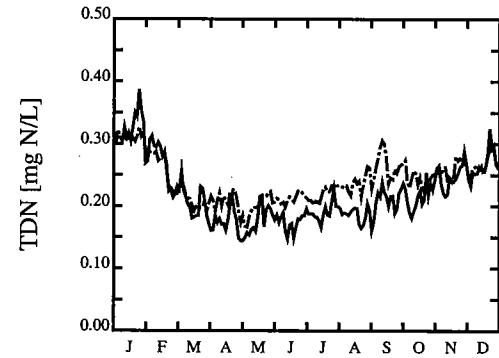
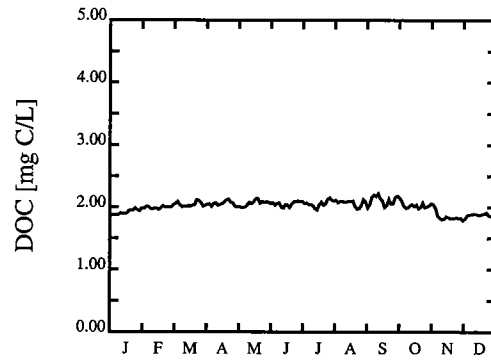
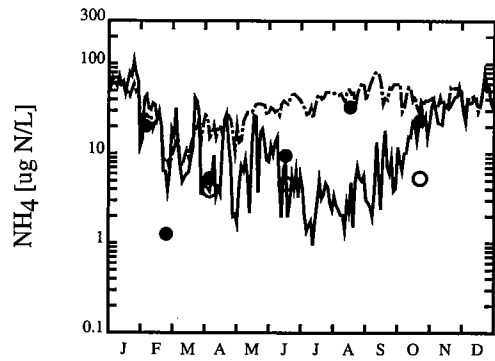
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 — std dev Surface Model
 - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (37,37) Vs Data Station F17



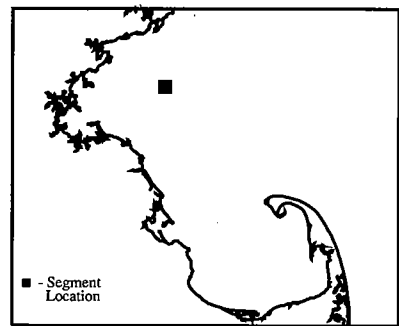
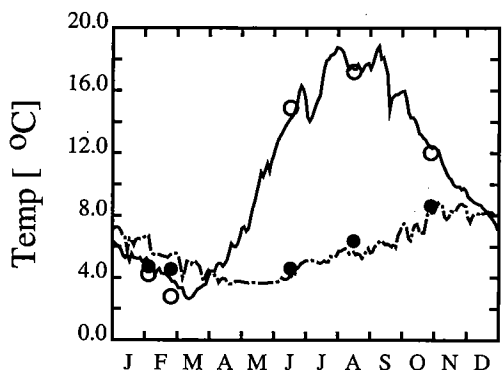
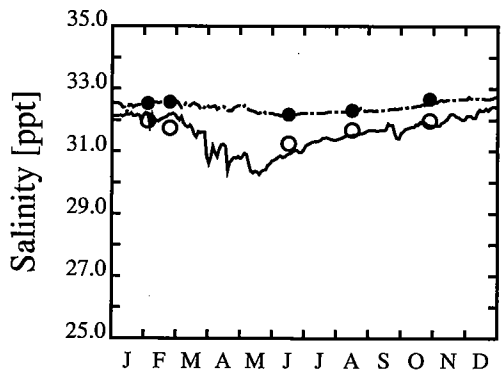
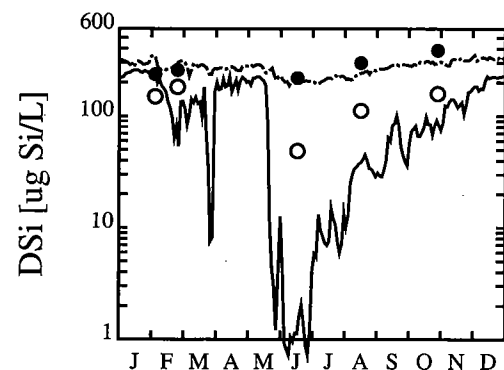
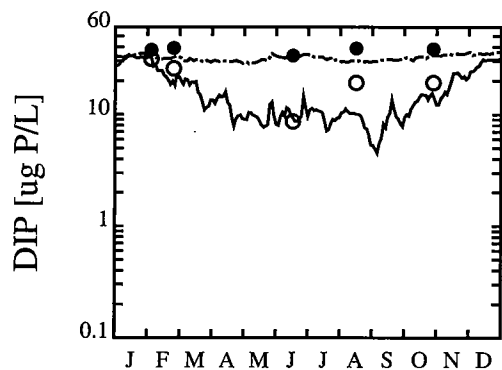
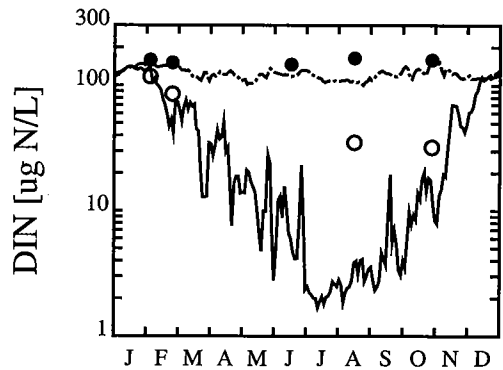
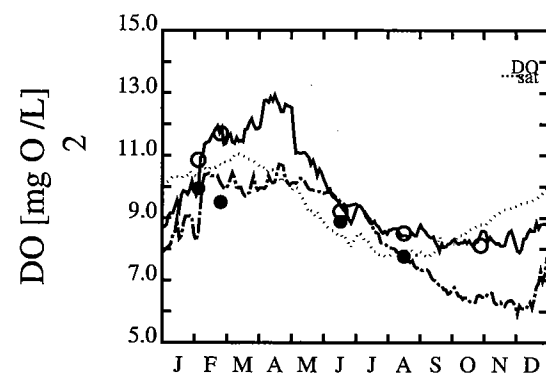
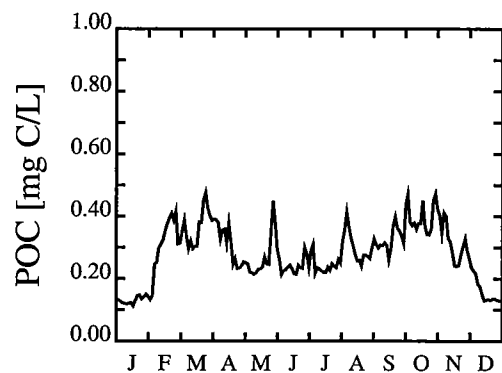
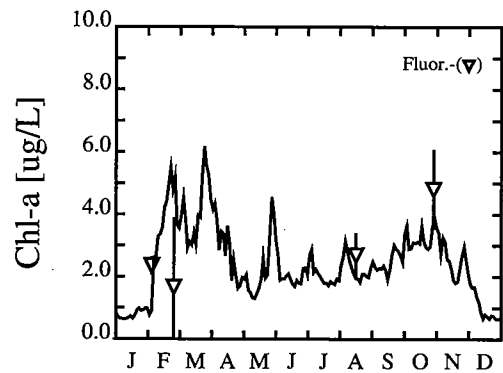
- LEGEND -----
- +/- Surface Data
 - Bottom Data
 - std.dev. Surface Model
 - Bottom Model

1999 Temporal Calibration Results for Grid Cell (31,55) Vs Data Station F18



----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 — std.dev Surface Model
 - - - - - Bottom Model

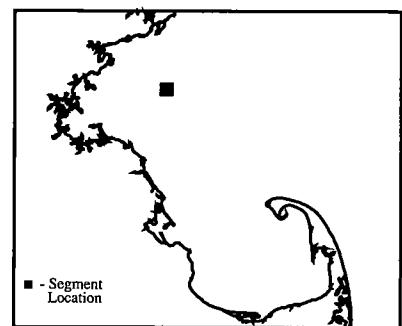
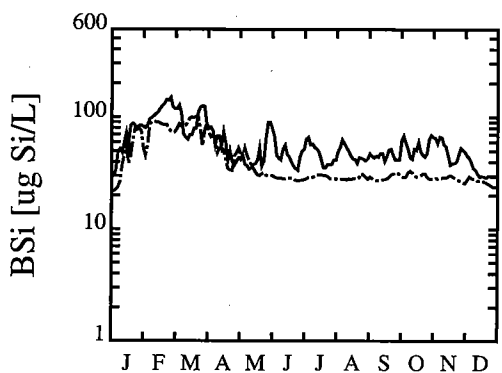
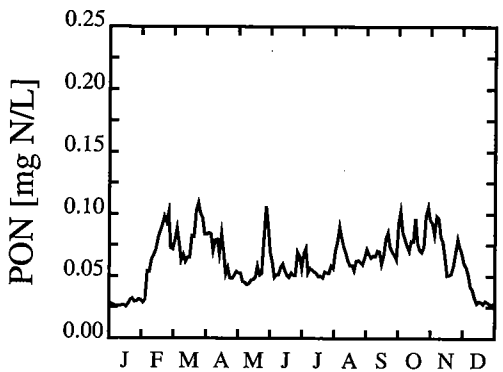
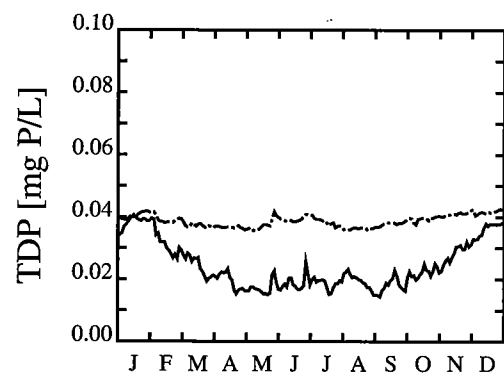
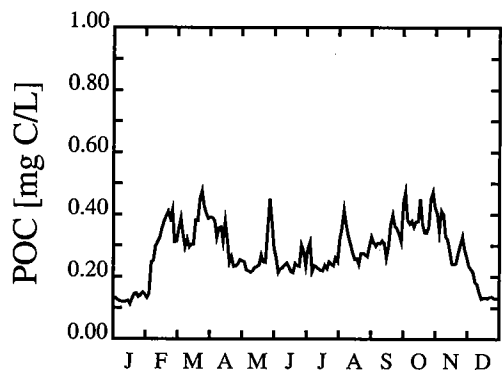
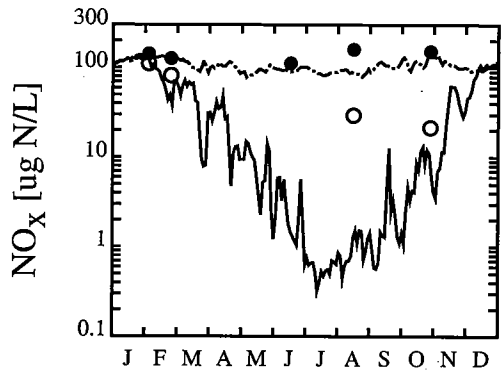
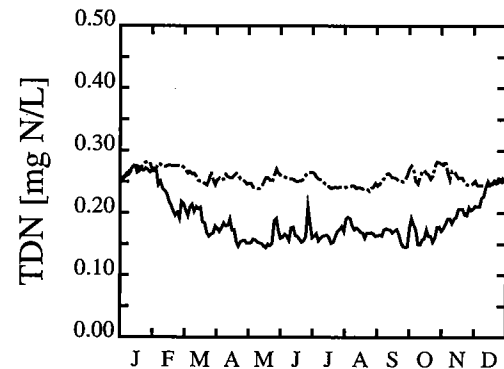
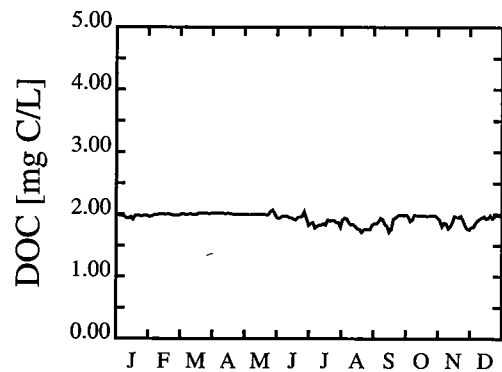
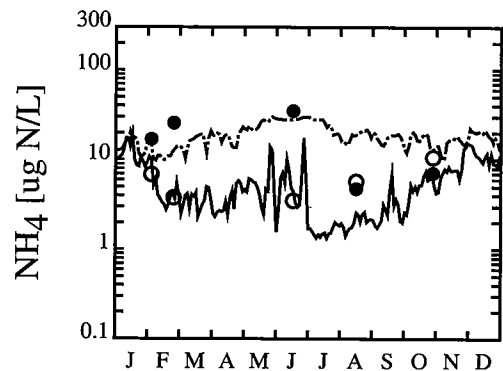
1999 Temporal Calibration Results for
 Grid Cell (31,55) Vs Data Station F18



