Boundary sensitivity for the Bays Eutrophication Model (BEM)

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SECTION 1

INTRODUCTION

During the past several years, modeling analyses of Massachusetts and Cape Cod Bays have shown that the Gulf of Maine has a major influence on the water quality conditions within the bays (HydroQual, 1995; HydroQual, 1999). A mass balance analysis of the bays indicated that more than 90 percent of the total nitrogen that enters the bays, enters from the Gulf of Maine at the northern boundary of Massachusetts Bay near Cape Ann (HydroQual, 1999). Modeling analyses also show that the boundary conditions assigned to the water quality model greatly influence the model results. Therefore, it is very important that the model boundary conditions are accurately defined. Unfortunately, limited data availability makes it difficult to assign boundary conditions on a temporal and spatial basis. Recognizing this, the Model Evaluation Group (MEG) for the Bays Eutrophication Model (BEM) recommended that boundary sensitivity analyses be conducted to determine how sensitive the water quality model is to changes in the boundary conditions. Based on the recommendations made by the MEG, the Massachusetts Water Resources Authority (MWRA) funded a series of model sensitivities to determine the water quality model's response to changes to the boundary conditions. This letter report provides the results of these sensitivity analyses. Two constituents were identified for sensitivity analysis, dissolved oxygen (DO) and dissolved inorganic nitrogen (DIN) (the sum of nitrate, nitrite and ammonium nitrogen). Dissolved oxygen was identified because it is a critical parameter for aquatic organisms and sometimes falls below the Massachusetts state standard of 6.0 mg/L and 75 percent DO saturation. DIN was identified because nitrogen is an important nutrient for phytoplankton growth, and nitrogen tends to be the limiting nutrient in Massachusetts and Cape Cod Bays.

SECTION 2

BOUNDARY CONDITION SETUP

2.1 DISSOLVED OXYGEN

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. Figure 2-1 presents the study area. In the far field, there are two stations, F26 and F27 (established in 1994), close enough to the water quality model boundary to provide insight into the water quality entering the bays from 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. Using the data that are available, boundary conditions are 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. In this sensitivity analysis, an effort was made to determine if there is a better way to assign DO at the boundary in light of the fact that more data have been collected near the boundary since the initial model calibration.

Since the near field area is sampled more often than the far field, it was hoped that a relationship could be found between the near field data and the data collected at stations F26 and F27, so that boundary conditions could be prescribed for periods when there are no data at stations F26 and F27. Initially, a relationship between the average percent saturation at the near field stations and at stations F26 and F27 (referred to here as far field stations) was sought. Data sampled from specific depths were averaged for each of the standard levels. Level 1 was assigned data sampled from depths of 0-10 meters, level 2 was assigned data from 10-30 meters, level 3 was assigned data from 50-70 meters, and level 4 was assigned data sampled at depths greater than 70 meters. Figures 2-2 and 2-3 present a comparison of the monthly average percent saturation data for the years 1994 to 1999 at all of the near field and F26 and F27 stations at the four standard levels assigned at the boundary. Data are plotted at the beginning of the month in which they were sampled. The error bars represent the range of the values used to compile the average. Figure 2-2 shows that, at the top two standard levels, the percent saturation is similar between the near field stations and F26 and F27. During the colder months the DO levels are at or below saturation, and during the warmer months the data are generally above DO saturation. Figure 2-3, shows that at standard level three, the data at the near field and far

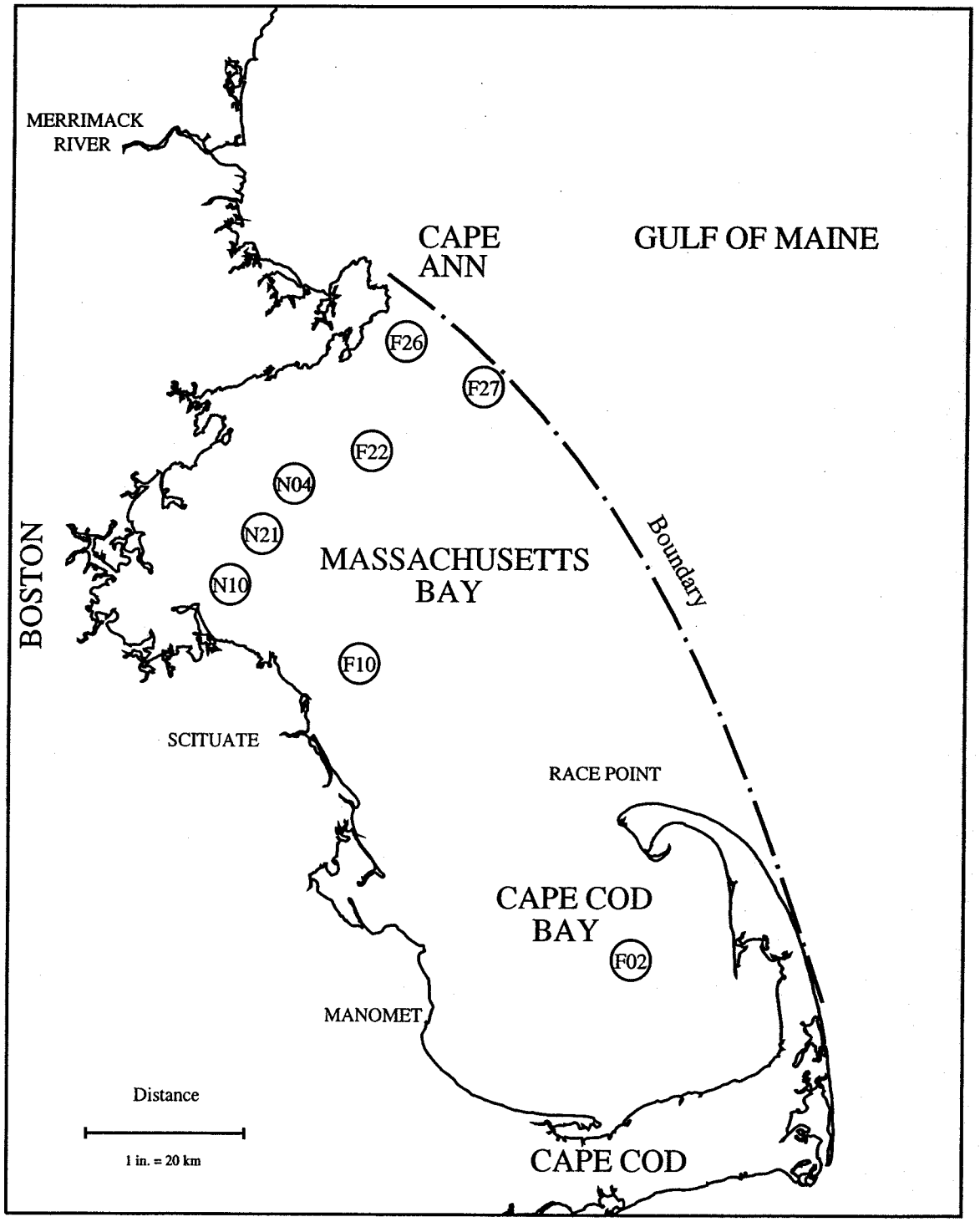

Figure 2-1. Study Area.

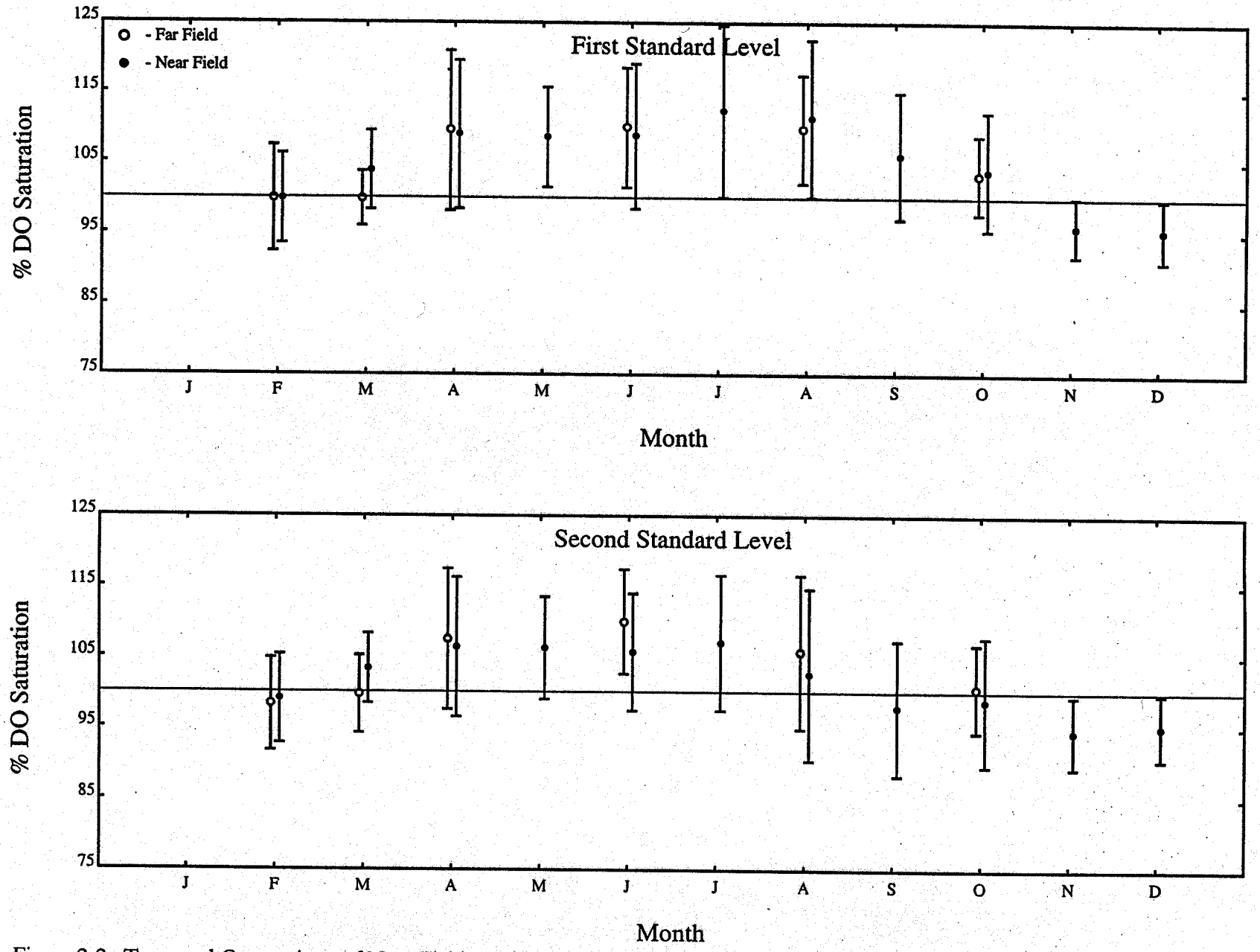

Figure 2-2. Temporal Comparison of Near Field and Far Field Monthly Average Percent DO Saturation at Standard Levels 1 and 2.

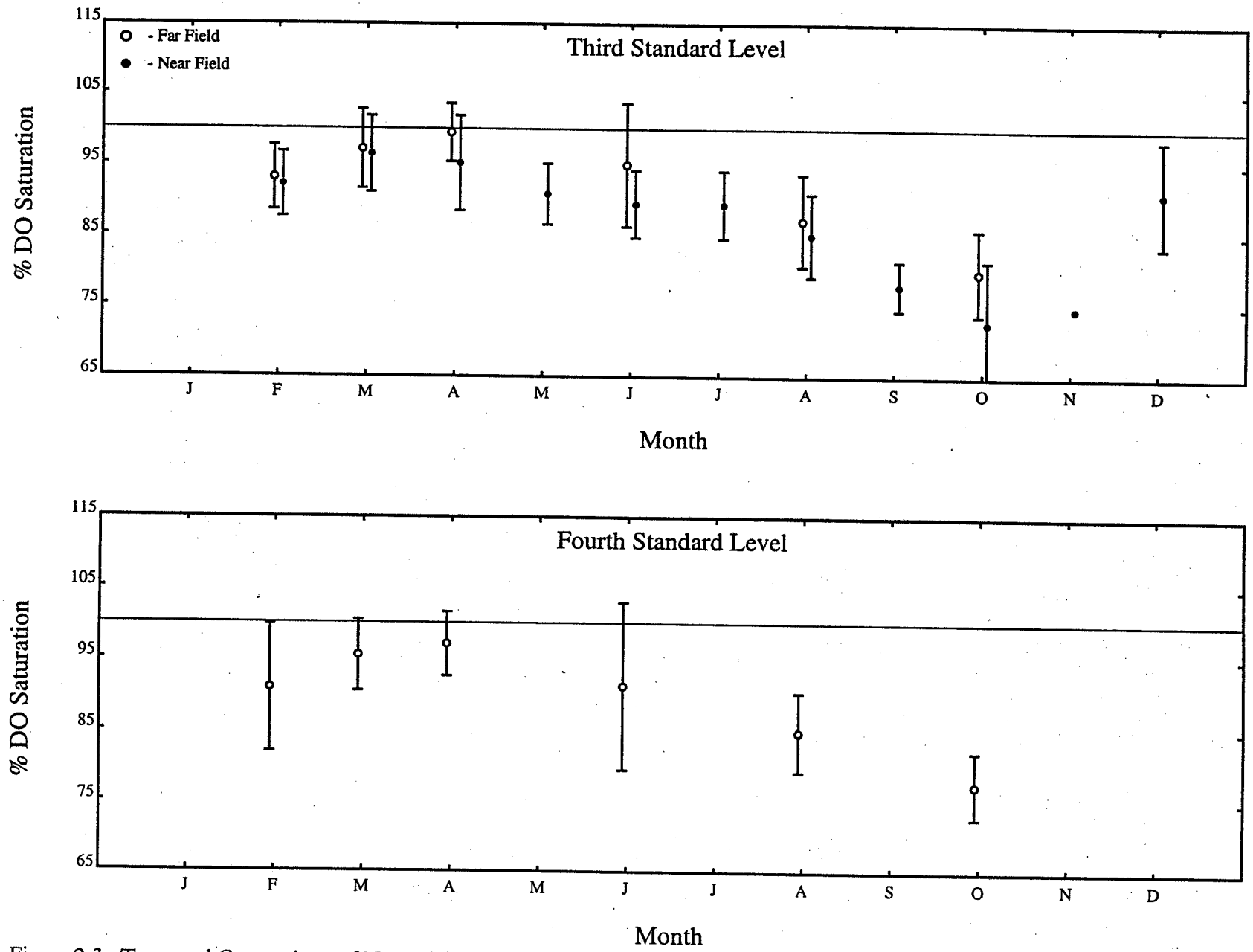

Figure 2-3. Temporal Comparison of Near Field and Far Field Monthly Average Percent DO Saturation at Standard Levels 3 and 4.

field are similar in the early portion of the year, but the near field tends to have a lower percent DO saturation later in the year. Also, the dissolved oxygen levels tend to be below saturation at this depth. Only four stations (No. 4, No. 5, No. 6, and No. 7) were deep enough to be included in the standard level 3 average. The near field area is not deep enough to compare to the boundary data at the fourth standard level. Later, a relationship between standard levels three and four will be presented.

Since the comparison of percent saturation looked promising the analysis moved forward with a comparison of the DO saturation concentration (i.e. the concentration of DO at 100% saturation) itself calculated from the temperature and salinity data. Figures 2-4 and 2-5 present the DO saturation concentrations, computed from ambient temperature and salinity, on a monthly average basis for the near field stations and stations F26 and F27. These figures show that the concentrations of DO saturation are generally within a few tenths of a milligram per liter of each other. Based on Figures 2-2 through 2-5 it would be expected that the DO concentrations in the near field and at stations F26 and F27 are very similar and Figures 2-6 and 2-7 show that this is the case. Based on this screening analysis it was hypothesized that near field DO and DO saturation concentrations would be a good indicator as to the DO boundary conditions.

The first attempt at developing a relationship between the average DO of near field stations and the DO boundary conditions was the development of probability figures. Figure 2-8 presents the ratio of near field to F26 and F27 monthly average percent DO saturation. This figure shows that at the surface the percent saturation is similar at the two locations with a median of the ratio near 1.0 and a maximum difference around two to four percent. At the second standard level the variation is larger and the median is near 1.015. At standard level three there is a clear indication that stations F26 and F27 have a higher percent saturation than the near field stations with the median of the ratios near 1.03. A comparison of the percent saturation between levels 3 and 4 at stations F26 and F27 is presented in the lower right corner. This figure shows that ratio of the fourth level to the third level ranges between about 0.96 and 0.98.

Figure 2-9 presents probability figures for the ratio of monthly average DO saturation concentration between the near field stations and stations F26 and F27 (far field). This figure shows that on a monthly basis the DO saturation concentrations at these locations are generally within two percent of each other. The DO saturation values at stations F26 and F27 for standard levels three and four are very similar. The ratio for DO itself is presented in Figure 2-10. The results are what would be expected by combining the results of Figures 2-8 and 2-9.

Another method for determining the relationship between the near field stations and stations F26 and F27 is to plot the monthly average at one location against the monthly average at the

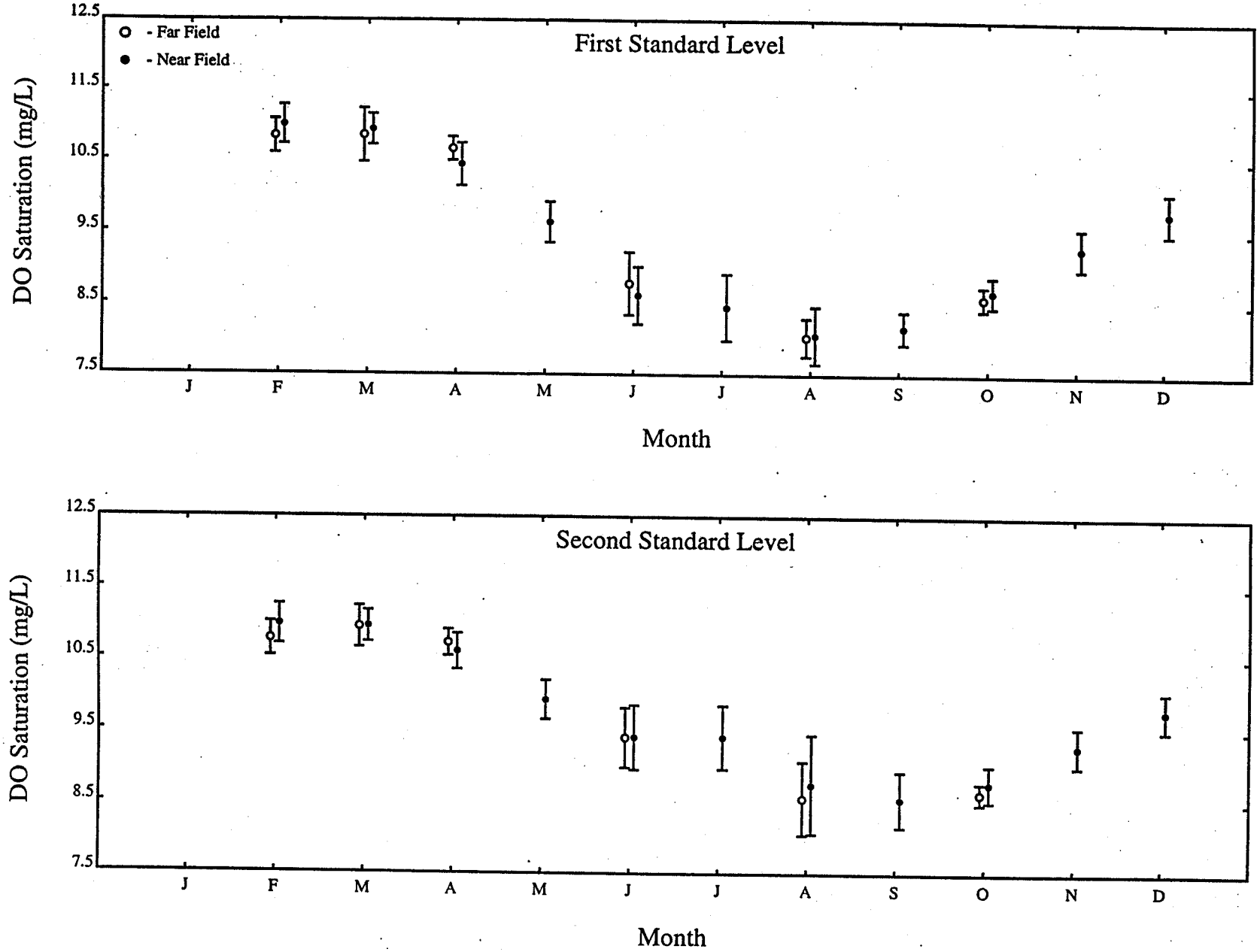

Figure 2-4. Temporal Comparison of Near Field and Far Field Monthly Average DO Saturation Concentrations at Standard Levels 1 and 2.

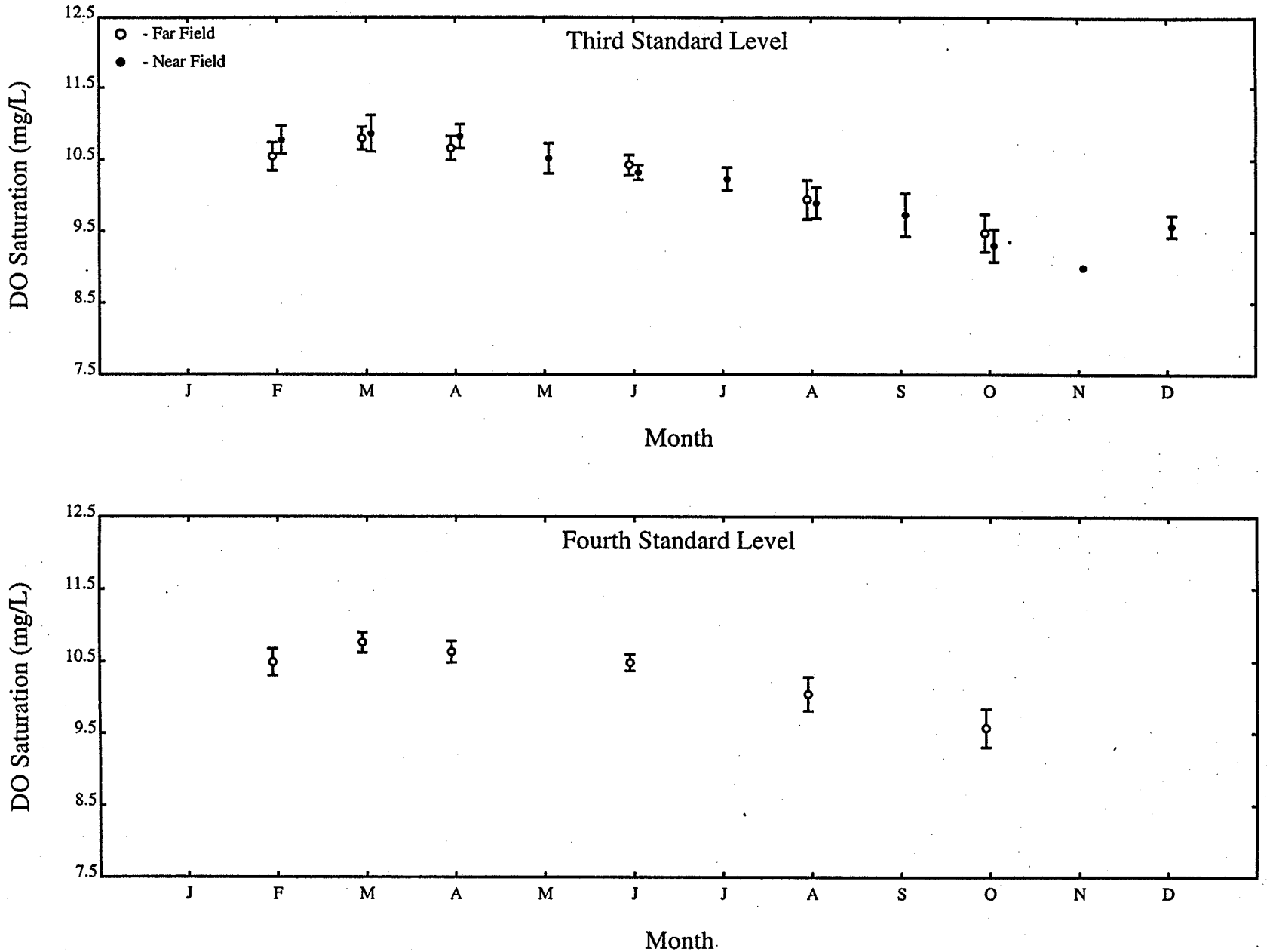

Figure 2-5. Temporal Comparison of Near Field and Far Field Monthly Average DO Saturation Concentrations at Standard Levels 3 and 4.

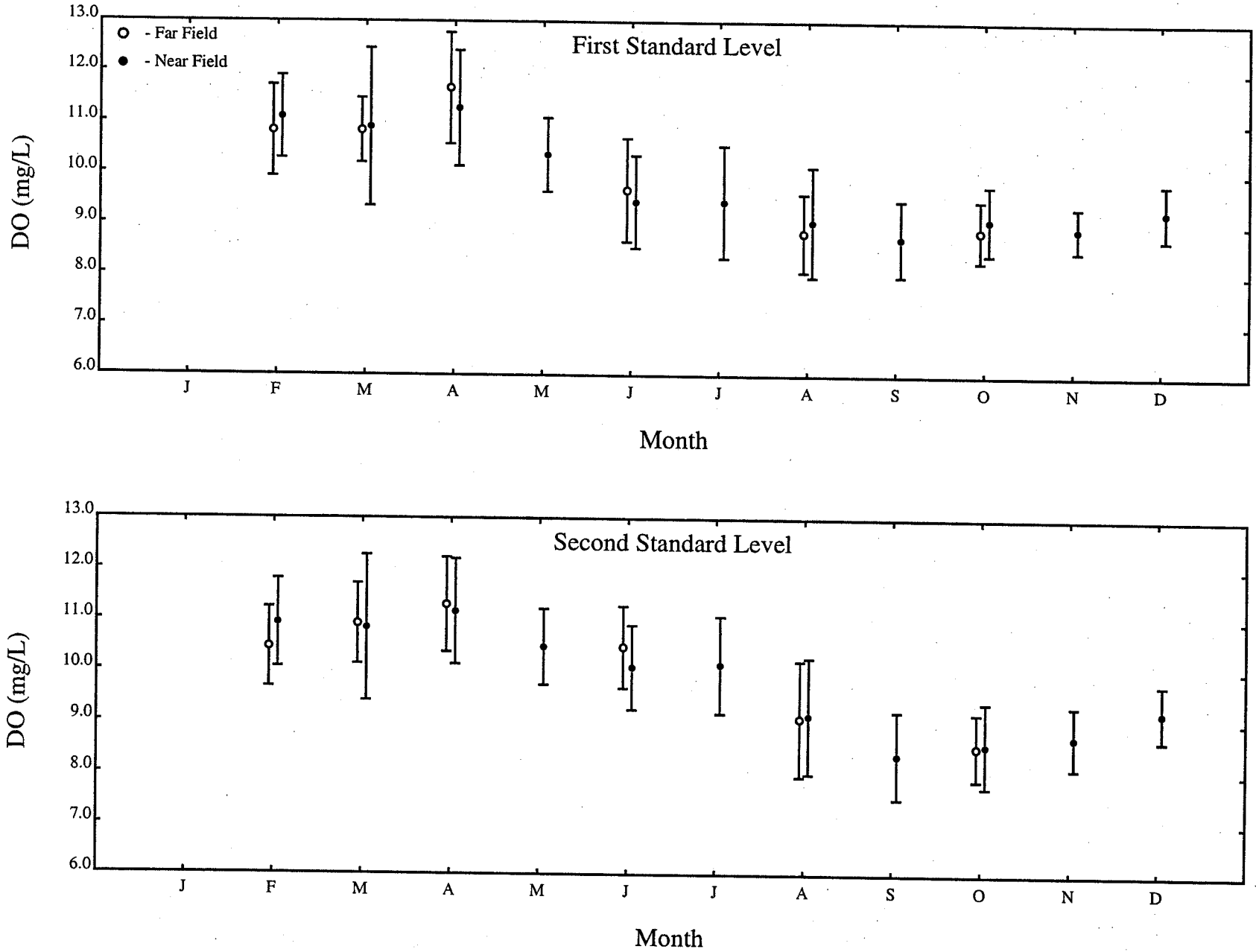

Figure 2-6. Temporal Comparison of Near Field and Far Field Monthly Average DO Concentrations at Standard Levels 1 and 2.

