Comparisons of model-predicted and measured productivity in Massachusetts Bay

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Comparisons of Model-Predicted and Measured Productivity in Massachusetts Bay

Prepared by:

Kenneth E. Keay[1]

Wendy S. Leo[1]

And

P. Scott Libby[2]

[1]Environmental Quality Department, Operations Division

Massachusetts Water Resources Authority

100 First Avenue, Boston, MA 02129

[2]Battelle

397 Washington Street, Duxbury, MA 02332

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1 INTRODUCTION

Revisions to MWRA's Ambient Monitoring Plan for the MWRA Effluent Outfall (MWRA 2010) were approved by regulators and became effective in December 2010; the changes included ending direct measurements of primary productivity, the rate of growth of marine plants in the presence of sunlight and nutrients. However, the Ambient Monitoring Plan Revision 2 does require MWRA to produce two reports on estimates of primary production. This report summarizes comparisons made between field measurements of primary productivity and those modeled using MWRA's water quality model, the Bays Eutrophication Model (BEM). MWRA is preparing a second report evaluating comparisons between productivity estimates and light-biomass models, for example BZ_pI_0 (Cole and Cloern 1987).

2 APPROACH

Methods and results from MWRA's primary productivity study are in numerous technical reports available on MWRA's website MWRA Environmental Quality Department Technical Reports List (for method details see Libby *et al.* 2005 Appendix C; results are reported in the annual Water Column Monitoring reports). Primary production was measured at two nearfield stations and one station at the mouth of Boston Harbor, using a small volume/short incubation time method (Lewis and Smith,1983) using procedures from Strickland and Parsons (1972). Details of the BEM and model results are also available on-line at MWRA's website MWRA Environmental Quality Department Technical Reports List. Field data from the ambient monitoring program, including primary productivity measurements, are maintained indefinitely by MWRA. However, outputs from BEM runs are not archived in electronic form. Consequently, this report excerpts and summarizes model-data comparisons that have been made in various modeling reports but does not contain any new comparisons.

It is important to note that the BEM and the hydrodynamic model that feeds it have evolved through time. Some of these changes, for example the addition of a third algal group before the model runs for calendar year 1998, have directly changed how the model calculates primary productivity. Other changes, for example changes to how boundary nutrient conditions are estimated between older and more recent model runs, have the potential to indirectly change model estimates of productivity. Because of this, the model runs MWRA has conducted to date do not have a completely consistent primary productivity formulation, and the year by year comparisons made in existing model reports are the best that are available. It is also worth noting that no BEM runs were conducted for 1995 through 1997, so there are no model-data comparisons available for those years.

The following section provides a summary of the numerous comparisons that have been conducted between modeled and measured productivity by MWRA between 1992 and 2010. Attachment A contains, for reference, relevant text, figures and tables from MWRA technical reports.

3 MODEL-DATA COMPARISONS

Early reports on model-data comparisons suggested that BEM estimates of net primary productivity reproduced much of the seasonal pattern observed in field productivity measurements, but that model estimates tended to be lower and less variable than the measured data through 1992 (Hydroqual and Normandeau 1995).

A report on BEM runs for 1992-1994 (Hydroqual 2000) drew similar conclusions for the model-data comparison for data through 1992 and for the 1993 comparisons, but noted that the modeled productivity for 1994 (both gross and net) tended to be higher than field measurements, especially for the second half of the year (Hydroqual 2000).

Two teams conducted model runs for 1998 and 1999. Hydroqual (2003) found that the model substantially over-predicted field measurements for most surveys and stations in 1998, but was in much better agreement with field measurements in 1999, especially at the two nearfield stations. The report goes on to note that the BEM successfully reproduced other features observed in the data, for example that 1998 had much lower winter-spring productivity than 1999 (Hydroqual 2003). The second team modeled calendar years 1998 and 1999 as a model validation exercise to ensure they were running the model the same way as had been done before. Jiang and Zhou (2003) did not directly compare modeled productivity estimates to field data, but did compare their projections to those of the Hydroqual team. The teams' gross and net productivity estimates were nearly identical (Jiang and Zhou, 2003).

BEM runs for 2000 substantially over-predicted primary productivity at the Boston Harbor station through most of the year, but were in fair agreement at the two nearfield stations at which field measurements were made, though the model did not reproduce the substantial blooms that were observed at one nearfield station (Jiang and Zhou 2004). The model did a somewhat better job of reproducing field measurements for the 2001 data (Jiang and Zhou 2004).

Observations similar to these were made in more recent BEM reports in which measurements of primary productivity have been compared to model projections. In some years at some stations (e.g. station F23 in 2002) (Jiang and Zhou, 2006) field data from a station appeared to match the model projections moderately closely, while other station-years (e.g. Station N04 in 2007, Tian *et al*. 2009) the model projections exceeded measured productivity for almost the entire year.

In addition to the visual comparisons of time-series of measured and projected primary productivity, BEM reports have included other relevant evaluations. BEM runs for calendar years 2002 through 2005 (Jiang and Zhou 2006, 2008) included exploratory regression analysis between modeled and measured estimates of primary productivity at the nearfield stations. These analyses suggest a modest positive correspondence between the modeled and measured productivity, with an R^2 ranging from 0.15 for 2002 data to 0.37 for the 2003 data. The best fit lines for all four years suggest that BEM projections over-predicted field measurements of productivity in the nearfield (Jiang and Zhou 2006, 2008).

Model-data comparisons of primary productivity for the 2002 through 2004 data were also included (among other parameters computed by the BEM) in a series of sensitivity analyses conducted by Jiang and Zhou (2006). These sensitivity analyses evaluated the impact of using the Platt *et al.* (1980) formulae for phytoplankton growth, rather than the Laws and Chalup (1990) formulation built into the BEM, and also included an evaluation of the sensitivity of the BEM to the inclusion of nitrogen in

MWRA's effluent (Jiang and Zhou, 2008). These sensitivity analyses suggested that the addition of effluent nutrients had had only a minor effect on nearfield productivity.

In addition to conducting model-data comparisons using the 2006 and 2007 measured and modeled productivity results, Tian *et al*. (2009) carried out a similar sensitivity exercise evaluating the inclusion or exclusion of effluent nutrients. As seen in many previous comparisons, the model tended to over-predict productivity compared to the measurements at the three stations where productivity is measured, for almost all surveys for those two years. Also, as observed in previous sensitivity evaluations, the inclusion of nutrients from MWRA effluent had only a modest impact on modeled productivity in the 2006 and 2007 runs.

Model-data comparisons for 2009 and 2010 showed that modeled productivity was relatively close to field measurements at the Boston Harbor station. However, at the two nearfield stations where field productivity measurements were made, the model tended to over-predict measured productivity during most surveys (Tian *et al.* 2011).

4 MODEL ASSESSMENT

As with many of the biological parameters (i.e. chlorophyll and particulate organic carbon (POC)), the BEM has shown a relatively high degree of variability in its capability to reproduce features observed in the monitoring data such as winter/spring and fall blooms. As noted earlier, except for the early years of monitoring (up through 1992), the BEM typically overestimates primary production and often misses or mistimes major, sporadic bloom events. It is unclear why BEM seems to have underestimated productivity for the earlier datasets. However, since this finding is based on comparisons against older datasets that were not modeled (1973-74 (Parker 1974) and 1987-88 (MWRA 1988, 1990)) and the 1992 dataset that used oxygen methods to estimate primary production, these earlier comparisons are not included in our model assessment.

For 1993-94 and 1998-2010 comparisons, the BEM tended to overestimate productivity. Table 1 presents a qualitative review of the modeling estimates of primary production from 1998-2010. The 1993-1994 modeling reports do not provide plots comparing modeled and observed primary production and have not been included in Table 1. Based on this review, the tendency to overestimate productivity switched between station F23 near the mouth of Boston Harbor and the nearfield station depending on which models were used for the BEM. In 1998-2007, the Estuarine and Coastal Ocean Model-semi-implicit hydrodynamic model (ECOM-si) driving the Row Column Advanced (RCA) water quality model was used to model the system. In 2008 and after, the BEM was switched over to a Finite-Volume Coastal Ocean Model hydrodynamic model (FVCOM) driving an unstructured-grid version of RCA water quality model (UG-RCA). The comparability of model results using the two modeling approaches has been verified (Chen *et al.* 2010), but there may be slight differences in how the two approaches estimate primary production in the harbor and nearfield areas.

Table 1. Qualitative review of model-data comparisons for 1998-2010 at stations F23, N18, and N04.

Year	F23 (mouth of Boston Harbor)	N18 (2.5 km south of outfall)	N04 (7 km northeast of outfall)	Modelers	Model
1998	Poor - overestimated	Good - low prod year	Good - low prod year	HydroQual	ECOMsi/RCA
1999	Fair - captured spring peak, overestimated 2nd half year	Good - missed August peak	Good - followed seasonal trends and levels	HydroQual	ECOMsi/RCA
2000	Poor - missed spring peak, overestimated rest	Fair - captured peaks in spring, but missed summer and fall peaks	Good - followed seasonal trends and levels	UMass-Boston	ECOMsi/RCA
2001	Good - most of year, overestimated fall levels	Good - only missed December peak	Good - only missed December peak	UMass-Boston	ECOMsi/RCA
2002	Poor - missed spring peak and overestimated summer and fall	Fair - missed seasonal peaks and overestimated in fall	Fair - missed seasonal peaks and overestimated in fall	UMass-Boston	ECOMsi/RCA
2003	Fair - captured lower levels in winter and spring, overestimated 2nd half year	Good - slight overestimate in summer	Good - though showed some peaks that were not captured in observations	UMass-Boston	ECOMsi/RCA
2004	Fair - captured levels in winter and spring, overestimated 2nd half year	Good - though showed spring and fall peaks that were not captured in observations	Good - though showed spring and fall peaks that were not captured in observations	UMass-Boston	ECOMsi/RCA
2005	Fair - generally matched with observed, but much more variable and higher between surveys - odd	Fair - generally matched with observed, but much more variable and overestimated summer	Fair - generally matched with observed, but much more variable and overestimated summer	UMass-Boston	ECOMsi/RCA
2006	Good - slight overestimate, especially winter/spring	Fair - overestimated winter/ spring and fall blooms	Fair - overestimated winter/ spring and fall blooms	UMass-Dartmouth	ECOMsi/RCA
2007	Good - slight overestimate, especially winter/spring	Good - slight overestimate, especially winter/spring	Fair - overestimated winter/ spring and fall blooms	UMass-Dartmouth	ECOMsi/RCA
2008	No productivity comparison in modeling reports			UMass-Dartmouth	FVCOM/ UG-RCA
2009	Very good - captured overall levels and seasonal trends	Poor - good early and late with low production, but overestimated summer and missed October peak	Fair - good early and late with low production, but overestimated summer	UMass-Dartmouth	FVCOM/ UG-RCA
2010	Very good - captured overall levels and seasonal trends	Fair - captured peaks, but overestimated other periods	Fair - captured spring peak, but overestimated other periods and had a number of high peaks	UMass-Dartmouth	FVCOM/ UG-RCA

The ECOM-si/RCA approach tended to do a better job at estimating primary productivity at the nearfield stations than at station F23 (Table 1). In the harbor, the model tended to overestimate primary productivity over most of the 10 years from 1998-2007, while it often did a good job capturing most of the variability and magnitude of primary production in the nearfield. For 2009-2010, FVCOM/UG-RCA did a very good job capturing the overall levels and seasonal patterns at harbor station F23, but overestimated productivity in the nearfield.

Jiang and Zhao (2003) noted that one of the possible reasons that BEM (ECOM-si/RCA) overestimated productivity in 1998 and 1999 at station F23 is that the model may be using inadequate light attenuation coefficients (i.e. the water in these shallow areas may be more turbid than the model is considering) and that the geographically specific base coefficient (K_{ebase}) used in the harbor (and other shallow waters) may need to be modified. Chen *et al.* (2010) note that FVCOM/UG-RCA is structurally better suited for modeling shallow, heterogeneous shorelines such as Boston Harbor due to having much higher spatial resolution. The model also has the capability to use multiple light attenuation functions, that may result in the apparent improvement in productivity modeling in shallow harbor waters.

Another factor affecting the models ability to estimate productivity is the growth formulae that are being used within the models. Jiang and Zhou (2006) evaluated the sensitivity of model productivity estimates to using the Platt *et al.* (1980) phytoplankton growth formulae instead of Laws and Chalup (1990). The Platt *et al.* (1980) equations are the same set used to calculate productivity based on the field measurements/incubation experiments (see Libby *et al.* 2005 for details). When applied in the model for 2003, the Platt et al. equations improved the comparison of model vs. observed production primarily by reducing production during periods of model overestimation (Figure 4.10 in Jiang and Zhou 2006). Although Laws and Chalup (1990) appears to continue to be the default set of equations, FVCOM/UG-RCA does have the option of using a “standard” set of phytoplankton growth functions. The use of this set of growth equations should be evaluated and considered if model estimates of productivity are to be used as a proxy for measured productivity in the future.

There are other differences in how the two modeling approaches function; one that could be germane to this evaluation is the use of total short-wave radiation and photosynthetically active radiation (PAR) to drive phytoplankton growth. Chen *et al.* (2010) discuss this change and show that there are no differences in model output for chlorophyll, dissolved inorganic nitrogen, or dissolve oxygen (Figure 3.22 in Chen *et al.* 2010). It is unclear how this change might affect production, but the lack of an impact on chlorophyll suggests it should be minimal.

Most of the productivity comparisons discussed in the various modeling reports focus on direct comparisons of the year long model output against the individual survey observations at each station. One of the drawbacks of productivity field measurements is the cost and thus the inability to make high resolution measurements (i.e. only three stations a few times a year). Although the model may not be getting the timing of events consistently, the use of an annual light field and calculation of productivity on a daily basis compared to the less frequent field observations may provide adequate estimates of monthly mean or annual mean production. Jiang and Zhou (2006) present a statistical analysis looking at correlations between monthly mean primary productivity values (monthly averaged model values vs.

monthly average of interpolated observed values). All three years (2002-2004) examined showed significant correlations between the monthly values with correlation coefficients of 0.15, 0.37, and 0.25, respectively (see Figure 3.26 in Jiang and Zhou 2006). They provided a table in the report from which the plots in Figure 1 were prepared (Table 3.2 from Jiang and Zhou 2006 is provided in the appendix).

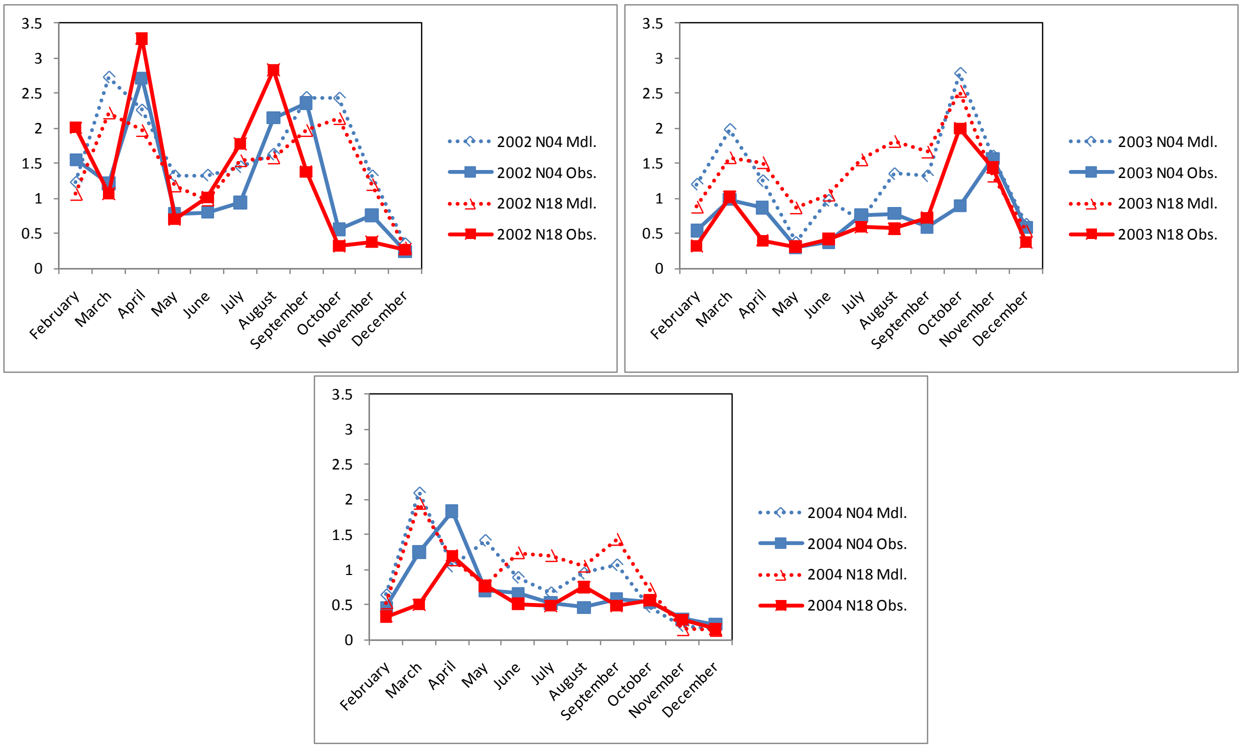

Figure 1. Monthly mean production (gC m^{-2} d^{-1}) at stations N04 and N18 for 2002, 2003, & 2004. Values calculated as average of modeled results and interpolated over the year for observed results.