LEGEND

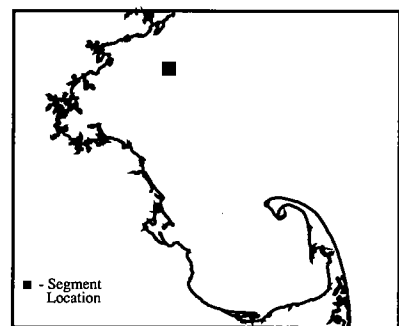
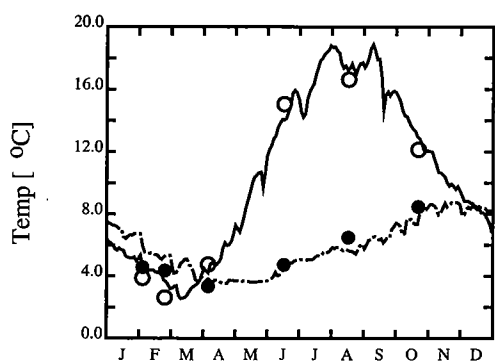
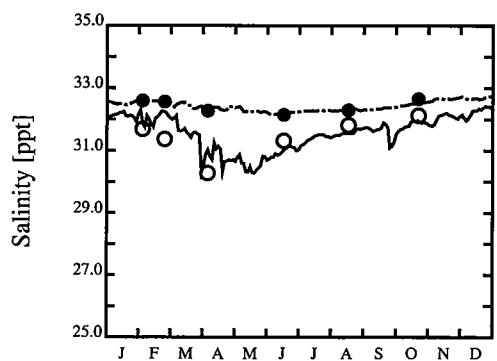
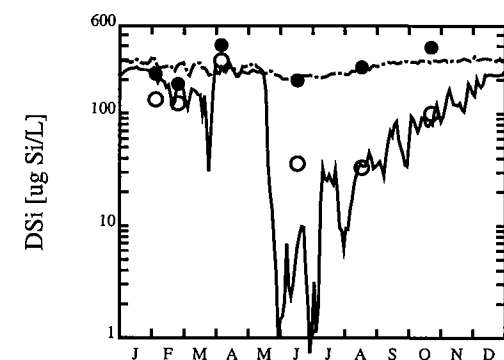
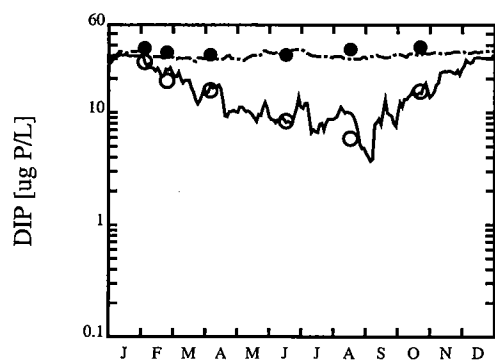
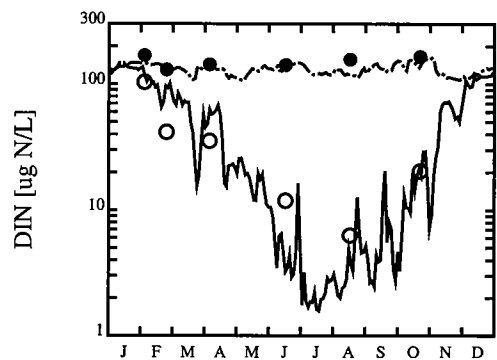
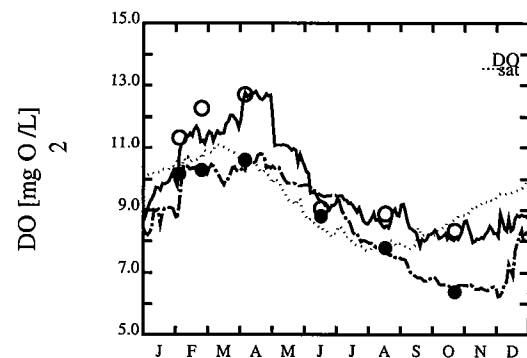
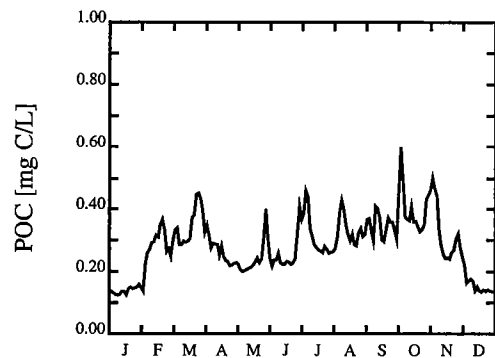
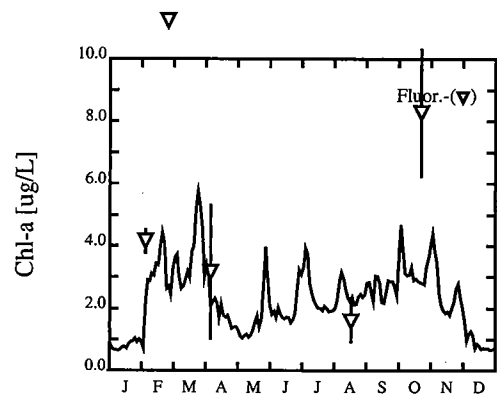
- +/- Surface Data
- Bottom Data
- std.dev Surface Model
- Bottom Model

1999 Temporal Calibration Results for Grid Cell (39,42) Vs Data Station F19



LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - std dev. Surface Model
 ——— Bottom Model

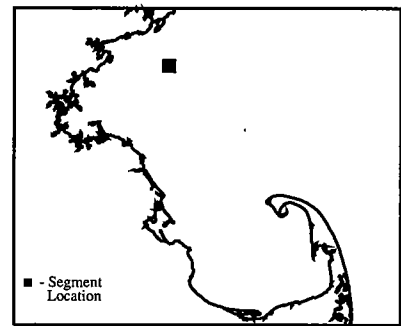
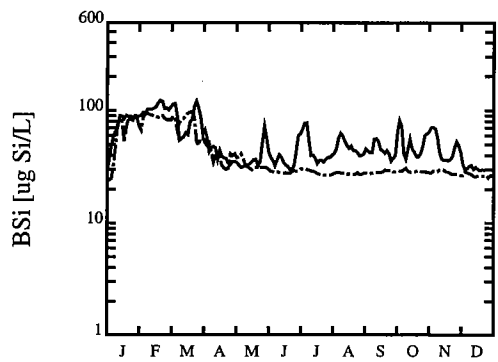
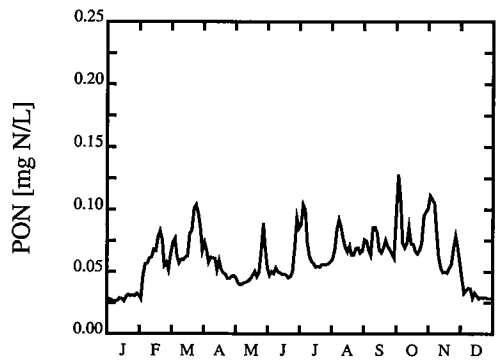
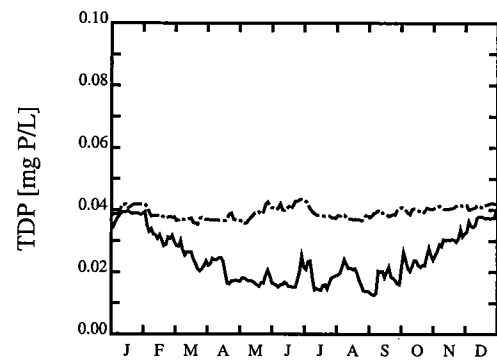
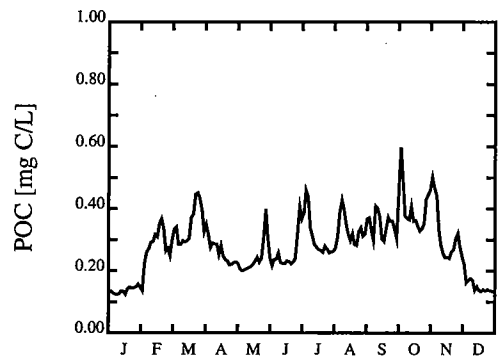
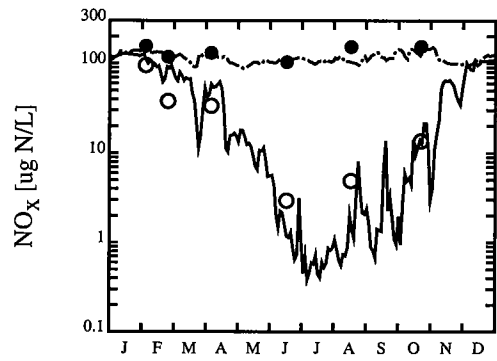
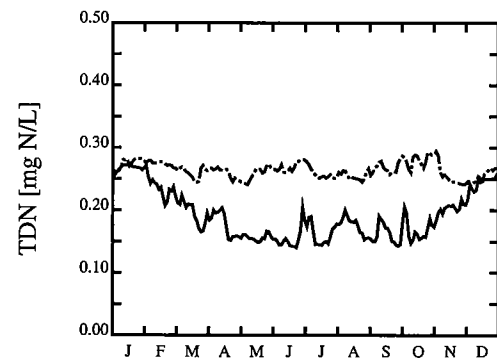
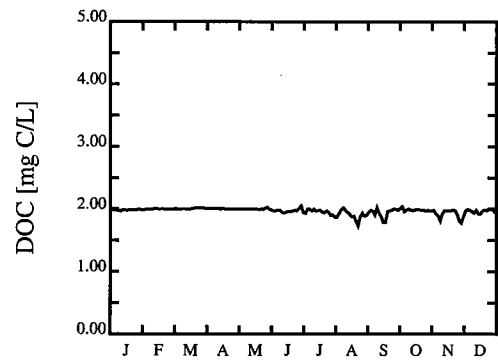
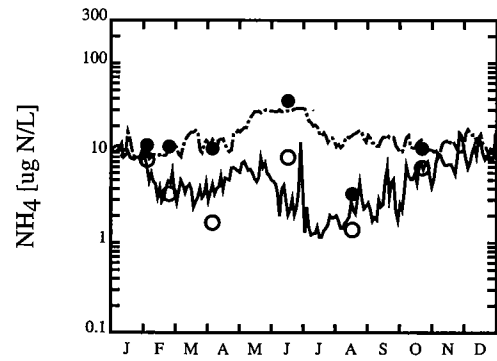
1999 Temporal Calibration Results for Grid Cell (39,42) Vs Data Station F19



LEGEND

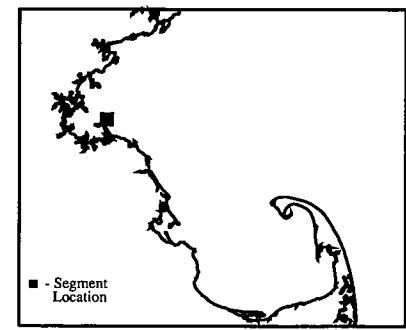
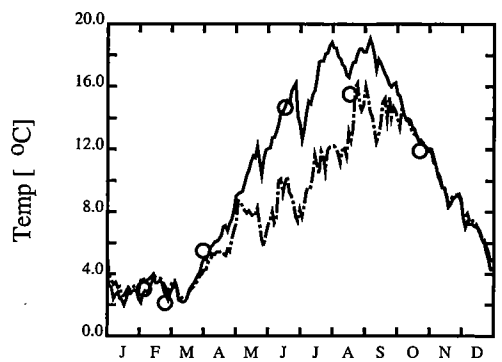
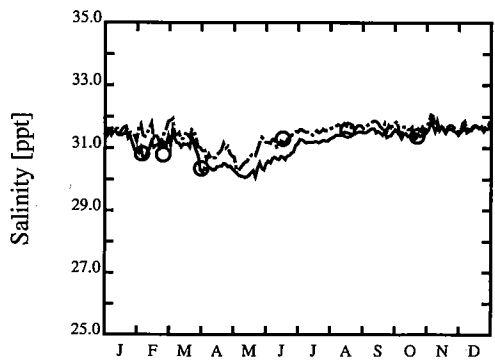
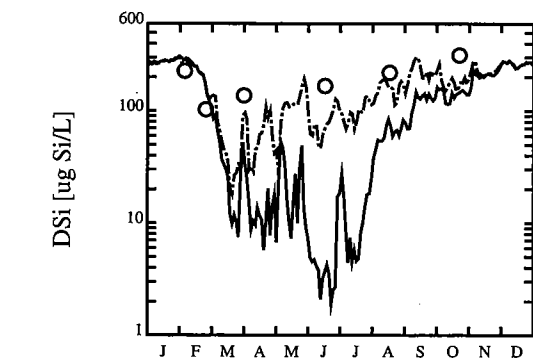
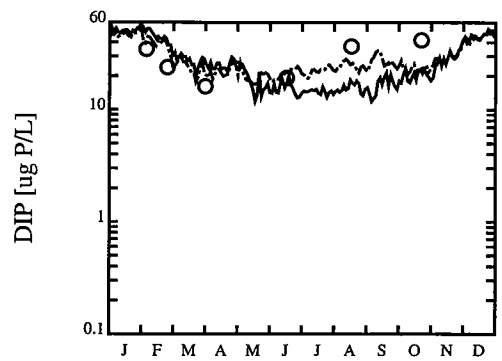
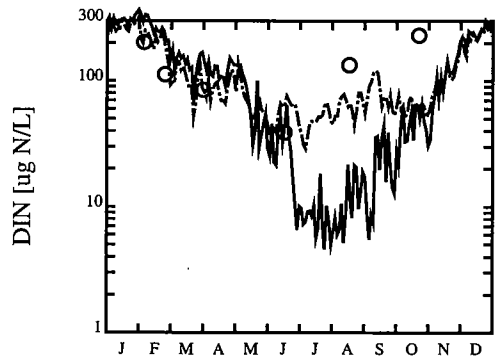
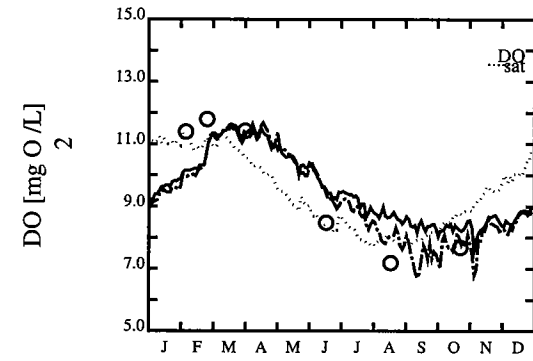
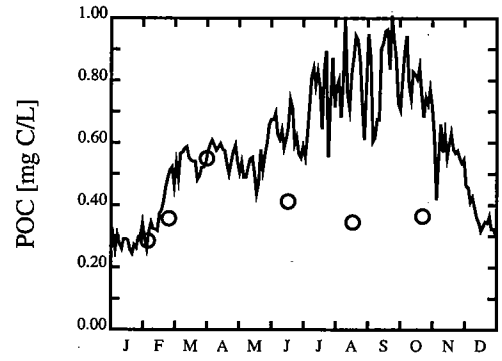
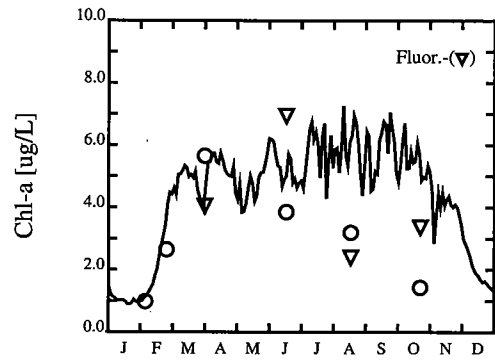
- +/- Surface Data
- Bottom Data
- std.dev. Surface Model
- Bottom Model