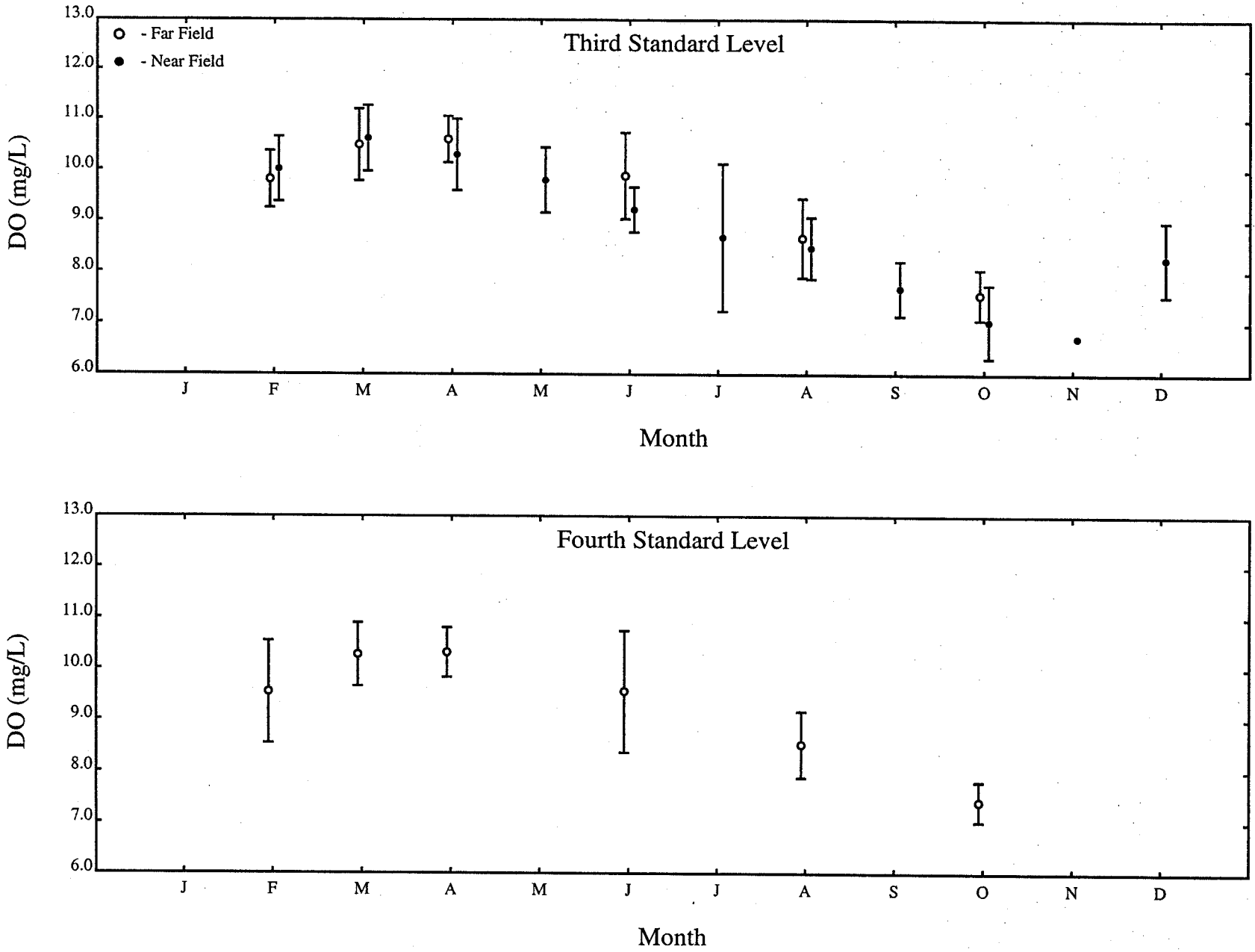

Figure 2-7. Temporal Comparison of Near Field and Far Field Monthly Average DO Concentrations at Standard Levels 3 and 4.

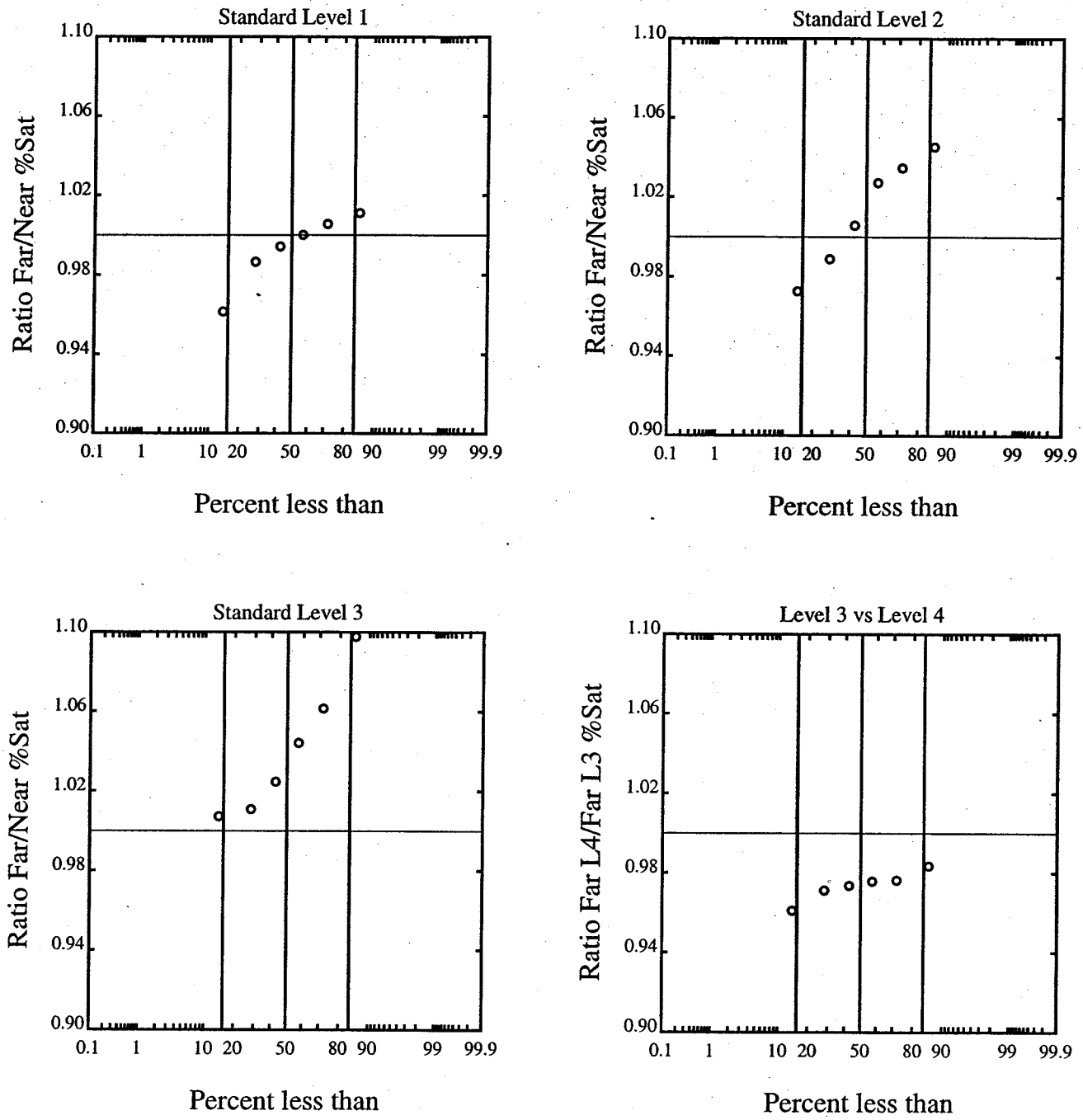

Figure 2-8. Probability Distribution of the Ratio of Near Field to Far Field Monthly Average Percent DO Saturation by Standard Level.

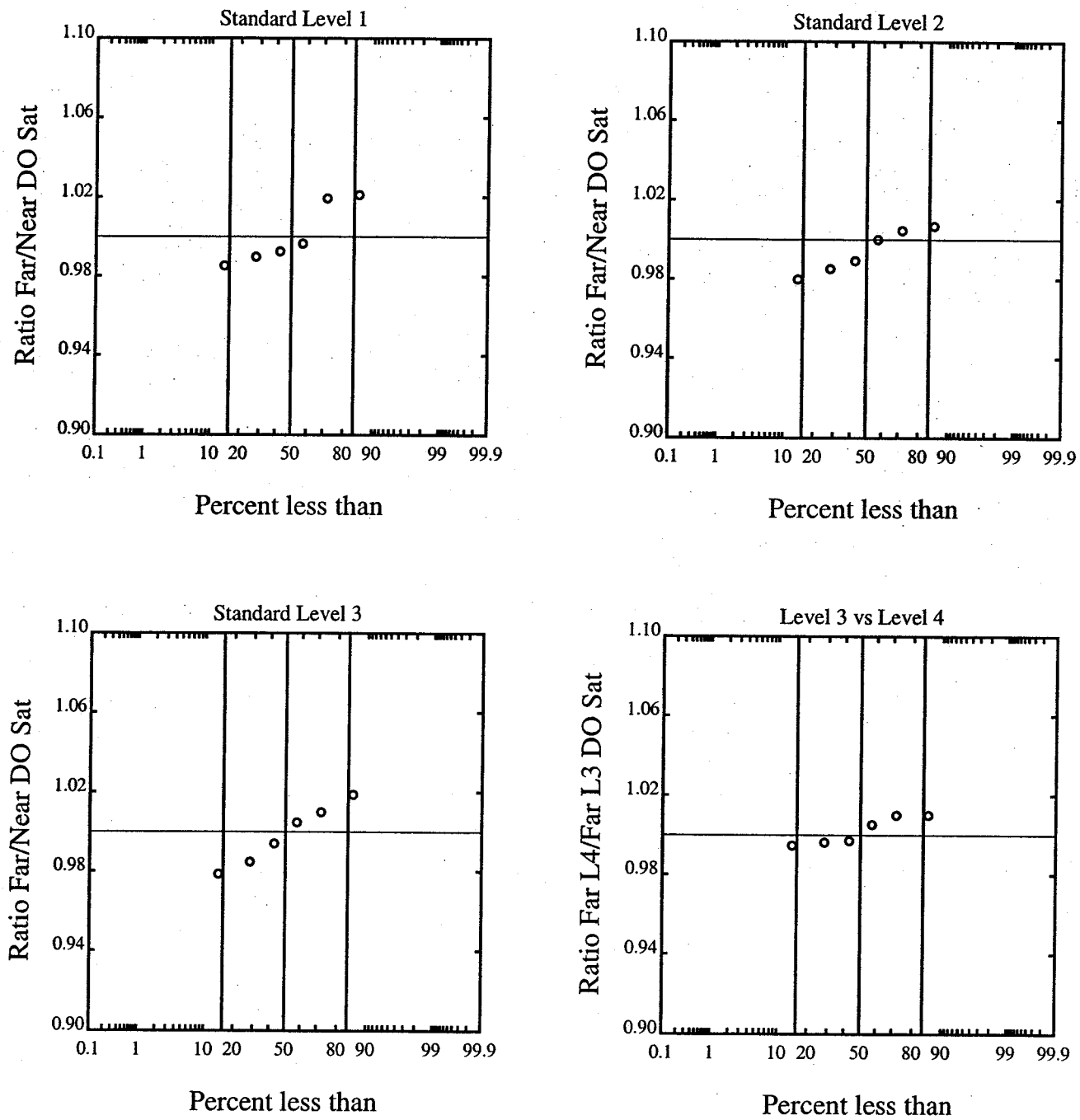

Figure 2-9. Probability Distribution of the Ratio of Near Field to Far Field Monthly Average DO Saturation Concentrations by Standard Level.

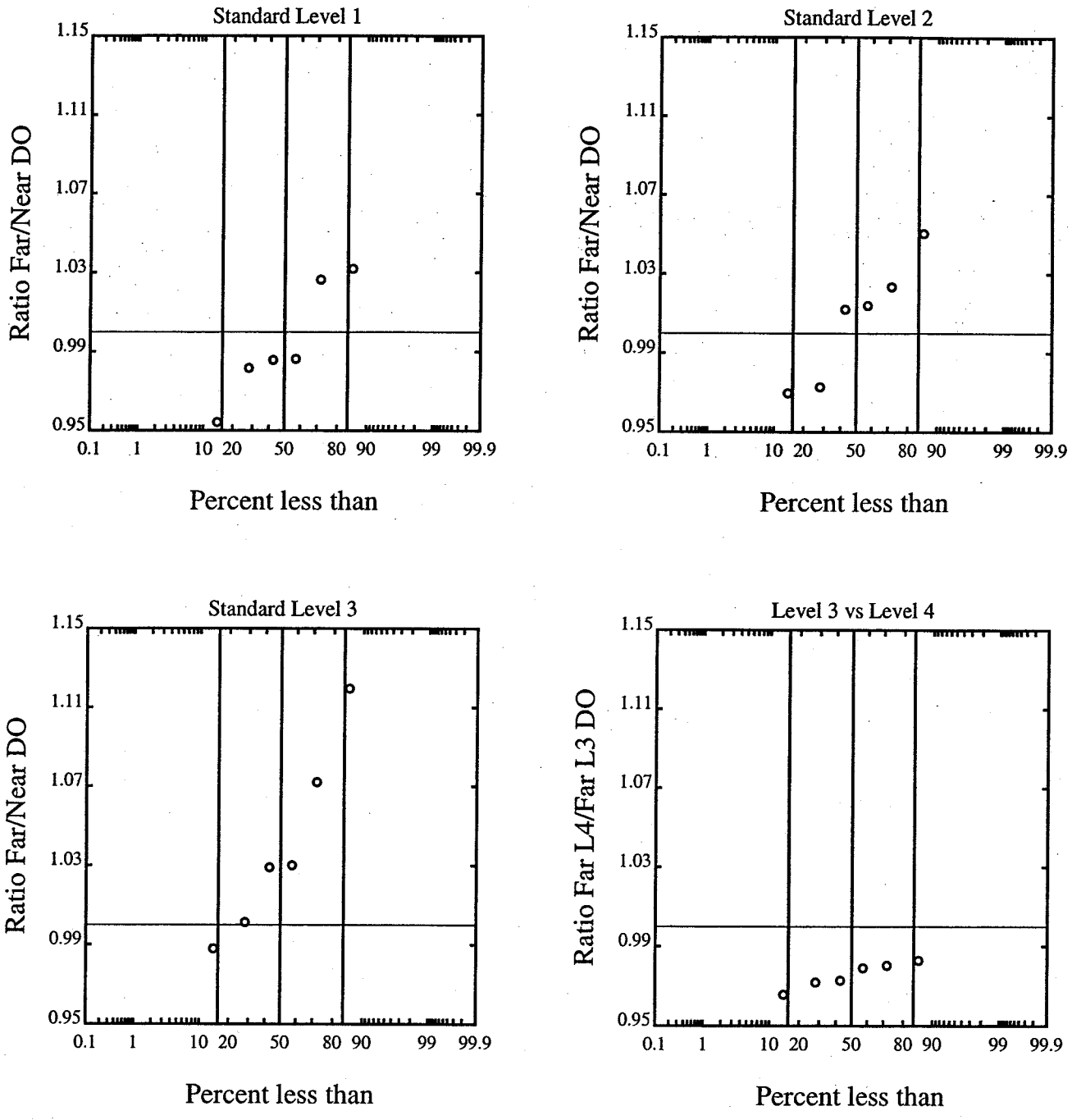

Figure 2-10. Probability Distribution of the Ratio of Near Field to Far Field Monthly Average DO Concentrations by Standard Level.

other location. This was done in Figures 2-11 to 2-13 for percent DO saturation, DO saturation and DO, respectively. These figures show that there is nearly a one to one ratio for the data. It is clear for the percent DO saturation and the DO concentration that the data are higher in the far field than in the near field at standard layer three. Also the percent DO saturation and DO concentrations are higher at standard level three than at standard level four.

The previous several figures show that there is a relationship between the DO concentration at stations F26 and F27 and the near field stations on a monthly average basis. Also, this relationship is very nearly one to one. However, a small percentage difference does matter because, at a DO concentration of 10.0 mg/L, each one percent difference corresponds to a 0.1 mg/L change in DO. The figures presented thus far do not determine if the monthly averaged differences between the near field and far field data are random, or if there is a temporal pattern. The ratios of the percent DO saturation, DO saturation concentration, and DO concentration between the far field and near field were plotted on a monthly basis to determine if a seasonal pattern existed. Figure 2-14 presents the temporal distribution of the ratio of the far field to near field percent saturation at each of the standard levels. The ratio at standard level 1 hovers around 1.0 with the suggestion of an increase in the first part of the year and a decline into August. At standard level 2 a wide range of ratios are observed. There is a general increase into June and then a decline in August and October. At level 3, a wider range of ratios are found and instead of a continued decline from August into October there is an increase in October. At the deepest level, the ratio between level 4 and level 3 is fairly constant near 0.975.

Figure 2-15 presents the far field to near field ratio for the DO saturation concentration on a temporal scale. As noted earlier, the range of the ratios at the four levels is small ranging from approximately 0.98 to 1.02. At the first two standard levels, the ratios tend to be at or less than 1.0 except during April and June. At level three there is a general trend upwards throughout the year. The ratio between level three and four tends to be marginally less than 1.0 during the spring and higher than 1.0 afterwards. The ratios for the DO concentration is presented in Figure 2-16. Figures 2-14 through 2-16 indicate that there is some seasonality in the relationship between the far field stations and the near field stations, so there should not be a constant ratio used to relate one to the other. Using this assumption, curves were drawn through the temporal figures to determine the ratio to be used for each month. These curves were used to develop Table 2-1. Using the percent DO saturation ratios and the saturation concentration ratios, boundary conditions were estimated for DO. Similarly, the DO concentration ratios were used to estimate boundary conditions for DO. The boundary conditions for DO were developed by multiplying the far field to near field DO concentration ratios in Table 2-1 for each month and each standard level by the average monthly near field DO concentrations for each month and at each standard level. The level 4 boundary conditions for DO were developed using a constant fraction of 0.97 of the level 3 DO boundary condition concentrations. Two sets of boundary

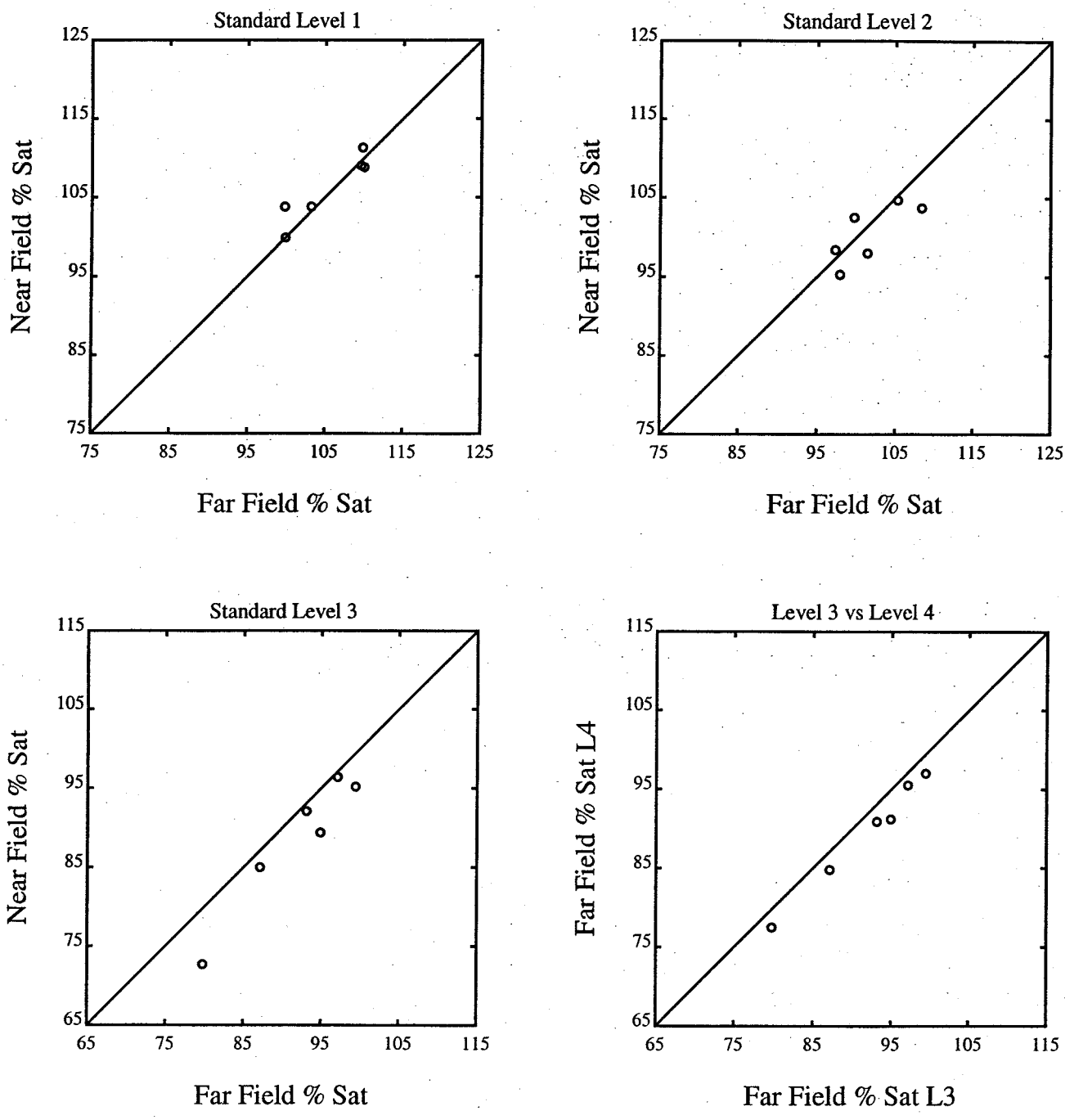

Figure 2-11. Far Field vs. Near Field Monthly Average Percent DO Saturation by Standard Level.

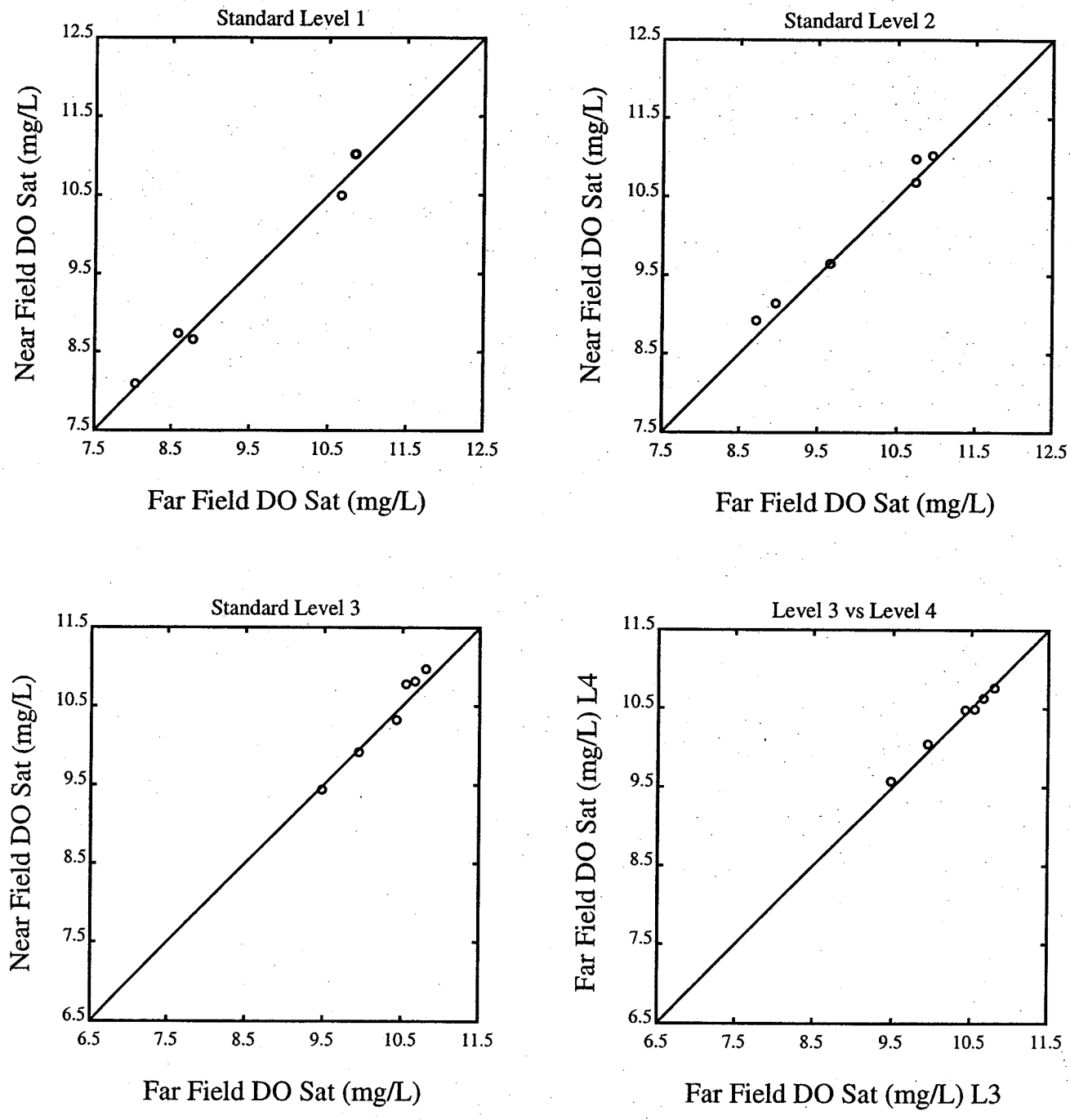

Figure 2-12. Far Field vs. Near Field Monthly Average DO Saturation Concentration by Standard Level.