As with the direct comparison of model and observed results, there is variability between the monthly means and, except for the bloom events with high observed productivity, the model tends to overestimate the observed values (Figure 1). However, a qualitative review of the various plots shows that the model and observations match up more closely within years than between years suggesting that the model is capturing some of the natural variability in productivity. For example, although the model missed the timing of the spring and fall blooms some years, it did capture the relative magnitude of the blooms with large spring and fall blooms in 2002, larger fall bloom (compared to spring bloom) in 2003, and the larger spring bloom (compared to fall bloom) in 2004 (Figure 1). The statistical analyses conducted by Jiang and Zhao (2006, 2008) are the only time monthly mean values were calculated or examined. The thought has always been “if we can’t figure out how to get the model to match the observed trends then how can we expect to understand what comparisons of monthly or annual mean values actually mean”. However, given the difference in “sampling” resolution between the model and field, it might make more sense to examine these mean values than to continue trying to match up specific points – especially since the model does a moderately good job of capturing the yearly variability in productivity. Any future modeling efforts should provide estimates of monthly mean production for comparison with observed trends in phytoplankton abundance and chlorophyll concentrations – the current indicators of bloom events.

5 SUMMARY

The BEM predicts primary productivity that is generally within a factor of about two of the range observed in the field data. Additionally, model runs tend to reproduce some seasonal features observed in the field data, such as higher productivity in spring versus winter. Other features observed in the field data, such as individual blooms, are not consistently reproduced in the model. Neither data (Libby *et al.* 2011) nor model (Zhao *et al.* 2011) show changes in productivity or in levels of chlorophyll in western Massachusetts Bay due to the outfall discharge.

The most common observation from the model-data comparisons is that for most stations and most surveys, model predictions tend to be higher than field measurements of productivity. Technological advancements in modeling have been incorporated into the BEM and recent runs using the FVCOM/UG-RCA models suggest that it can get a better handle on productivity in the shallow coastal waters. This model configuration also has additional capabilities to explore its sensitivity to various light attenuation and phytoplankton growth functions.

Although primary productivity is no longer measured as part of the HOM program, comparison of modeled production, especially as monthly mean production, with observed productivity analogs (i.e. phytoplankton abundance) would continue to help inform data interpretation and understanding of the Massachusetts Bay system.

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7 APPENDIX A

Appendix A: **Summary of existing analyses comparing BEM productivity results with measurements**

This document contains text, figures, and tables relevant to those model-data comparisons which were done using the BEM.

The model framework was modified between the 1994 and 1998 runs (addition of third algal group) and between the 2007 and 2008 model runs (change to new hydrodynamic model and unstructured grid), as well as other changes such as grid refinements over the years.

1992 productivity measurements were made using the dissolved oxygen method, all other years with ^{14}C.

1989, 1990, 1991

Growth Equations HydroQual (1993))

This report uses 1989-91 data, but does not discuss primary productivity. The monitoring program had not begun yet.

For reference here are the original growth equations from HydroQual (1993).

TABLE A-2. PHYTOPLANKTON NET GROWTH EQUATIONS

Net Growth Rate

$$S_P = (G_{Pmax} \bullet G_T(T) \bullet G_I(I) \bullet G_N(N) - k_{PR}(T) - k_{sP}(T) - k_{grz}(T)) \bullet P_c$$

Temperature Correction

$$G_{Pmax}(T) = G_{Pmax}(T_{opt}) \bullet \theta_P^{(T-T_{opt})} \qquad T \leq T_{opt}$$

$$G_{Pmax}(T) = G_{Pmax}(T_{opt}) \bullet \theta_P^{(T_{opt}-T)} \qquad T > T_{opt}$$

Light Reduction

$$G_I(I) = \frac{ef}{k_e H} \bullet (e^{-\alpha_1} - e^{-\alpha_0})$$

$$\alpha_1 = \frac{I_o}{I_s} e^{-k_e H} \qquad \alpha_o = \frac{I_o}{I_s}$$

$$k_e = k_{e_{base}} + 1{,}000\ k_c \bullet P_c / a_{cchl}$$

Nutrient Uptake

$$G_N(N) = \mathrm{Min}\left(\frac{DIN}{K_{mN} + DIN}, \frac{DIP}{K_{mP} + DIP}, \frac{Si}{K_{mSi} + Si}\right)$$

DIN = dissolved inorganic nitrogen = $NH_3 + NO_2 + NO_3$
DIP = dissolved inorganic phosphorus
Si = available silica

Model Results HydroQual and Normandeau (1995)

From HydroQual and Normandeau (1995): **5.4.4 Primary Productivity and Community Respiration**

Another measure of the water quality model calibration can be determined by comparing model computations of system metabolism (the production and consumption of organic matter) versus observed data. Two measures of metabolism which can be made from field data are primary productivity and community respiration.

Figure 5-24 presents model versus data comparisons of integrated water column production. The upper panel (from Kelly, 1993) draws on data collected as part of the outfall monitoring program and shows estimates of integrated water column production. These estimates were derived from oxygen changes across a light-dark gradient for the six nearfield biology/productivity stations. Also plotted on this panel are:
1973-74 in situ measurements of primary productivity, as reported by Parker (1974), taken a few kilometers south of the proposed outfall diffuser; and a 1987/1988 data set derived from incubator measurements of water from three stations located in the vicinity of the current nearfield stations, in western Massachusetts Bay, as reported by MWRA (1988, 1990). The data presented on this panel show a marked variability not only between data sets but also within individual studies. Maximum rates of productivity are observed in March, June, and August; low rates of productivity are found during the winter months.

In the lower panel of Figure 5-24, model output, from the same six locations as the Battelle biology/productivity stations, is plotted to provide a comparison against the data from these previous field studies. The model computes maximum rates of productivity in March, June, and September. This closely mirrors the timing of the peak observed values in the data. While the magnitude of the productivity computed by the model falls within the range of measured observations, the model computations tend to be low. In addition, the model shows less variability than is observed in the data.

[text and figures regarding respiration are not included here]

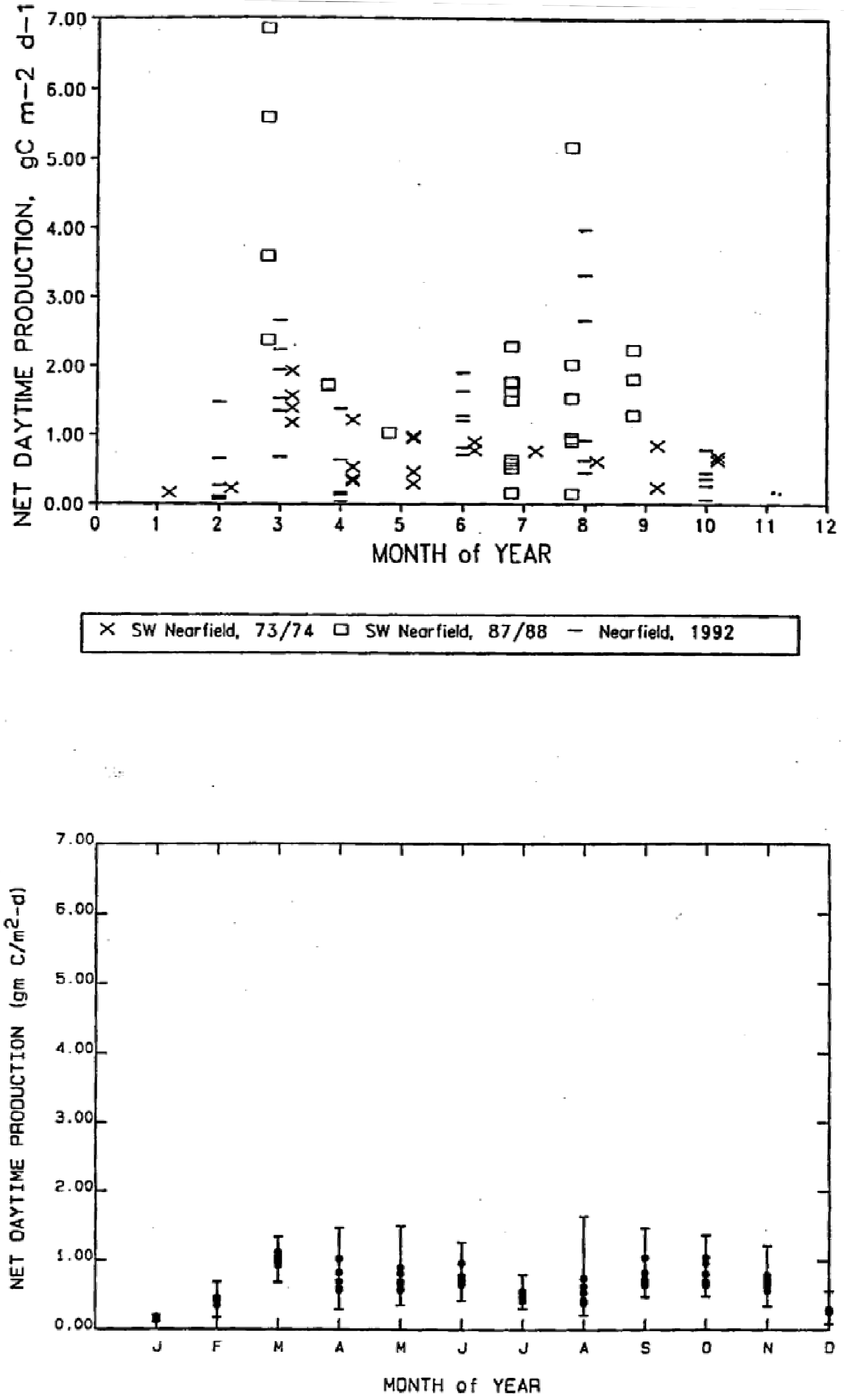


FIGURE.5-24. COMPARISONS OF OBSERVED AND MODEL COMPUTED NEARFIELD PRIMARY PRODUCTIVITY

[Figure from HydroQual and Normandeau (1995)]

1992, 1993, 1994

Model Results HydroQual (2000)

From HydroQual (2000): section **4.2.4.1 Primary Productivity**

Another measure of the water quality model calibration can be determined by comparing model computations of system metabolism (the production and consumption of organic matter) versus observed data. Two measures of metabolism which can be estimated from field data are primary productivity and community respiration.

In 1992, oxygen-based light bottle-dark bottle equipment were used to estimate primary production. In 1993 and 1994 oxygen light-dark bottles were replaced by 14C techniques. Measurements of primary production were made during February, March, April, June, August and October of each year. In 1992, six near field stations were used to estimate primary productivity. In 1993, 10 stations were used to estimate primary productivity. These stations included the six near field stations, two far field stations in Cape Cod Bay, and two coastal far field stations. However, in 1994 only two stations were used to estimate primary productivity, namely station F23P, a coastal station, and N01P, a near field station.

Since there is some controversy as to whether gross or net primary production is measured by oxygen light-dark bottles and 14C techniques due to (1) the length of the time period used for the incubation and (2) the assumptions used to convert short and mid-length incubations to daily production estimates, the model computations of both net primary production (NPP) and gross primary production (GPP) will be compared to the data. Figure 4-38 presents a comparison between the 1992 near field estimates of primary productivity and the water quality model estimates of NPP and GPP. The data figure also includes: 1973/1974 *in situ* measurements of primary productivity, as reported by Parker (1974), taken a few kilometers south of the future outfall diffuser; and a 1987/1988 data set derived from incubator measurements from three stations located in the vicinity of the current near field stations, in western Massachusetts Bay, as reported by MWRA (1988,1990). The data presented on this panel show a marked variability not only between data sets, but also within individual studies. Maximum rates of productivity in 1992 were observed in March, June and August; low rates of productivity were found during the winter months.

The model results for NPP and GPP in 1992 differ by approximately 50 percent with the GPP being higher. The model computations only partially match the observed data. During the early part of 1992, model and data trends are similar with a peak in primary production in March followed by a drop off in late spring. The model predicts low productivity in June while the data indicate a small peak in June. The data indicate high primary productivity in August followed by low productivity in October. While the model predicts increasing primary productivity in August it does not peak until September and October.

A comparison of model versus data for 1993 primary productivity is presented in Figure 4-39. This figure provides a spatial as well as seasonal picture of primary productivity throughout the Massachusetts Bays system. In Cape Cod Bay the highest primary productivity was measured in February. Lower primary productivity rates were observed in March, April, June and August followed by slightly higher rates in October. At the near field and coastal sites, low primary productivity rates were observed in February and March, followed by elevated rates in April, June and August. The rates at the near field and coastal sites diverge in October when near field rates increase and coastal rates remained similar to August rates.

The model matches the 1993 production data fairly well. At the nearfield stations, the model primary productivity begins to increase earlier than the data, peaking in March rather than April. The model computed GPP rates match the June and August observations fairly well. Both the model and data show the highest primary production rates in October. In Cape Cod Bay, the model predicts higher productivity than at the other locations for January, but both model NPP and GPP rates are lower than the February data. The model computes higher primary productivity in the summer and lower primary productivity in the fall than were observed in Cape Cod Bay. The model reproduces the February and March coastal data, but misses the timing of the increase in April. Beginning in June the model reproduces the coastal station data fairly well. Again the observation can be made that the model computed GPP is approximately 50 percent greater than the NPP.

Model versus data comparisons for the 1994 primary productivity are shown in Figure 4-40. The two stations sampled show similar patterns except that the near field station has a peak primary productivity rate in March and again in October, whereas the harbor edge station does not peak until April and the October rates are not much higher than the August rates. Overall, 1993 had the highest measured primary productivity rates and 1992 and 1994 had similar primary productivity rates. However, the estimates of primary productivity can vary a great deal based on the weather conditions on the date a site was sampled and the patchiness of the phytoplankton biomass.

The model computations for 1994 for both NPP and GPP appear to be high relative to the observed data, particularly in the later part of the year. The model reproduces the February through April data fairly well, reproducing the peak observed in March. The model GPP over predicts the June and August 14C production estimates, while the model NPP computations compare more favorably. Both the model NPP and GPP greatly over predict the October data.