1999 Temporal Calibration Results for Grid Cell (43,44) Vs Data Station F22



----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 — std.dev Surface Model
 - - - Bottom Model

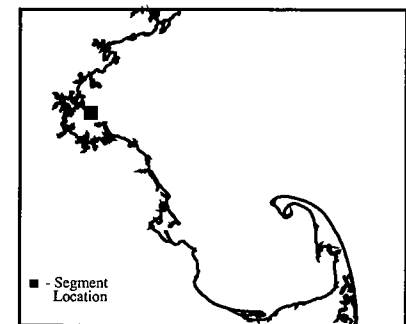
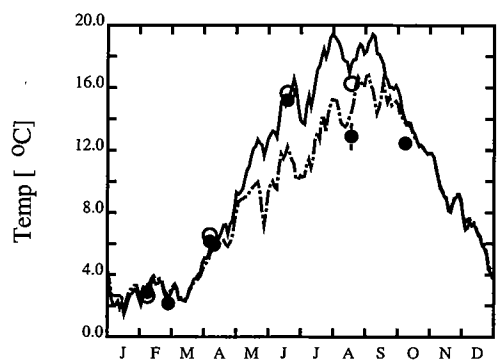
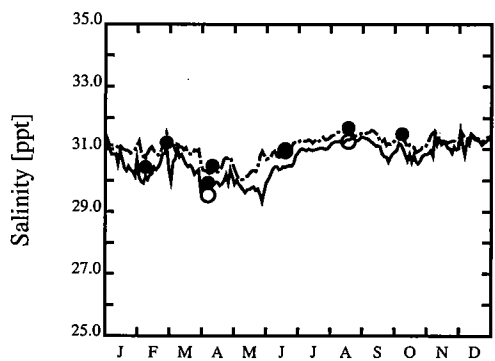
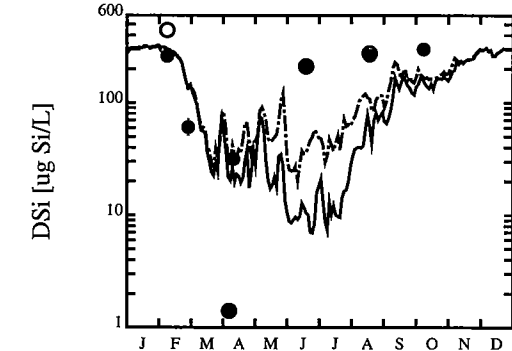
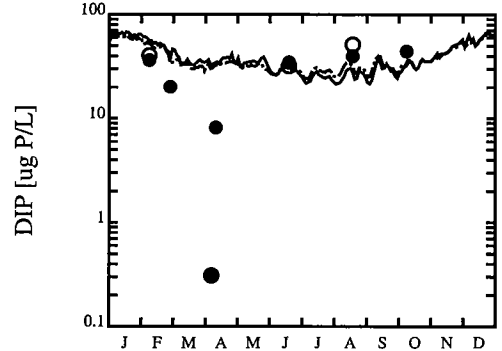
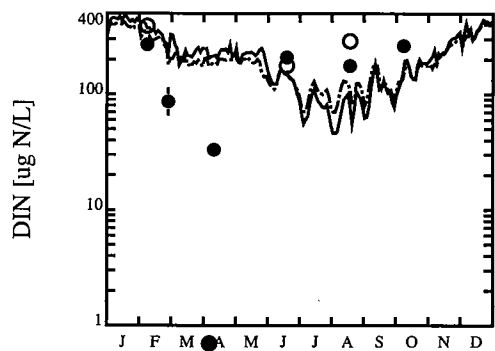
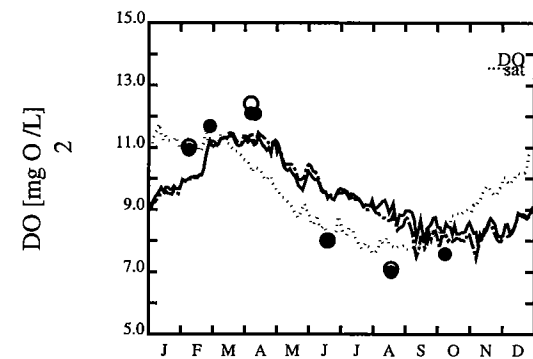
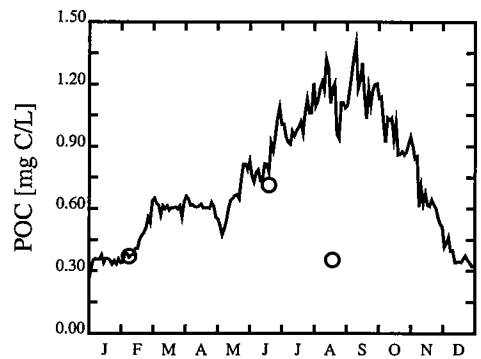
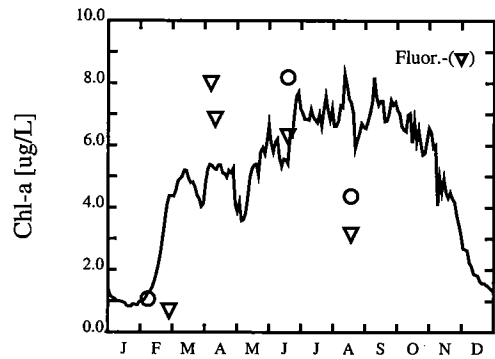
1999 Temporal Calibration Results for Grid Cell (43,44) Vs Data Station F22



LEGEND

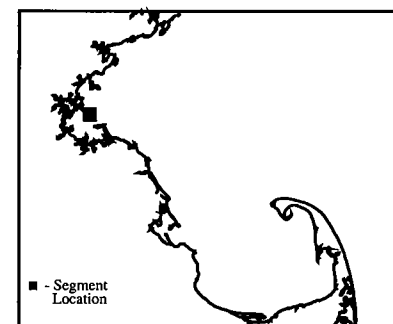
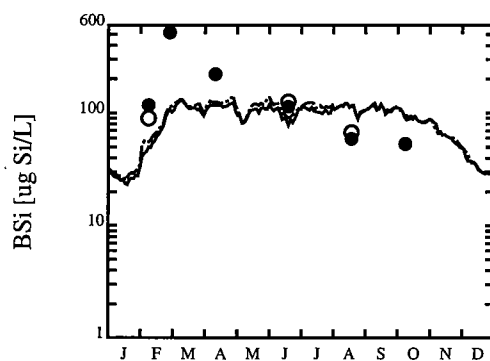
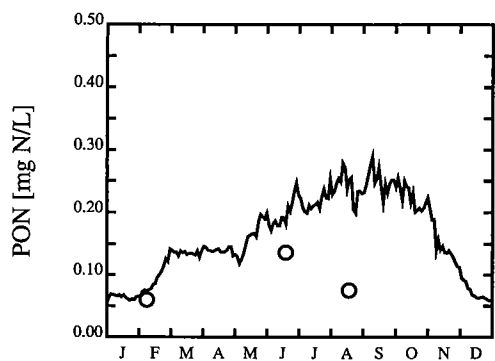
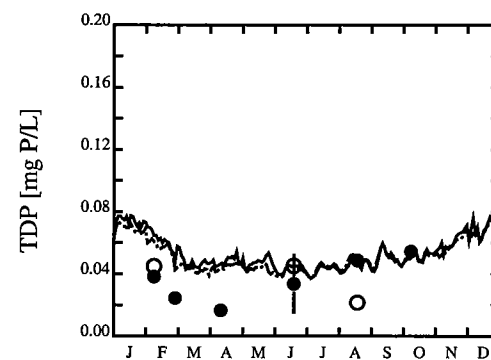
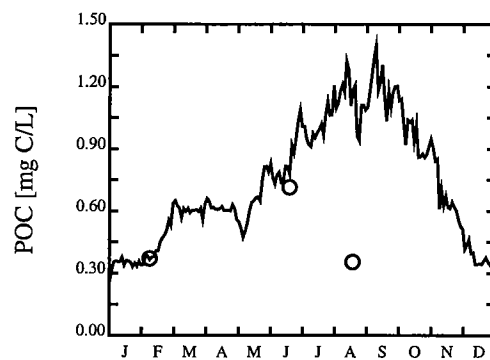
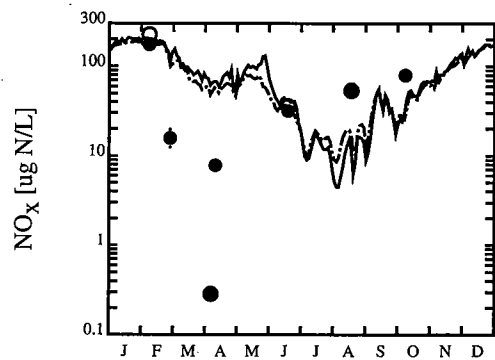
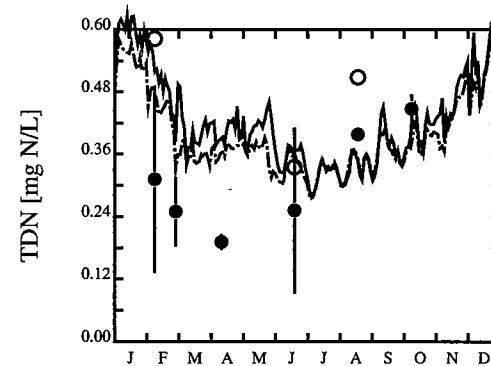
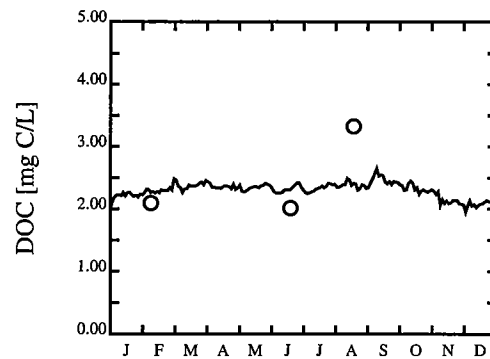
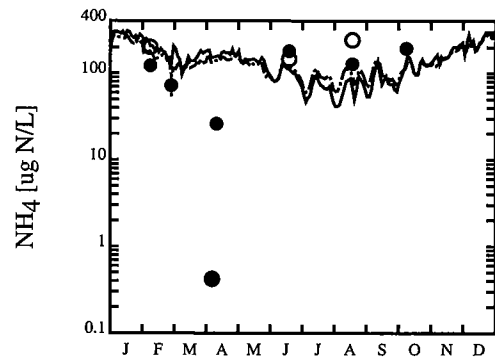
- +/- Surface Data
- Bottom Data
- std dev Surface Model
- - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (21,49) Vs Data Station F25