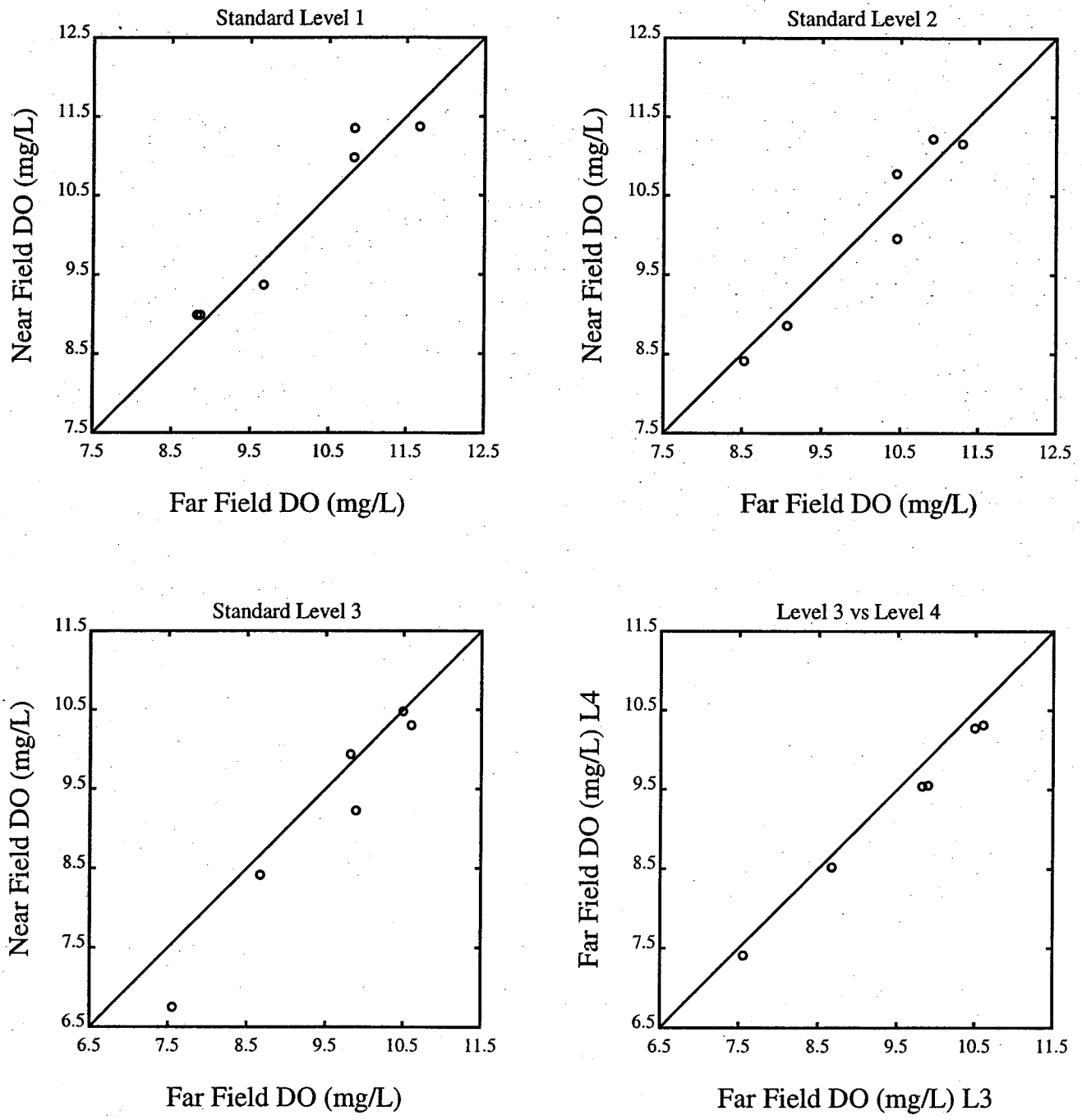

Figure 2-13. Far Field vs. Near Field Monthly Average DO Concentrations by Standard Level.

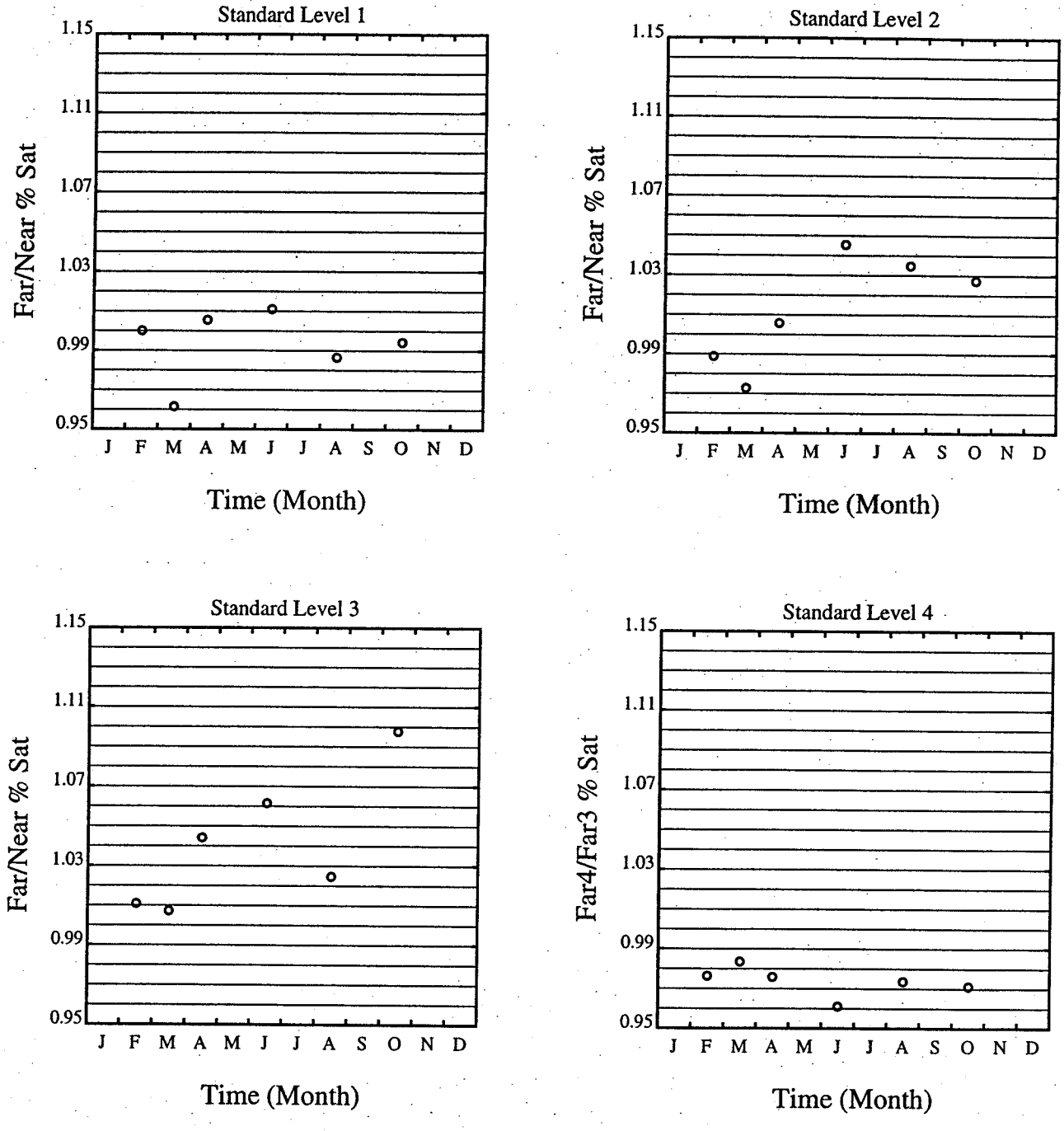

Figure 2-14. Temporal Distribution of the Ratio of Far Field to Near Field Monthly Average Percent DO Saturation by Standard Level.

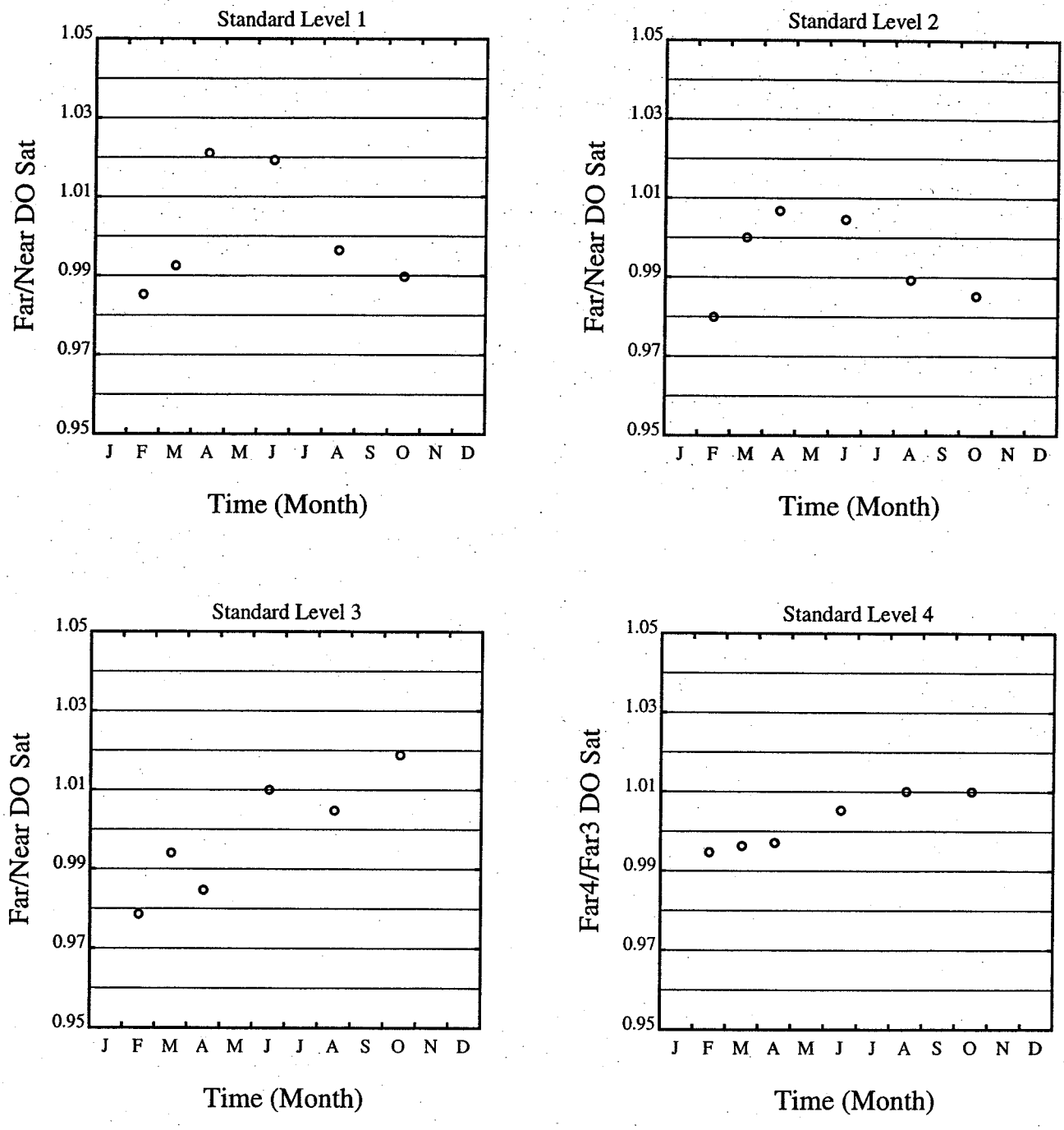

Figure 2-15. Temporal Distribution of the Ratio of Far Field to Near Field Monthly Average DO Saturation Concentration by Standard Level.

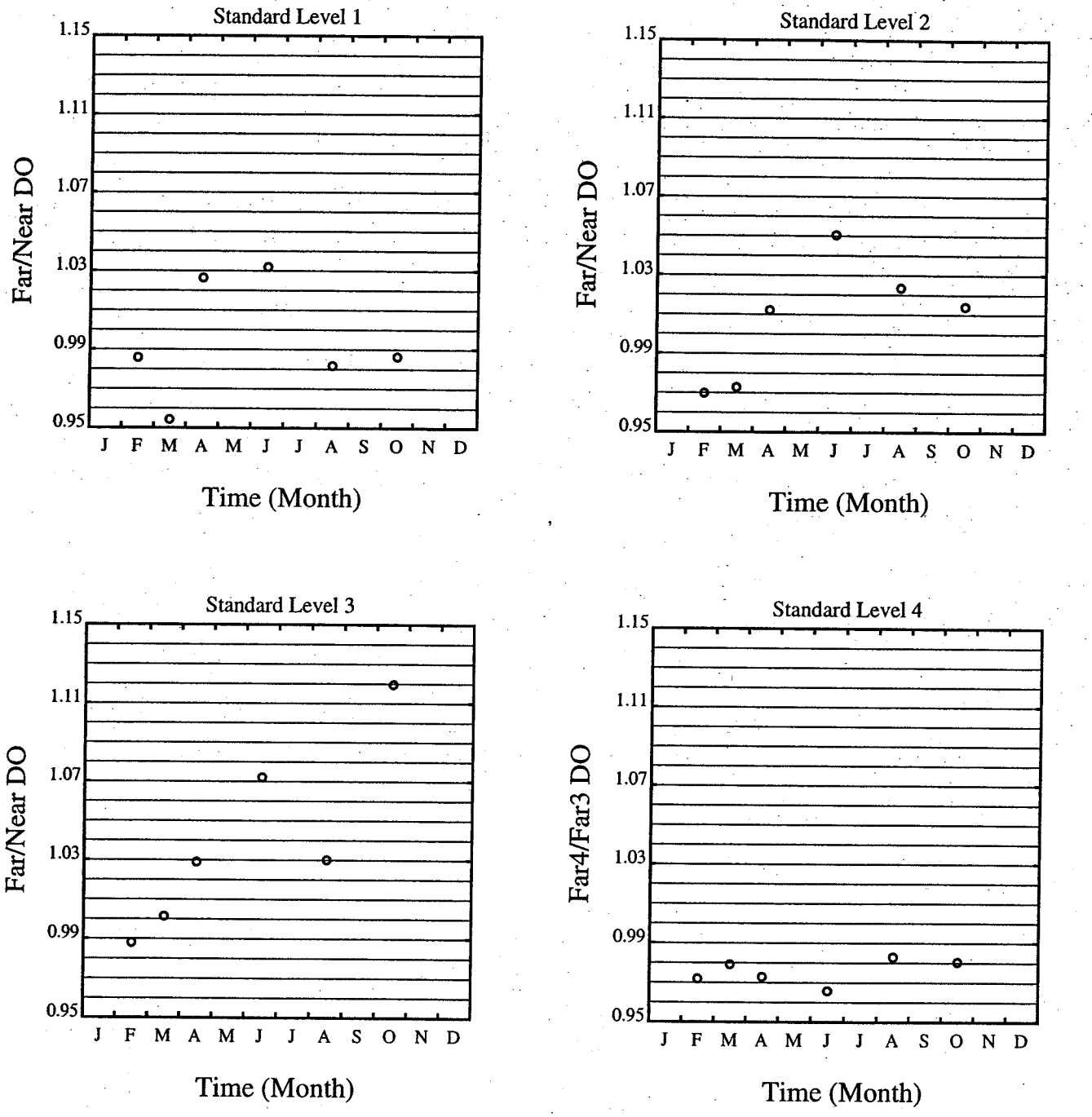

Figure 2-16. Temporal Distribution of the Ratio of Far Field to Near Field Monthly Average DO Concentrations by Standard Level.

Table 2-1. 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				

conditions were developed for sensitivity runs to be compared to the 1992 calibration. The first sensitivity was developed using the monthly average near field DO concentrations for the period of 1994 through 1999. These monthly averages were then multiplied by the ratios in Table 2-1.The second sensitivity was developed using the monthly average for the near field DO data in 1992 only. Again, these monthly averages were then multiplied by the ratios in Table 2-1 to create the boundary conditions.

Figure 2-17 presents a comparison between the DO boundary conditions used for the 1992 calibration ("Calibration") and the boundary conditions developed using the monthly average near field DO concentrations for 1994 -1999 ("Sensitivity 1"). The major differences between these two sets of boundary conditions are that in the sensitivity set of boundary conditions (1) the springtime DO maxima occur later, (2) there is no April/May minimum, and (3) the fall minimum is lower.

Figure 2-18 presents the DO boundary condition comparison for the 1992 calibration and the boundary developed using the 1992 near field data ("Sensitivity 2"). The major differences between these two sets of boundary conditions are that the sensitivity boundary conditions (1) have a springtime peak in DO which occurs earlier, (2) in the bottom two layers the peak lasts longer, (3) the DO decline in May and increase in June is more pronounced, and (4) the year-end DO concentrations are lower.

2.2 DISSOLVED INORGANIC NITROGEN

The initial attempt to create boundary conditions for DIN followed a procedure similar to that used for DO. Figures 2-19 and 2-20 present temporal comparisons between near field and far field (stations F26 and F27) nitrite + nitrate ($NO_2 + NO_3 = NO_x$) monthly averages for the period of 1994 -1999 at the four standard levels. In the top two standard levels, the far field data tend to be slightly higher in the spring and then lower from June through the rest of the year. At the third standard level, the pattern is not as clear. However, from March to August NO_x , concentrations tend to be higher in the far field. Again, the near field is not deep enough to compare to the fourth standard level. Figures 2-21 and 2-22 present the ammonium (NH_4) data. For level one the far field NH_4 data are lower than the near field NH_4 data. This is true for the second standard level except for the data observed in March. For the third standard level the far field data from March to August are less than the near field data. To determine if there was a relationship between near field and far field DIN Figures 2-23 and 2-24 were created. Figure 2-23 presents near field NO_x versus far field NO_x. While there is a small correlation between NO_x at the two locations in the upper two levels, there is no such relation in standard level three. The concentrations in levels three and four appear to be fairly well correlated. Figure 2-24 presents the comparison for NH_4. The ammonium concentrations at the near field and far field stations do not appear to be well correlated. However there is some correlation between level three and level four in the far field. Given these observations, the approach of using near field DIN

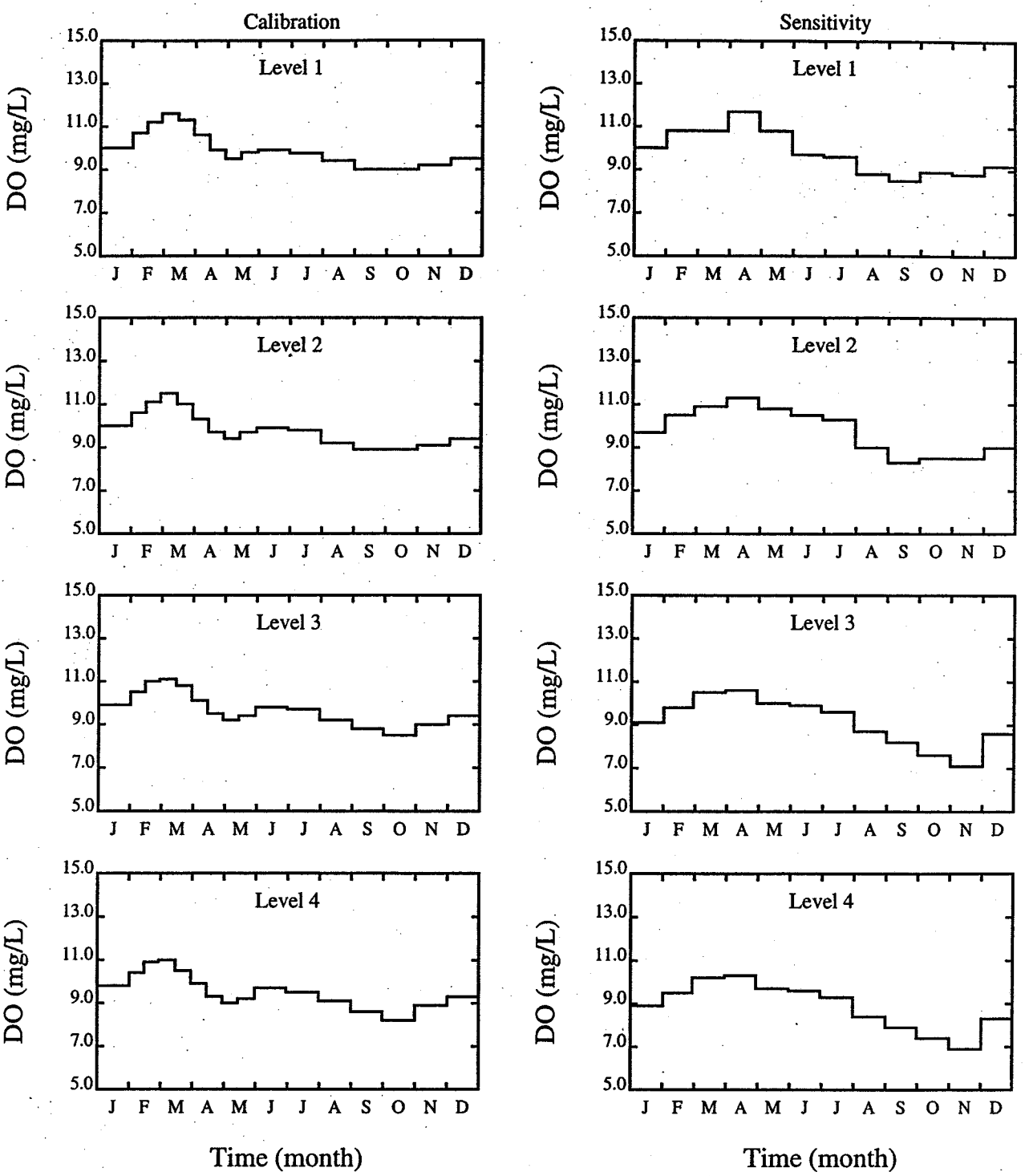

Figure 2-17. Temporal Comparison of 1992 Calibration DO Boundary Conditions to DO Sensitivity 1 DO Boundary Conditions.

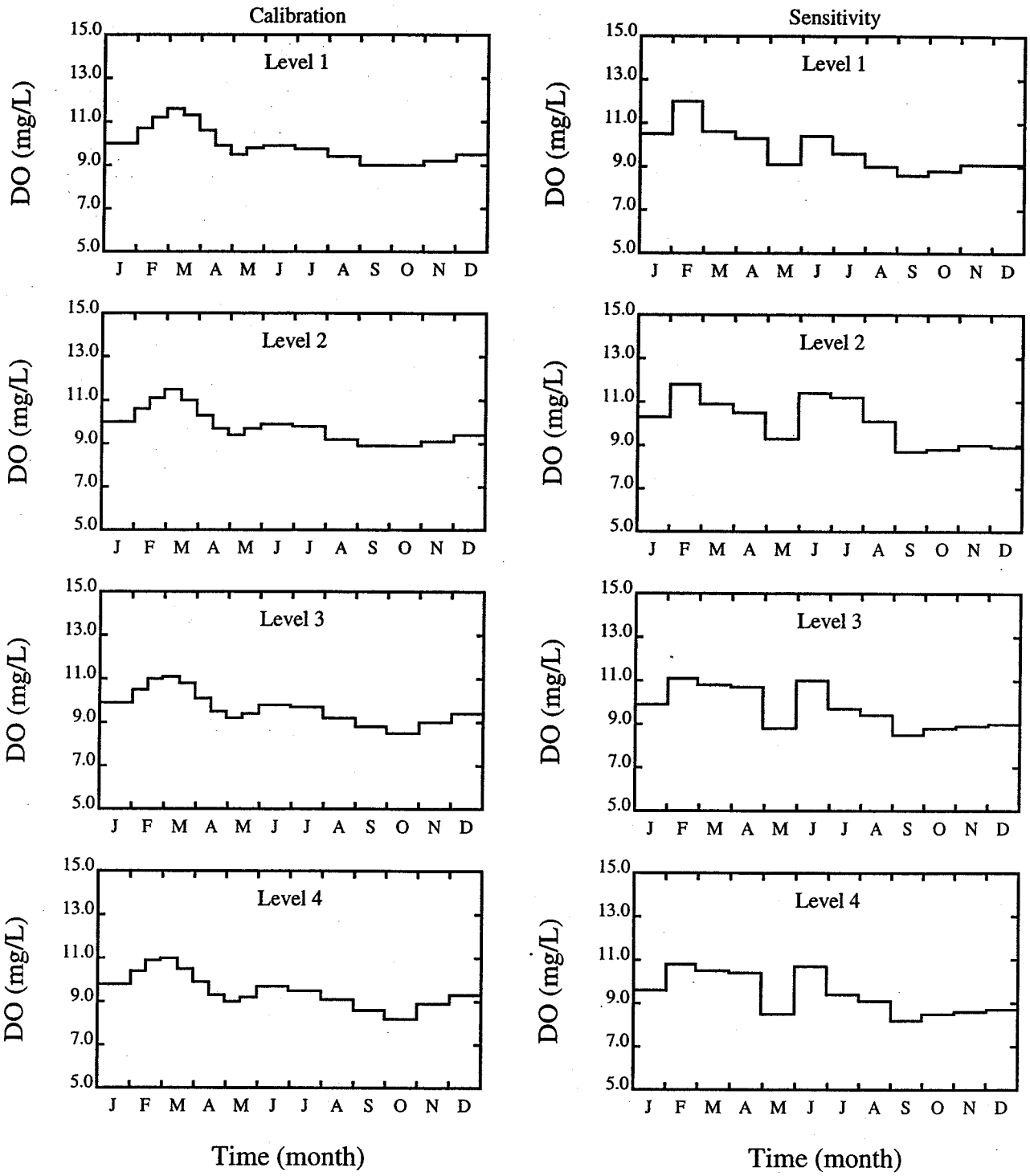

Figure 2-18. Temporal Comparison of 1992 Calibration DO Boundary Conditions to DO Sensitivity 2 DO Boundary Conditions.