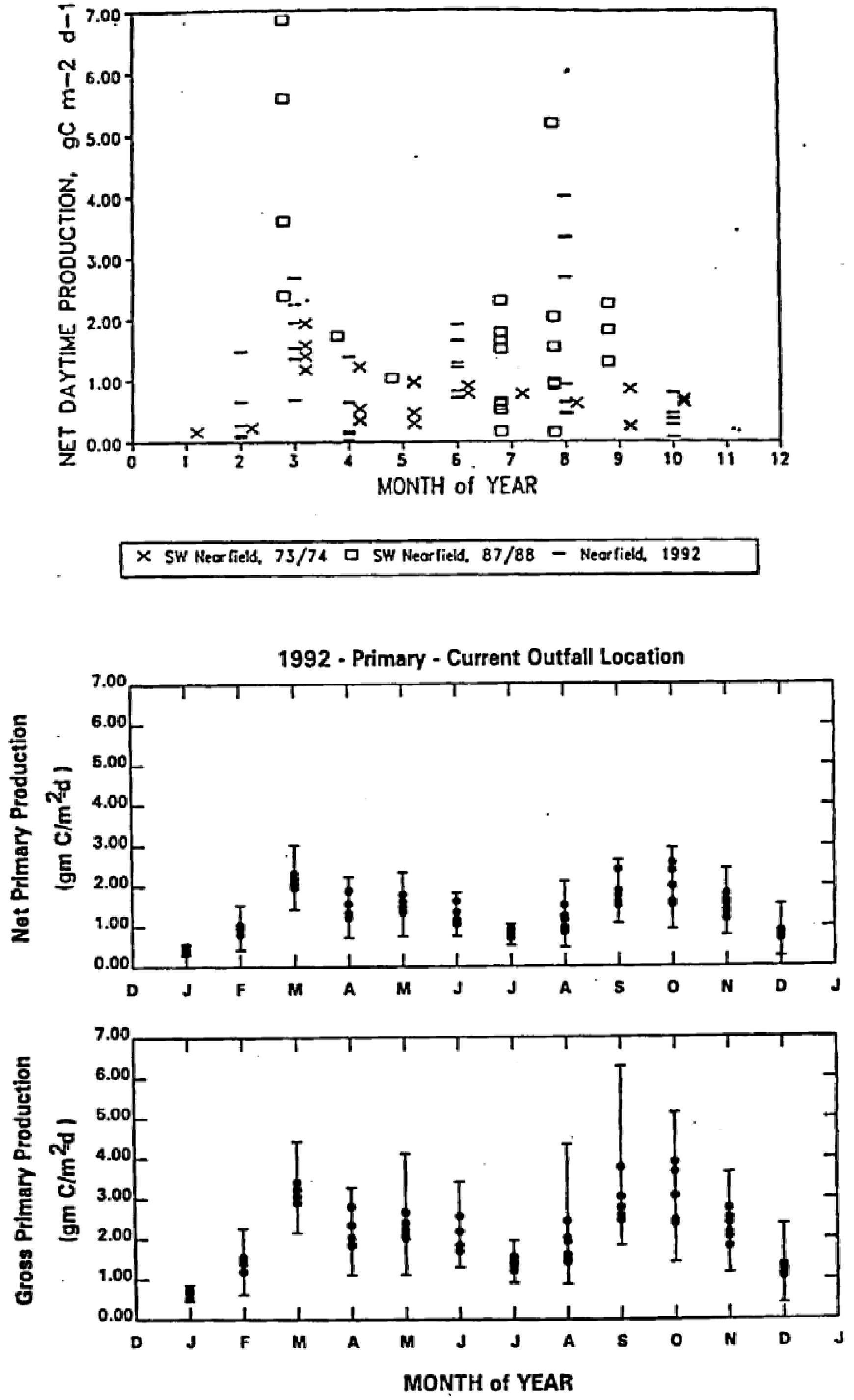


Figure 4-38. 1992 Primary Productivity Comparisons

[Figure from HydroQual (2000)]

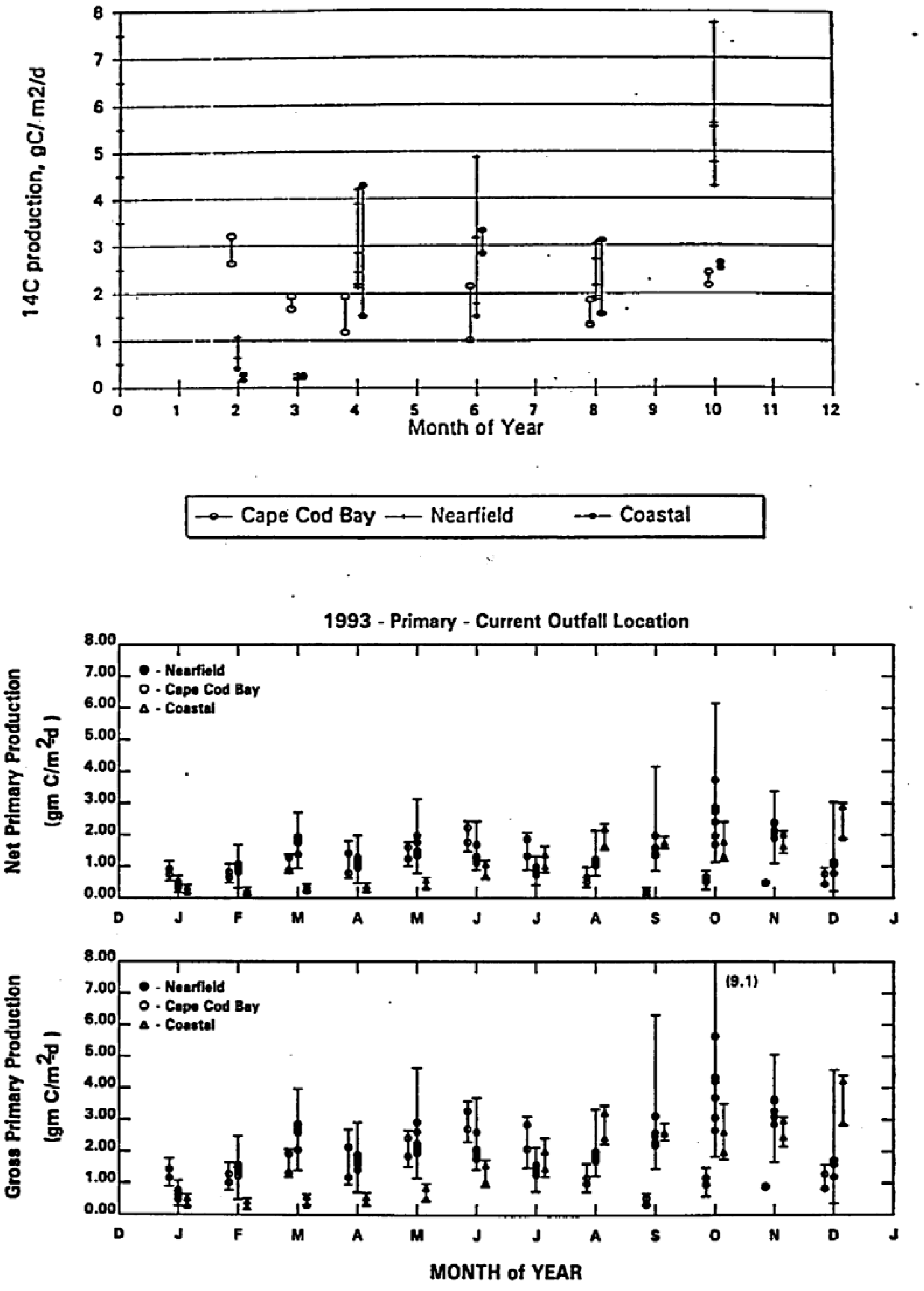


Figure 4-39. 1993 Primary Productivity Comparisons

Figure from HydroQual (2000)]

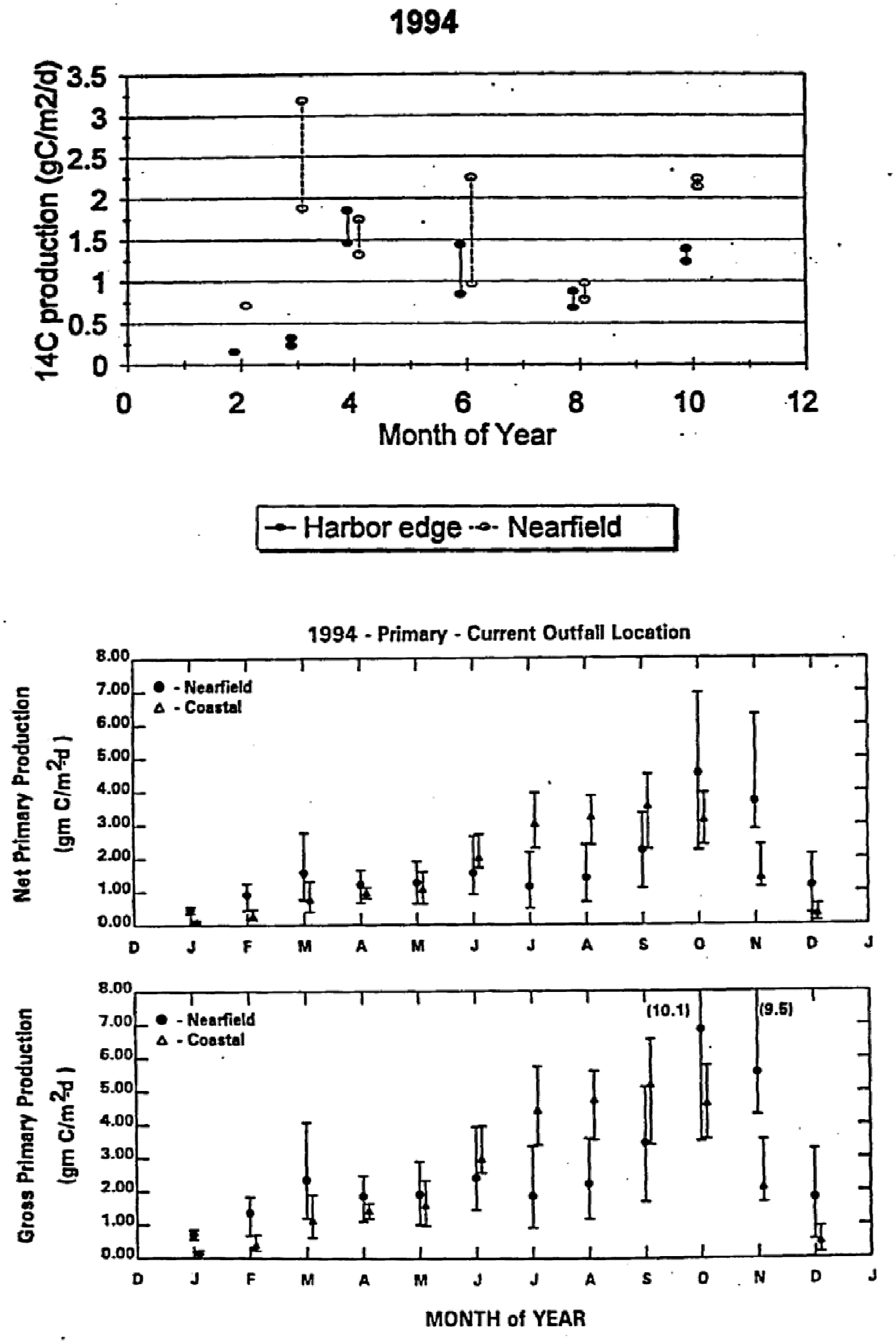


Figure 4-40. 1994 Primary Productivity Comparisons

Figure from HydroQual (2000)]

Other HydroQual Reports

HydroQual (2001a) Addendum to "Bays Eutrophication Model (BEM): modeling analysis for the period of 1992-1994".

Nothing about primary productivity in this report.

HydroQual (2001b) Boundary sensitivity for the Bays Eutrophication Model (BEM).

Nothing about primary productivity in this report.

HydroQual (2001c) Analysis of the addition of a third algal group to the Bays Eutrophication Model (BEM) kinetics.

Nothing about primary productivity in this report, although it notes in the conclusions:

> Another apparent cause of a fall bloom would be a large influx of algae from the Gulf of Maine. While this may appear as if there was a great deal of biological productivity in the bays, the growth would have actually occurred outside the bays.

HydroQual (2002) Sensitivity of the Bays Eutrophication Model (BEM) to changes in algal model coefficients.

Nothing about primary productivity in this report.

Note that years 1995-1997 were not modeled.

1998, 1999

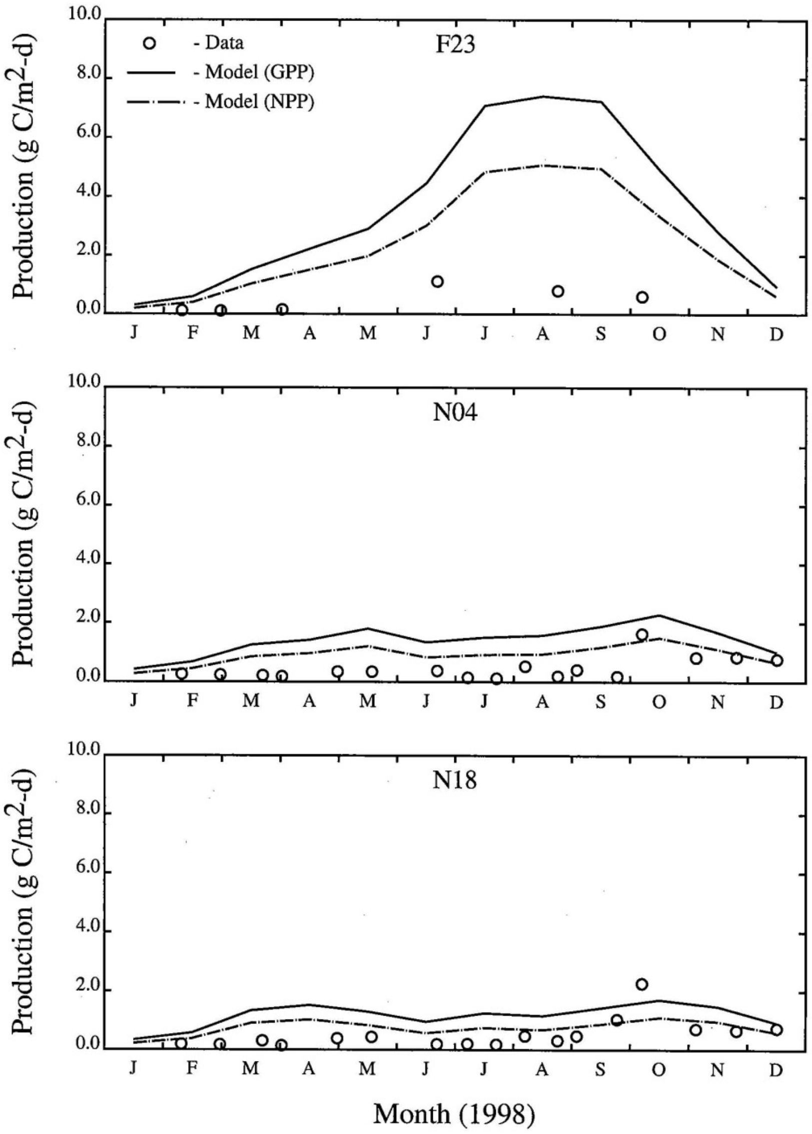
HydroQual HydroQual (2003)

From HydroQual (2003): section 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, 14C 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).

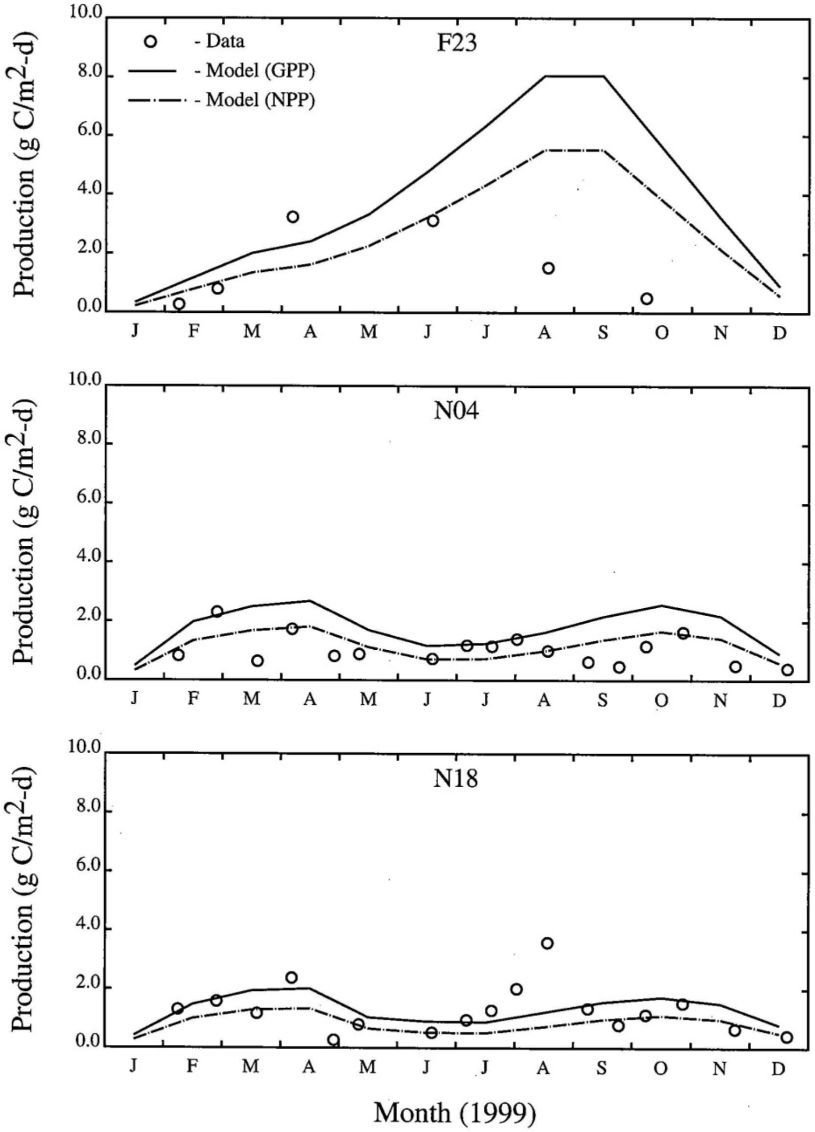
Figure 4-67 presents the 1998 areal productivity data with the monthly average model results for gross primary productivity (GPP) and the net primary productivity (NPP). At station F23, the model results are substantially higher than the data except for early February. At the near field stations, the 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 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 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.



4-67. 1998 Primary Productivity Comparison

[Figure from HydroQual 2003]



4-68. 1999 Primary Productivity Comparison

[Figure from HydroQual 2003]

Jiang and Zhao

Jiang and Zhao (2003)

This report does not have model-data comparisons, just a comparison of the two group's model implementations. The figure for productivity is shown.