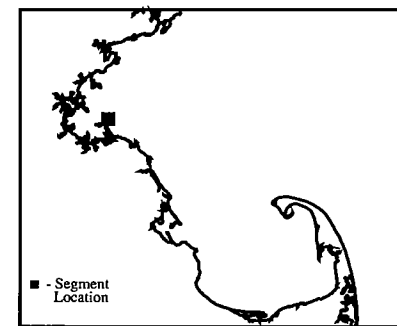
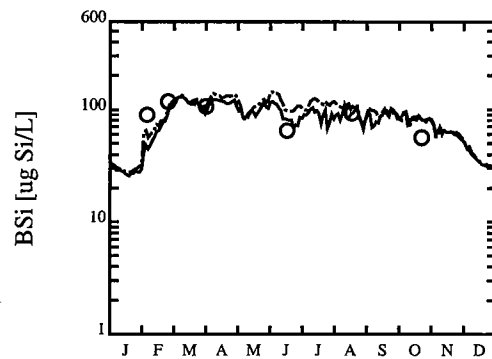
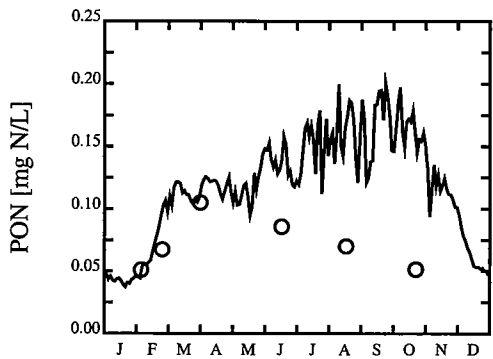
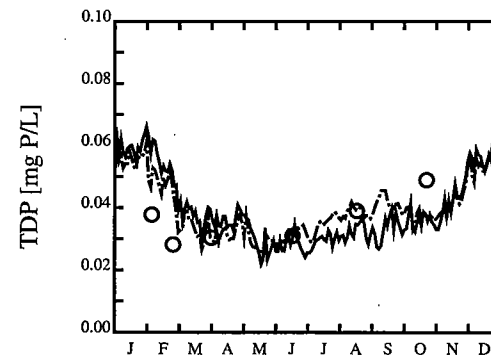
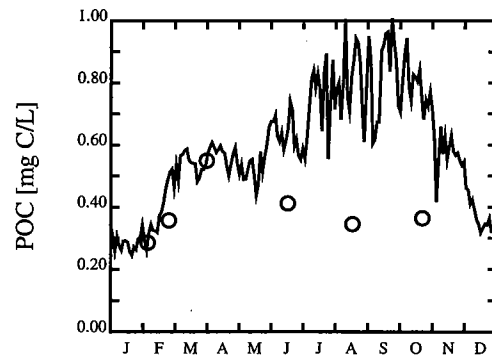
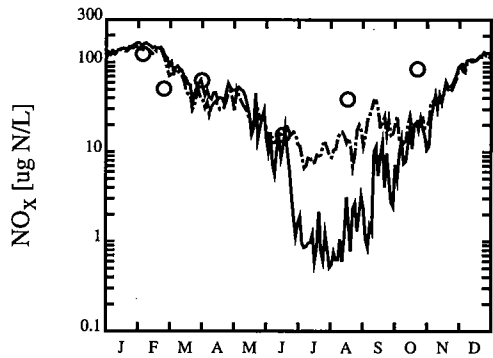
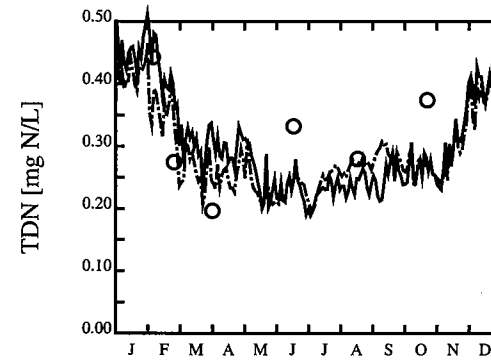
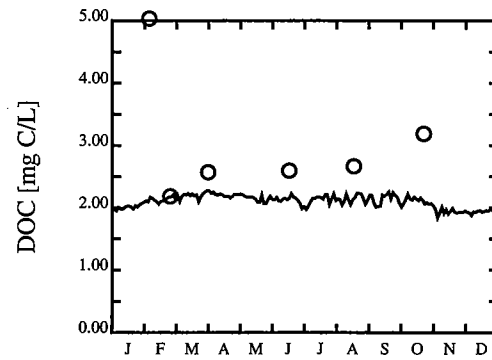
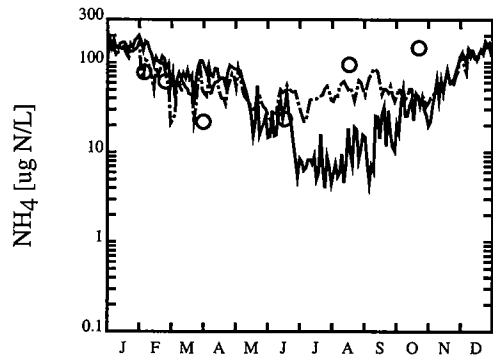
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev Surface Model
 - Bottom Model

1999 Temporal Calibration Results for Grid Cell (20,54) Vs Data Station F23P



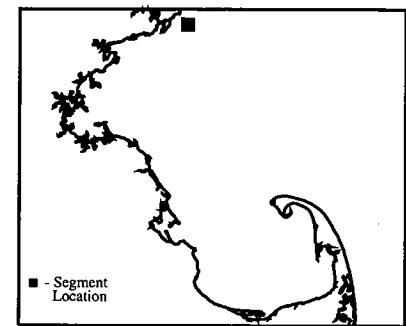
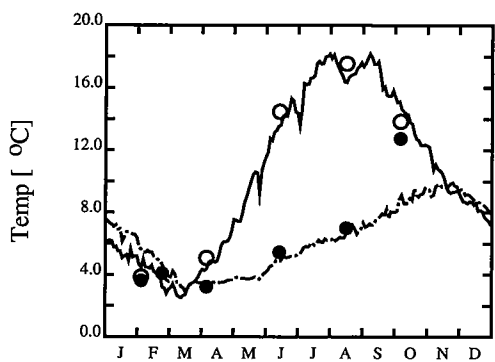
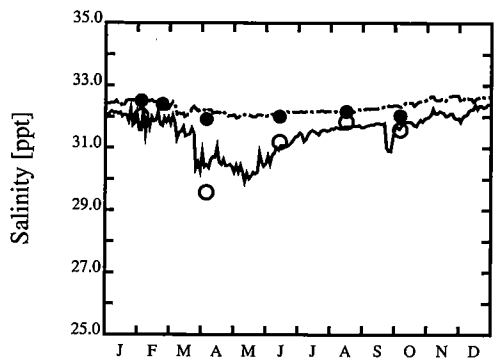
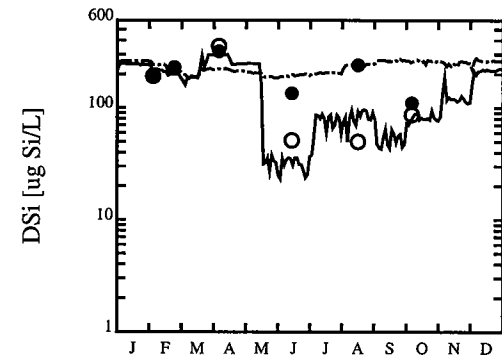
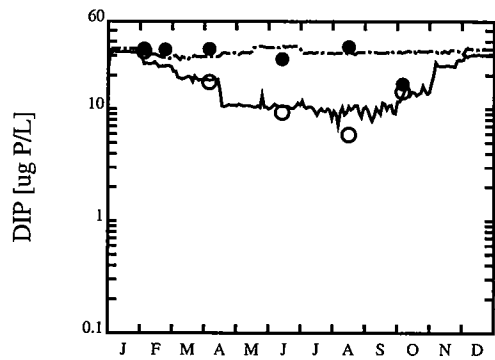
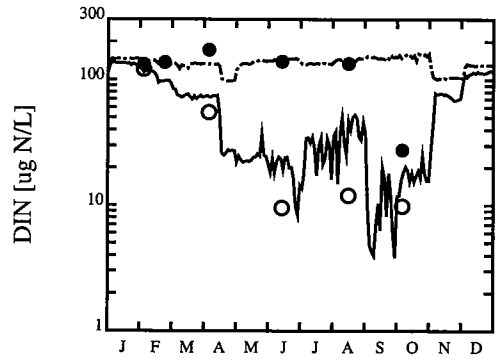
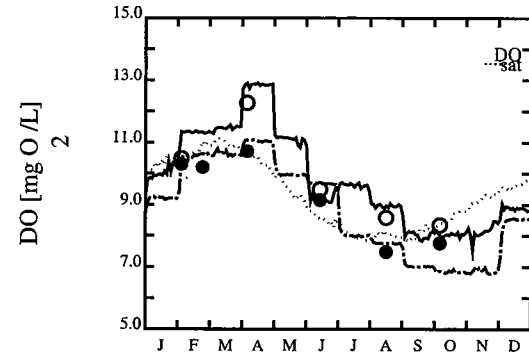
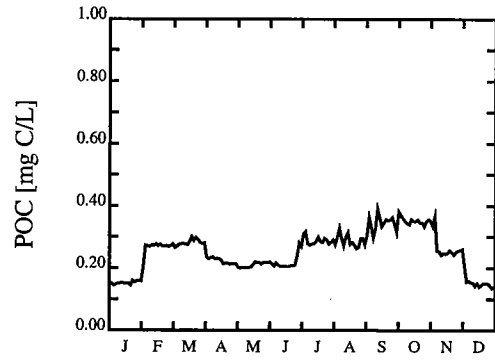
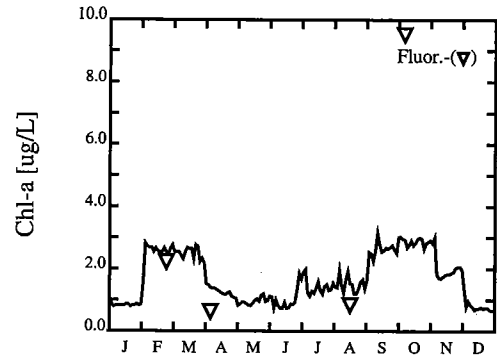
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 — sid dev Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for
 Grid Cell (20,54) Vs Data Station F23P



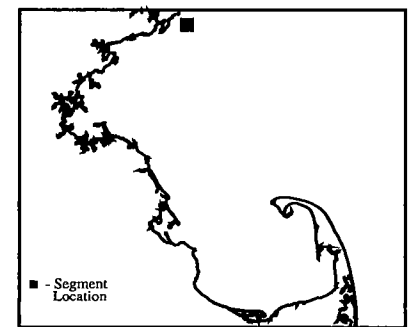
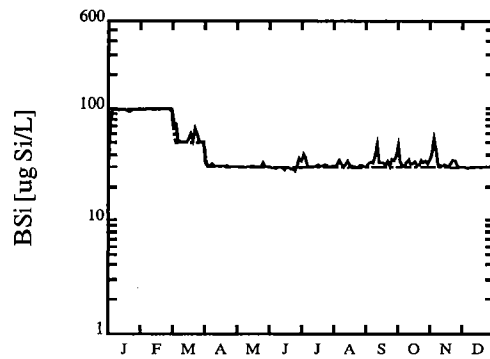
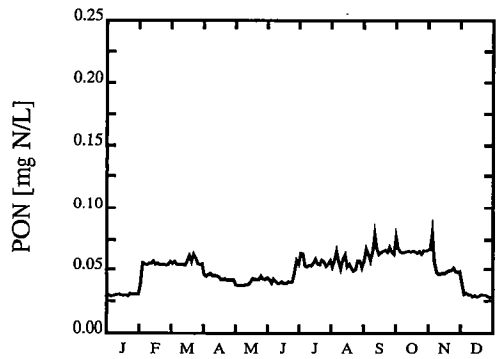
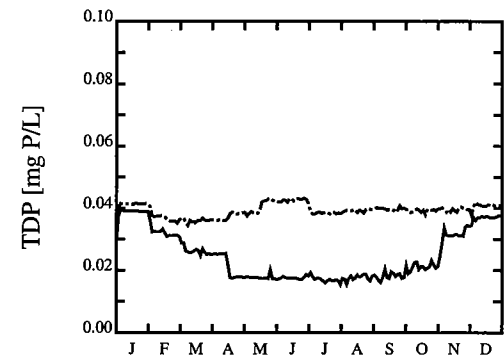
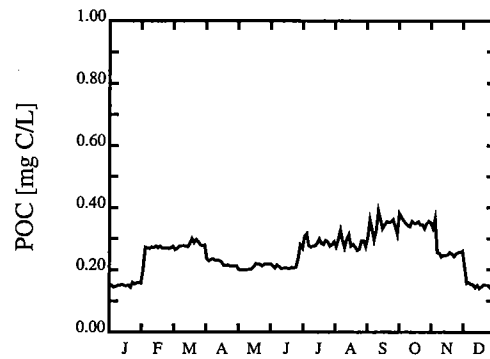
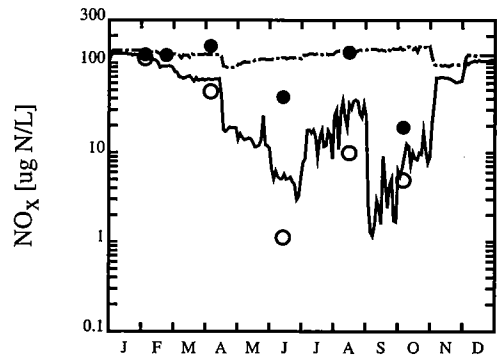
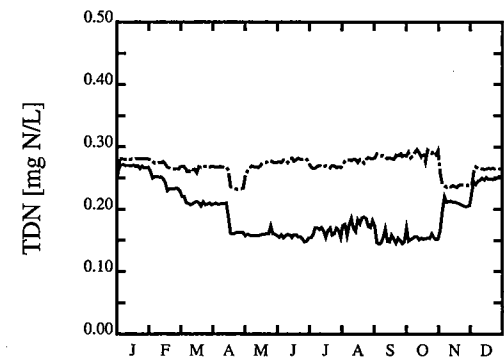
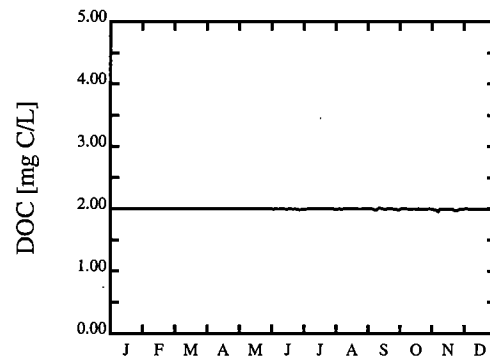
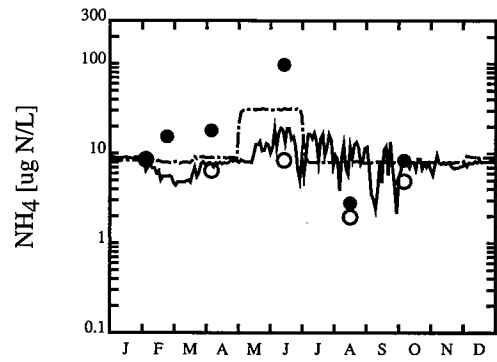
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev- Surface Model
 - Bottom Model