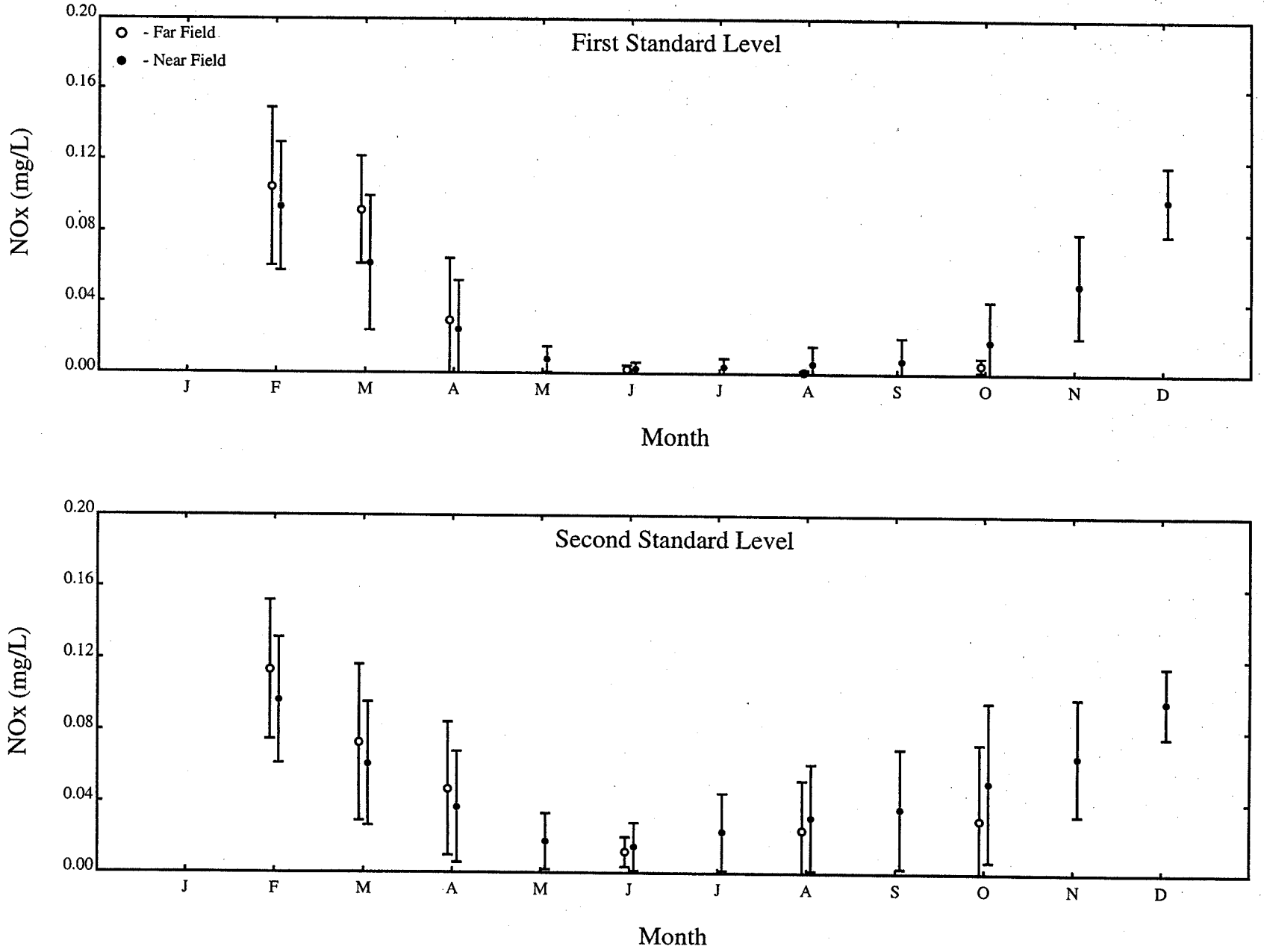

Figure 2-19. Temporal Comparison of Near Field and Far Field Monthly Average Nitrite + Nitrate Concentrations at Standard Levels 1 and 2.

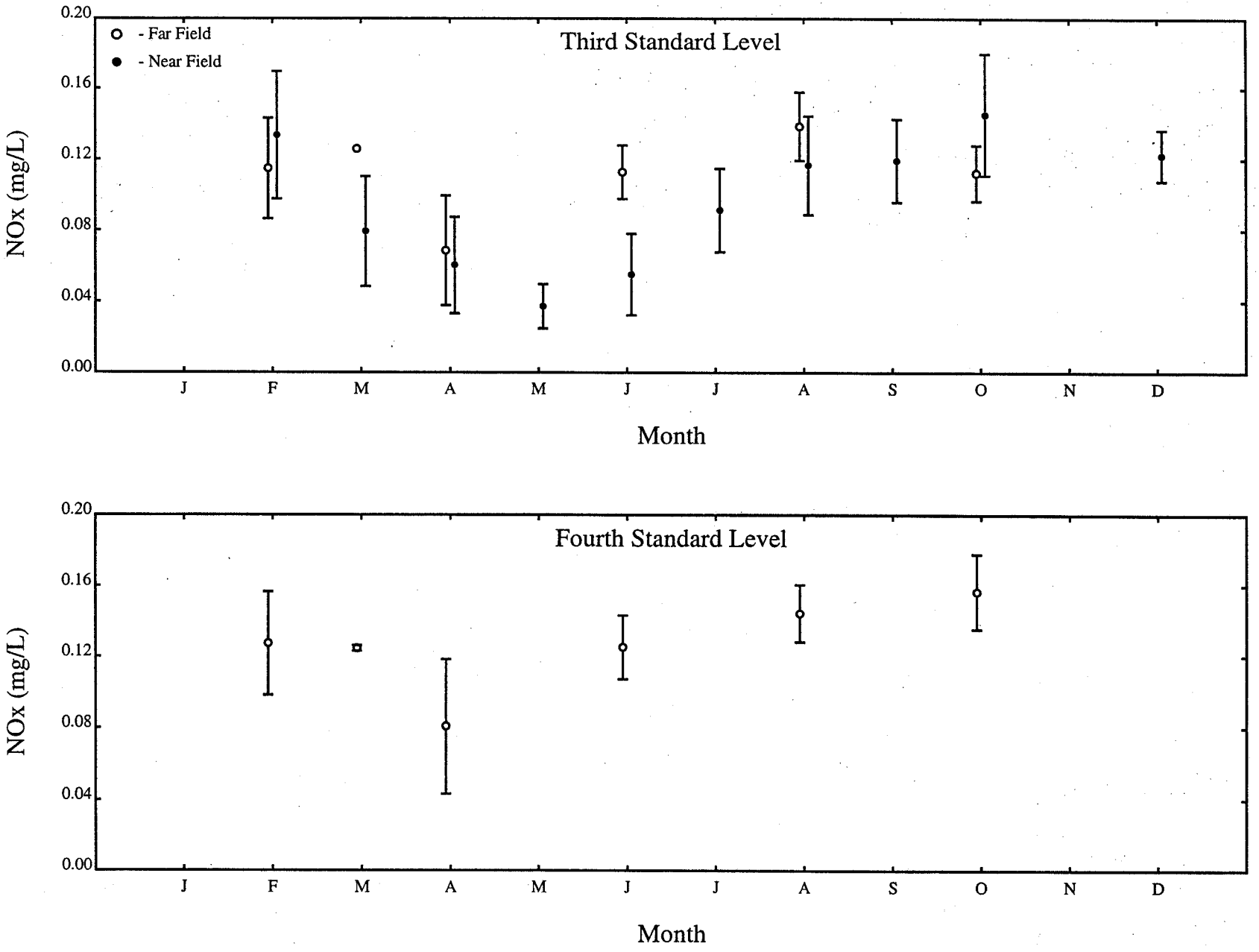

Figure 2-20. Temporal Comparison of Near Field and Far Field Monthly Average Nitrite + Nitrate Concentrations at Standard Levels 3 and 4.

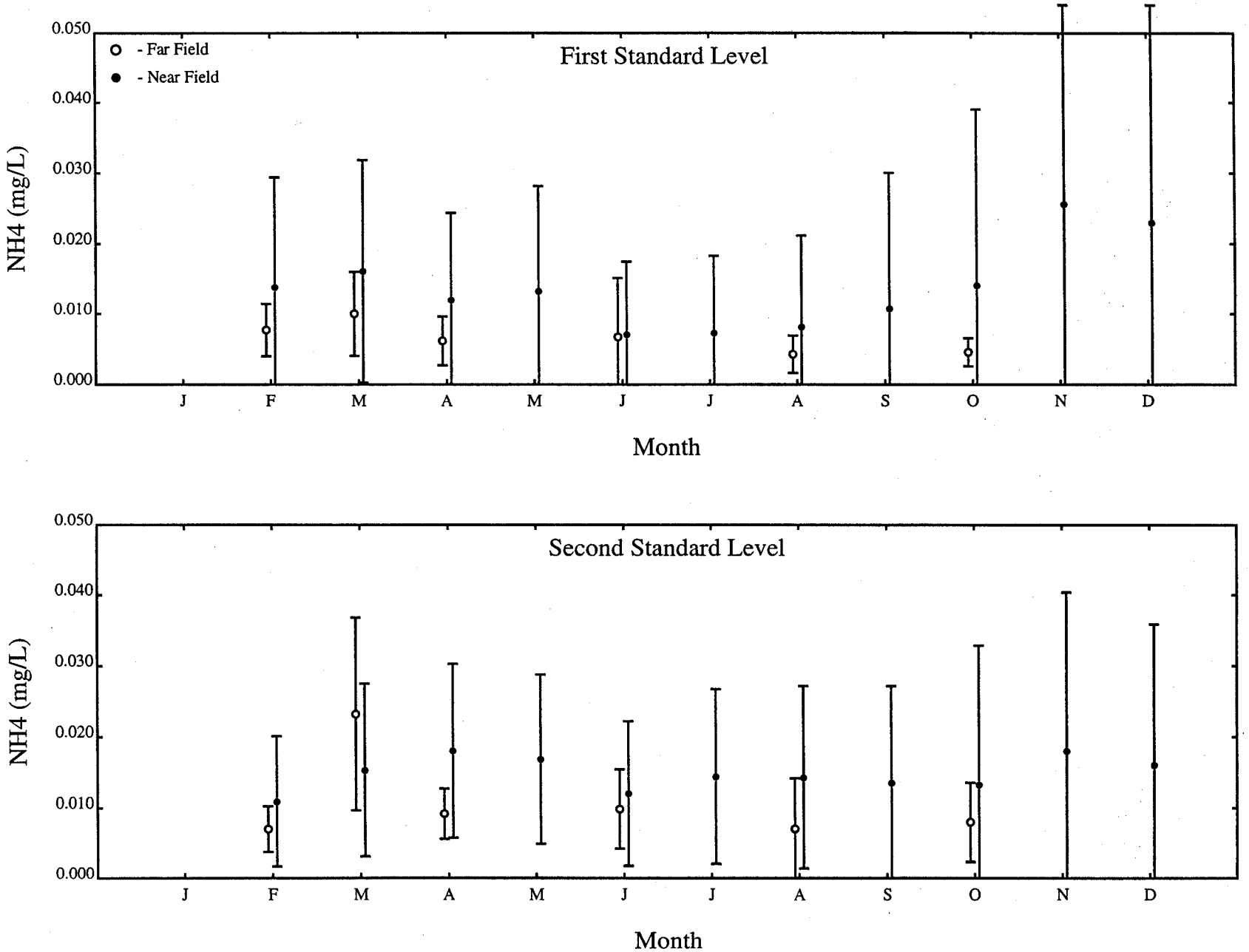

Figure 2-21. Temporal Comparison of Near Field and Far Field Monthly Average Ammonium Concentrations at Standard Levels 1 and 2.

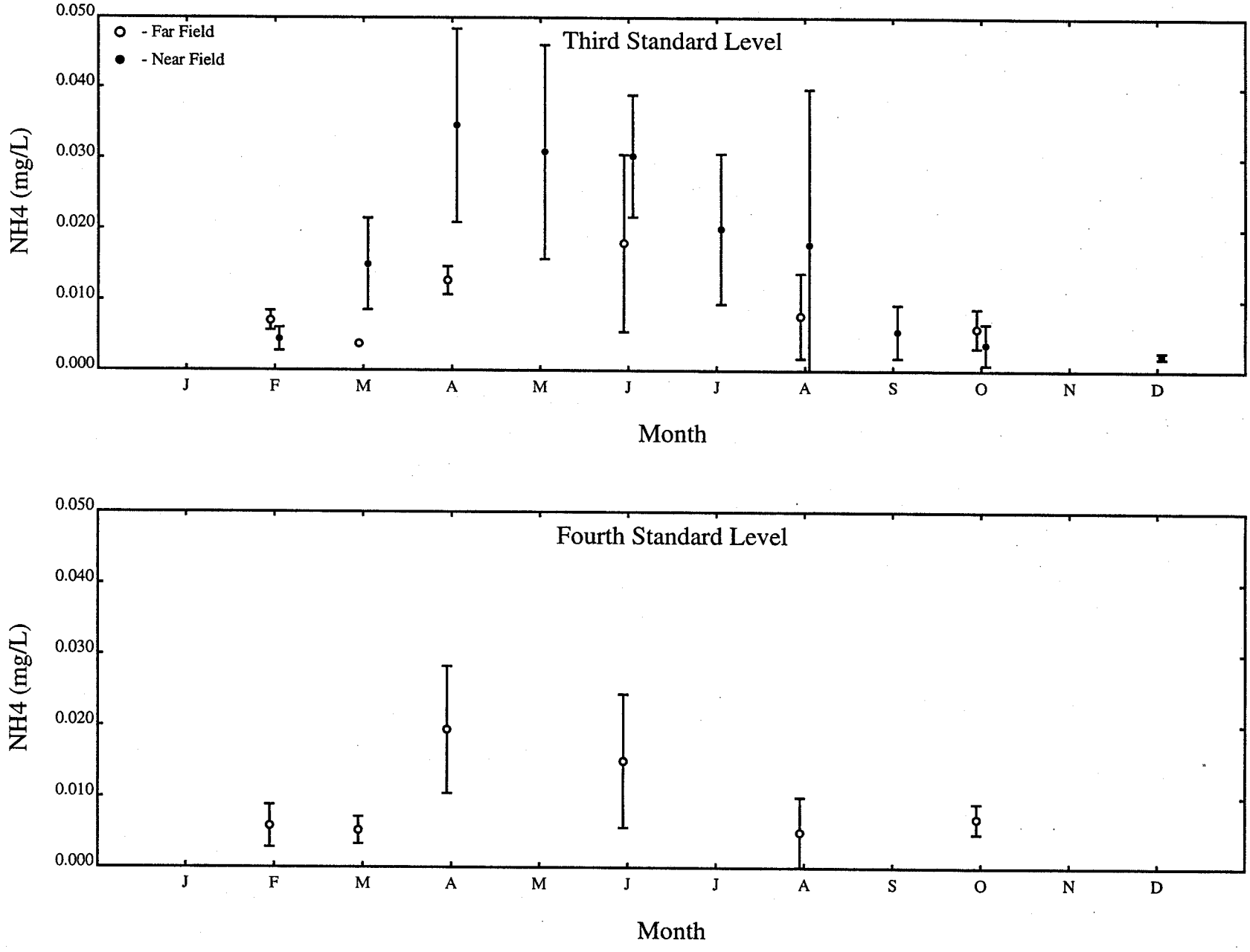

Figure 2-22. Temporal Comparison of Near Field and Far Field Monthly Average Ammonium Concentrations at Standard Levels 3 and 4.

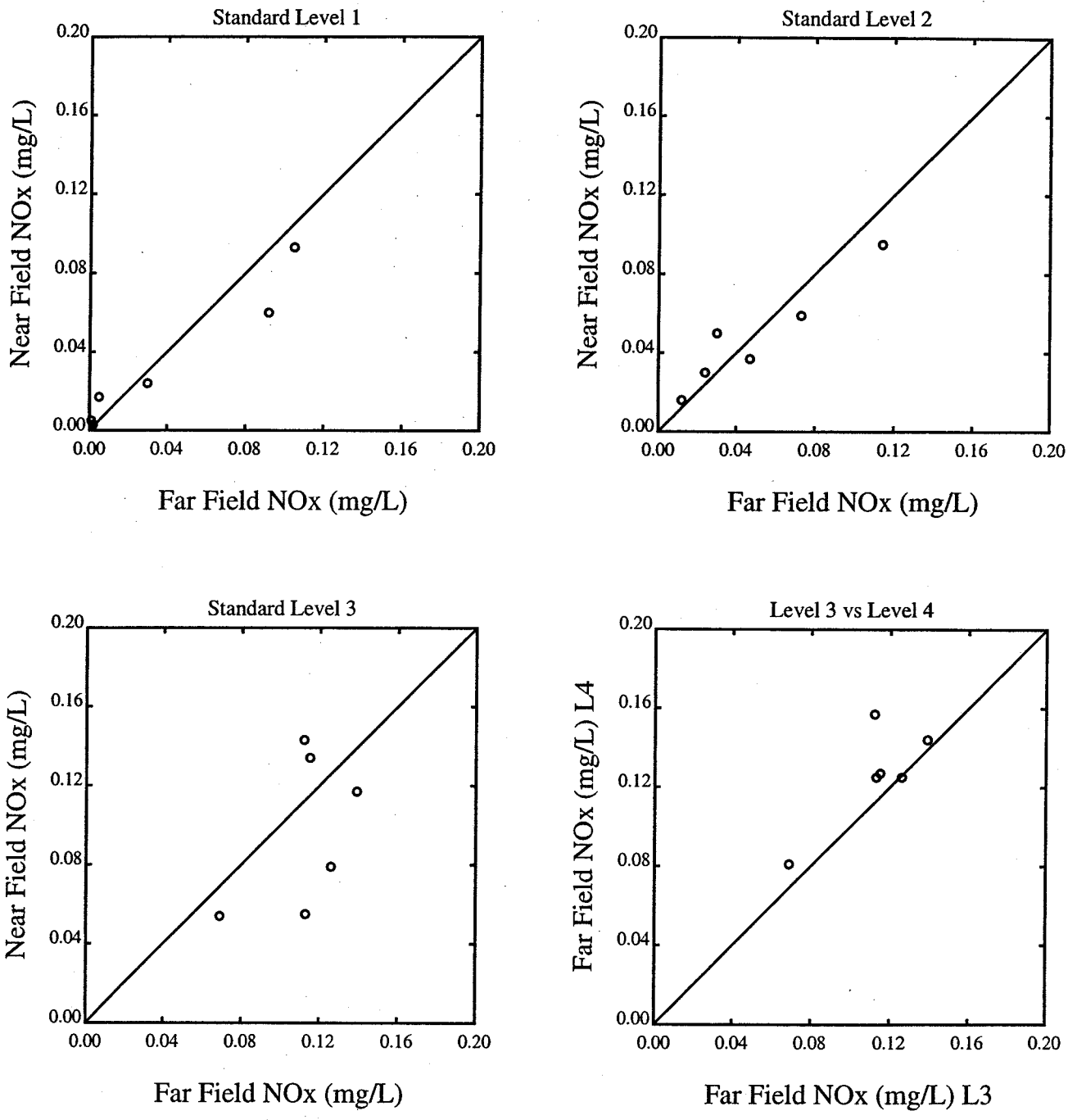

Figure 2-23. Far Field vs. Near Field Monthly Average Nitrite + Nitrate Concentrations by Standard Level.

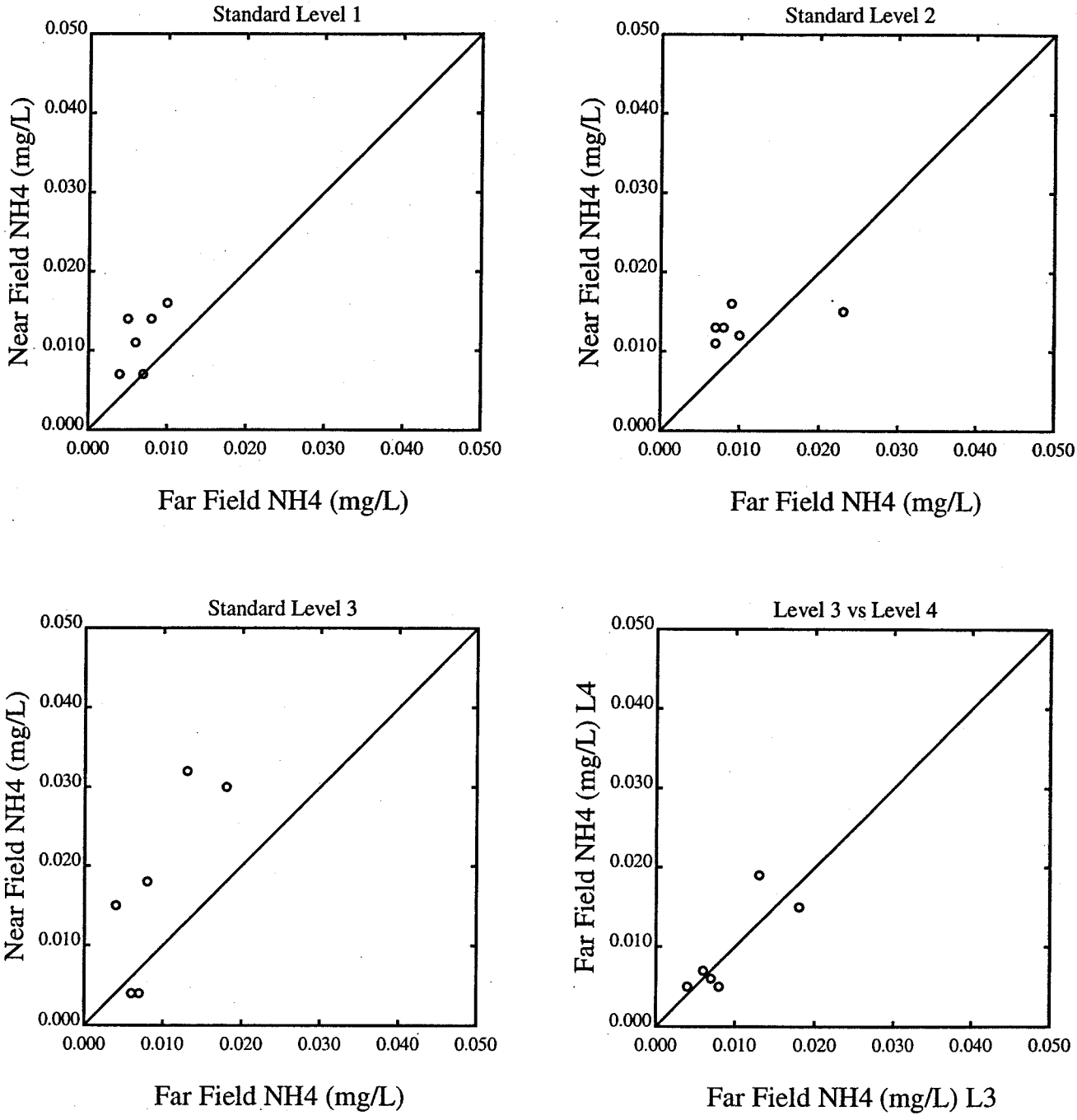

Figure 2-24. Far Field vs. Near Field Monthly Average Ammonium Concentrations by Standard Level.

concentrations to assign boundary conditions was abandoned and a simple boundary sensitivity analysis was performed instead.

To come up with boundary conditions for the sensitivity runs, a simple approach was taken. Four sensitivities were developed. The first sensitivity run approximated boundary conditions using average conditions from stations F26 and F27 for the period of 1994-1999. For months where no data existed boundary conditions were visually interpolated and/or extrapolated. The primary focus of this sensitivity was to determine if average DIN conditions would be adequate to specify boundary conditions to produce and improved 1992 calibration. For the remaining sensitivities, the existing 1992 boundary conditions for NO_x and NH_4 were increased by a set percentage during part of the year. These sensitivities included increasing the spring boundary concentrations by 20 percent for the entire water column (DIN Sensitivity 2), increasing the summer boundary concentrations by 20 percent for the entire water column (DIN Sensitivity 3), and increasing concentrations in the bottom two standard levels by 20 percent during the summer (DIN Sensitivity 4). While the choice of 20 percent was somewhat arbitrary, this percentage increase is within the range of variability observed in the data.

The boundary conditions developed for the DIN boundary sensitivities are presented in Figures 2-25 through 2-32. Figures 2-25 and 2-26 present the boundary conditions used for the calibration and for Sensitivity 1 (average 1994-1999) for NO_x and NH_4, respectively. The shape of the level three and four boundary conditions is quite different between the two runs (Calibration versus Sensitivity 1) . Figures 2-27 and 2-28 present the boundary conditions used for the 20 percent increase in the spring DIN for NO_x and NH_4, respectively. Spring was considered to be March, April and May. The boundary conditions used for the 20 percent increase in the summer throughout the water column are displayed in Figures 2-29 and 2-30. Summer was defined as June through September. The boundary conditions used for the 20 percent increase in the bottom waters during the summer are presented in Figures 2-31 and 2-32 .

Table 2-2 presents a summary of the sensitivity runs described this section.

Table 2-2. Sensitivity Summary

Run Name	Description
Calibration	1992 Calibration as presented in HydroQual (2000) for both DO and DIN
DO Sensitivity 1	1994-1999 near field average * far field/near field ratios for 1994-1999
DO Sensitivity 2	1992 near field average * far field/near field ratios for 1994-1999
DIN Sensitivity 1	Average far field 1994-1999
DIN Sensitivity 2	1992 conditions with spring time boundary concentrations increased by 20% for all layers
DIN Sensitivity 3	1992 conditions with summer time boundary concentrations increased by 20% for all layers
DIN Sensitivity 4	1992 conditions with summer time boundary concentration increased by 20% at bottom two standard levels only

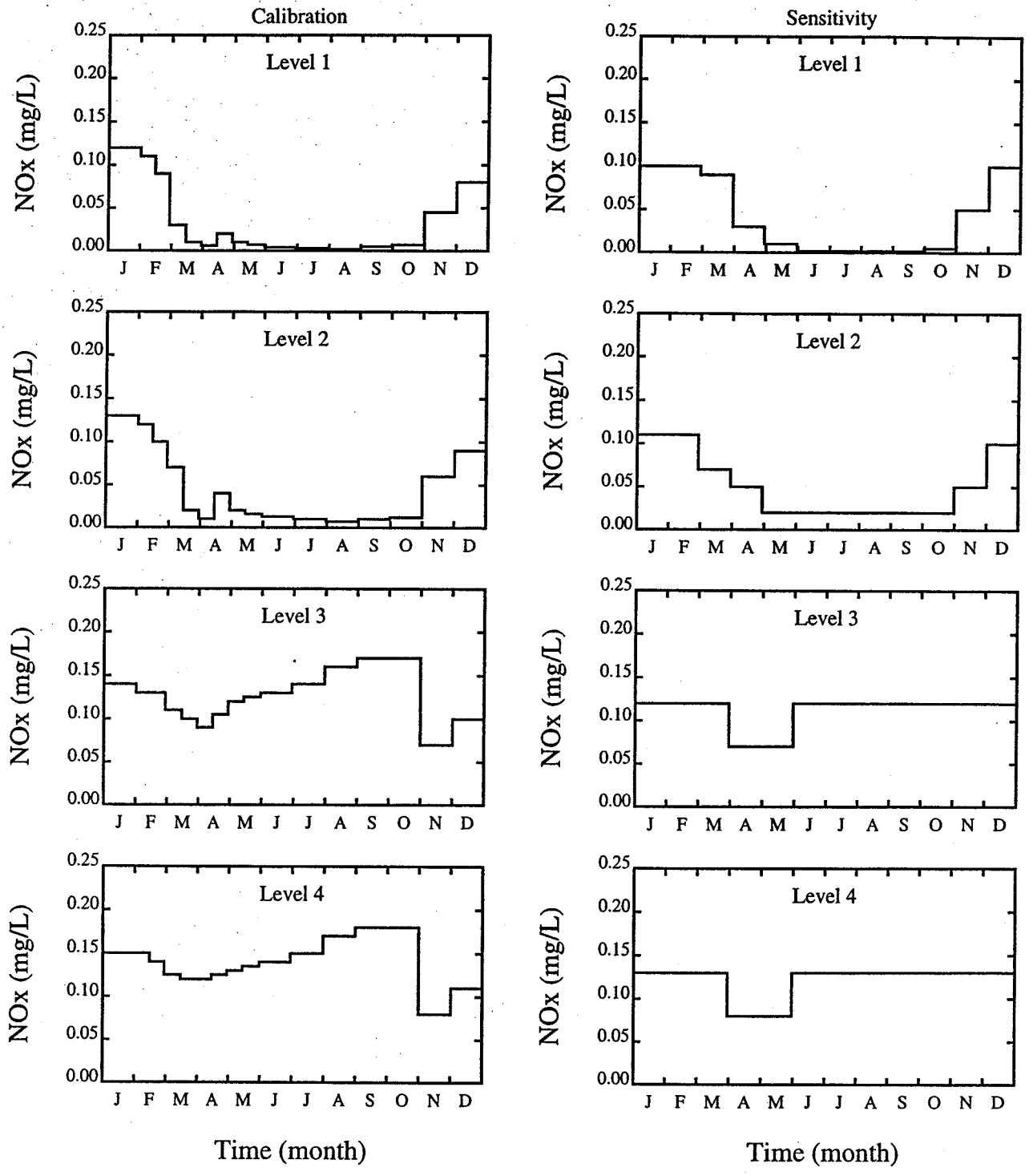

Figure 2-25. Temporal Comparison of 1992 Calibration and Sensitivity 1 $NO_2 + NO_3$ Boundary Conditions.