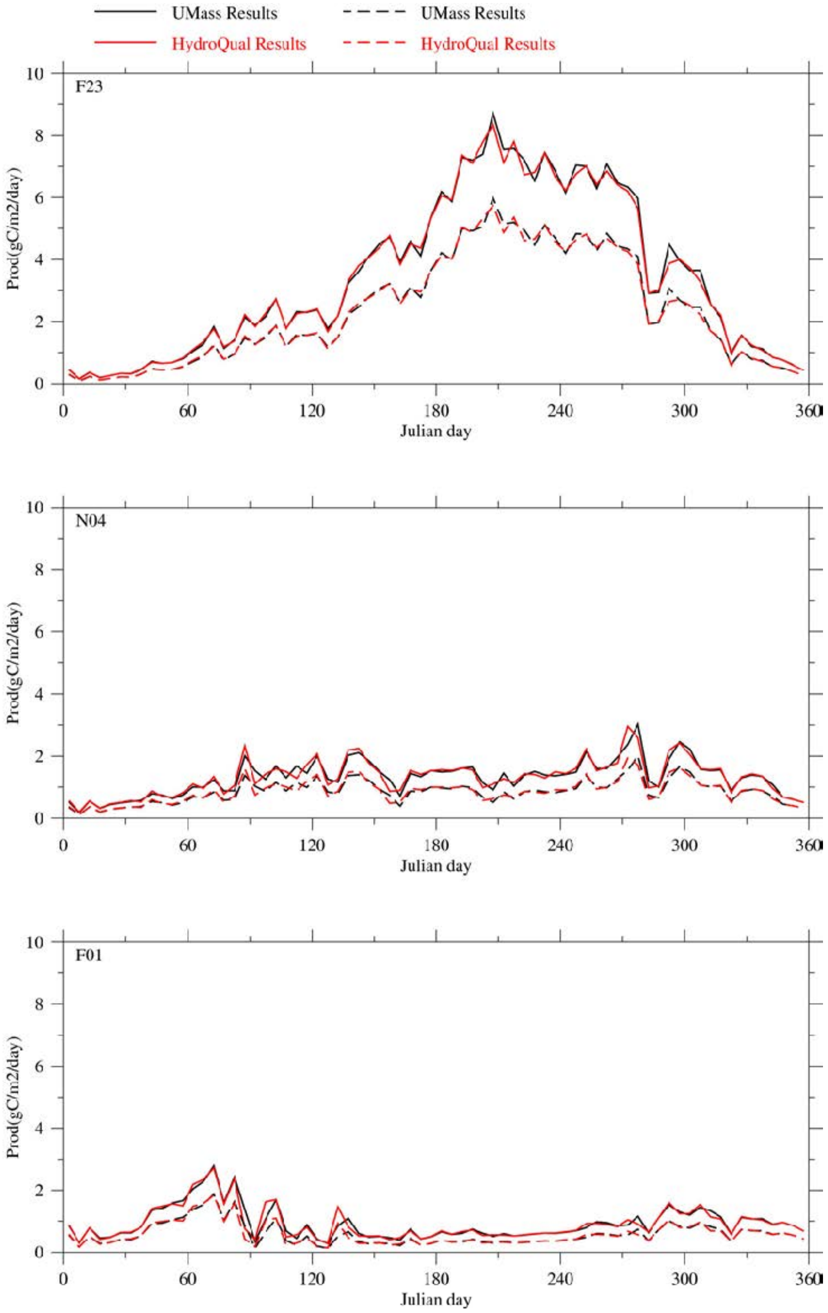


Figure 3.7. Primary productivity at selected stations (Solid lines: gross primary productivity, dashed lines: net primary productivity)

[Figure from Jiang and Zhao (2003)]

The authors do have some recommendations:

From Jiang and Zhao (2003): **Section 4. Future improvements, 4.1 Productivity**

The HydroQual report compares the modeled primary production with observed data (Figure 4.1 in HydroQual 2001b), and indicates that the modeled primary production at Station F23 in Boston Harbor is much higher than the observed values throughout 1998, in particular, the second half of the year. Similar results were found in the second half of year 1999. By contrast, the estimates of modeled productivity at Stations N04 and N18 further into Massachusetts Bay are approximately equal to observed values. Because of limited observed data, it is unclear whether the productivity is overestimated by the model only in Boston Harbor or generally in all shallow areas. Because the chlorophyll and POC are overestimated only at Station F23 and are underestimated at all other stations during both fall 1998 and 1999, we speculate that the productivity is overestimated only in Boston Harbor.

One of the causes for the overestimation is that [Hydroqual] used inadequate light attenuation coefficients in the model, which determines the light penetration, and in turn affect the productivity in water column. In Boston Harbor, the average water depth is approximately 4.9 m, and the maximum tidal current is approximately 50 cm s^{-1}. The turbidity produced by tidal mixing is very high from river loads and resuspension. In the model, the light attenuation is described as two parts: the geographically specific base coefficient (K_{ebase}) and the addition due to chlorophyll (K_c*Chl) where K_c is an empirical constant and Chl is the biomass of chlorophyll. K_{ebase} should theoretically include the effect of turbidity. Historic data in this region are limited. Because of the difference between observed values and model estimates of productivity, the model coefficients (K_{ebase}) used in Boston Harbor may need to be recalibrated or verified from field observations.

2000, 2001 Jiang and Zhao (2004)

From Jiang and Zhao (2004): Section **3.3 Primary productivity**

The comparisons of vertically integrated primary production (PP) and net primary production (NPP) between modeled and observed in 2000 are shown in Figure 3.12, where the NPP is defined as PP minus respiration. The modeled PP and NPP at station N04 agree fairly well with observed data. The modeled PP and NPP at N18 also agree with the observed data except that the model under-predicts the production during three major blooms. At station F23, the observed PP and NPP were lower than 1 gC m-2 day-1 except in early April when both PP and NPP were higher than 5 gC m-2 day-1. This observed seasonal pattern of production is very different from the modeled production, which increases continuously from winter to late summer and declines sharply in fall. This difference between modeled and observed production has been encountered during earlier simulations (HydroQual, 2000; HydroQual, 2003). For example, the observed PP and NPP peaked in early April and mid-June 1999 while the modeled PP and NPP peak in late August 1999.

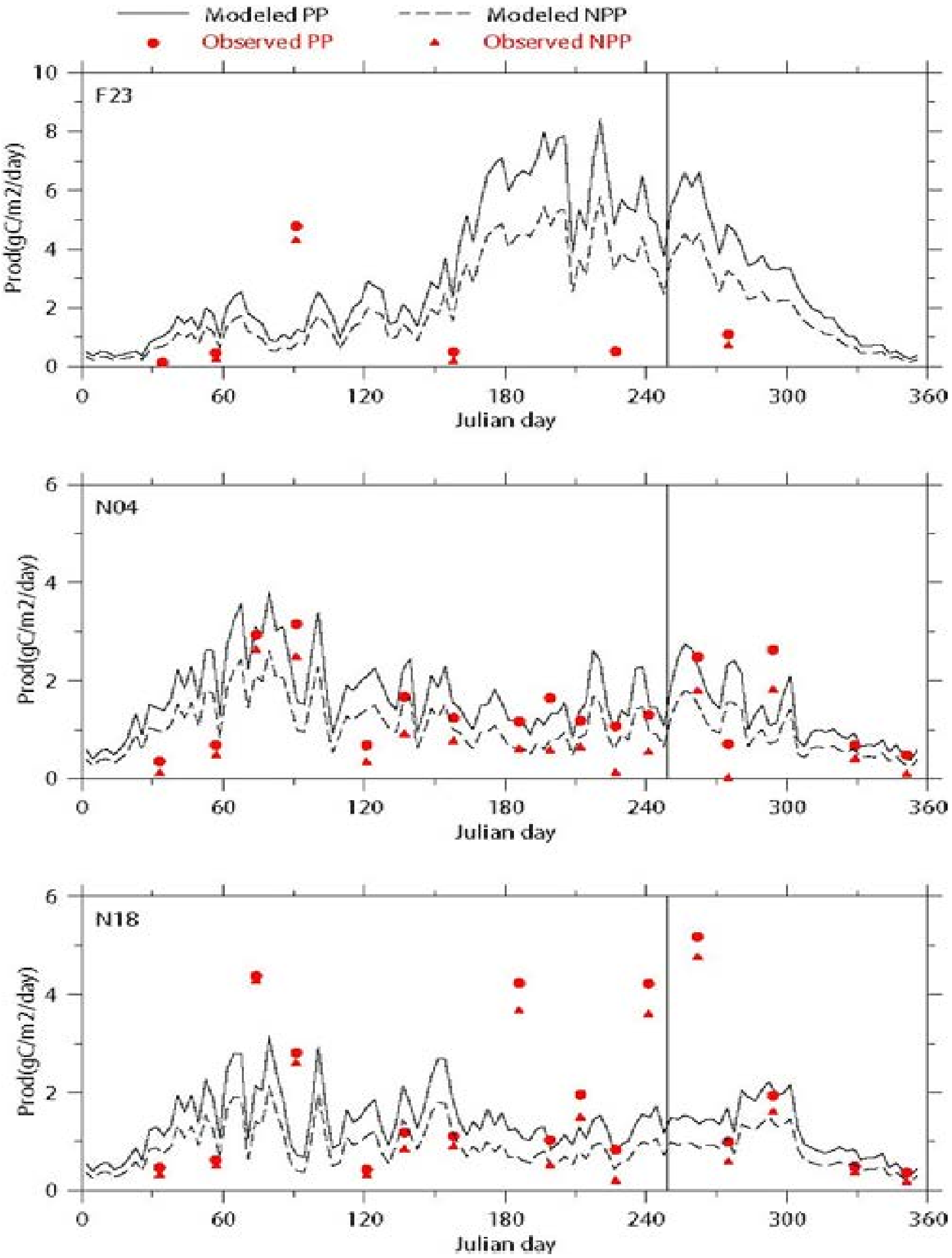


Figure 3.12. Modeled and observed primary production (PP) and net primary production (NPP) in 2000. The solid vertical line marks the startup of new outfall discharge (day 249).
[Figure from Jiang and Zhao (2004)]

The modeled PP and NPP in 2001 show similar seasonal variations to the observed at all these three stations (Figure 3.13). High PP and NPP during fall indicate a strong fall bloom as well, though the chlorophyll concentration was lower than that of fall 2000 (Figures 3.2a and 3.3a). In December, high productivity was observed at the two nearfield stations, which might be due to the presence of stratified conditions or increased nutrient availability (Libby et al., 2002). At station F23, the model clearly reproduces the seasonal pattern observed, though it still over-predicts the production in fall.

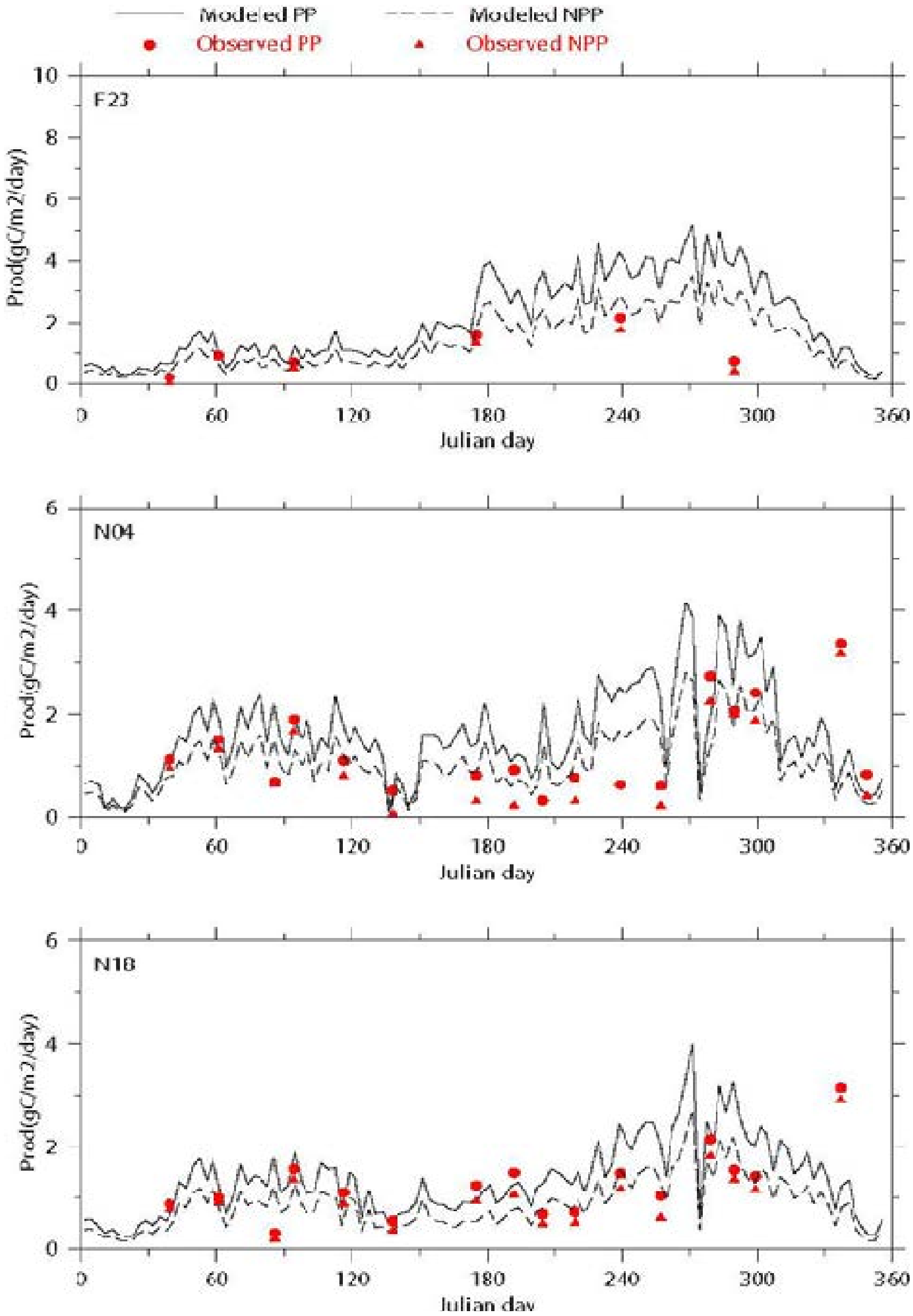


Figure 3.13. Modeled and observed primary production (PP) and net primary production (NPP) in 2001. [Figure from Jiang and Zhao (2004)]

From Jiang and Zhao (2004): Section **4. Sensitivity Experiments**

Table 4.1. Summary of the numerical experiments. [productivity was analyzed for only two of these]

Experiment Name	Descriptions
CONTROL (VOBC)	Standard experiment
GRAZ	Delayed grazing, τ = 7 day, *kp* = 0.01 mgC/l
BCHL	Increase chlorophyll at OBC in March and April by 20%
UOBC	Use open uniform open boundary conditions, node = 45

[Table from Jiang and Zhao (2004)]