1999 Temporal Calibration Results for Grid Cell (21,49) Vs Data Station F25



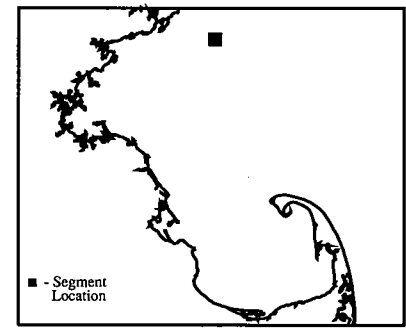
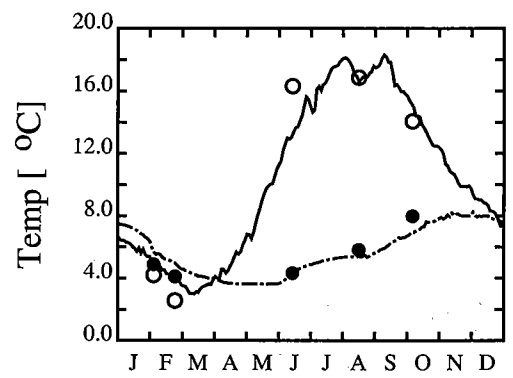
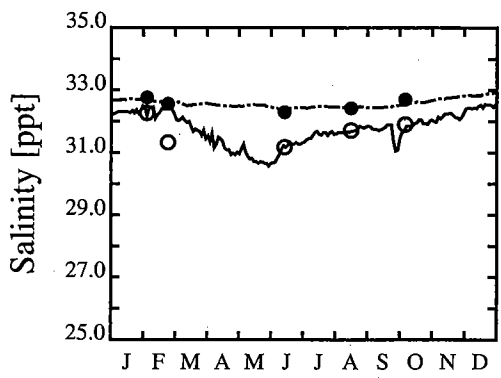
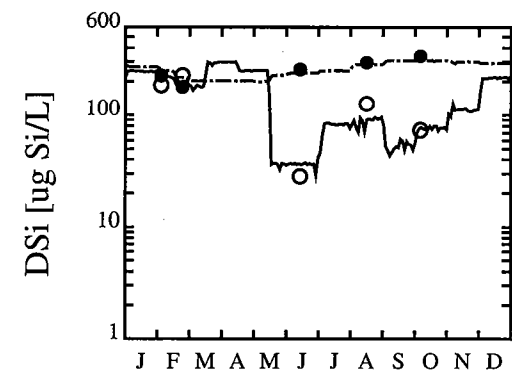
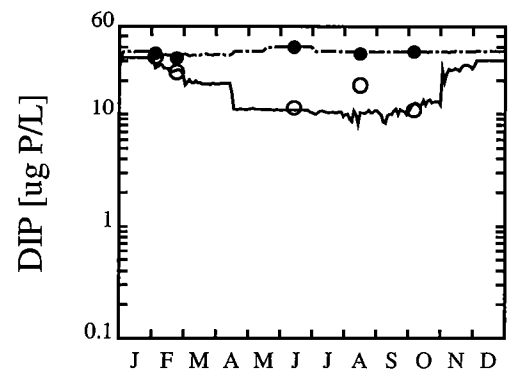
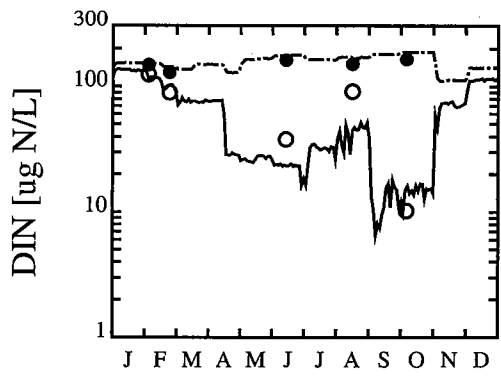
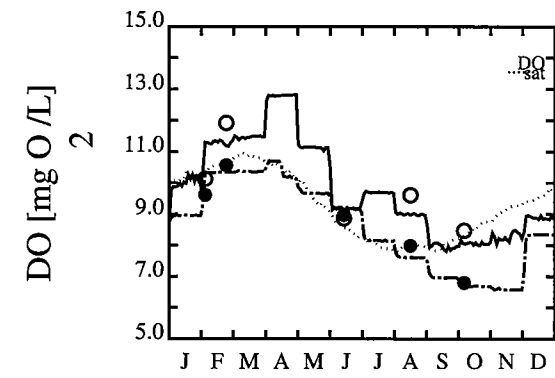
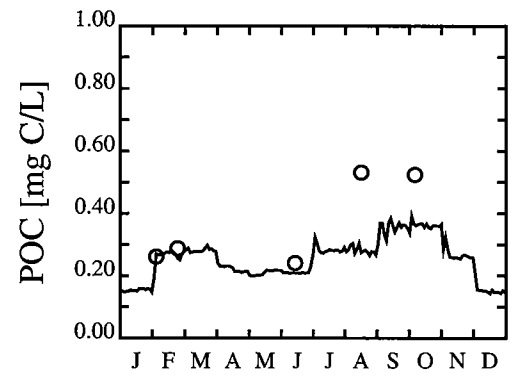
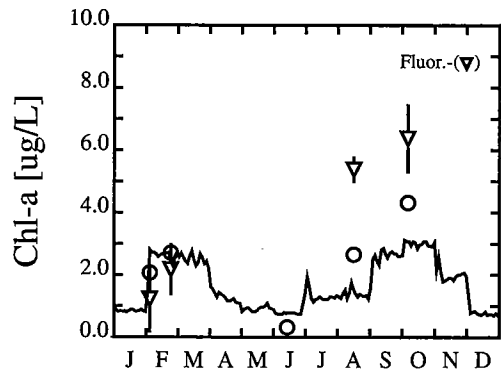
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev- Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (51,47) Vs Data Station F26



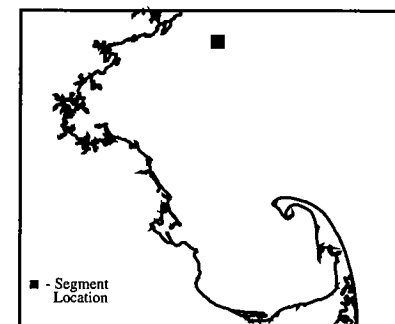
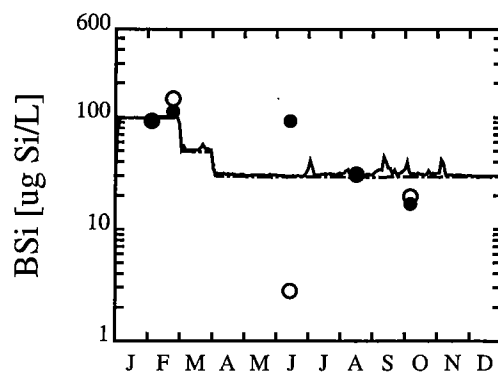
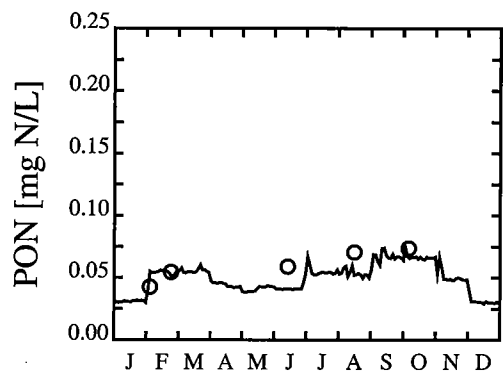
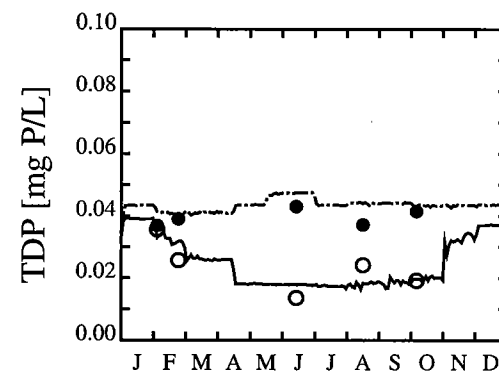
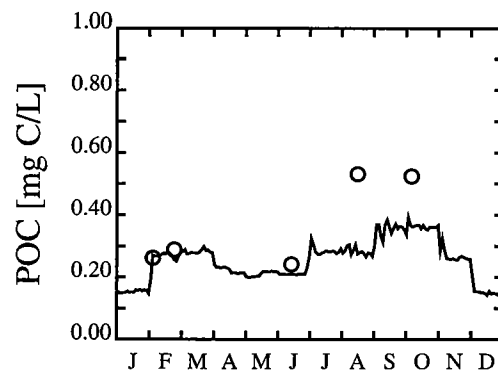
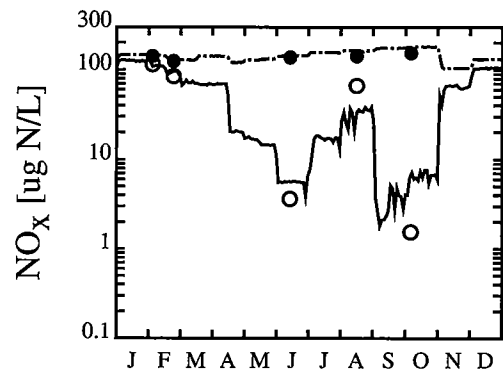
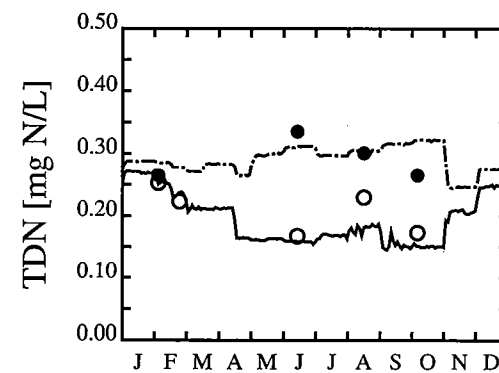
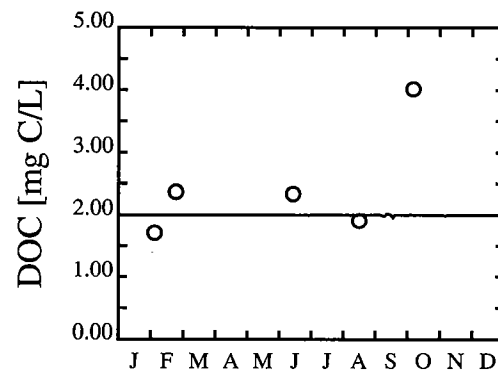
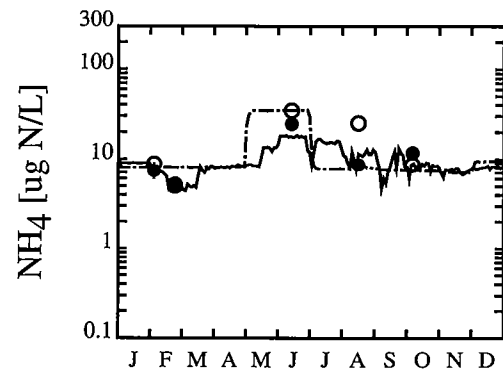
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 — std dev Surface Model
 - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (51,47) Vs Data Station F26