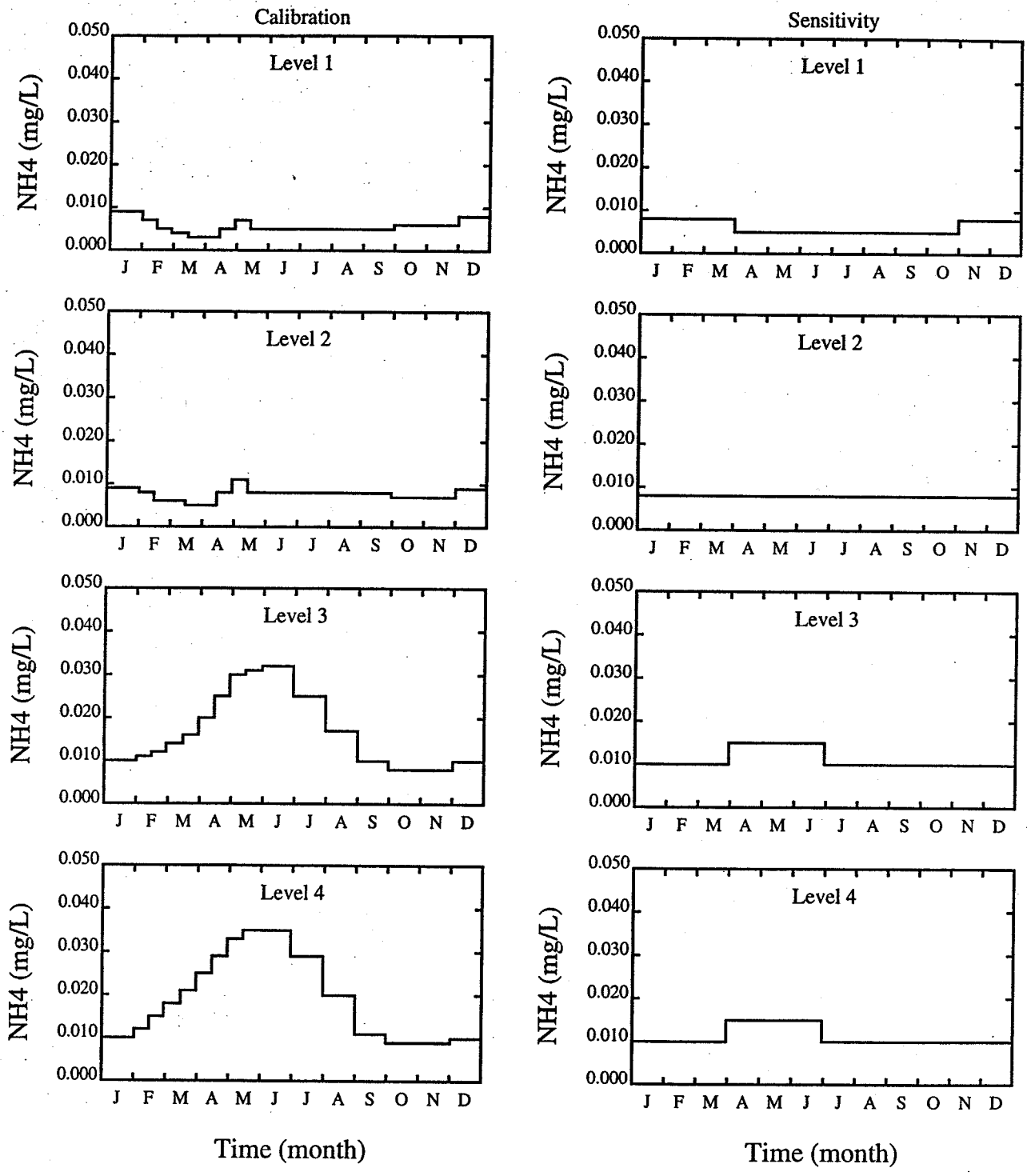

Figure 2-26. Temporal Comparison of 1992 Calibration and DIN Sensitivity 1 NH_4 Boundary Conditions.

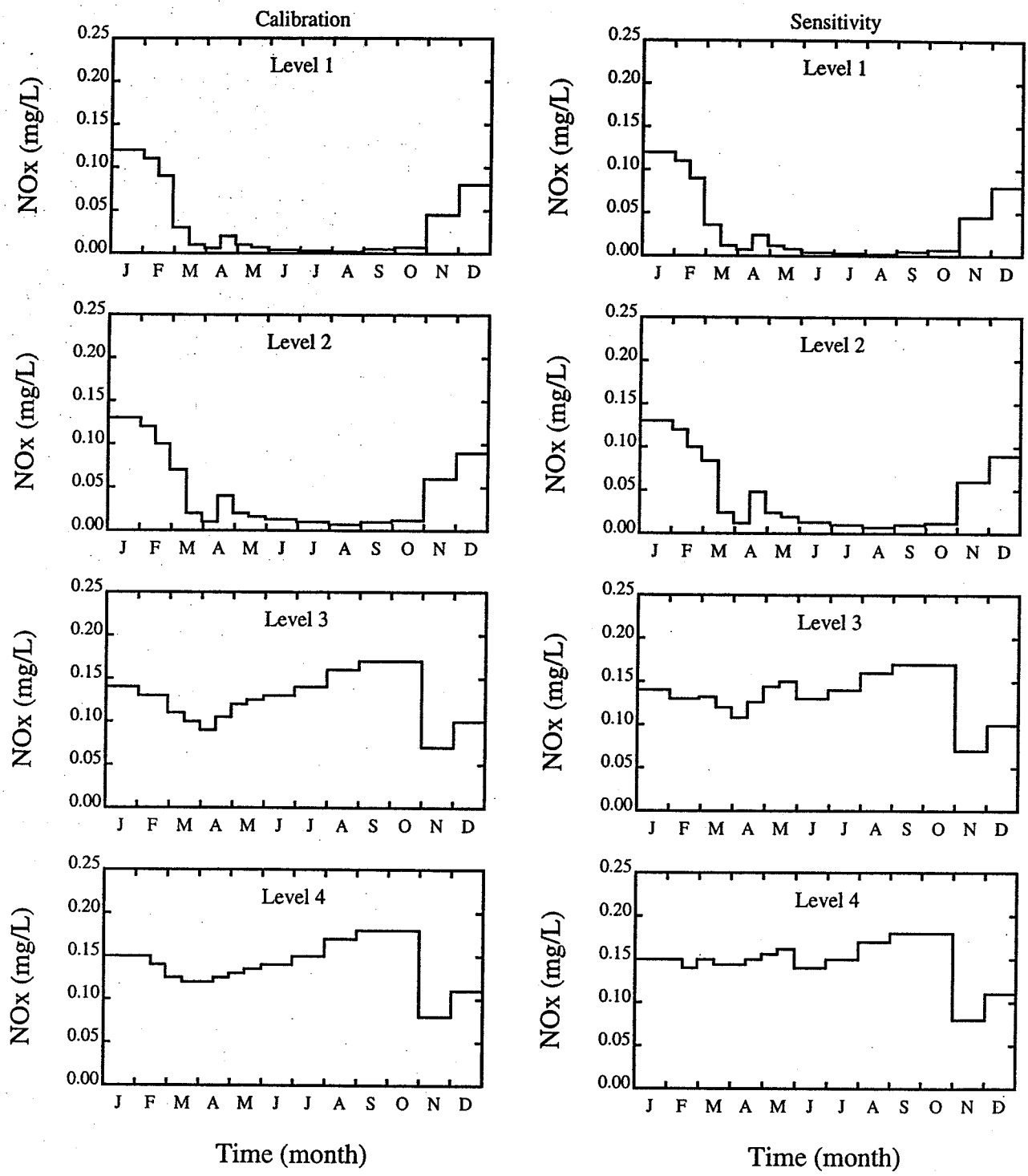

Figure 2-27. Temporal Comparison of 1992 Calibration and DIN Sensitivity 2 $NO_2 + NO_3$ Boundary Conditions.

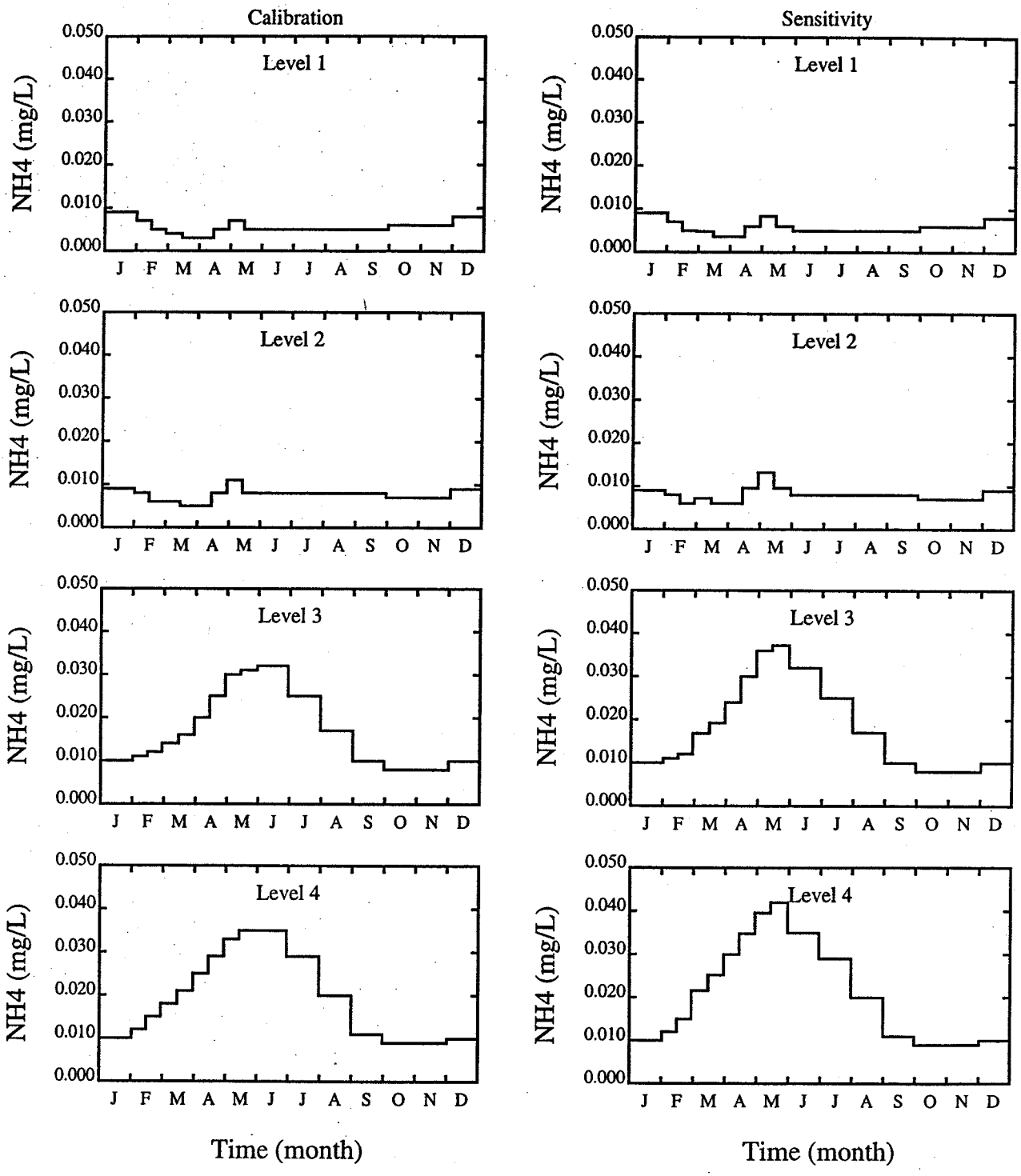

Figure 2-28. Temporal Comparison of 1992 Calibration and DIN Sensitivity 2 NH_4 Boundary Conditions.

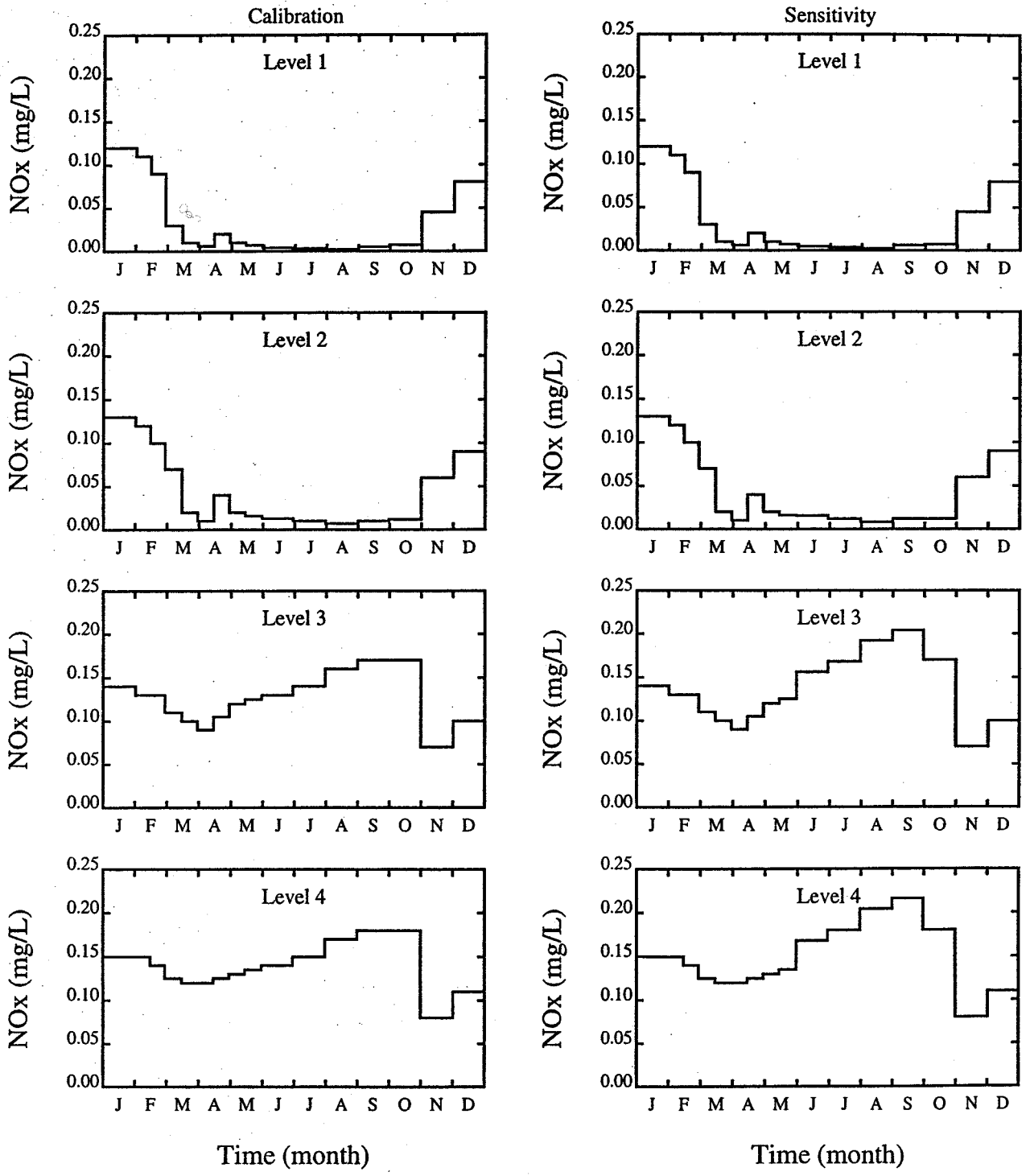

Figure 2-29. Temporal Comparison of 1992 Calibration and DIN Sensitivity 3 NO_2 + NO_3 Boundary Conditions.

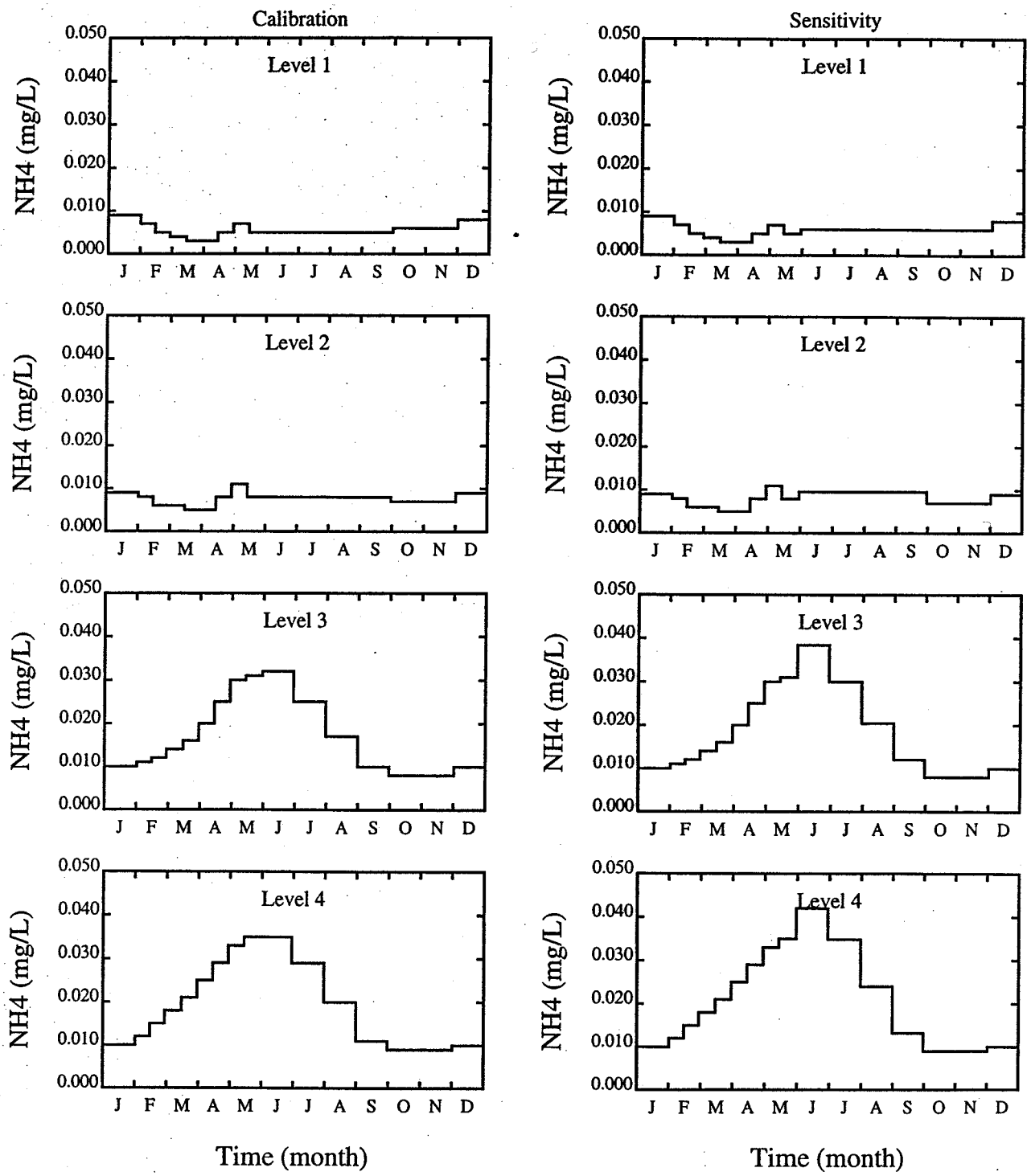

Figure 2-30. Temporal Comparison of 1992 Calibration and DIN Sensitivity 3 NH_4 Boundary Conditions.

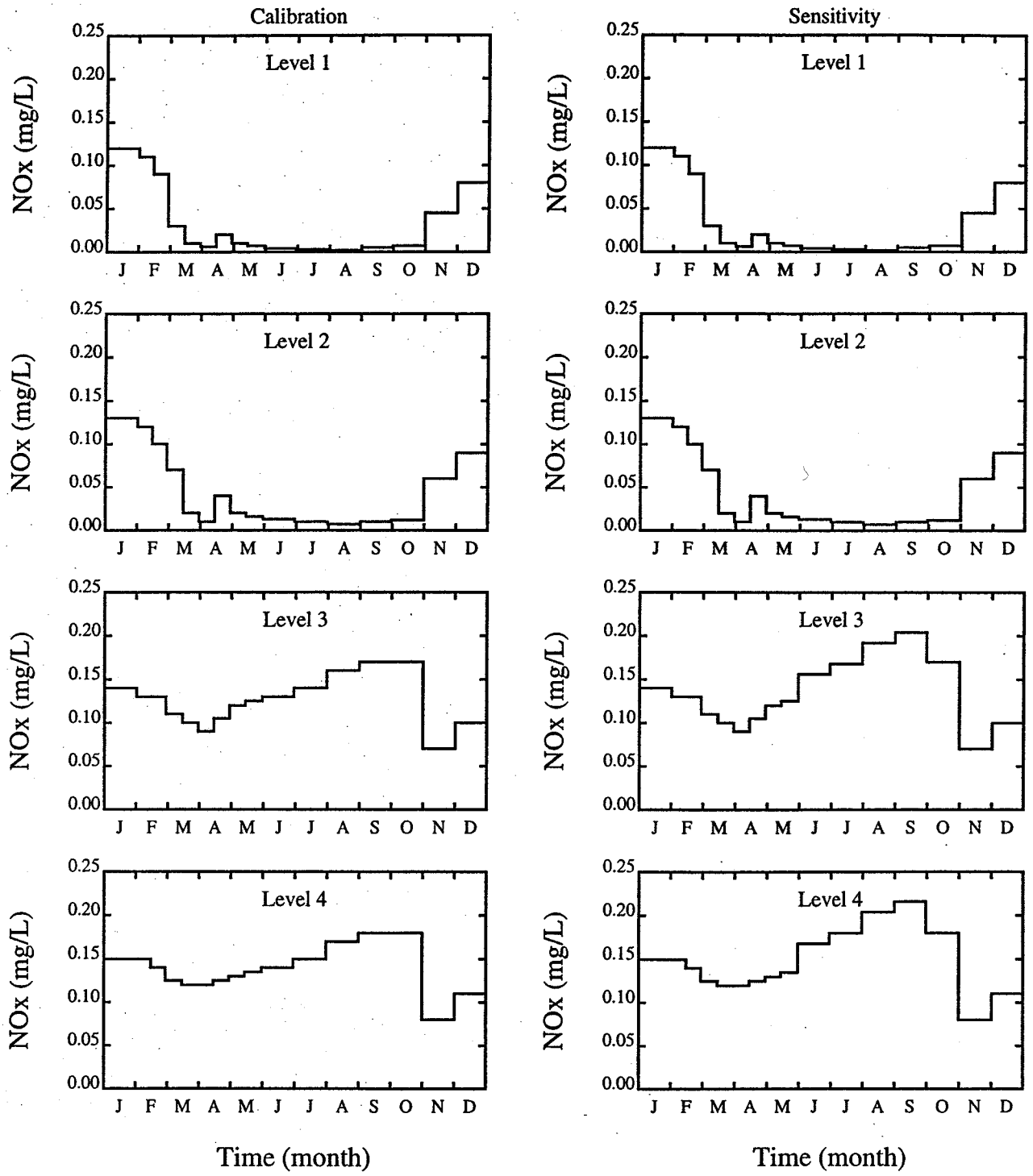

Figure 2-31. Temporal Comparison of 1992 Calibration and DIN Sensitivity 4 $NO_2 + NO_3$ Boundary Conditions.

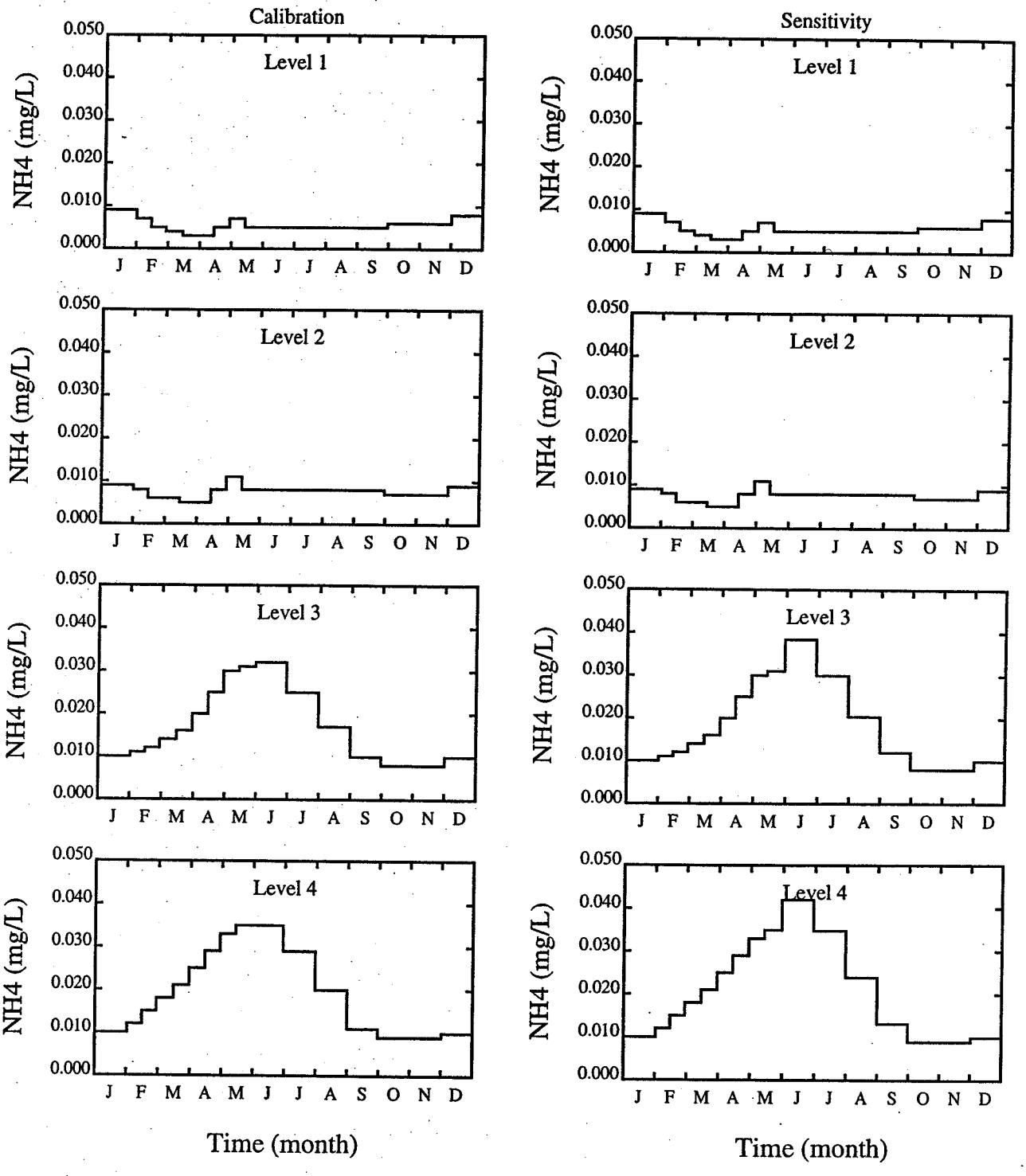

Figure 2-32. Temporal Comparison of 1992 Calibration and DIN Sensitivity 4 NH_4 Boundary Conditions.