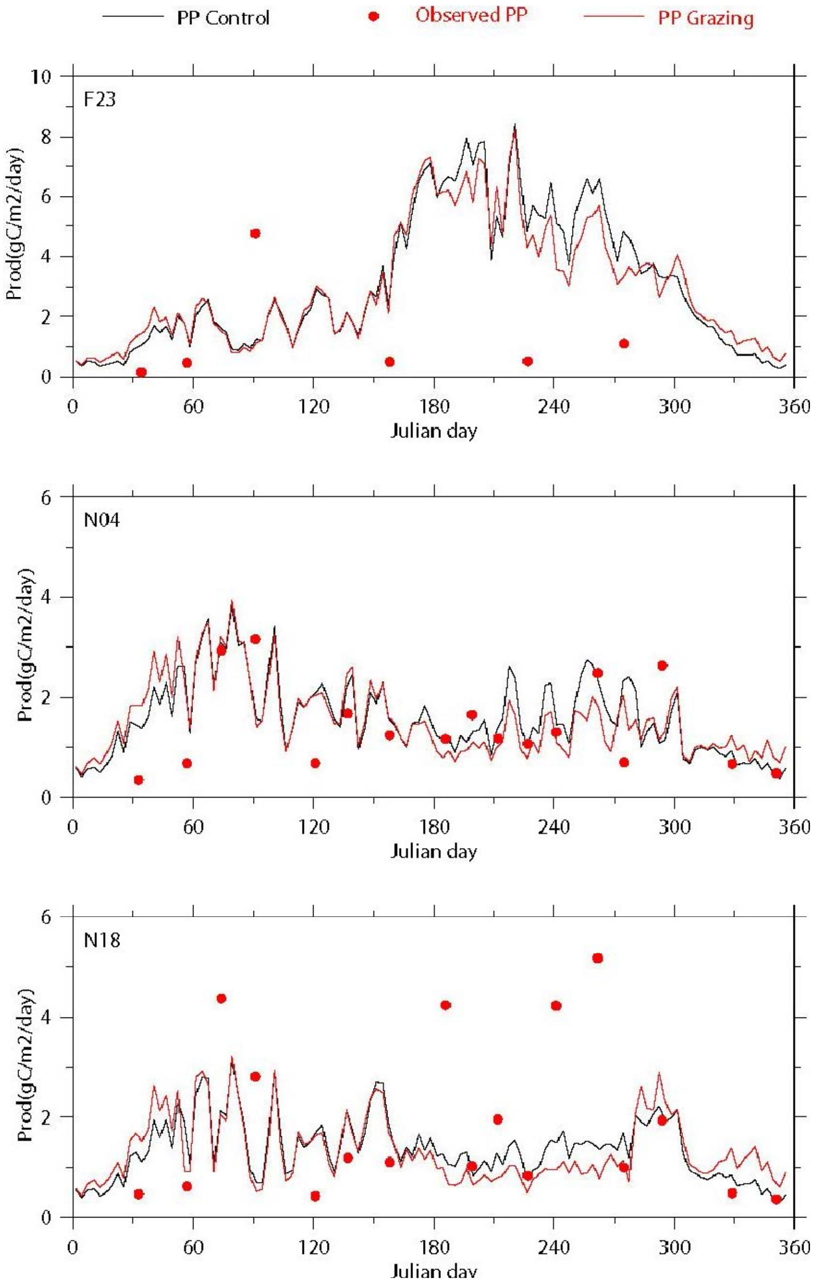


Figure 4.4. Primary production in the CONTROL and GRAZ experiments.
[Figure from Jiang and Zhao (2004)]

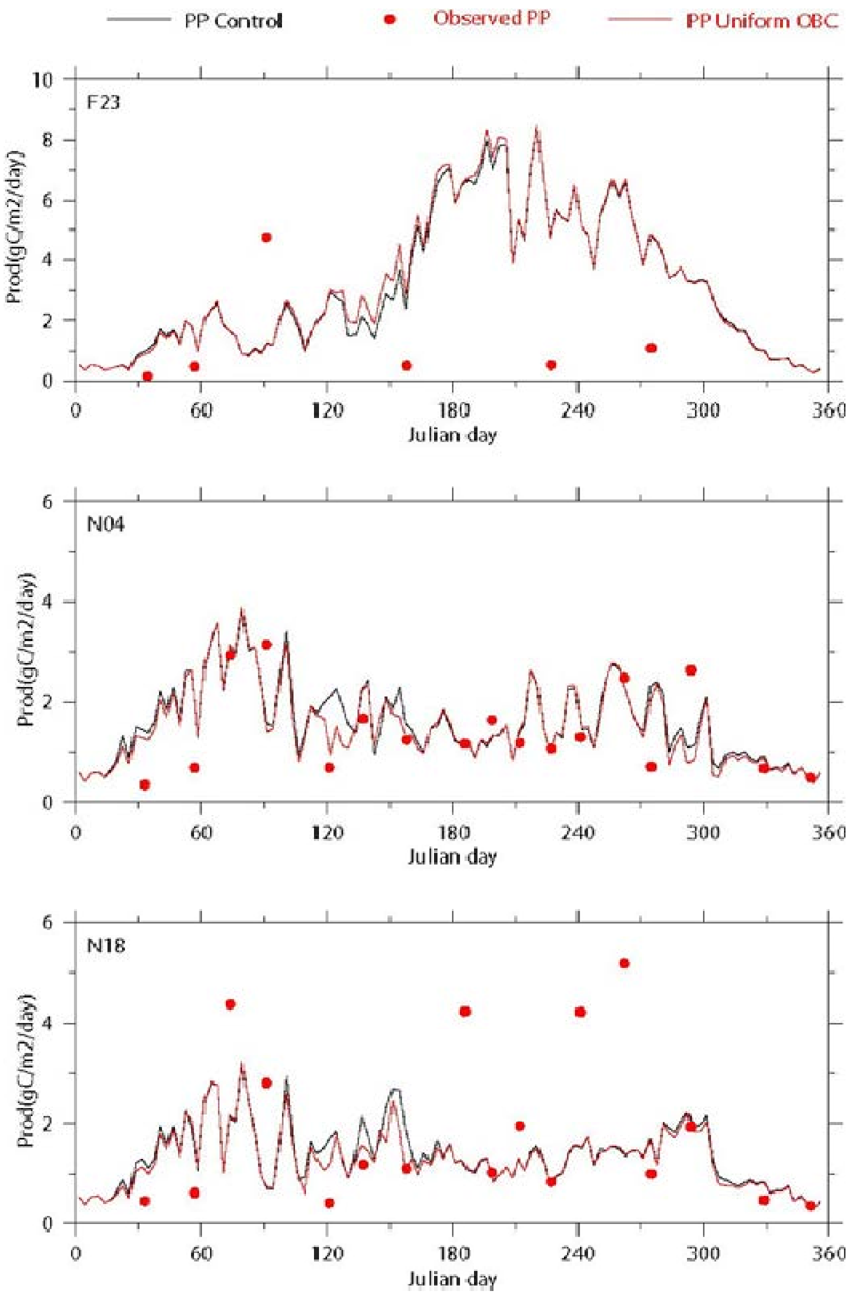


Figure 4.11. Primary production in the CONTROL and UOBC experiments
[Figure from Jiang and Zhao (2004)]

2002, 2003, 2004 Jiang and Zhao (2006)

From Jiang and Zhao (2006): Section **3.4 Primary productivity**

2002. The comparison of vertically integrated primary production (PP) between modeled and observed values in 2002 is shown in Figure 3.17 and Table 3.2. The observed PP at stations N04 and N18 showed a seasonal cycle consistent with observed chlorophyll concentrations: an early bloom in February, a spring bloom in March-April and a fall bloom in August-September. At station F23, the observed PP showed two peaks in February and August, and was lower than 1 gC m-2 day-1 in the rest of the year. The modeled PP at both N04 and N18 generally agreed with observed data except that during the spring bloom the modeled PP increased earlier than the observed, and during the fall bloom modeled high PP lasted much longer than the observed. The modeled PP at F23 showed a similar pattern to the observed, but the predicted spring bloom was about 2~3 weeks behind the observed, and the production in the summer was higher than the observed. The over-prediction of production at F23 during summer and fall had been encountered during earlier simulations (HydroQual, 2000; HydroQual, 2003; Jiang and Zhou, 2004c).

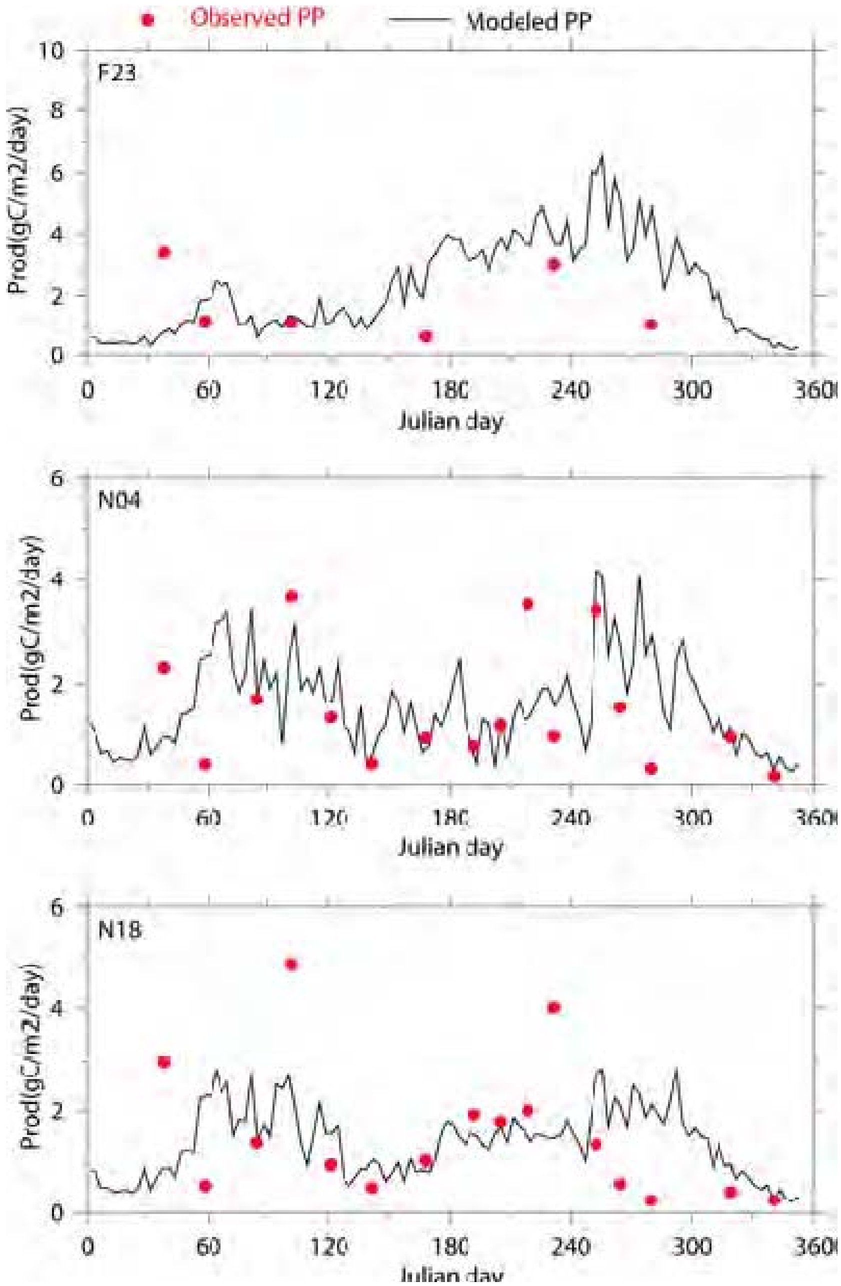


Figure 3.17. Modeled and observed primary production (PP) in 2002.
[Figure from Jiang and Zhao (2006)]

2003. The comparison of modeled and observed PP in 2003 is shown in Figure 3.18 and Table 3.2. The observed PP showed a weak spring bloom in March and a strong fall bloom in September and October, and remained low throughout the rest of the year. The modeled PP showed similar seasonal variations to the observed at these monitoring stations, though the model tended to over-predict both spring and fall blooms at N04 and N18. The modeled summer PP at F23 was higher than the observed as well.

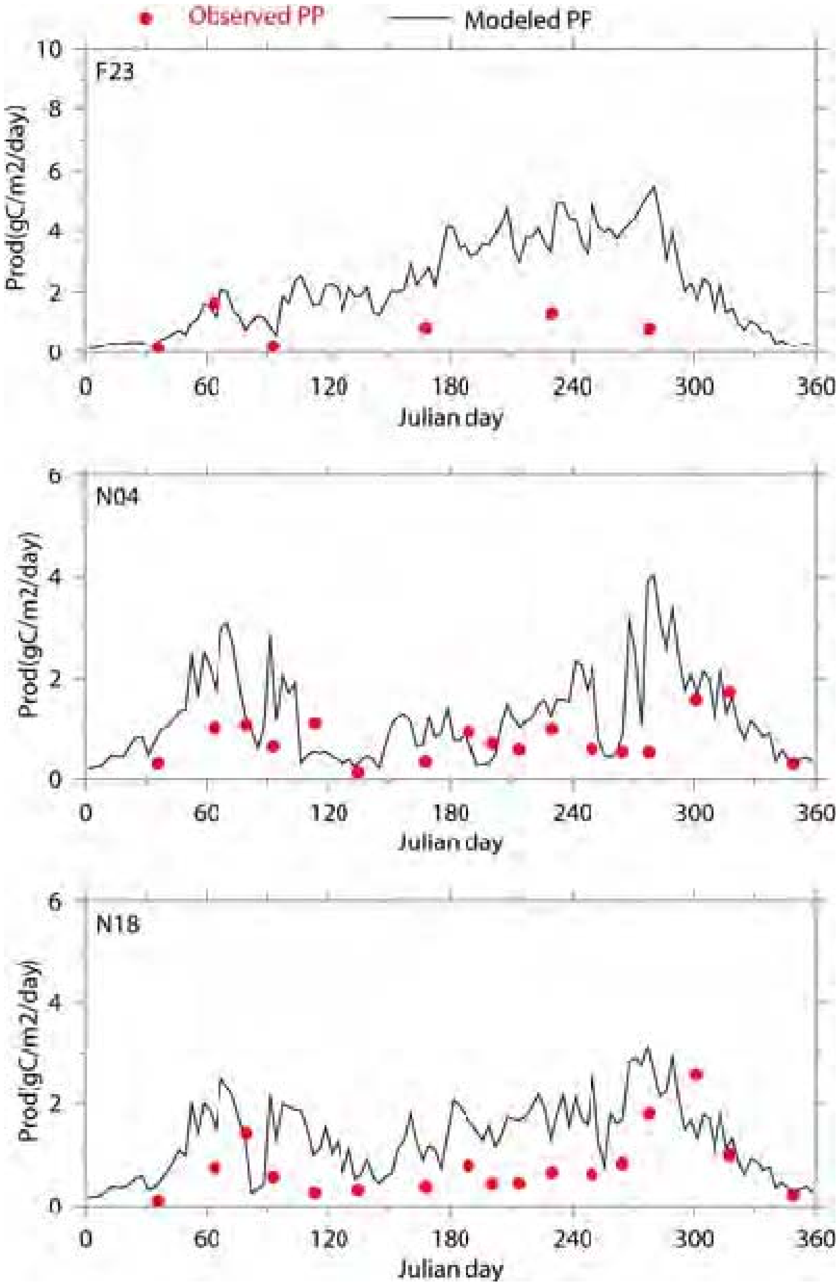


Figure 3.18. Modeled and observed primary production (PP) in 2003.
[Figure from Jiang and Zhao (2006)]

2004. The comparison of modeled and observed PP in 2004 is shown in Figure 3.19 and Table 3.2. The observed PP values at stations N04 and N18 showed a moderate spring bloom in April and were lower than 1 gC/m2/day in the rest of the year. No fall bloom was observed. The observed PP at F23 was fairly constant except the low values in early February and August. The modeled PP showed some differences from the observed: (1) the model predicted a stronger and earlier (2 weeks) spring bloom than the BEM simulation for 2002-2004 observed; (2) the modeled PP at N04 and N18 were higher than the observed during 2 summer events; and (3) in summer, the modeled PP at F23 was higher than the observed.

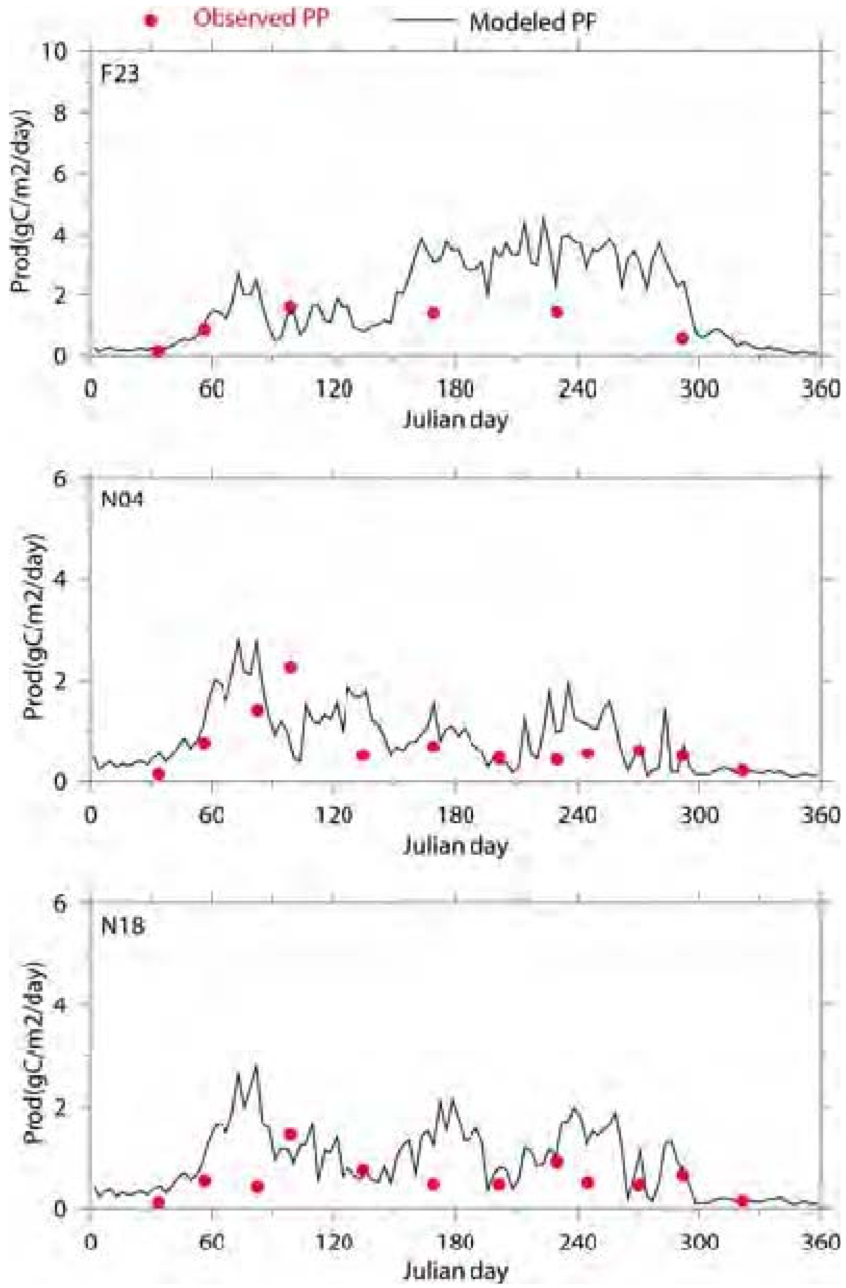


Figure 3.19. Modeled and observed primary production (PP) in 2004.
[Figure from Jiang and Zhao (2006)]

From Jiang and Zhao (2006): Section **3.6 Statistical analysis**

The correlations between modeled and observed primary production are shown in Figure 3.26. To calculate these correlations, observed PP were interpolated over the year to derive monthly mean values (excluding January since there was no observation in January), and modeled results were averaged to derive monthly means for N04 and N18 (total 22 data points in each year). The results at F23 were not used because only 6 measurements per year were made. These results indicated that the modeled PP had significant correlations with the observed values (with *p*<0.05 for 2002, *p*<0.01 for 2003, and *p*<0.05 for 2004, respectively), similar to the regression results of chlorophyll. Modeled results showed smaller variations than the observed did. Modeled PP had the lowest correlation with data in 2002.