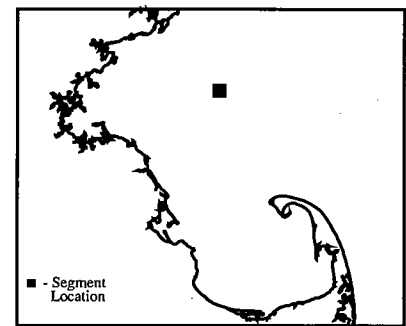
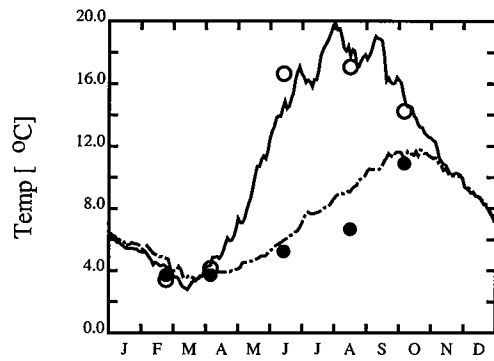
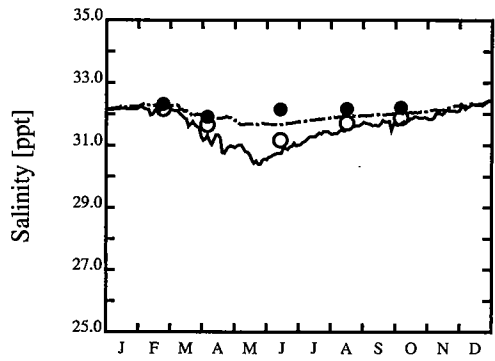
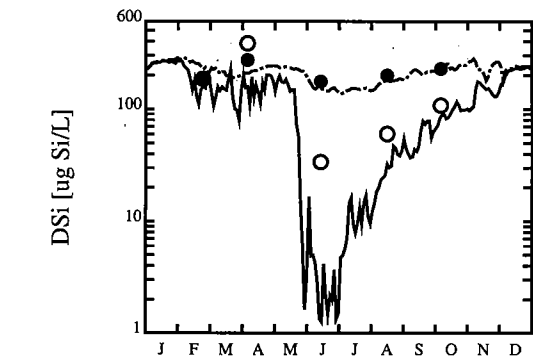
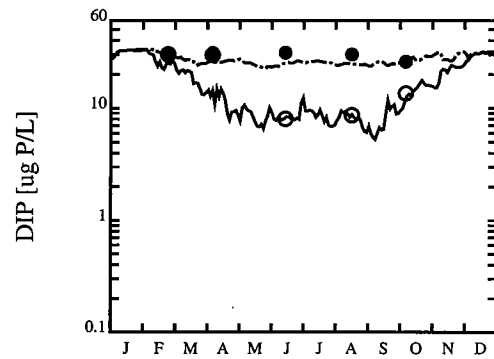
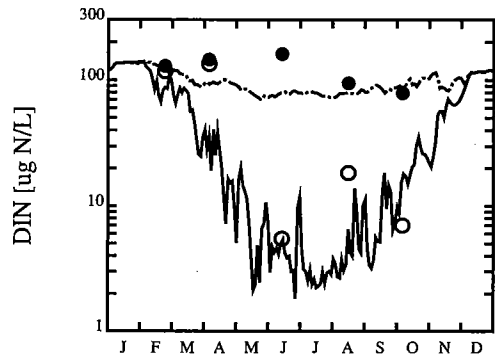
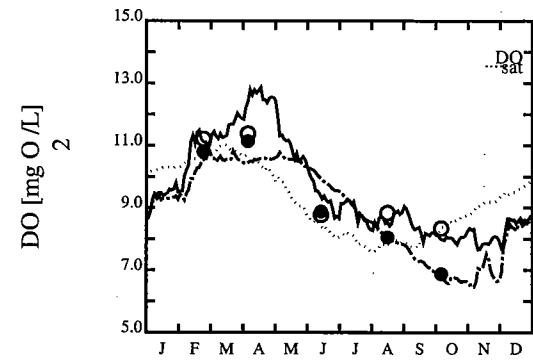
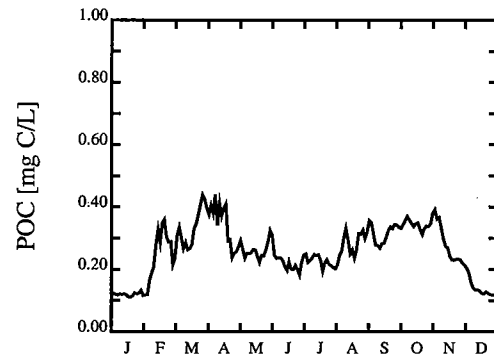
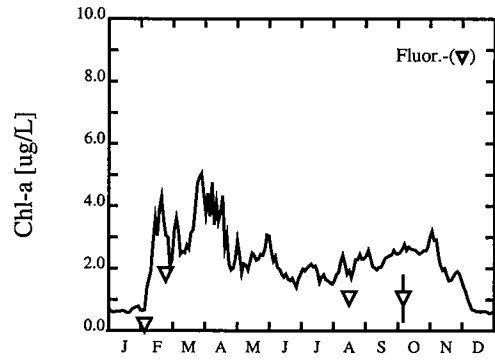
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 -std dev- Surface Model
 - Bottom Model

1999 Temporal Calibration Results for Grid Cell (52,42) Vs Data Station F27



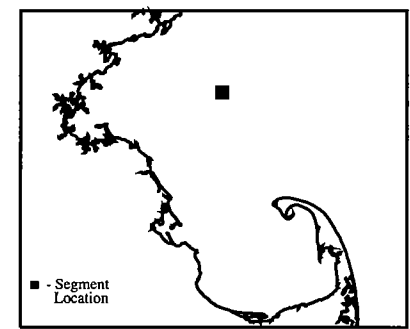
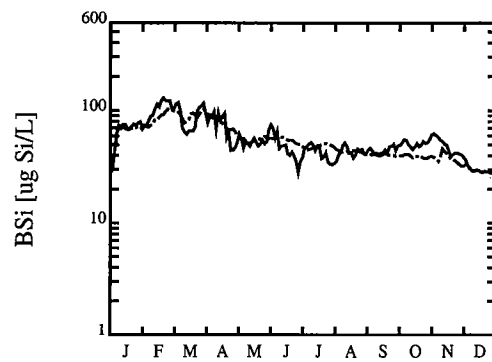
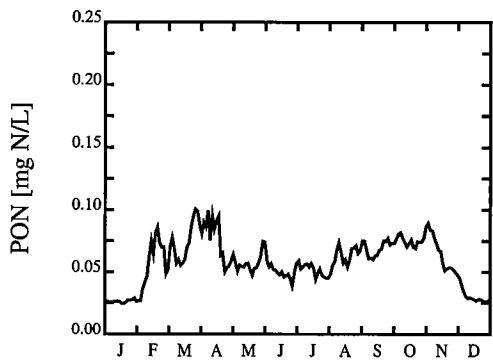
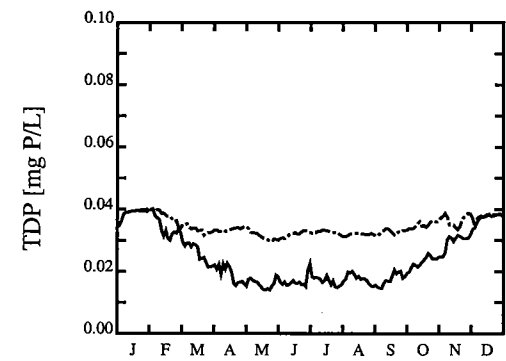
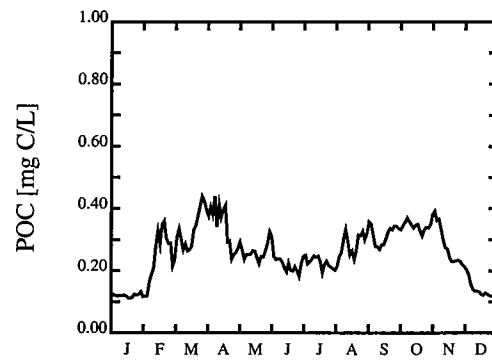
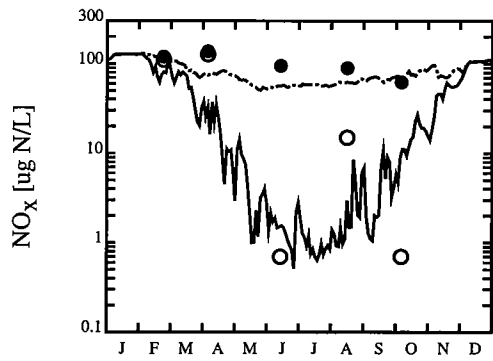
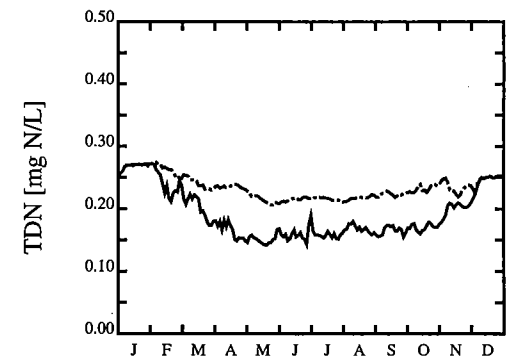
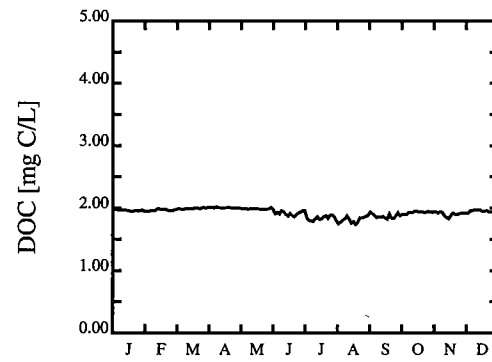
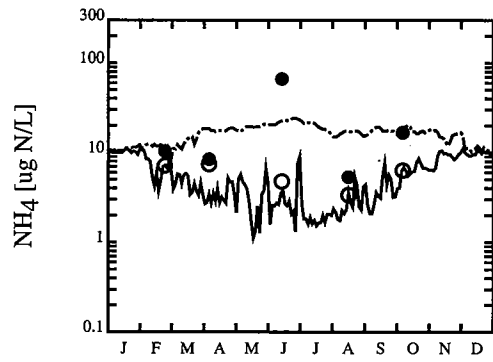
LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 — sid dev Surface Model
 - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (52,42) Vs Data Station F27



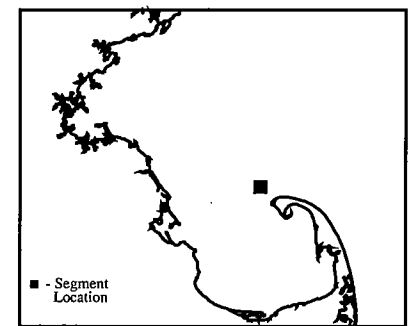
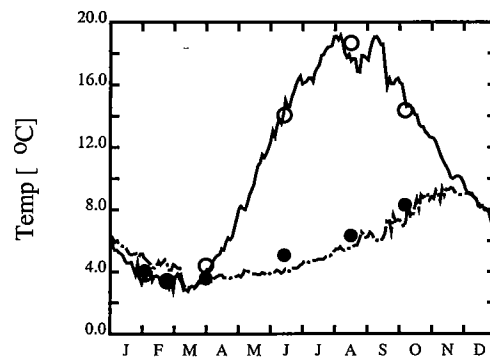
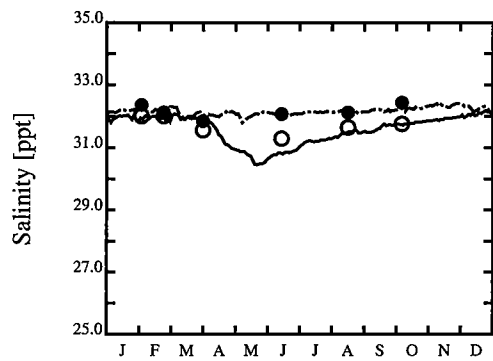
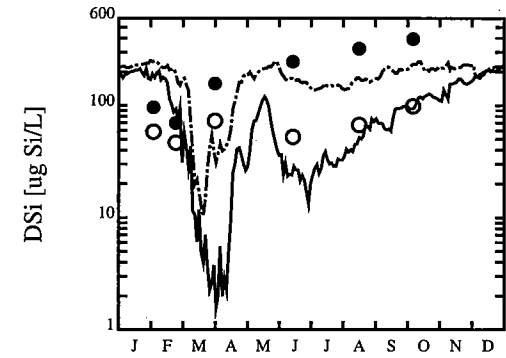
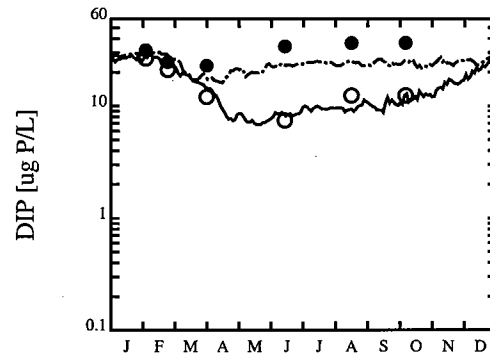
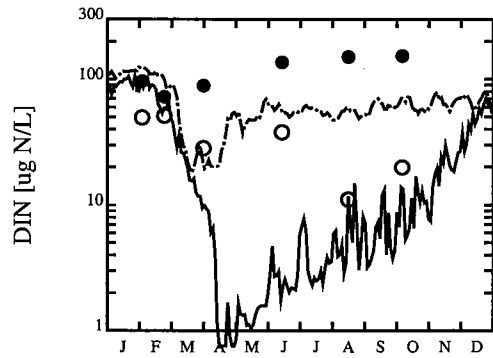
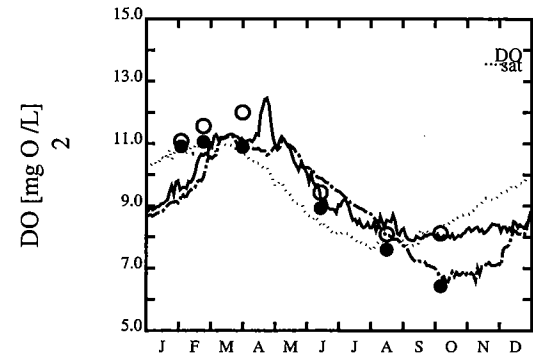
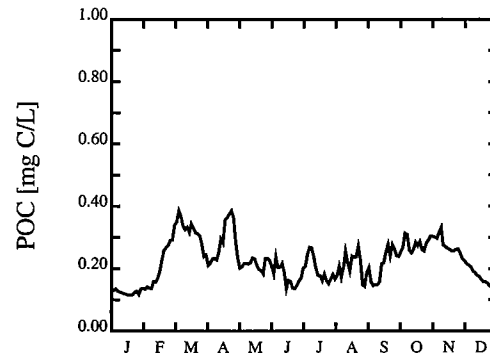
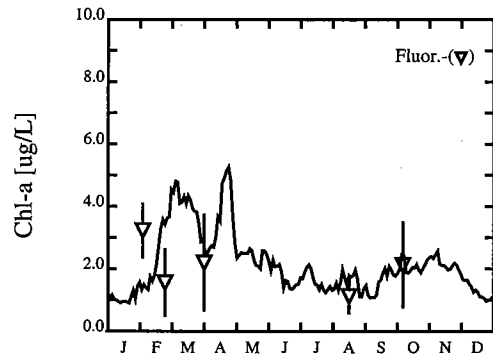
- LEGEND -----
- +/- Surface Data
 - Bottom Data
 - sid.dey Surface Model
 - Bottom Model