SECTION 3

RESULTS

3.1 DISSOLVED OXYGEN

From a visual inspection of model output, the modification of the dissolved oxygen boundary conditions had little or no effect on the other state-variables in the model. Therefore, only results for DO will be presented. The results for the two DO boundary condition sensitivities compared with the 1992 calibration results in the near field area are presented in Figure 3-1. Some of the shortcomings of the original calibration were that the high DO concentrations measured in February were not reproduced and the model did not reproduce the decline in DO that occurred in April and May followed by an increase in June and July. The latter DO concentration increase was more pronounced in the bottom water than in the surface water. Under the average DO boundary conditions (Sensitivity 1) the peak spring DO concentrations computed by the model shifted from March to April, further away from the observed peak in February. The decline and subsequent increase in DO concentrations observed in the data during the late spring and earlier summer is not reproduced by the DO boundary conditions prescribed by Sensitivity 1. The model also computes a larger difference between the surface and bottom DO concentration than is observed in the data during the fall.

Using the near field DO data from 1992 to specify the boundary conditions (Sensitivity 2), improves upon the original dissolved oxygen calibration. While the February DO concentrations are still underestimated by the model, there is some improvement, especially in the central near field, relative to the original calibration. While the model misses the timing of the decline and increase in the DO observed in the data by a small margin, the model does reproduce the larger increase in the bottom DO that is observed in the data as compared to the surface waters. With some further trial and error runs, the calibration to DO might be improved in the near field for sensitivity 2 by shifting the boundary conditions in time to account for the time of travel from the boundary to the near field.

Figure 3-2 presents the results from the calibration and the two sensitivities for three far field stations: F22 in northeastern Massachusetts Bay, F10 in Central Massachusetts Bay and F02 in Eastern Cape Cod Bay. Without data in late April and May it cannot be concluded as to whether or not the decline and subsequent increase observed in the near field area DO occurred in the rest of the Massachusetts Bay and Cape Cod Bay system. The model calibration looks fairly good. While the high DO concentrations observed in February and March are still underestimated and the low DO concentrations at F22 in October are overestimated, there is a reasonable fit to the temporal trends

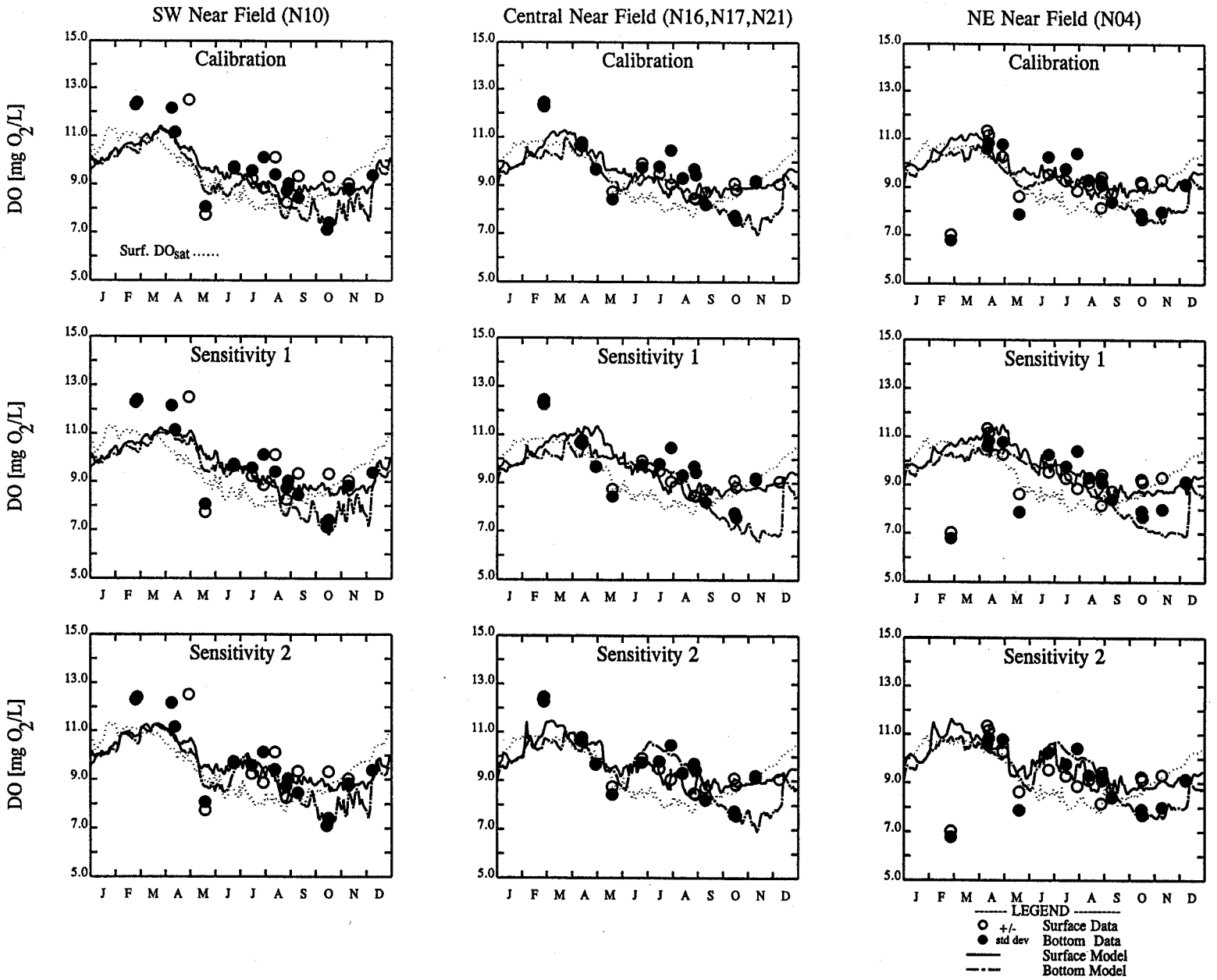

Figure 3-1. Temporal Comparison of Computed DO Concentrations Between the 1992 Calibration, DO Sensitivity 1 and DO Sensitivity 2 at Three Near Field Stations.

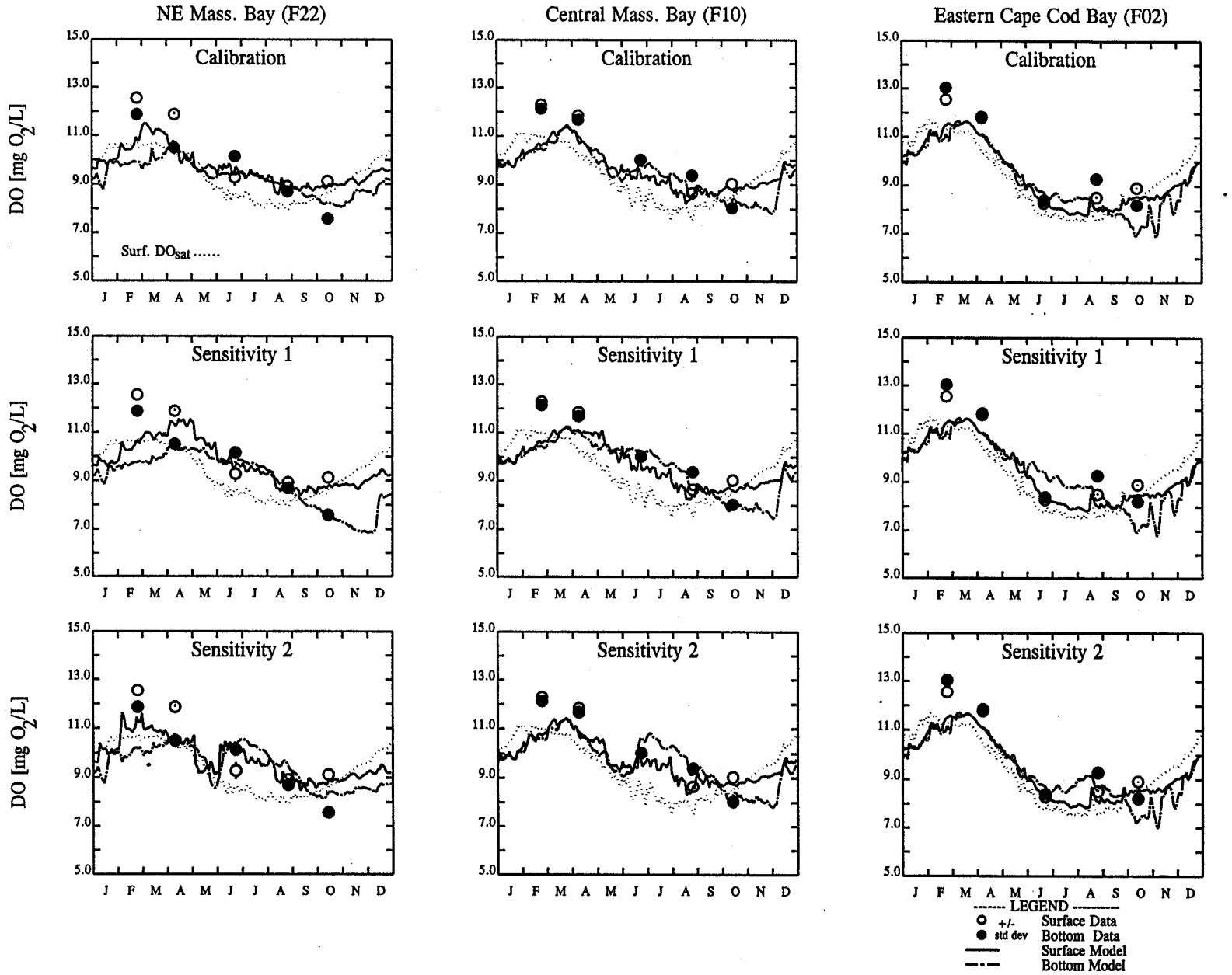

Figure 3-2. Temporal Comparison of Computed DO Concentrations Between the 1992 Calibration, DO Sensitivity 1 and DO Sensitivity 2 at Three Far Field Stations.

observed in the data. The differences between the DO declines from April to June observed at the various far field locations (F22, F10 and F02) are generally reproduced by the model. In sensitivity 1, the results are somewhat different from the calibration, but it could be argued that the comparison to the data is as good as the calibration's fit to the data. In northeastern Massachusetts Bay, the high February DO concentrations are not reproduced, but the April data comparison is improved. The results from the sensitivity in central Massachusetts Bay are similar to the calibration results with a notable difference being the slight decline in DO concentrations computed in the calibration in May. The calibration results and sensitivity 1 results are very similar in eastern Cape Cod Bay with the exception of the greater stratification computed in sensitivity 1 in the summer.

The sensitivity 2 results do not show the improvement in the far-field station calibration that was apparent at the near field stations. The results for the first four months of sensitivity 2 are similar to those from the calibration. The decline in DO specified in May at the boundary is observed in the model results in northeastern and central Massachusetts Bay, however, there are no data with which to compare the results. In June, the sensitivity 2 results overestimate the surface DO at station F22, but the remaining data are reproduced fairly well. The model compares favorably with the August data. In October, the difference between the surface and bottom DO concentration results is not reproduced as well as in the calibration at station F22. The October results at stations F10 and F02 are similar for sensitivity 2 and the calibration. As the results from the three model runs are quite similar in eastern Cape Cod Bay it appears that the boundary conditions do not have as much of an impact on the computed DO in this location. In eastern Cape Cod Bay, the dissolved oxygen concentrations closely follow the surface water DO saturation curve (shown as a dotted line on Figures 3-1 and 3-2).

The results from these modeling sensitivities indicate that the northeastern portion of Massachusetts Bay, and the near field are sensitive to the assigned boundary conditions, i.e., to dissolved oxygen imported from the Gulf of Maine. These boundary conditions appear to be the major factor that shapes the magnitude and temporal variability in the dissolved oxygen concentrations at these locations. The influence of the boundary conditions appears to diminish with distance from the northern boundary of Massachusetts Bay.

3.2 DISSOLVED INORGANIC NITROGEN

Unlike changing the DO boundary conditions, changing the DIN boundary conditions has an effect on other state-variables in the model. Nitrogen tends to be the limiting nutrient in Massachusetts and Cape Cod Bays. An exception is the short silica limitation, which occurs during spring diatom blooms. An increase in DIN at the boundary, therefore, increases the available nitrogen for the phytoplankton uptake, thereby increasing the phytoplankton biomass (assuming that nitrogen

is the limiting factor). Also, additional phosphorus and silica will be taken up by the phytoplankton, as available DIN increases. The increase in phytoplankton biomass changes the chlorophyll-a concentrations and can increase DO in the surface where photosynthesis occurs and decrease DO at the bottom where additional phytoplankton biomass undergoes respiration and decomposition once it settles to the sediment. In this section figures will be presented that illustrate the changes in DIN, chlorophyll-a and DO resulting from modifications to the boundary conditions.

Figure 3-3 presents a comparison between the 1992 calibration, sensitivity 1 (average DIN conditions 1994-99), and sensitivity 2 (20% DIN increase during the spring) at three near field locations. Under the average DIN boundary conditions, the decline in the DIN concentration in the spring occurs approximately two weeks later and the surface DIN remains higher than in the calibration run until May. The computed bottom DIN concentrations in sensitivity 1 are higher in April than the calibration, but remain lower than the calibration in the following months. The model results are not improved relative to the calibration by using average conditions. The sensitivity 2 results are higher in the bottom during the spring than the calibration, but the differences are small and are somewhat difficult to discern. For this reason, the results for sensitivities 2, 3 (20% increase in the summer DIN), and 4 (20% increase in the summer bottom DIN) will be presented via difference plots.

Figure 3-4 presents a comparison between the 1992 calibration, sensitivity 1 and sensitivity 2 at three far field locations. For sensitivity 1 in northeastern Massachusetts Bay, there is a large difference in the bottom DIN concentration as compared to the calibration. The calibration DIN bottom concentrations are much higher in May and in the fall. The surface DIN concentrations are higher for sensitivity 1 in the February through April time frame. However, the surface concentrations are similar between the two runs during the remainder of the year. In central Massachusetts Bay, the impact of the boundary is less noticeable as the calibration and sensitivity 1 results are quite similar. A peak in the bottom water DIN concentration in the May/June calibration results is the most obvious difference between the two runs. Further south, in eastern Cape Cod Bay, the differences between the two runs are less noticeable with small differences in the April DIN concentrations.

While sensitivity 1 is not drastically different from the calibration it does not compare as well to the data. Originally, it was hoped that using data closer to the boundary might improve the calibration even if they were not collected during the same year (1994-1999) as the calibration (1992). Apparently, there is enough variability at the boundary to justify year to year variability in the boundary conditions. Based on this result, no further analysis of sensitivity 1 was conducted. However, for completeness sake, additional calibration type figures will be presented later in this section.

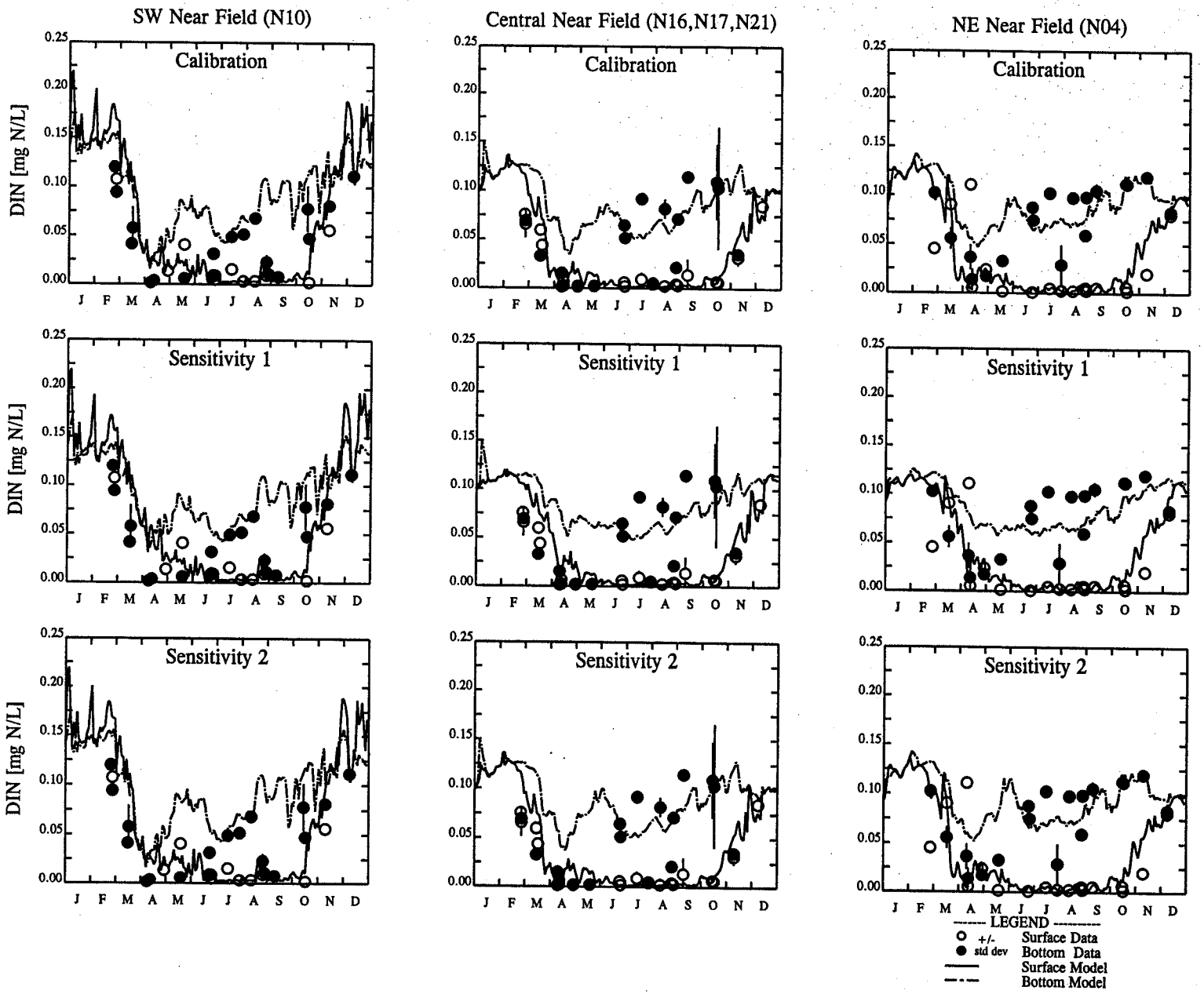

Figure 3-3. Temporal Comparison of Computed DIN Concentrations Between the 1992 Calibration, DIN Sensitivity 1 and DIN Sensitivity 2 at Three Near Field Stations.

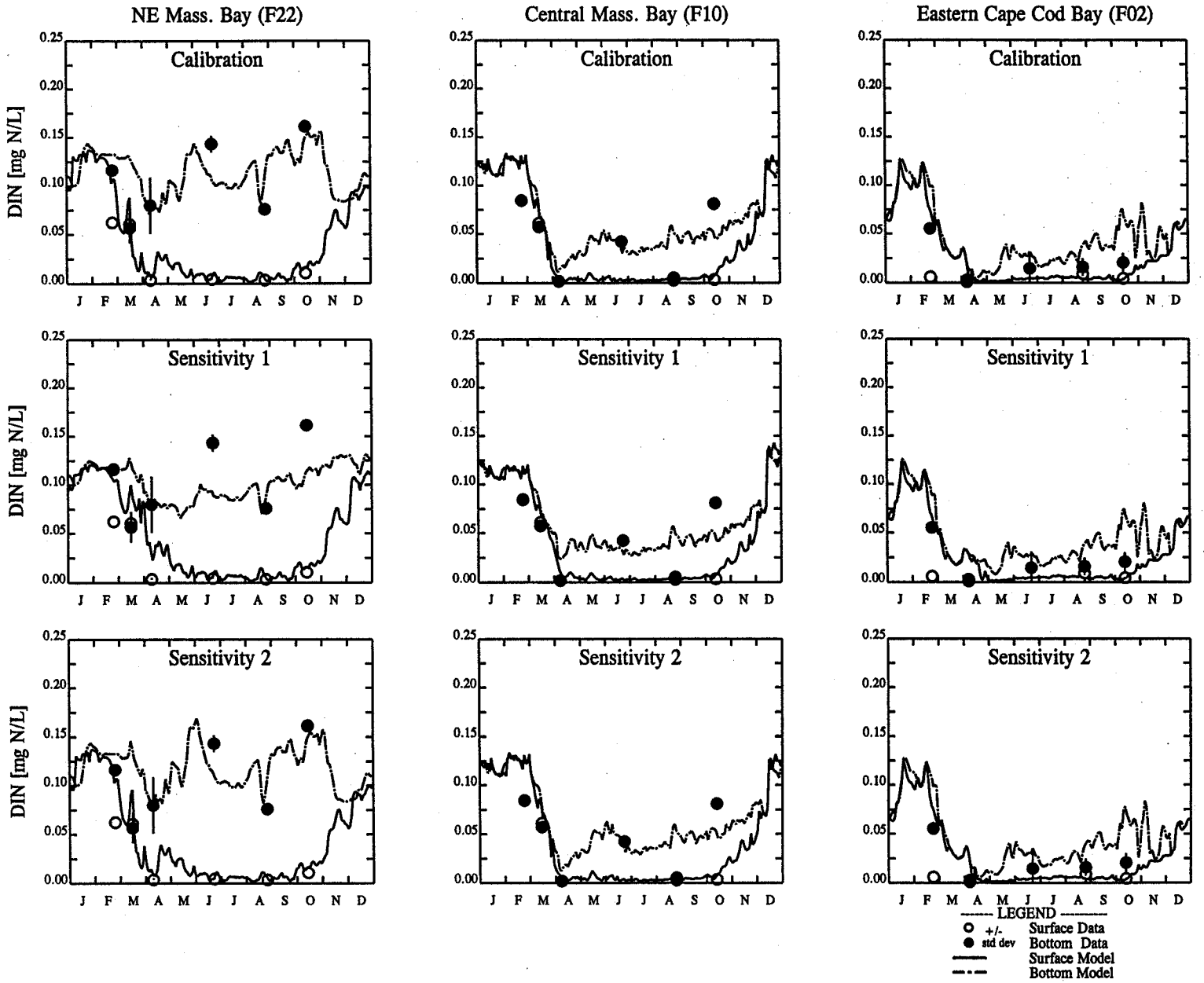

Figure 3-4. Temporal Comparison of Computed DIN Concentrations Between the 1992 Calibration, DIN Sensitivity 1 and DIN Sensitivity 2 at Three Far Field Stations.

Due to the difficulty of discerning the differences between the sensitivity runs when plotted using the model versus data figures, difference plots were developed to highlight differences between the calibration and the sensitivity runs. This was only performed for sensitivity runs 2 through 4 since these model runs were made using a fixed set percentage increase in boundary concentrations, relative to the calibration, and would therefore be easier to make a direct comparison as to the effect of the boundary condition changes. Figure 3-5 presents the net difference in DIN concentration at three near field locations. For sensitivity run 2, (the spring increase in DIN boundary concentrations run), there is little difference between the surface and bottom DIN concentrations during March and April when the water column is well mixed. During this period the increase in DIN concentration is less than 5 μg/L. As the system becomes more stratified, the difference in bottom water DIN concentrations increase. At the most north eastern section of the near field area, the bottom water DIN concentrations approaches 18 μ g/L. There is almost a factor of two difference between the change in bottom water DIN concentrations at the most north eastern location versus the most south western portion of the near field area. This can be explained by the fact that there is a large depth difference between the two locations and their respective proximities to the boundary.

For sensitivity run 3, the relative differences in bottom water DIN between the sensitivity run and the calibration are of approximately the same magnitude as computed under sensitivity run 2. However, computed differences in the surface layers are smaller. There are two reasons for this. The first is that summer surface DIN concentrations are lower than the spring time concentrations, so a 20 percent increase in the summer concentration does not produce as large a difference in the DIN concentration. Second, the system is more stratified during the summer when the boundary conditions were modified and increases in bottom water DIN tend to remain trapped below the pycnocline. The increases in bottom DIN concentrations for sensitivity run 3 approach the same magnitude as the increases in bottom DIN concentrations in sensitivity 2. The spatial pattern across the near field is also similar to sensitivity 2. Elevated DIN concentrations remain into December despite the return to the original boundary concentrations at the end of September. Sensitivity run 4 (change in bottom DIN boundary conditions only) looks quite similar to sensitivity run 3 (change in surface and bottom boundary conditions). However, both the surface and bottom DIN concentration increases are slightly lower in sensitivity run 4 relative to run 3. Since the near field area is only 15 to 35 meters deep the difference in the boundary concentration specified at the 20 meter depth (Level 2) could explain the difference observed at the bottom in these two runs.

Figure 3-6 presents differences in DIN concentrations between the calibration results and the results for sensitivities 2 through 4 at three far field locations. In northeastern Massachusetts Bay, closer to the boundary, higher increases in DIN are computed than were computed for the nearfield area. Increases in DIN concentrations of approximately 25 μ g/L are computed. The temporal pattern

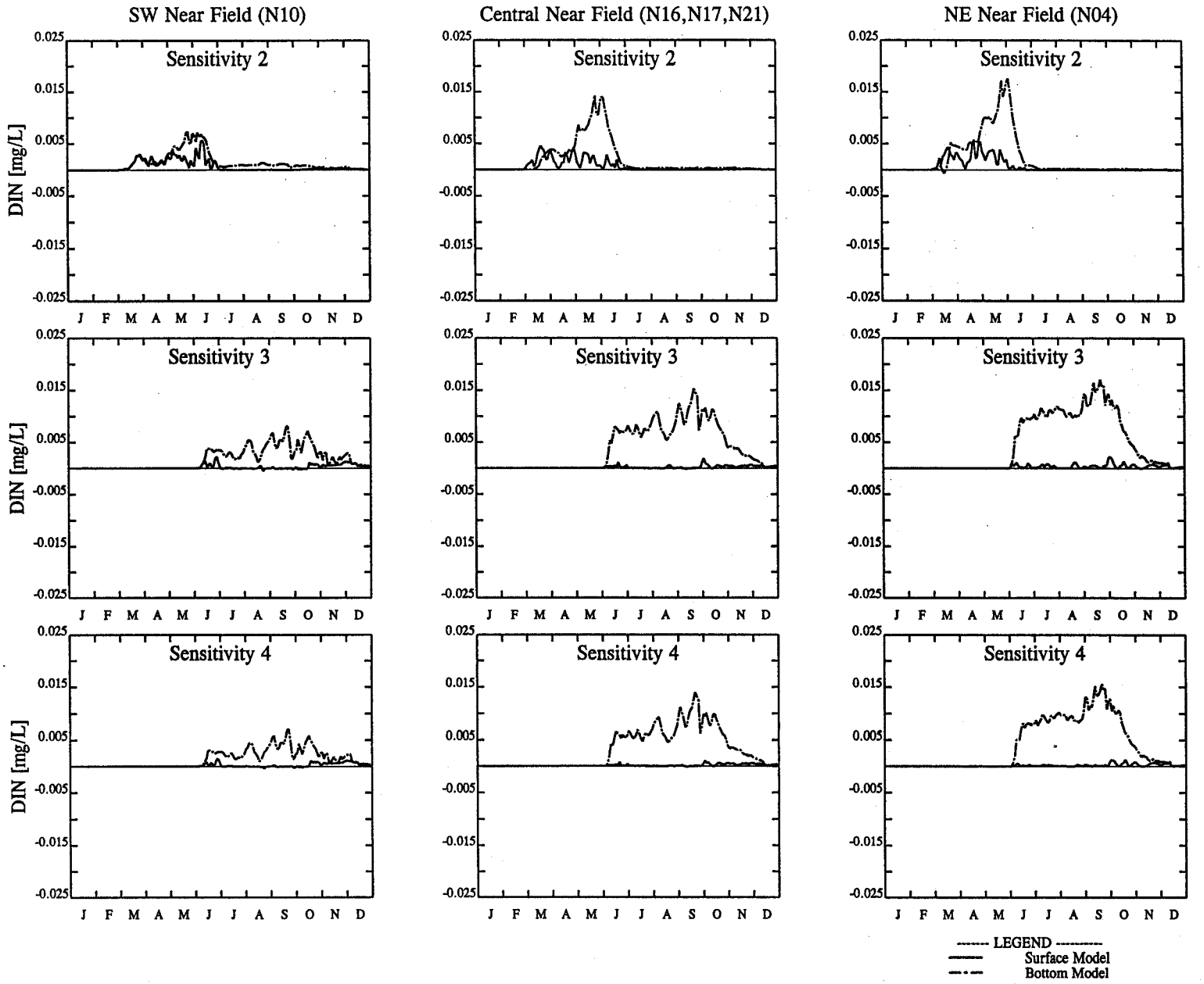

Figure 3-5. Net Difference in DIN Concentrations Between the 1992 Calibration and DIN Sensitivities 2, 3, and 4 at Three Near Field Stations.