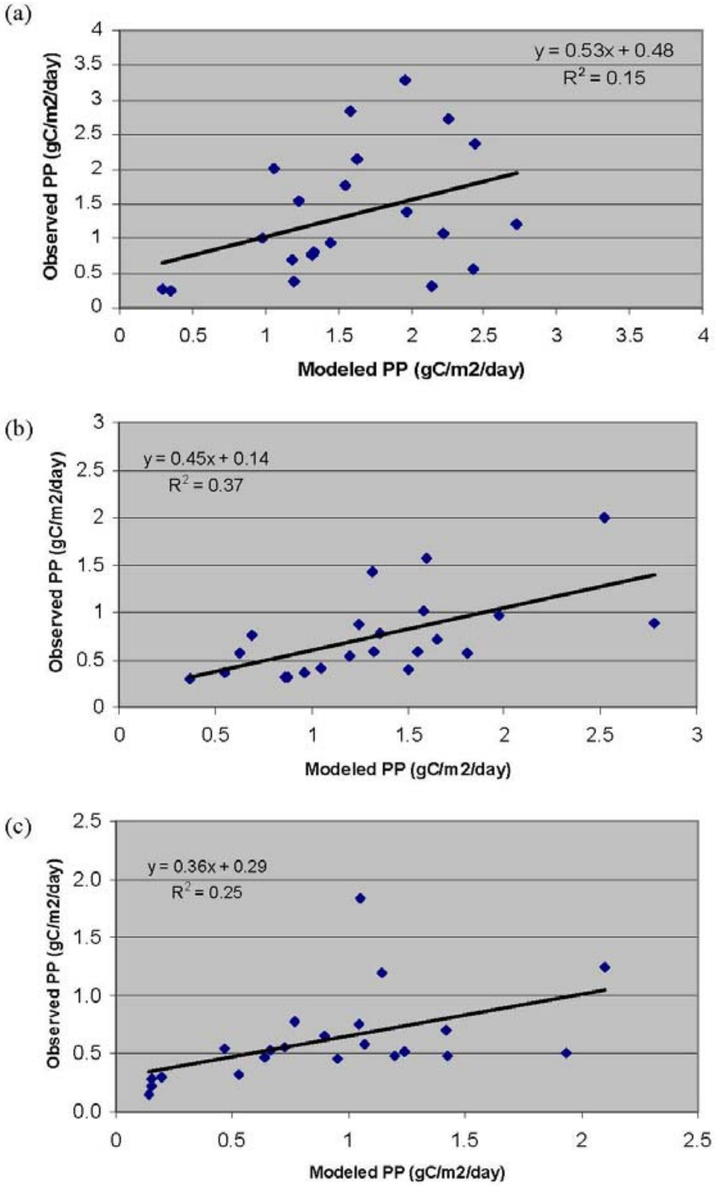
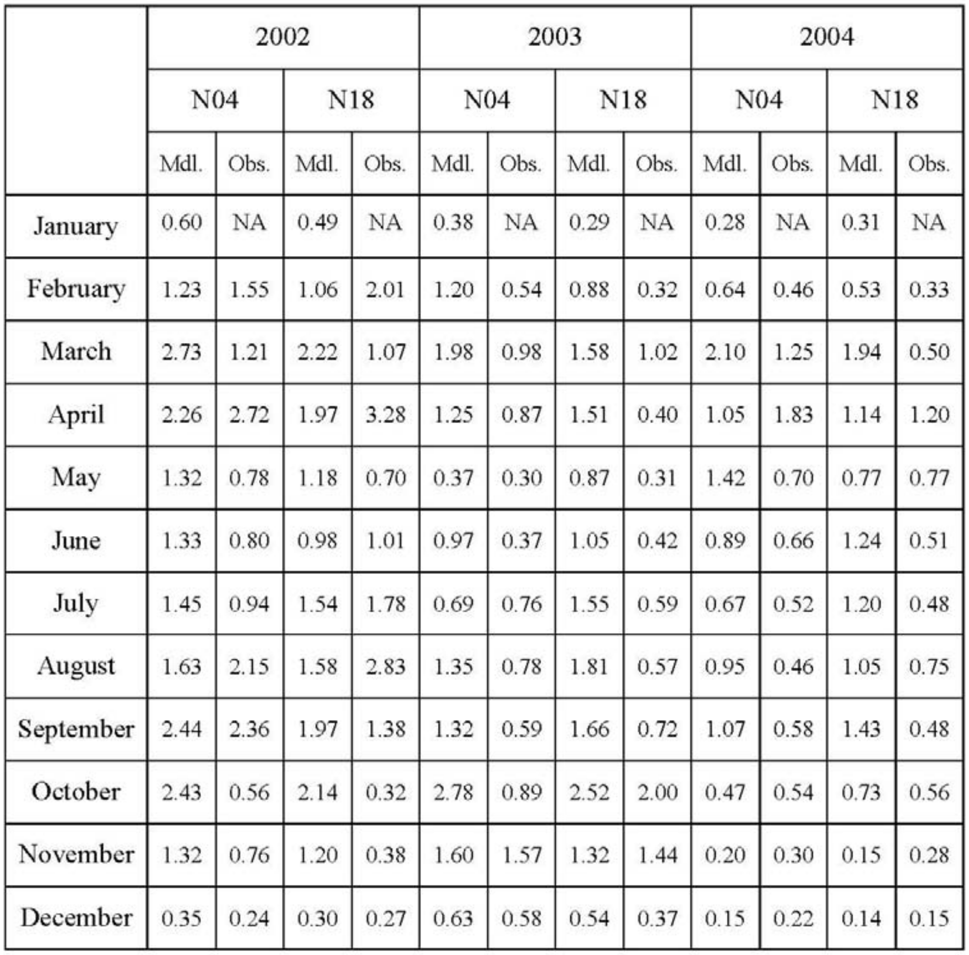


Figure 3.26. Correlations between modeled and observed primary productivity (PP): (a) 2002, (b) 2003 and (c) 2004. Also shown are the best linear fits (solid lines) and the values of R^2.
[Figure from Jiang and Zhao (2006)]

Table 3.2 Modeled and observed primary production at N04 and N18



	2002				2003				2004			
	N04		N18		N04		N18		N04		N18	
	Mdl.	Obs.	Mdl.	Obs.	Mdl.	Obs.	Mdl.	Obs.	Mdl.	Obs.	Mdl.	Obs.
January	0.60	NA	0.49	NA	0.38	NA	0.29	NA	0.28	NA	0.31	NA
February	1.23	1.55	1.06	2.01	1.20	0.54	0.88	0.32	0.64	0.46	0.53	0.33
March	2.73	1.21	2.22	1.07	1.98	0.98	1.58	1.02	2.10	1.25	1.94	0.50
April	2.26	2.72	1.97	3.28	1.25	0.87	1.51	0.40	1.05	1.83	1.14	1.20
May	1.32	0.78	1.18	0.70	0.37	0.30	0.87	0.31	1.42	0.70	0.77	0.77
June	1.33	0.80	0.98	1.01	0.97	0.37	1.05	0.42	0.89	0.66	1.24	0.51
July	1.45	0.94	1.54	1.78	0.69	0.76	1.55	0.59	0.67	0.52	1.20	0.48
August	1.63	2.15	1.58	2.83	1.35	0.78	1.81	0.57	0.95	0.46	1.05	0.75
September	2.44	2.36	1.97	1.38	1.32	0.59	1.66	0.72	1.07	0.58	1.43	0.48
October	2.43	0.56	2.14	0.32	2.78	0.89	2.52	2.00	0.47	0.54	0.73	0.56
November	1.32	0.76	1.20	0.38	1.60	1.57	1.32	1.44	0.20	0.30	0.15	0.28
December	0.35	0.24	0.30	0.27	0.63	0.58	0.54	0.37	0.15	0.22	0.14	0.15

[Table from Jiang and Zhao (2006)]

From Jiang and Zhao (2006): Section **4. Sensitivity Experiments**

Table 4.1. Summary of the numerical experiments. [productivity was analyzed for only two of these]

Experiment Aliases	Descriptions
CONTROL	Standard simulations for 2001, 2002, and 2003
W92	2002 simulation Air-sea O2 exchange formulation by Wanninkhof (1992)
PL80	2003 simulation Phytoplankton growth formulation by Platt et al. (1980)
No-sewage	2001 simulation Set nutrient concentrations in the effluent as zero

[Table from Jiang and Zhao (2006)]

From Jiang and Zhao (2006): Section **4.2 Phytoplankton growth formulation**

[Use Platt et al. (1980) formula for growth rate $\mu_{max} = g_{max}\,[1 - \exp(-\alpha I\, g_{max})$ instead of Laws and Chalup (1990). Note from the appendix: The total primary productivity is determined by $GPP = (\mu + k_{PR})P_c$.]

The PL80 experiment generally produced lower bottom chlorophyll concentrations in summer and fall, which were compared better with data… Given the improvements of chlorophyll and DIN concentrations, the modeled PP in the PL80 experiment were also improved, especially during the second half of the year (Figure 4.10). In brief, this test demonstrated that both modeled chlorophyll and PP can be improved by adjusting the vertical profile of growth rates.

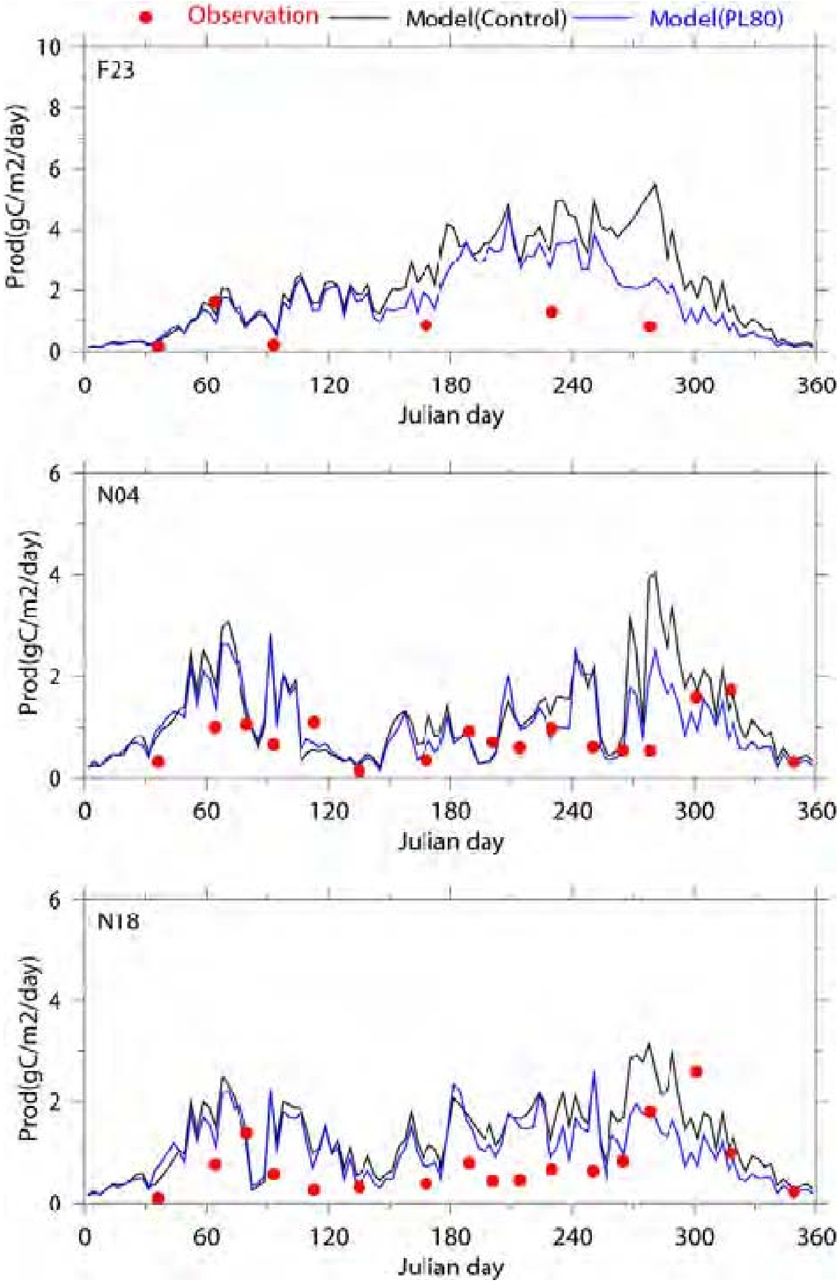


Figure 4.10. Comparison of primary production between the Control and PL80 experiments in 2003. [Figure from Jiang and Zhao (2006)]

From Jiang and Zhao (2006): Section **4.3 Effects of effluent on phytoplankton growth**

In order to understand the contribution of sewage effluent to phytoplankton biomass in MB, an experiment was conducted using parameters and forcing data in year 2001 except the nutrient concentrations in the effluent, which were set to zero (referred to No-sewage hereafter), and compared to the standard experiment (referred to as CONTROL hereafter). The comparison between the CONTROL and No-sewage experiments suggested that the contributions of effluent nutrients to surface chlorophyll and PP were small in spring and winter, and largest in summer, reaching 1~2 µg/l and 1gC/m2/day, respectively (Figures 4.11-4.12). The influence of effluent was limited to the nearfield and the vicinity of BH, consistent with those results from previous simulations using a passive tracer in the hydrodynamic model (Signell et al., 1996).