1999 Temporal Calibration Results for Grid Cell (46,36) Vs Data Station F28



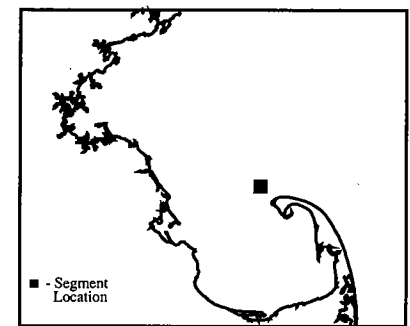
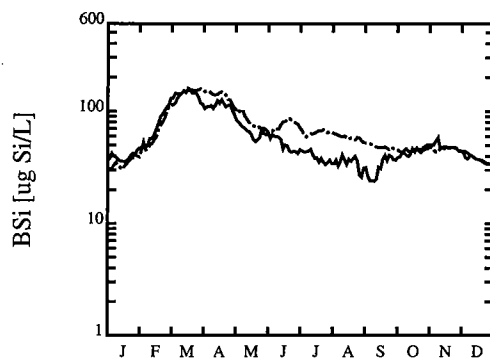
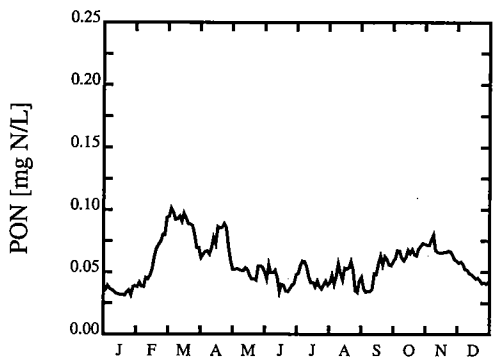
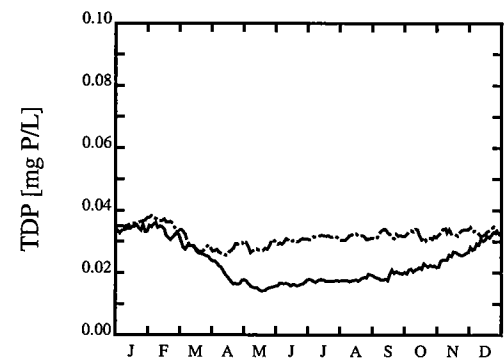
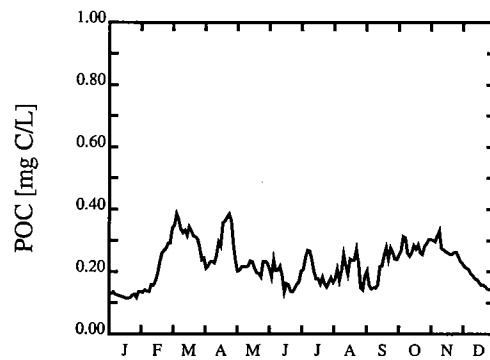
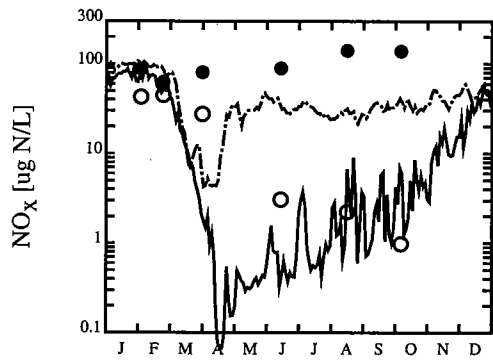
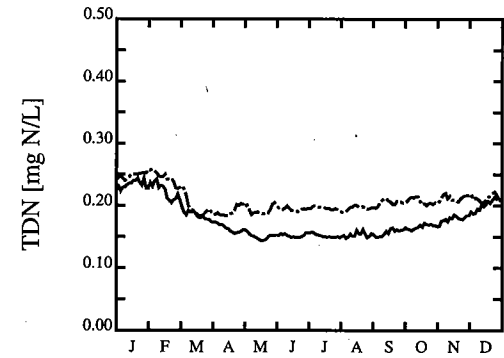
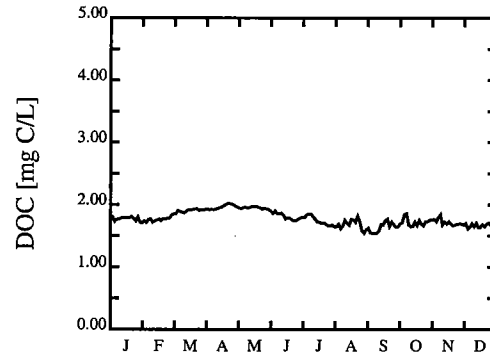
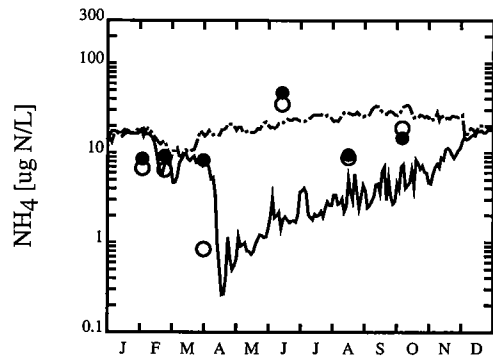
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 — sid dev Surface Model
 - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (46,36) Vs Data Station F28



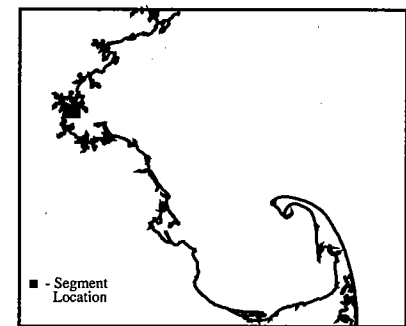
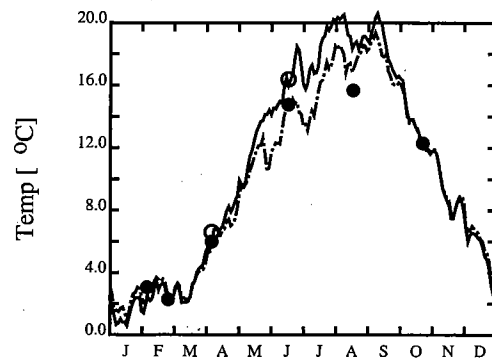
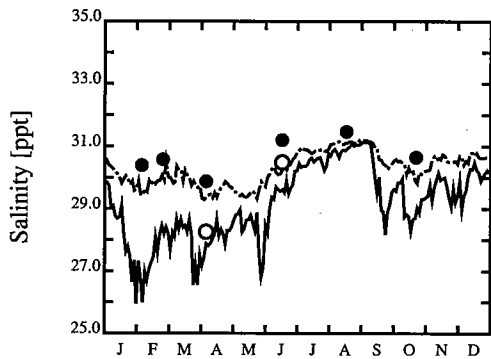
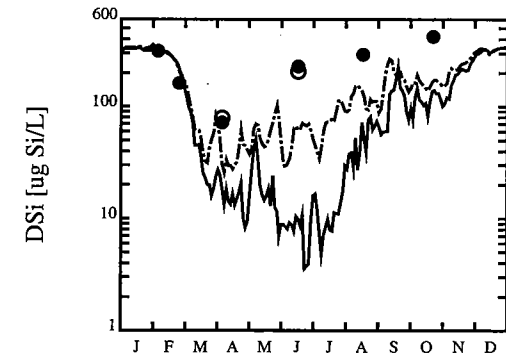
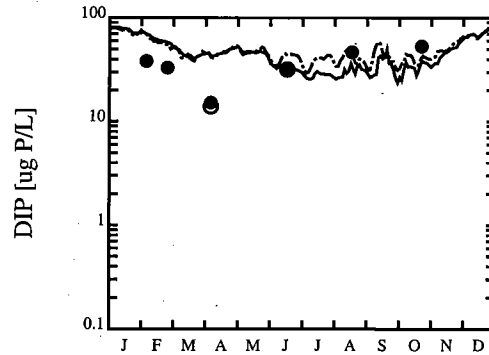
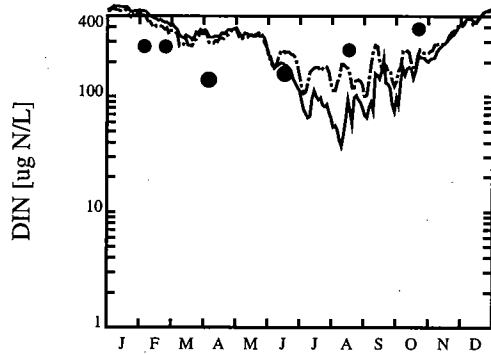
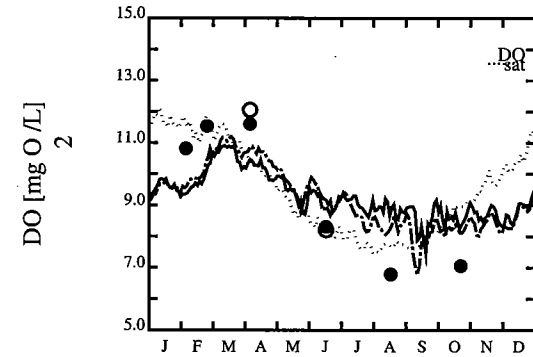
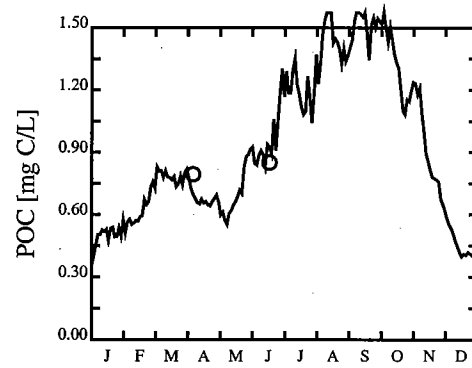
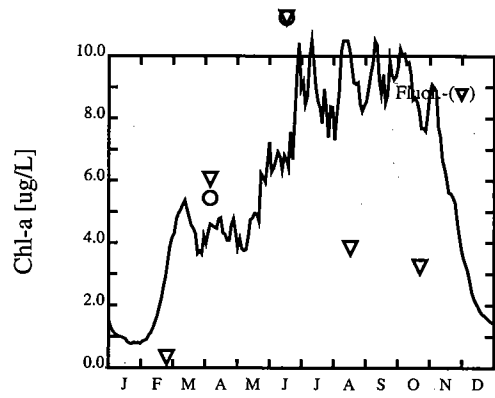
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 ---std.dev Surface Model
 - - - - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (41,21) Vs Data Station F29



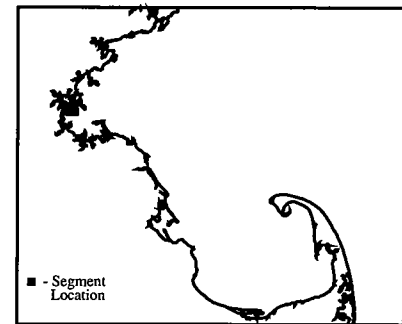
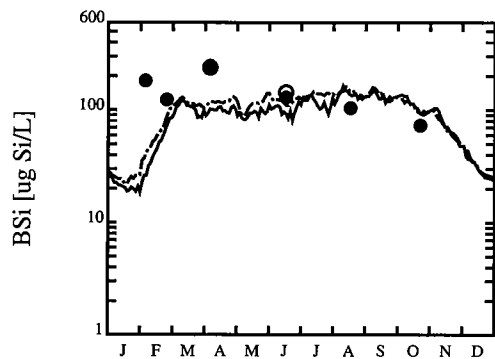
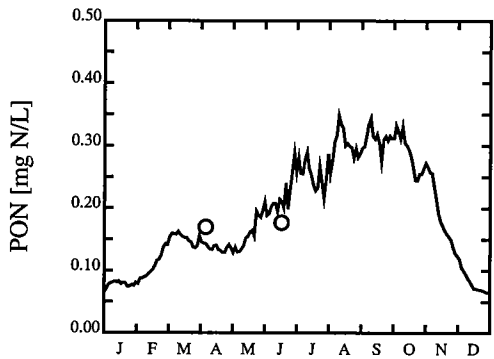
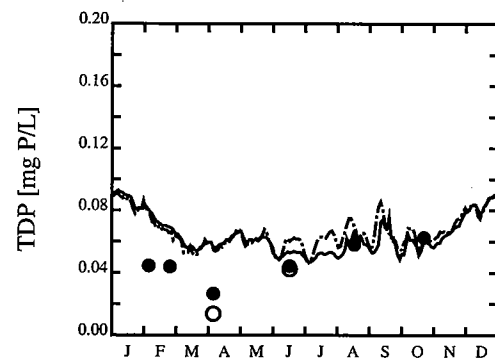
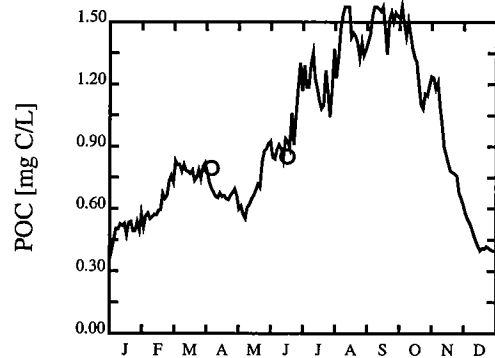
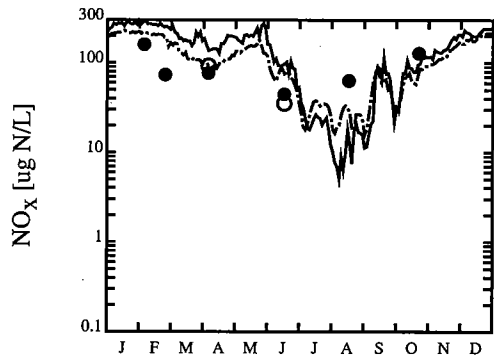
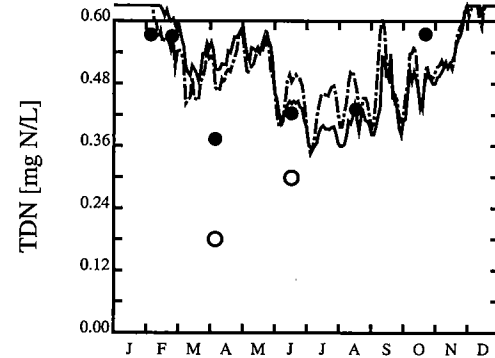
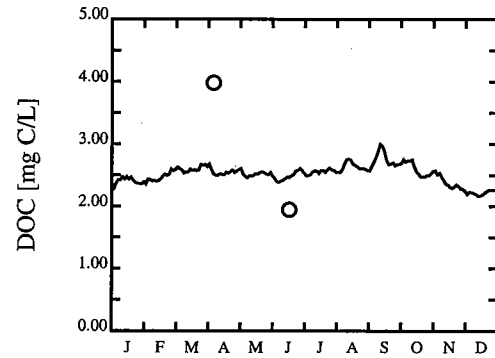
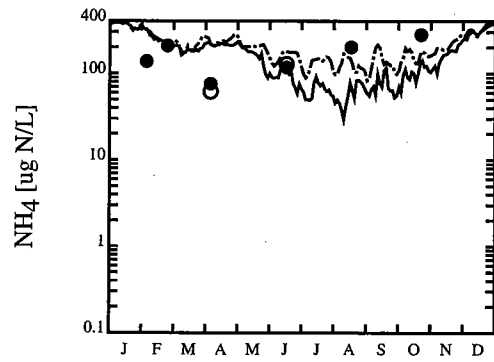
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 ———— std.dev. Surface Model
 - - - - Bottom Model