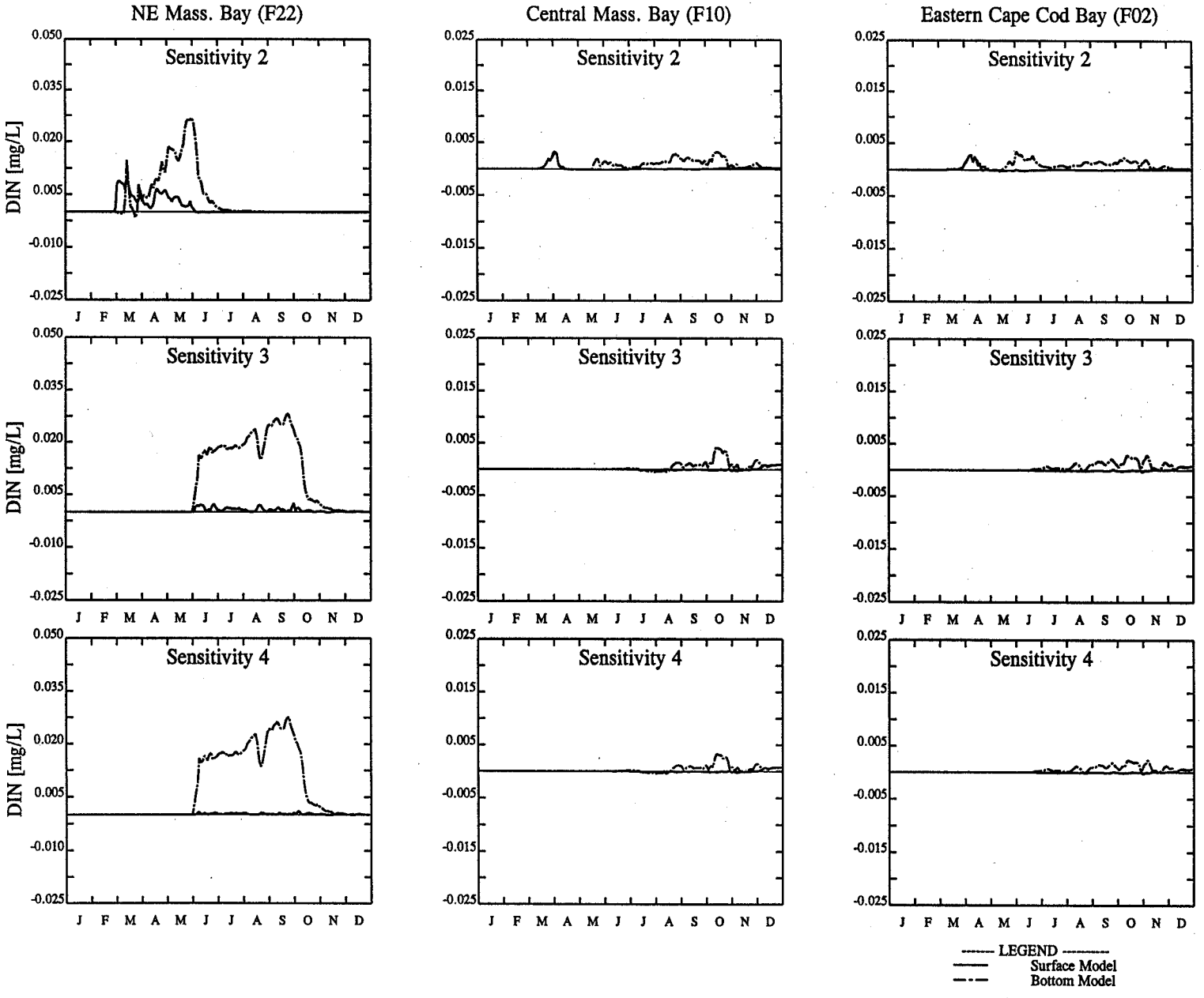

Figure 3-6. Net Difference in DIN Concentrations Between the 1992 Calibration and Sensitivities 2, 3 and 4 at Three Far Field Stations.

is quite similar to the nearfield area except that the elevated DIN concentrations do not persist as long after the concentrations of DIN are returned to their original calibration values.

In central Massachusetts Bay, the computed changes in DIN are relatively small, less than 5 μg/L in both the surface and the bottom. In fact, the only readily noticeable difference in the surface concentration is in the spring in sensitivity 2 when the water column is still well mixed. The increase in DIN persists longer in central Massachusetts Bay than in the northern portions of the bay. In eastern Cape Cod Bay the increase in DIN is also small, but again the effects of changing the boundary conditions are longer lasting.

Figure 3-7 presents the differences between the sensitivities and the calibration DIN concentration results at three near field stations, in terms of the percentage difference, since it is known that a 20 percent change in DIN concentrations was made at the boundary. In sensitivity 2, the surface DIN concentration generally remains at or below 20 percent during the time the boundary conditions were modified. In June the percentage increase increases above 20 percent. It is possible that this increase in surface DIN are due to upwelling events in June as indicated by the fact that the higher percentage increases are intermittent and are observed closer to the coast where upwelling effects are more pronounced. The percentage increase in the bottom DIN concentration increases fairly steadily during the period when the boundary concentrations were increased and remains below 20 percent.

In sensitivity 3, the same irregular behavior in the surface percent increases of DIN is observed in June. This spiked behavior also diminishes with distance from the shore again suggesting the influence of upwelling. At the south western corner of the near field the surface percentage increase in DIN concentration remains near zero while the bottom water percent increase is less than 10 percent. In the central near field the bottom water percentage increase is approximately 15 percent. In the northeastern portion of the near field the bottom water percentage increase remains near 18 percent while there is a more substantial percentage increase in the surface water than observed in the other locations. Results from sensitivity 4 are very similar to sensitivity 3; in sensitivity 4 smaller increases are computed, especially at the surface.

Figure 3-8 presents the percentage differences of DIN concentrations at three far field stations. In northeastern Massachusetts Bay, the results mimic the temporal changes in the boundary modifications. During the spring the surface water increase in DIN percentage is close to 20 percent for most of the season, while the bottom waters remain lower than 20 percent until the end of May. In sensitivity 3, the bottom water DIN concentrations stay elevated by almost a constant percentage of 20 percent. In sensitivity 3 there is probably some utilization of the extra DIN introduced into the system by phytoplankton to keep the DIN concentration increase below 20 percent.

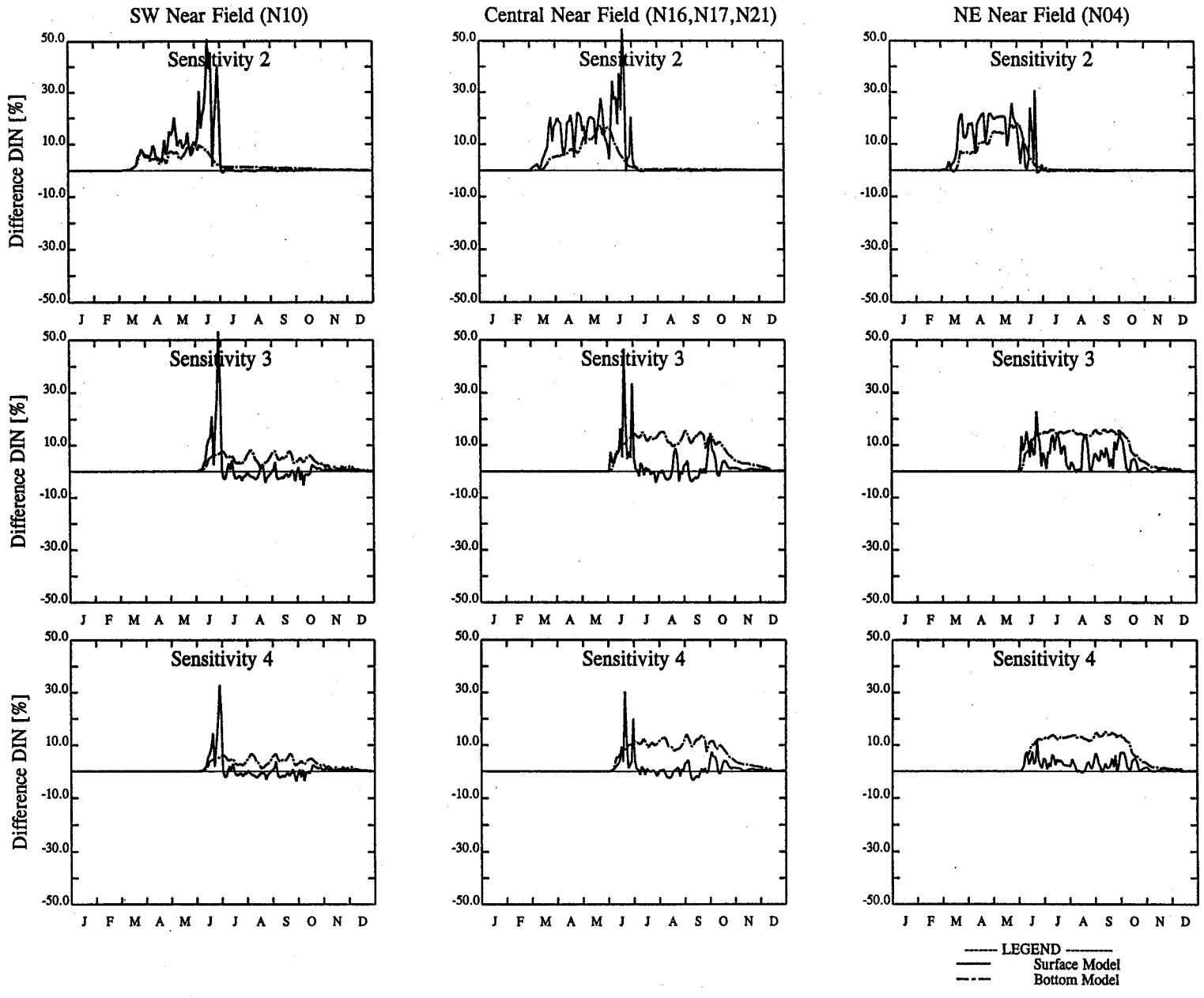

Figure 3-7. Percentage Difference in DIN Concentrations Between the 1992 Calibration and DIN Sensitivities 2, 3 and 4 at Three Near Field Stations.

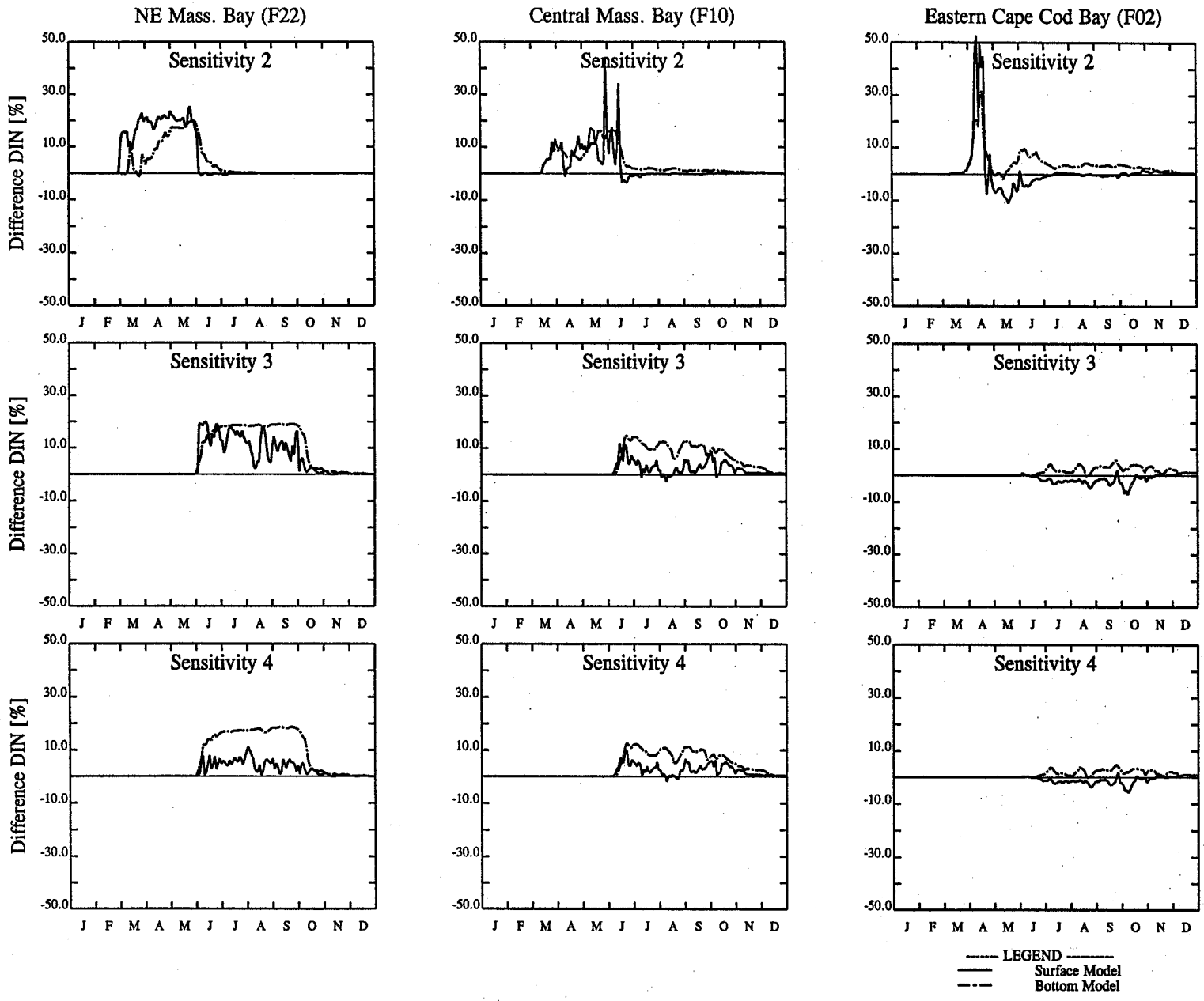

Figure 3-8. Percentage Difference in DIN Concentrations Between the 1992 Calibration and DIN Sensitivities 2, 3, and 4 at Three Far Field Stations.

In central Massachusetts Bay, sensitivity 2 shows similar percentage increases in the DIN concentration for both the surface and bottom ranging from 10 to 20 percent. However, there are two spikes in the percent DIN increase that occur in the surface waters in May and June. Sensitivity 3 and sensitivity 4 are quite similar. The increase in the bottom water is higher than at the surface with increases from 10 to 15 percent during the period when the boundary was modified. Elevated DIN concentrations remain until the end of the year.

In eastern Cape Cod Bay there is a large increase of greater than 50 percent that occurs during April in sensitivity 2. DIN concentrations are very low in Cape Cod Bay during this period in the calibration, so small changes make a big difference in the percentage increase. During the rest of the year, the increase in the bottom waters is less than 10 percent while there is actually a decrease in the surface DIN in the surface waters. This is also seen in sensitivities 3 and 4 were the bottom waters show a small (approximately 5 percent) increase and the surface waters show a decrease of similar magnitude.

The increased levels of DIN in the water column would be expected to cause more phytoplankton growth as the bays are often nitrogen limited during the periods when the boundary conditions were modified. A visual inspection of plots of the absolute chlorophyll-a concentrations for the calibration and the sensitivity runs showed little difference in chlorophyll-a levels (Figures 3-9 and 3-10). Therefore, it was decided to show resulting model computations using difference plots.

Figure 3-11 presents the changes in chlorophyll-a in comparison to the 1992 calibration at three near field locations for sensitivities 2, 3 and 4. The 20 percent increase in DIN at the boundary produces only a small change in the chlorophyll-a concentrations in the near field. In most cases the increase is less than 0.3 ug/L. In the south west corner of the near field, it is shallower so the chorophyll-a increase is similar at both the surface and bottom with the bottom chlorophyll-a levels increasing slightly more. At the other near field locations the surface chlorophyll-a concentration tended to increase more than the bottom.

The increases in chlorophyll-a at three far field stations are presented in Figure 3-12. In northeastern Massachusetts Bay, increases in the bottom chlorophyll-a are very small whereas the increases in the surface water chlorophyll-a are larger, but generally less than 0.20 ug/L. In central Massachusetts Bay, the increases in chlorophyll-a are larger than computed in northeastern Massachusetts Bay. The increases in the bottom chlorophyll-a tend to be larger then computed at the surface, yet the overall increases are generally less than 0.30 ug/L. For sensitivity runs 3 and 4 the increases in chlorophyll-a persist to the end of the year. In eastern Cape Cod Bay, the impact of the increased DIN concentrations at the boundary is greater in the spring (run 2) than during the summer

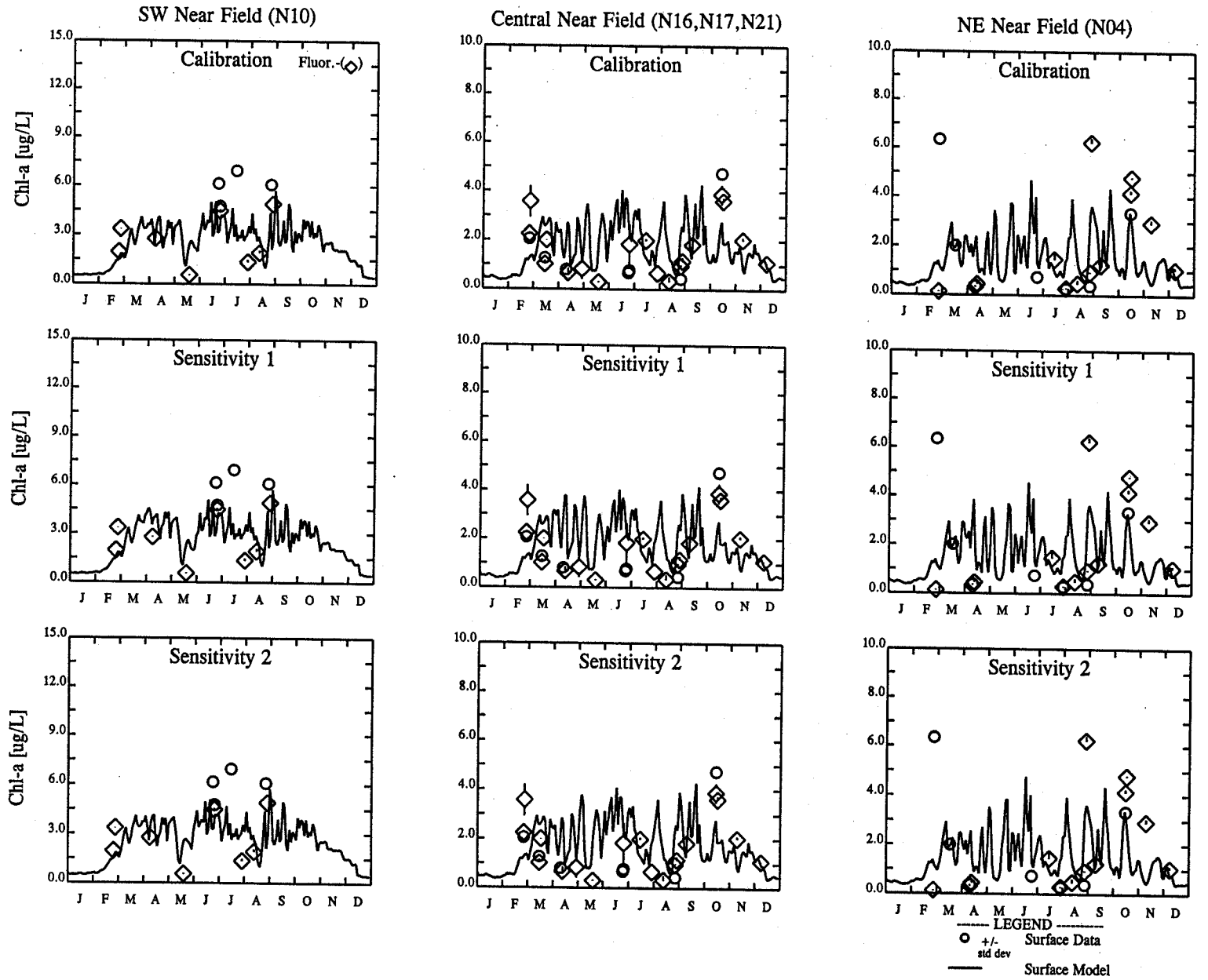

Figure 3-9. Temporal Comparison of Computed Chl-a Concentrations Between the 1992 Calibration, DIN Sensitivity 1 and DIN Sensitivity 2 at Three Near Field Stations.

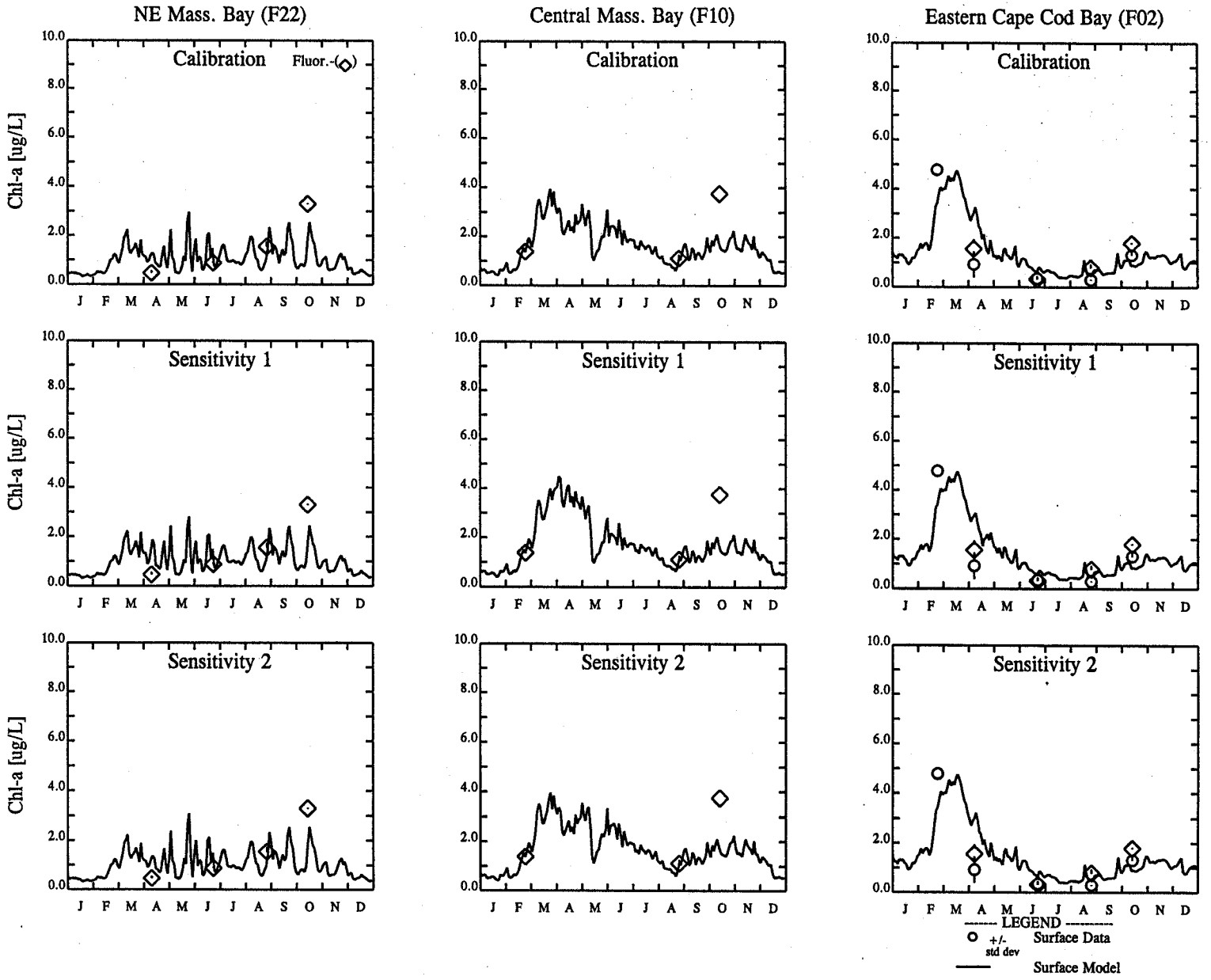

Figure 3-10. Temporal Comparison of Computed Chl-a Concentrations Between the 1992 Calibration, DIN Sensitivity 1 and DIN Sensitivity 2 at Three Far Field Stations.