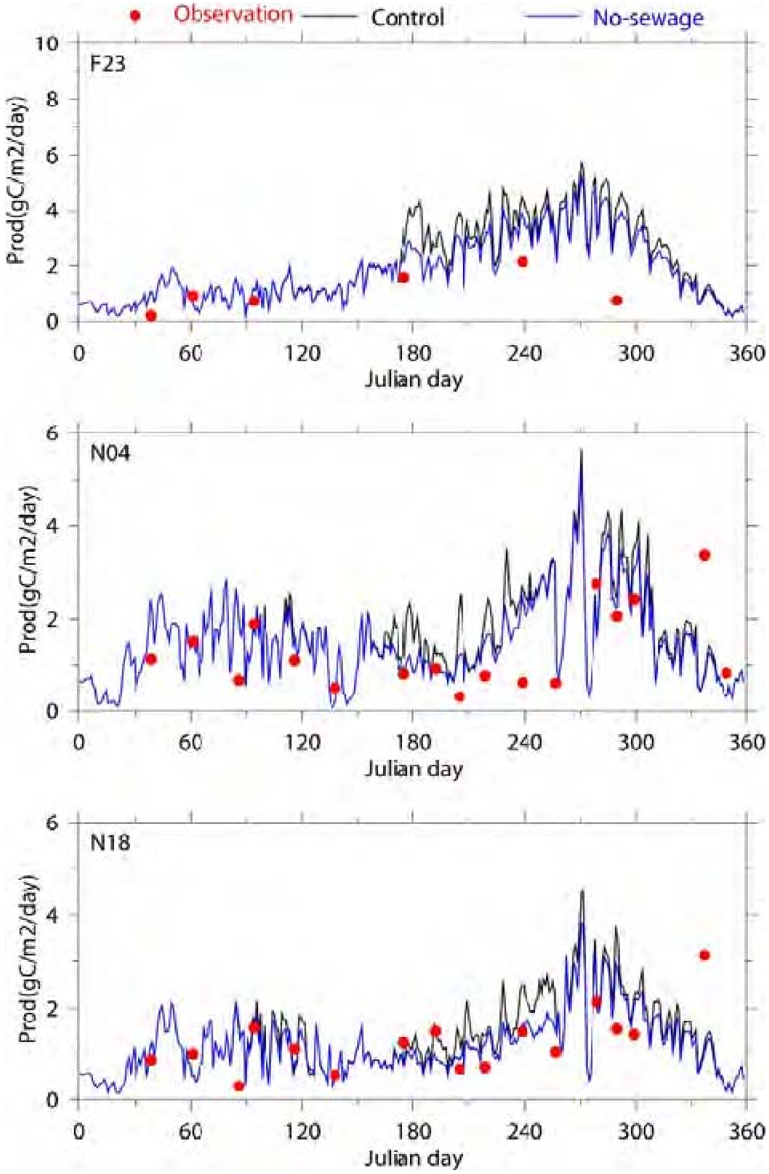


Figure 4.12. Comparison of primary production between the CONTROL and No-sewage experiments in 2001.
[Figure from Jiang and Zhao (2006)]

2005 Jiang and Zhao (2008)

[Note this report also discusses a nutrient budget during storms, which may affect production by of particular storms to production (e.g. from nutrient regeneration in the summer) but this analysis is not included here.]

From Jiang and Zhao (2008): Section **3.4 Primary productivity**

The comparison of vertically integrated primary production (PP) between modeled and observed values is shown in Figure 3.7. The observed PP at stations N04 and N18 showed a seasonal cycle consistent with observed chlorophyll concentrations: a spring bloom in late February and a fall bloom in August-September. At station F23, limited measurements showed a weak seasonality.

The modeled PP at both N04 and N18 generally agreed with observed data except that the model over-predicted primary production in the summer. At F23, the modeled PP agreed with all measurements, but the overall curve was above the measured. This suggests that modeled PP may be over-estimated, a problem that had been encountered during earlier simulations (HydroQual, 2000; HydroQual, 2003; Jiang and Zhou, 2004b, 2006b).

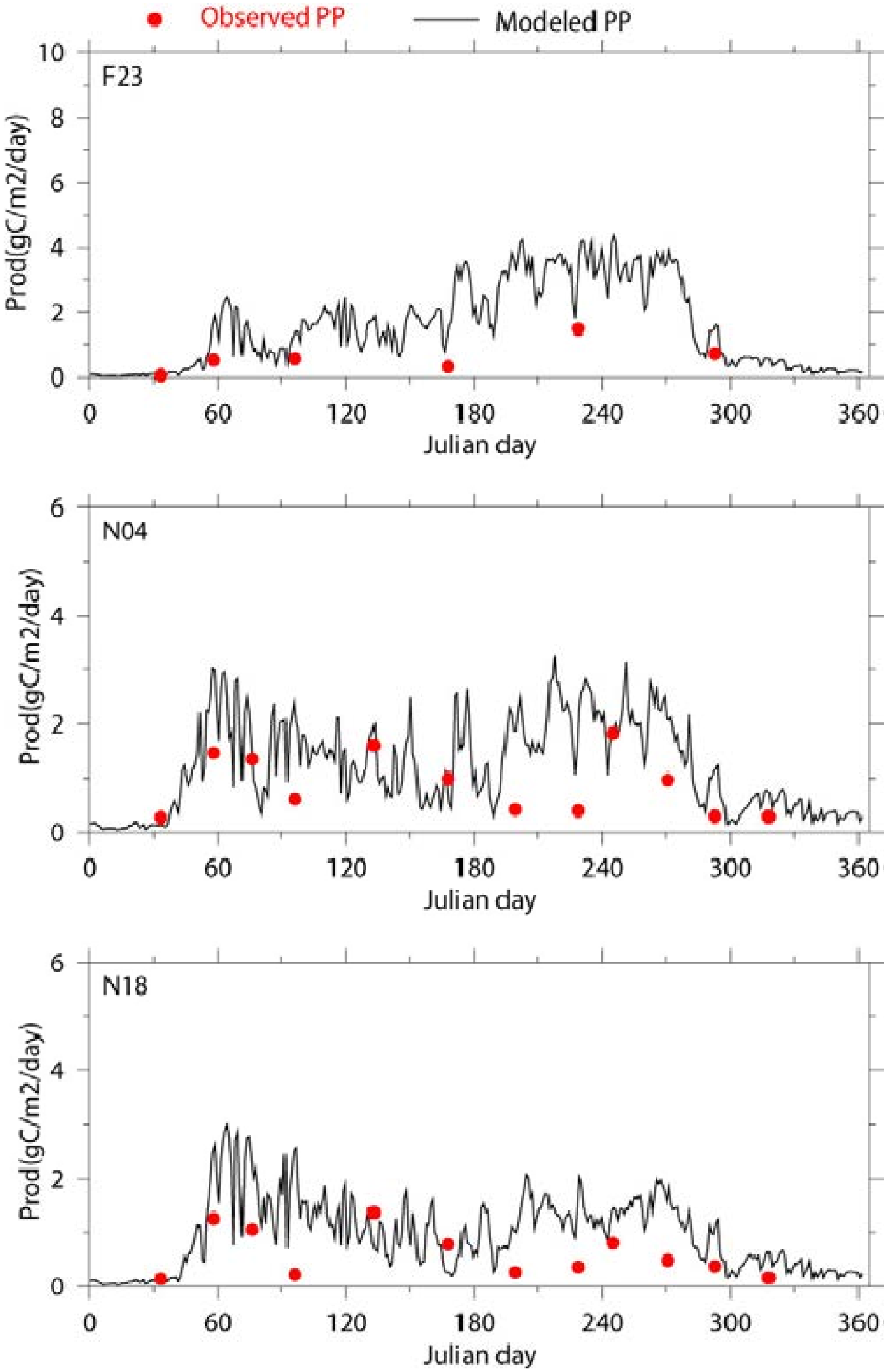


Figure 3.7. Modeled and observed primary production (PP).
[Figure from Jiang and Zhao (2008)]

From Jiang and Zhao (2008): Section **3.6 Statistical analysis**

In order to quantitatively evaluate the agreements and differences between modeled and observed results, a regression analysis was carried out for key biogeochemical variables. Correlation coefficients (r) and rms of the differences between modeled and observed salinity, chlorophyll, DO, DIN, and silicate at all sampled stations and depthintegrated primary production at N04 and N18 were computed. The rms is used to quantify the mean differences between modeled and observed values for each parameter. The results are summarized in Table 3.1 and the correlations of a subset of the parameters are shown in Figures 3.9. All correlations are significant with $p<0.01$.....

The correlation between modeled and observed PP is shown in Figure 3.10. Similar to previous reports, the observed PP were interpolated over the year to derive monthly mean values (excluding January since there was no observation in January), and modeled results were averaged to derive monthly means for N04 and N18 (total 22 data points). The results at F23 were not used because only 6 measurements were made. These results indicated that the modeled PP had significant correlations with the observed values ($p<0.05$), similar to the regression results of chlorophyll.

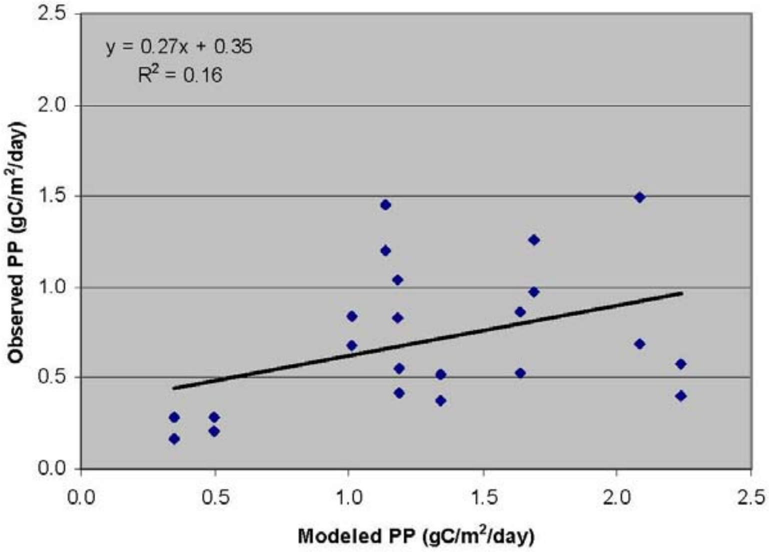


Figure 3.10. Correlations between modeled and observed primary productivity (PP). Also shown are the best linear fits (solid line) and the value of R^2.
[Figure from Jiang and Zhao (2008)]

From Jiang and Zhao (2008): Section **4.2 A nutrient budget for May 2005** [details not directly related to productivity are not included – see report for the full description]

The massive red-tide (*Alexandrium spp*) blooms in May 2005 were also accompanied by strong phytoplankton blooms, especially after the second storm (Libby et al. 2006; Figures 3.3-3.5). Prior this bloom in the late spring, surface nutrient concentrations were low due to the spring bloom and vertical fluxes were low because of strong stratification. One interesting question is: What were the nutrient sources for phytoplankton blooms during this red-tide period?

The phytoplankton blooms in late spring 2005 (April-June) were associated with a series of extraordinary events in this region as evident from the model results, e.g., in the central Stellwagen Basin (Figure 4.9). In April, two strong river discharge events (not shown) brought large amount of fresh water into the MBS, which greatly reduced the salinity and enhanced the vertical stratification. Between May 7 and 9, the first Nor'easter pushed waters from the GOM into the MBS. The surface mixed layer deepened from 15–20 m prior to the storm to 40 m after the storm. The deepening of the mixed layer brought deep nutrient–rich waters into the surface mixed layer. The stratification was gradually restored and the mixed layer depth reduced to 20 m after the storm. Phytoplankton growth was enhanced. The nutrients in the surface mixed layer were depleted again before the second storm arrived on May 22. This second storm again brought in a large amount of GOM waters and deepened the mixed layer to 40 m. The deep flow from the GOM also supplied significant amount of nutrients (3rd panel, Figure 4.9), which were brought into the surface layer by vertical mixing or coastal upwelling. The stratification was restored in a few days after the storm probably due to the large freshwater discharge in the Merrimack River, as evident from the continuous decrease of both model and observed surface salinity at GoMOOS A after the storm (see Figure 3.17 in Jiang and Zhou 2008). A much stronger phytoplankton bloom followed this second storm. During this period, the only available measurements of primary productivity at N04 and N18 on May 13 gave an average value of 1.5 gC/m^2/day, which was similar to the value during a spring bloom and much higher than the expected value this time of year. A primary production measurement on June 13 gave a mean value of 0.9 gC/m^2/day.

…[description of budget]…

The estimates indicate that the vertical mixing associated with these two storms contributed the majority (60%) of the nutrients for the primary production at the rate of 1.5 gC/m^2/day in May 2005. Rivers and background vertical mixing supplied about 8% nutrients required by the primary production. The MWRA and atmospheric loadings contributed less than 2% each. The vertical mixing flux due to the deep mixing after the first storm was able to contribute to the high production without nutrient limitation for 15 days.

Therefore, it can be further inferred that without the storms, the production in May 2005 would be less than 40% of the observed primary production, or about 0.6 gC/m^2/day. In this scenario, the DIN contribution from the effluent could be up to 5% if all nutrients were able to make it to the surface.

2006, 2007 Tian et al. (2009)

From Tian et al. (2009): Section **3.2. Data-model comparison for the 2006 simulation**

Primary production near the outfall exhibited similar seasonal cycles to that of chlorophyll with spring and fall phytoplankton blooms (Figure 3.16). A large fall bloom was also observed at station F23, which is close to BH. The model prediction was in general comparable with the observations. At station F23, however, the model appeared to overestimate the primary production. Observations of nutrient and oxygen fluxes at the sediment-water interface were mostly reproduced by the model without large discrepancies (Figures 3.17-3.21). Unlike biological production in the water column which had a bimodal distribution with high values in spring and fall, the nutrient flux and SOD on the bottom displayed a unimodal distribution with high values in summer and early fall and low values in winter. Although biodeposits provide organic substances to the sediments through the sinking of biogenic detritus, the diagenesis of these deposited materials functioned independently from the biological production in the water column. The dominant forcing determining the speed of sedimentary diagenesis and remineralization was the temperature, which reached high values in summer and fall and thus accelerated diagenesis in the sediment.

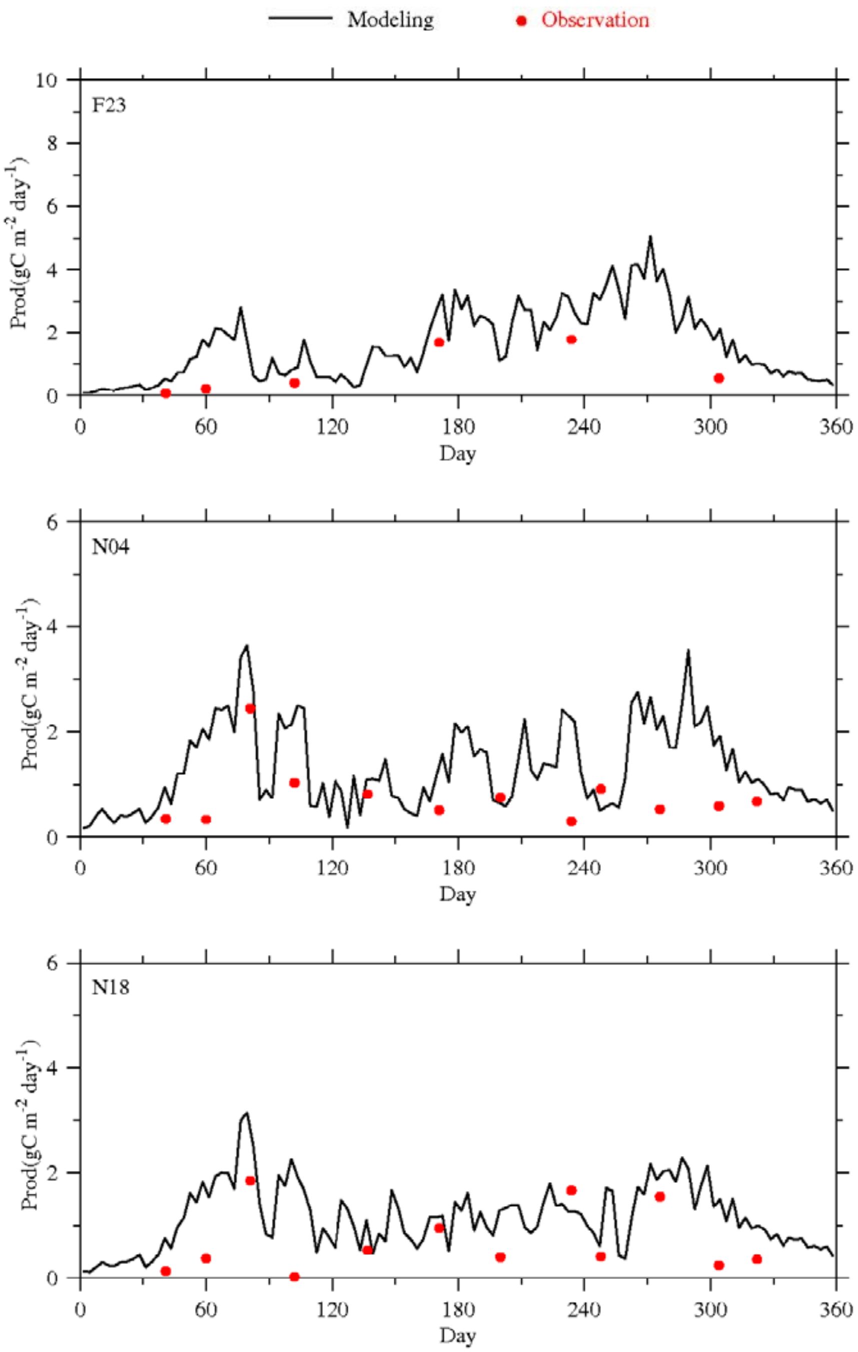


Figure 3.16 Comparison of observed (dots) and modeled (lines) time-series data of integrated primary production at MWRA monitoring stations in 2006.