1999 Temporal Calibration Results for
 Grid Cell (41,21) Vs Data Station F29



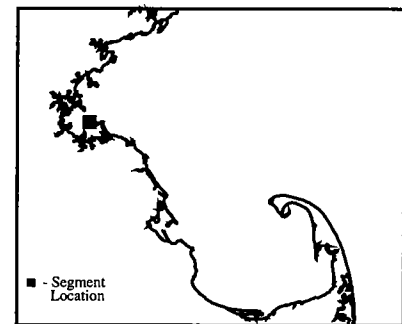
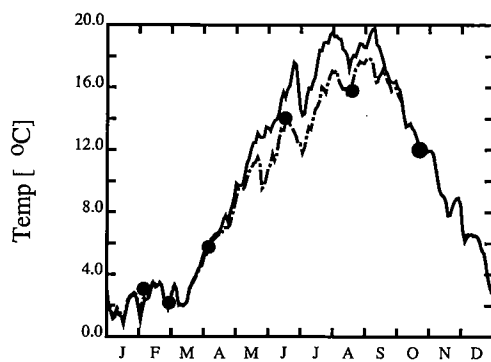
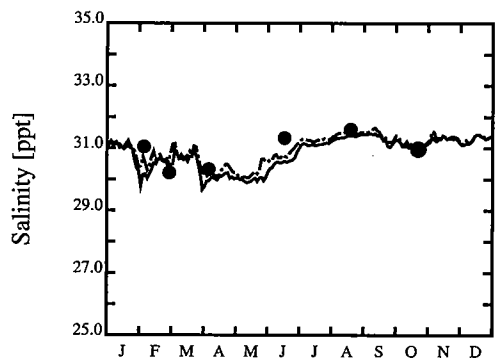
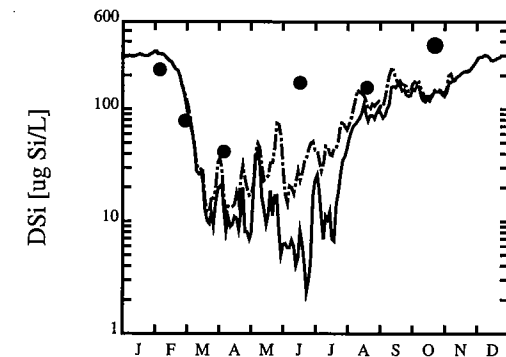
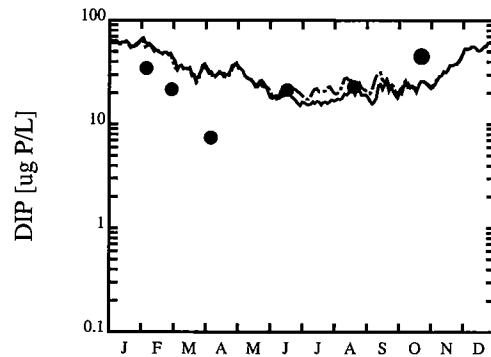
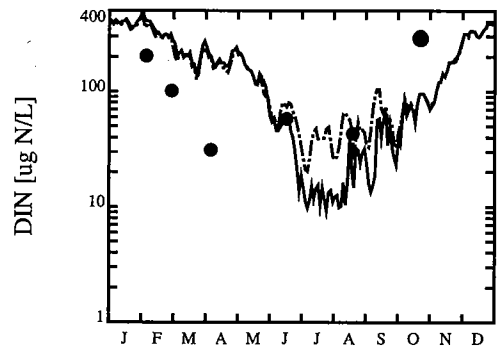
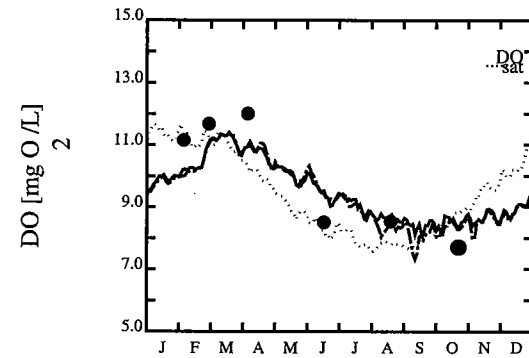
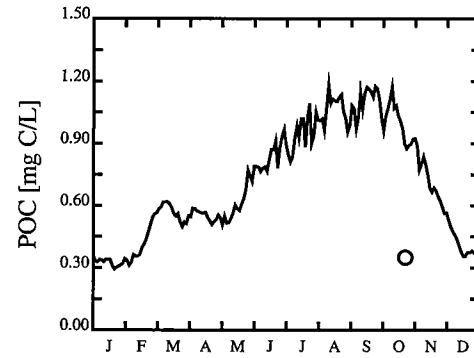
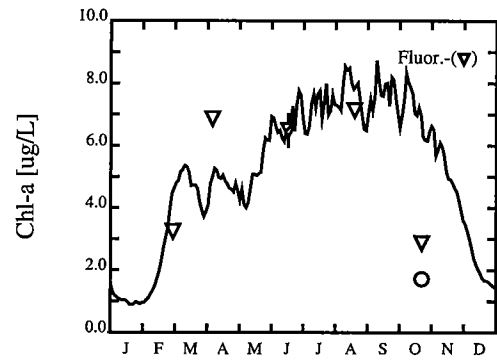
----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - std dev Surface Model
 ——— Bottom Model

1999 Temporal Calibration Results for Grid Cell (18,59) Vs Data Station F30



----- LEGEND -----
 ○ +/- Surface Data
 ● Bottom Data
 - - - - - std.dev. Surface Model
 - - - - - Bottom Model

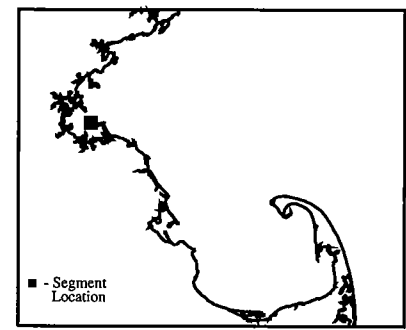
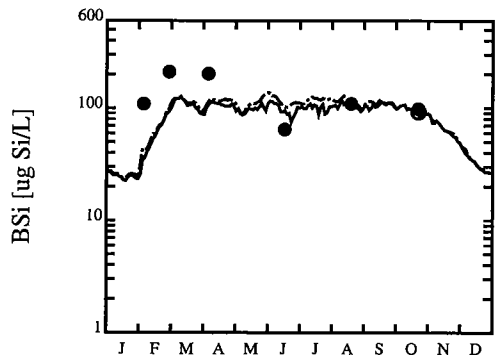
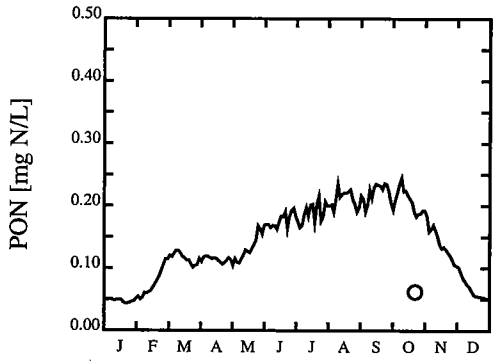
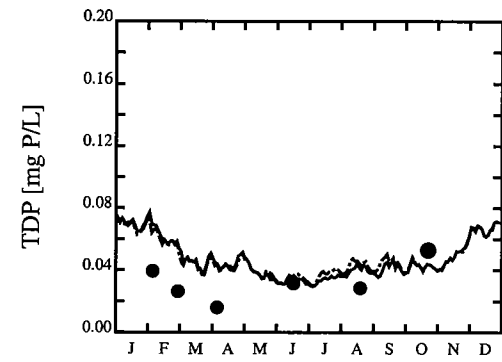
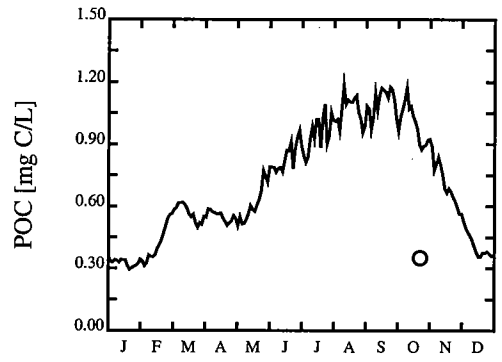
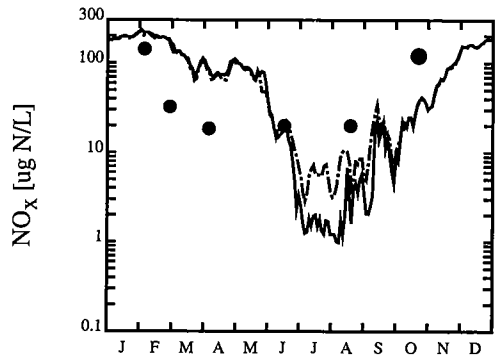
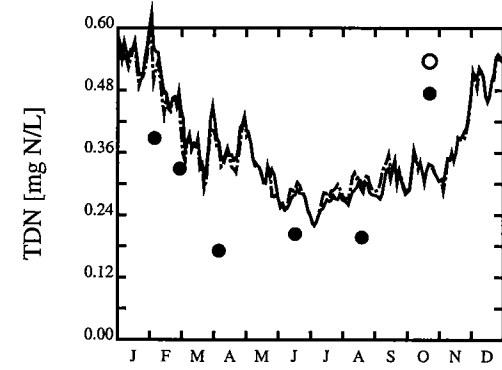
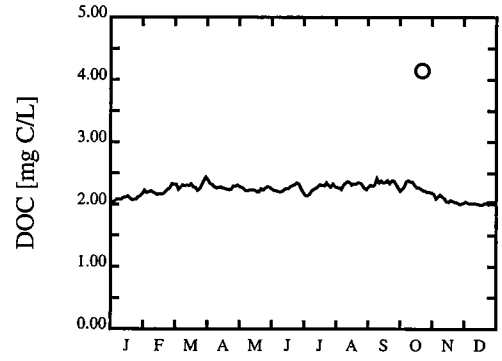
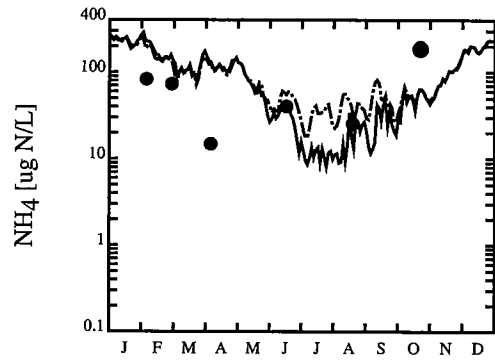
1999 Temporal Calibration Results for Grid Cell (18,59) Vs Data Station F30



LEGEND

- +/- Surface Data
- Bottom Data
- std.dev. Surface Model
- - - Bottom Model

1999 Temporal Calibration Results for Grid Cell (17,52) Vs Data Station F31



LEGEND
 ○ +/- Surface Data
 ● Bottom Data
 -std.dev- Surface Model
 - Bottom Model

1999 Temporal Calibration Results for Grid Cell (17,52) Vs Data Station F31



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