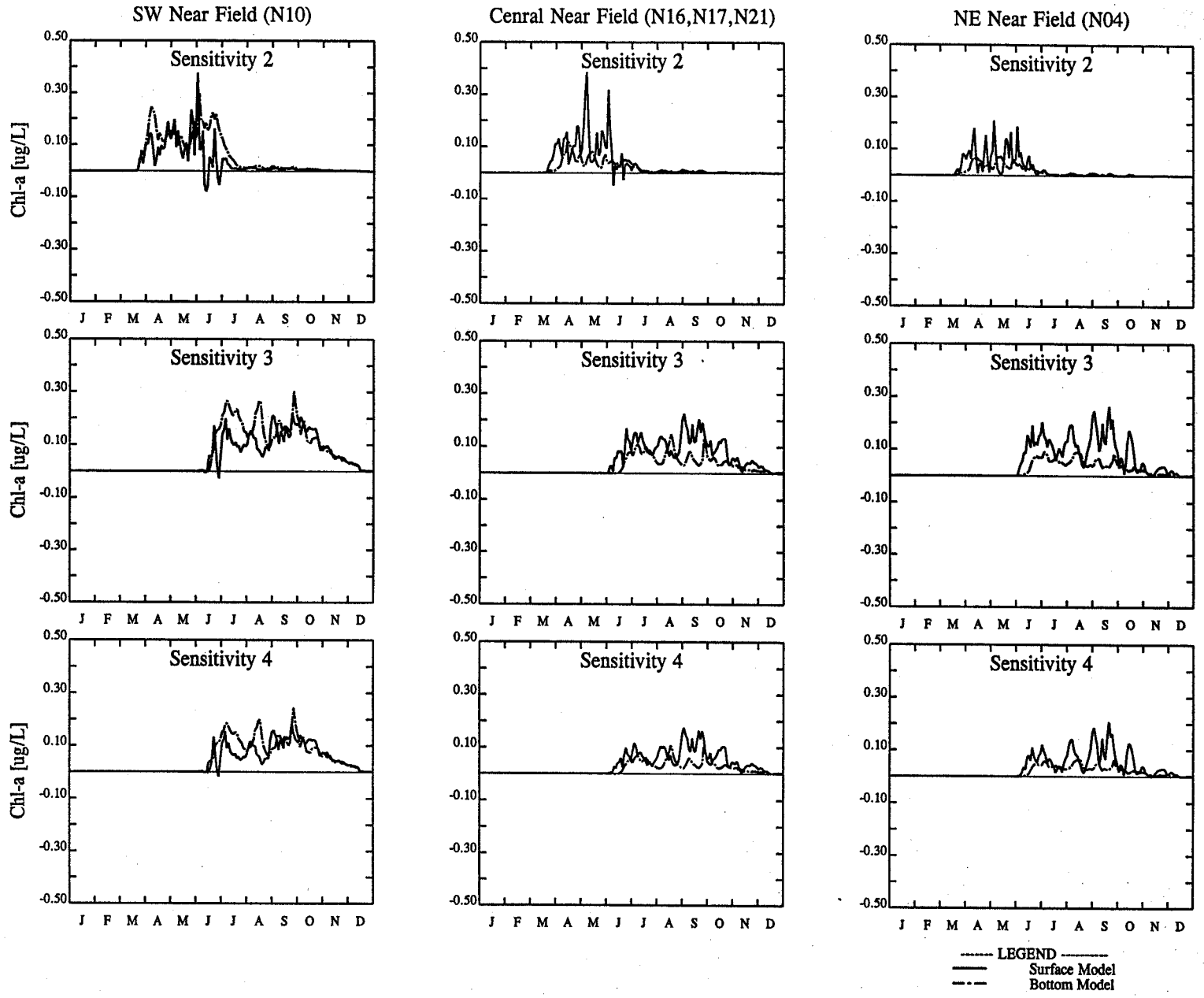

Figure 3-11. Net Difference in Chl-a Concentrations Between the 1992 Calibration and DIN Sensitivities 2, 3, and 4 at Three Near Field Stations.

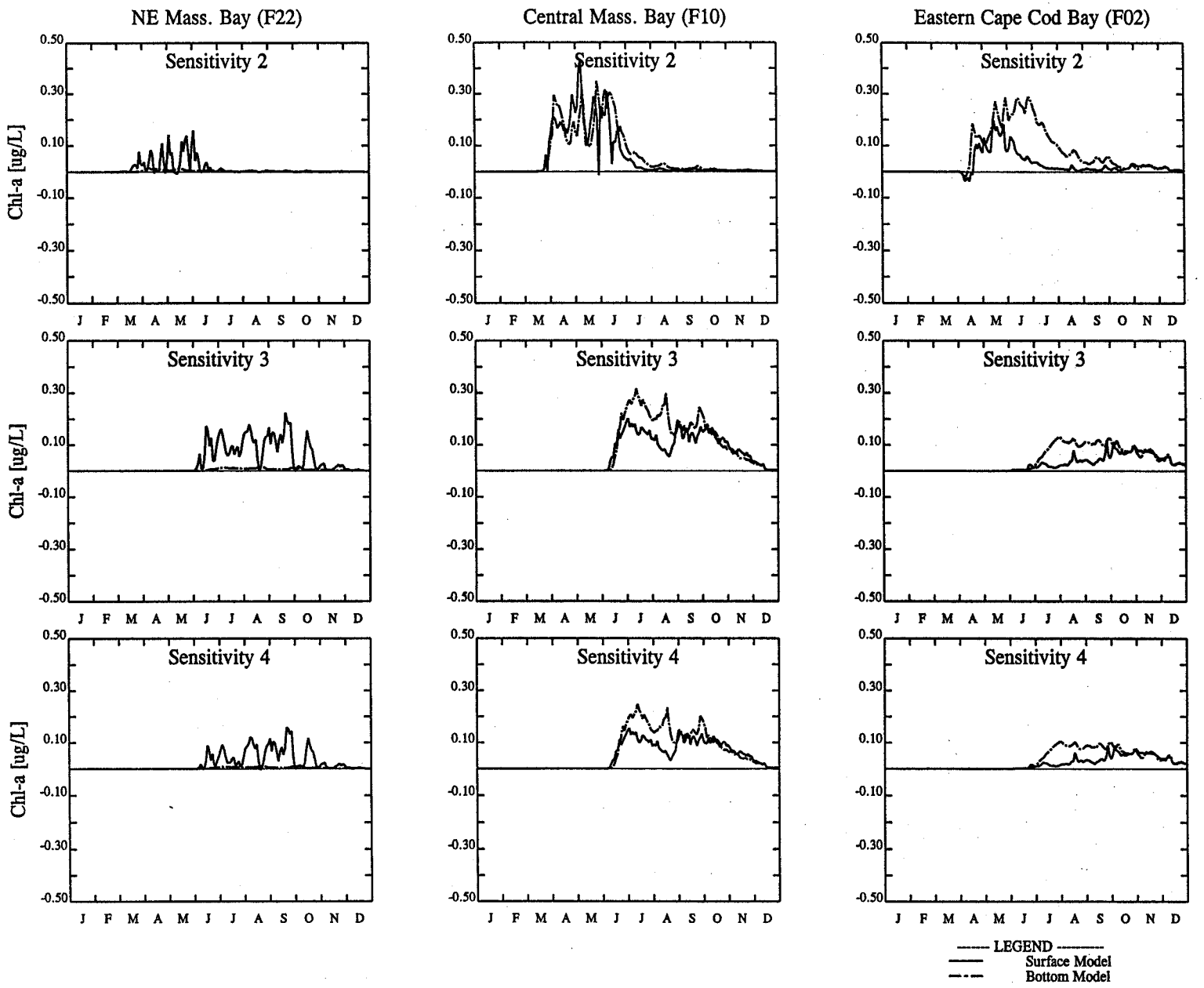

Figure 3-12. Net Difference in Chl-a Concentrations Between the 1992 Calibration and DIN Sensitivities 2, 3, and 4 at Three Far Field Stations.

(runs 3 and 4). The increases in chlorophyll-a, resulting from changes in boundary DIN in the spring persist well after the DIN concentrations were returned to calibration levels at the end of May. The largest increase in chlorophyll-a is computed in the bottom layer for sensitivity run 2. Yet, this increase is less than 0.3 ug/L. Changes in chlorophyll-a induced from modifications to the DIN boundaries in the summer period (runs 3 and 4) are not as large as compared to the spring (run 2). The bottom chlorophyll-a concentrations are again the ones that are computed to have a greater increase. This increase is less than 0.15 ug/L.

On a percentage basis, as shown in Figures 3-13 and 3-14, the increases in chlorophyll-a are less than 20 percent in the near field and far field. The computed range of increases in chlorophyll-a are generally between 5 to 15 percent. With the exception of the northeastern portion of Massachusetts Bay, which is deep and therefore the bottom is below the photic zone, the surface and bottom have very similar percent increases in chlorophyll-a.

The increases in boundary DIN concentrations have been shown to affect the chlorophyll-a concentrations in the bay. The increases in DIN and chlorophyll-a can in turn affect the concentrations of DO as a result of additional nitrification, photosynthesis and respiration of phytoplankton, and the decomposition of phytoplankton that may settle to the sediment.

Figures 3-15 and 3-16 present the computed differences between the calibration DO concentration and the DO concentrations computed for sensitivity runs 2 through 4. These figures show that the net effect is generally less than a 0.1 mg/L increase in DO. There are periods when a very small decrease is observed at the bottom. This decrease in DO is negligible. Since these changes in DO are very small when compared to the magnitude of the DO concentrations themselves, no percentage difference figures were created for DO.

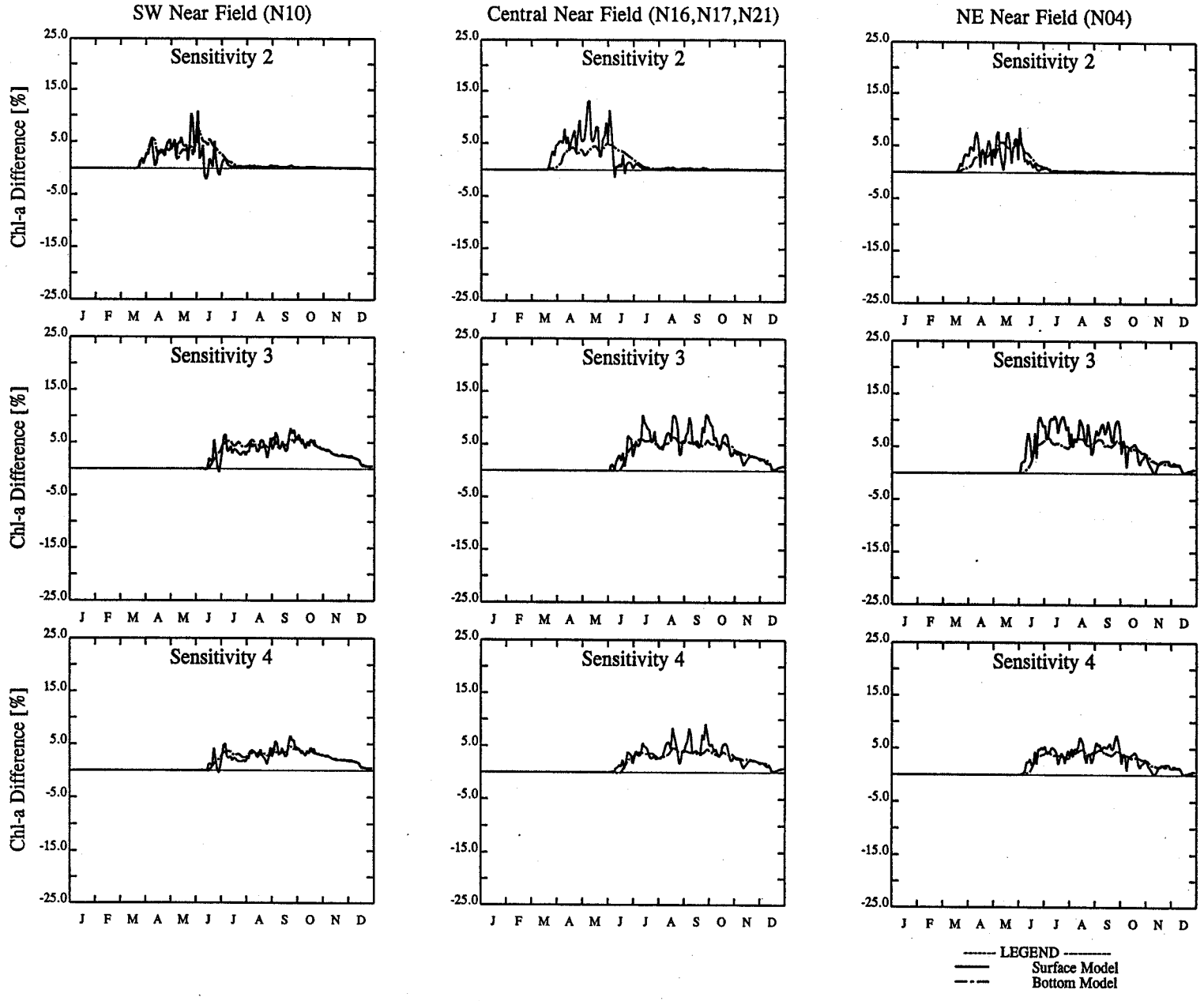

Figure 3-13. Percentage Difference in Chl-a Concentrations Between the 1992 Calibration and DIN Sensitivities 2, 3, and 4 at Three Near Field Stations.

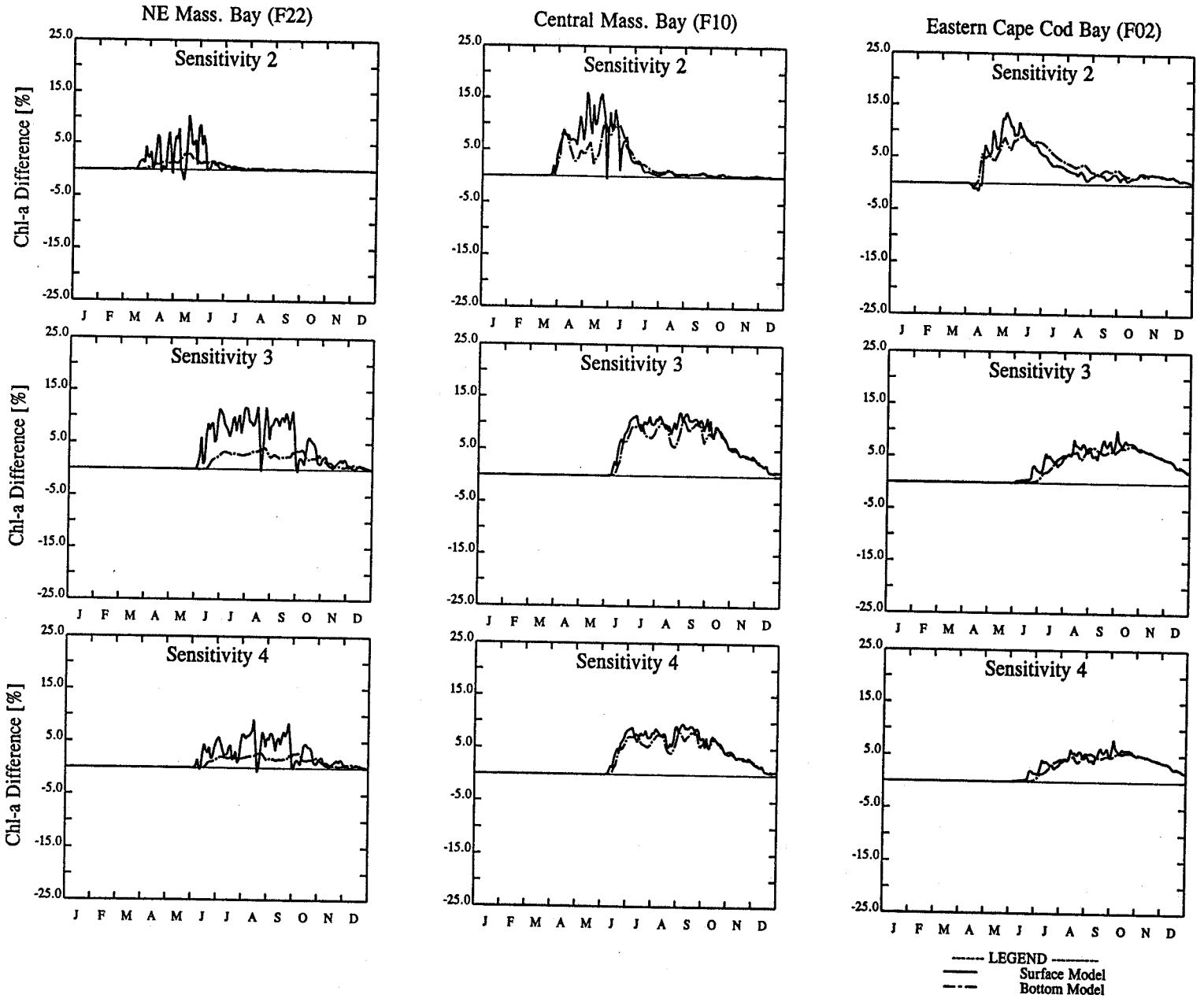

Figure 3-14. Percentage Difference in Chl-a Concentrations Between the 1992 Calibration and DIN Sensitivities 2, 3, and 4 at Three Far Field Stations.

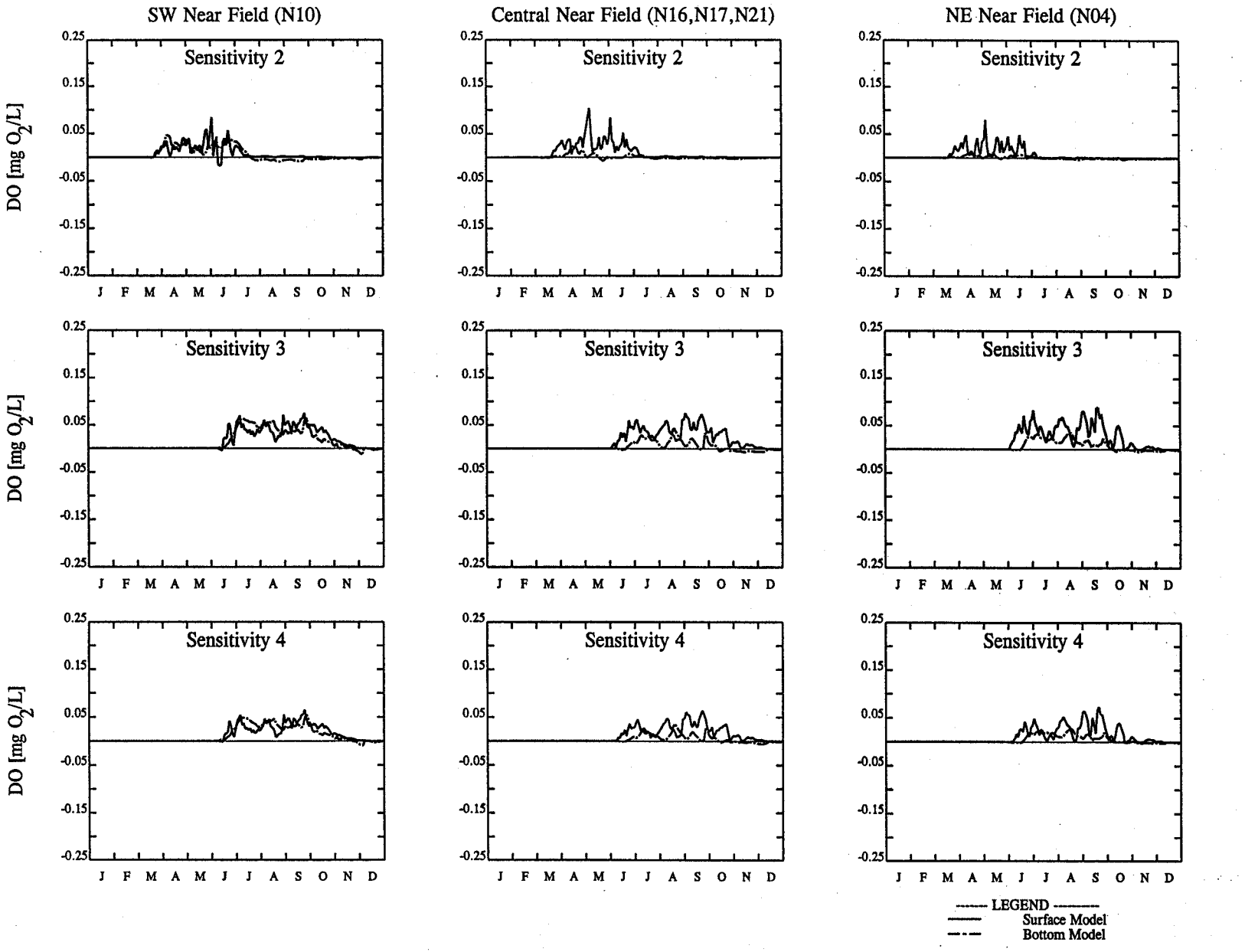

Figure 3-15. Net Difference in DO Concentrations Between the 1992 Calibration and DIN Sensitivities 2, 3, and 4 at Three Near Field Stations.

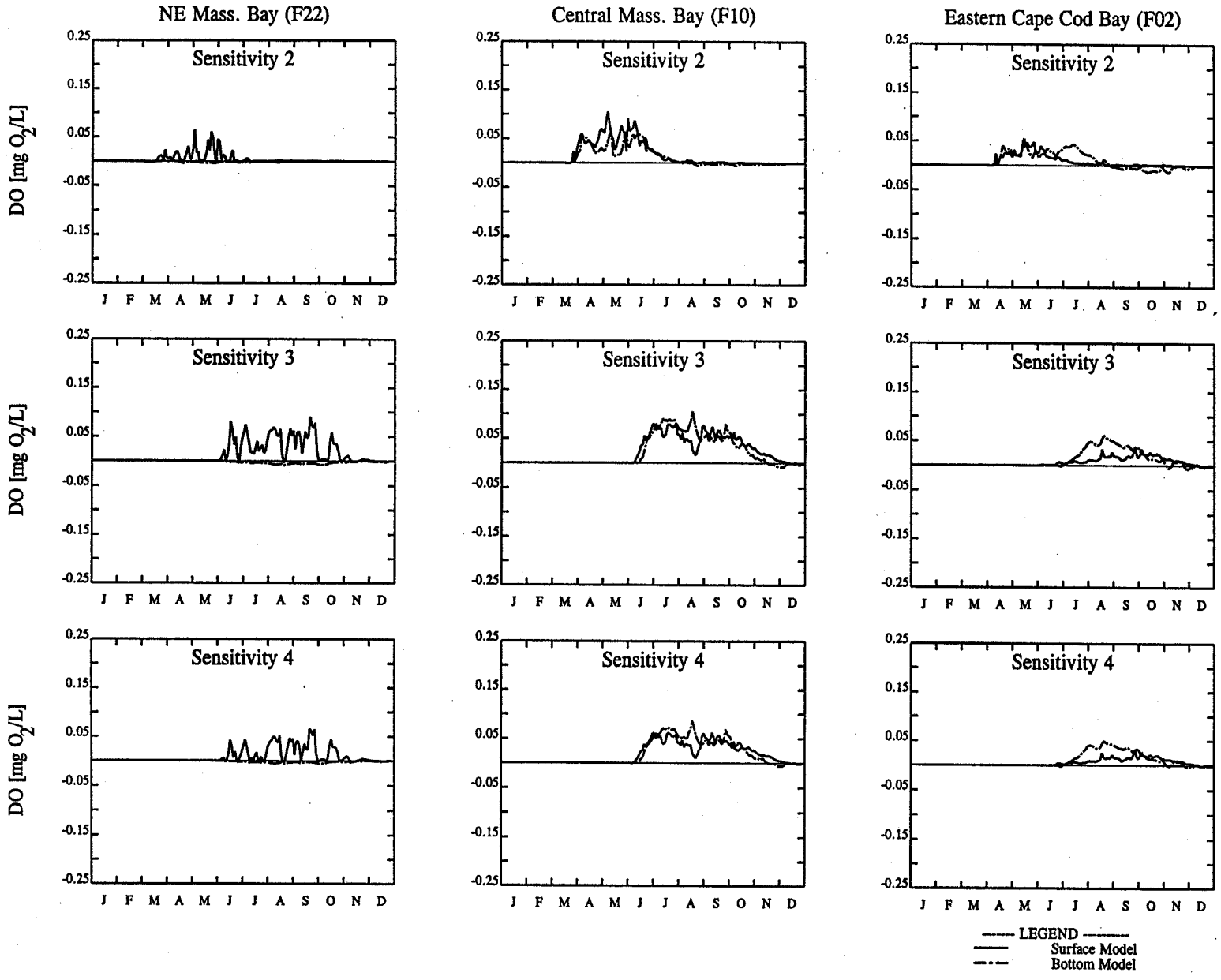

Figure 3-16. Net Difference in DO Concentrations Between the 1992 Calibration and DIN Sensitivities 2, 3, and 4 at Three Far Field Stations.

SECTION 4

CONCLUSIONS

Sensitivity analyses were conducted for dissolved oxygen and dissolved inorganic nitrogen to determine how important boundary conditions are in the results computed by BEM. Since more data have been collected since the 1992 model calibration was conducted, the additional data were analyzed to determine how the boundary conditions might vary. During this analysis it was determined that there is a strong correlation between the averaged monthly DO conditions observed in the near field and those observed at far field stations F26 and F27 close to the boundary. The DO data show that there is a fair amount of year to year variability in the timing and magnitude of the DO concentrations near the boundary. No correlation was found between the monthly averaged DIN concentrations collected at the near field and stations F26 and F27.

Using the conclusions of the data analysis, two DO sensitivity runs were conducted. The first run was conducted using averaged monthly concentrations at the near field stations from the period of 1994 through 1999 and a relationship of far field to near field data to specify the 1992 DO boundary conditions. This sensitivity produced unfavorable results in the near field area. South of the near field area the changed boundary conditions had less of an effect on the model results. The second sensitivity was conducted using a relationship between the near field DO data and the data collected at stations F26 and F27 from 1994 to 1999. This relationship was then used to create 1992 boundary conditions for DO using 1992 near field data. This sensitivity produced an improved comparison to the data in the near field than the calibration. South of the near field area, the changed boundary conditions had a smaller impact on the model results.

Based on the results of these sensitivities, it can be concluded that the model results for DO in the northern portion of Massachusetts Bay are highly dependent on the boundary conditions that are assigned. Model kinetics or "biology" appear to influence the DO computations more strongly in southern Massachusetts Bay and Cape Cod Bay. The model results support to the hypothesis that the decline and subsequent increase in DO concentrations observed in the near field area in the late spring of 1992 were caused by boundary influences rather than internal circulation and biology within the bays.

The lack of correlation between the near field and stations F26 and F27 for DIN led to a different choice of sensitivities for DIN assigned to the boundary. The first sensitivity was to assign averaged conditions from the period of 1994 to 1999 as the boundary conditions. The other three sensitivities involved percentage increases in the DIN boundary conditions used for the calibration. The

first of these was an increase in the DIN concentrations by 20 percent during the spring over the entire water column. The second was an increase of the DIN boundary conditions by 20 percent over the entire water column during the summer. The final sensitivity involved increasing the DIN concentration at the boundary during the summer at the bottom two standard levels.

The first sensitivity was conducted to determine if using average DIN concentrations at the boundary would be adequate for model calibration in 1992. When this sensitivity failed to produce satisfactory results, no further analysis of this sensitivity was conducted. For the remaining sensitivities an increase of DIN by 20 percent at the boundary generally produced less than a 20 percent increase in the DIN concentration in the near field area, although upwelling events did produce increases of DIN at the surface of greater than 20 percent. Generally, the increases in DIN at the surface were less than 20 percent, presumably due to uptake by phytoplankton. The influence of the boundary change was not seen as much in the southern half of the model domain.

The increase of DIN concentrations at the boundary did increase chlorophyll-a concentrations. The increases in chlorophyll-a concentrations were generally less than 0.5 ug/L which usually translated into an increase in the chlorophyll-a levels of 10 to 20 percent. Percent increases in chlorophyll-a were generally similar at the surface and the bottom except in deeper areas such as station F22. The increases in DIN at the boundary did little to affect the dissolved oxygen concentration in the bays. In general, there was an increase in the DO concentration by less than 0.1 mg/L. There were small decreases in the DO concentration in the bottom waters in the second half of the year in some cases. The decreases were in the range of 0.01 mg/L.

These boundary condition sensitivities provide further evidence of the importance of the boundary on conditions within Massachusetts and Cape Cod Bays, especially in the near field area. Data must continue to be collected in the northeastern portion of Massachusetts Bay near Cape Ann. These data will help provide insight as to whether or not conditions within the bay change due to boundary influences, or whether there is some impact from the newly relocated Deer Island Outfall.

SECTION 5

REFERENCES

HydroQual, Inc. and Normandeau Associates, 1995. A water quality model for Massachusetts and Cape Cod Bays: Calibration of the Bays Eutrophication Model (BEM). Boston: Massachusetts Water Resources Authority. Report ENQUAD 1995-08. 402 p.

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