[Figure from Tian et al. (2009)]

From Tian et al. (2009): Section **3.3. Data-model comparison for the 2007 simulation**

…The magnitude and seasonal cycle of primary production were similar between the two years (Figure 3.15 for 2006 and Figure 3.37 for 2007). The model tended to underestimate the primary production as compared with data when the production was high, such as during the spring phytoplankton bloom at all three stations and during the fall bloom at station F23….

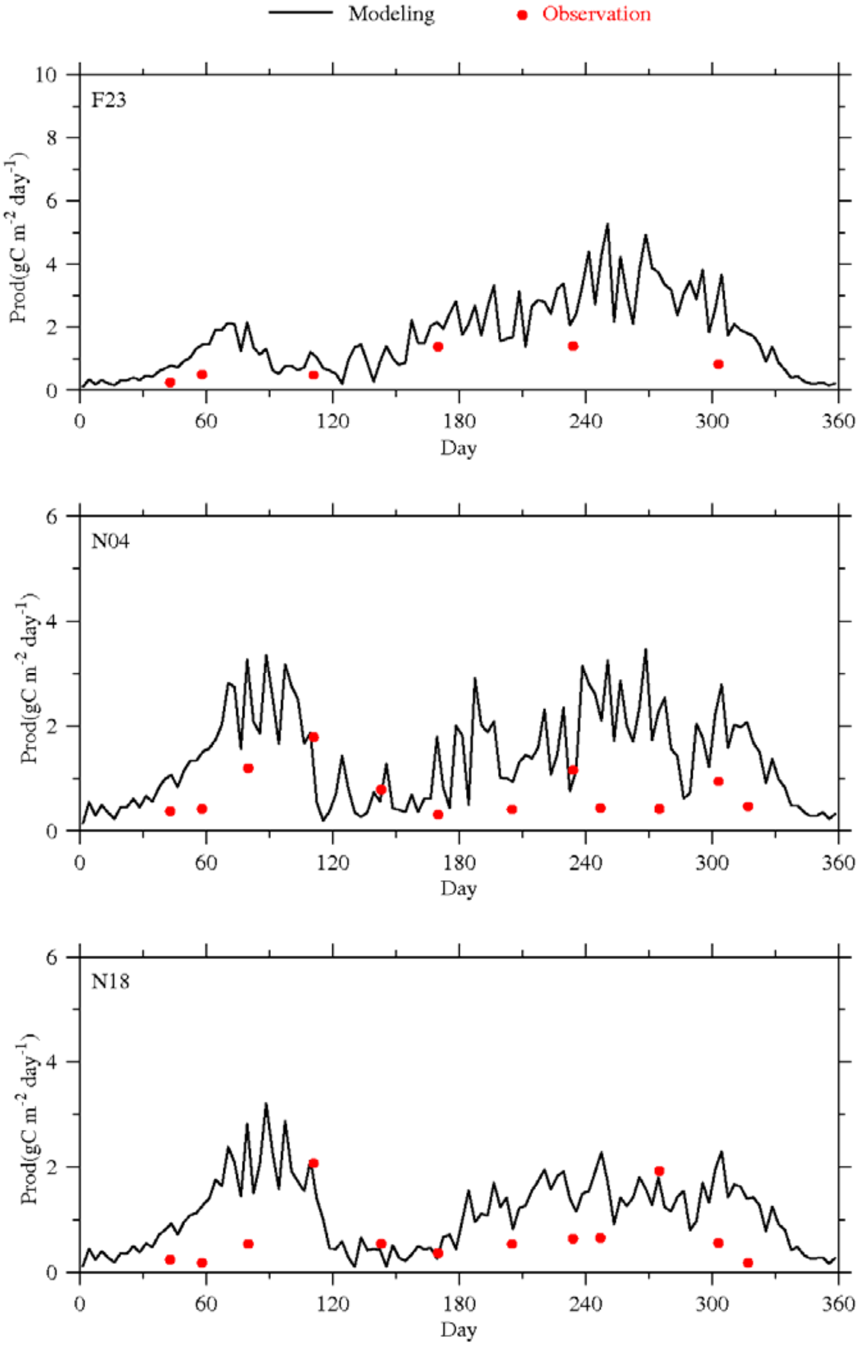


Figure 3.37 Comparison of observed (dots) and modeled (lines) time-series data of integrated primary production at MWRA monitoring stations in 2007.

[Figure from Tian et al. (2009)]

From Tian et al. (2009): Section **4. Projection of the influence of the MWRA outfall on the ecosystem function in Mass Bay**

…. [For 2006] The Non-sewage run predicted slightly lower primary production during the summer and fall seasons, but the difference between the two runs was minor (< 15%; Figure 4.4).

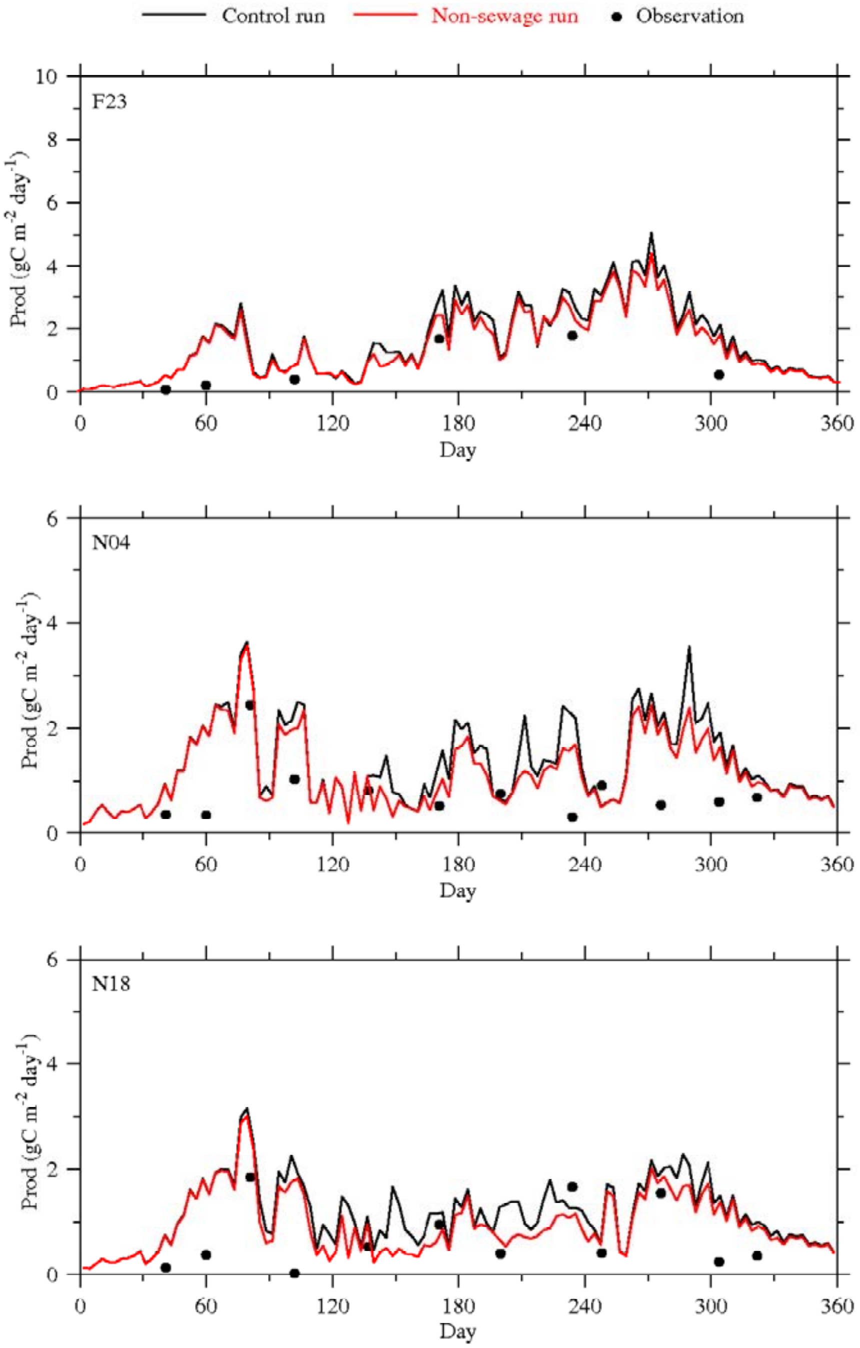


Figure 4.4 Comparison of integrated primary production between the Control and Non-sewage experiments at the MWRA monitoring stations in 2006.

[Figure from Tian et al. (2009)]

For 2007, …the vertically integrated primary production in the water column was slightly lower in the Non-sewage run than that in the Control run (< 17%; Figure 4.10), but this difference was not translated into other state variables such as surface chlorophyll concentration and bottom DO concentration and saturation.

+13%

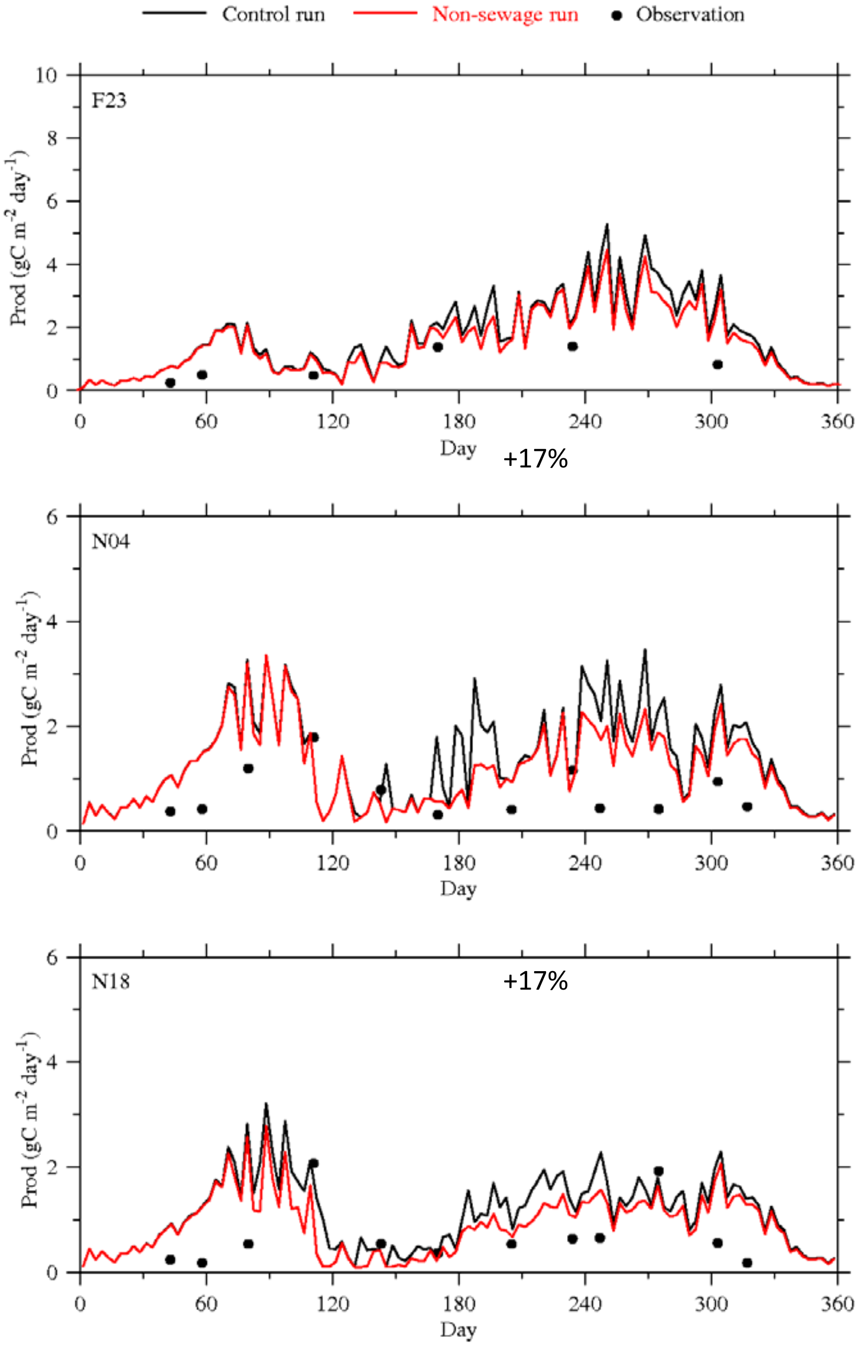


Figure 4.10. Comparison of integrated primary production between the Control and Non-sewage experiment at the MWRA monitoring stations in 2007.

[Figure from Tian et al. (2009)]

From Tian et al. (2009): Section **5. Sensitivity analysis with wind-field**

In 2006…Primary production was mostly similar between the Windfield and the Uniform-wind runs (**Figure 5.4**), but during the summer season, the Wind-field prediction tended to be slightly higher than that of the Uniform-wind run.

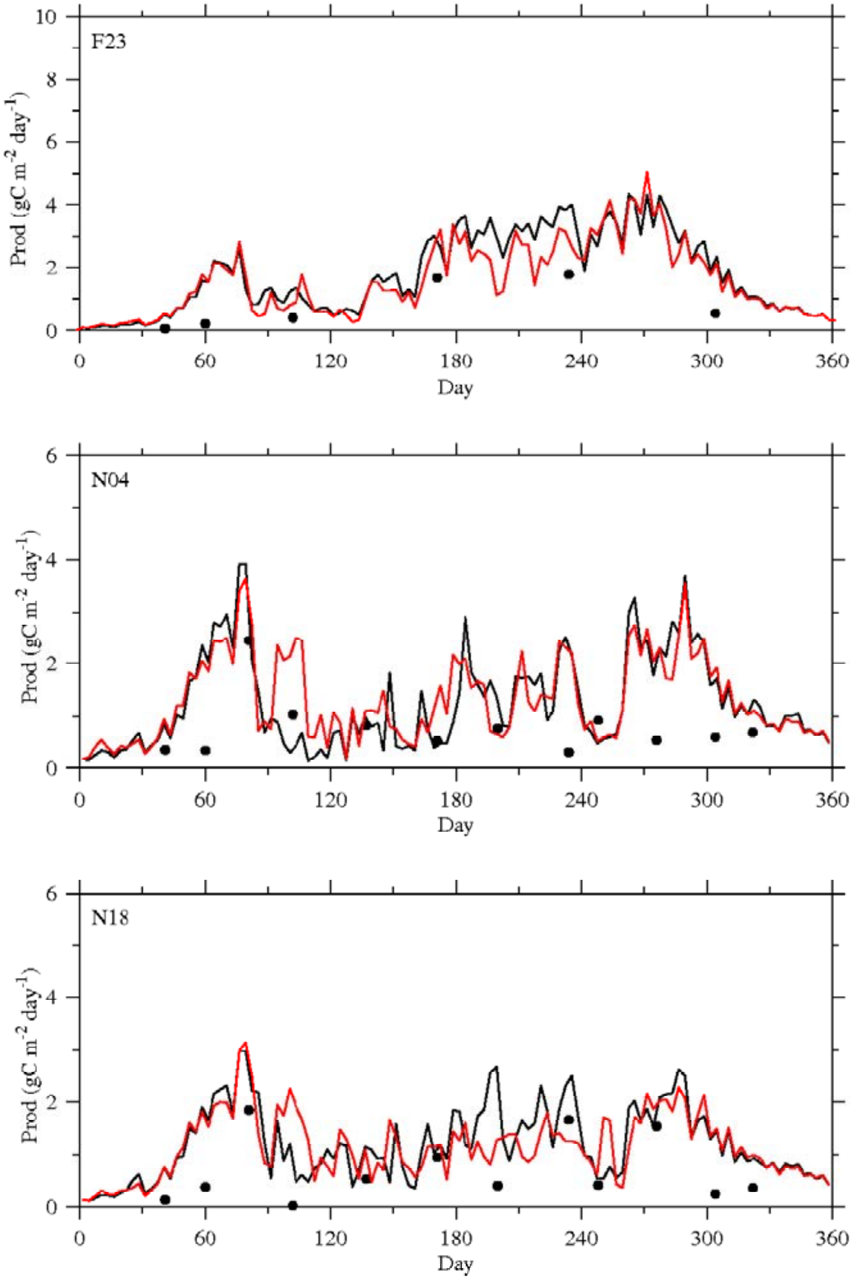


Figure 5.4 Comparison of integrated primary production between the Wind-field (black lines) and the Uniform-wind (red lines) runs at the MWRA monitoring stations in 2006.
[Figure from Tian et al. (2009)]

2008 Chen et al. (2010)

This report does not include an analysis of primary productivity (model or data).

2009 Tian et al. (2010)

[*From* Tian et al. (2010): Section 2. Methods, 2.2 UG-RCA]
…Model-simulated primary production was depicted at three monitoring stations where field observations were often conducted (primary production data were not available for 2009 at the time this report was prepared) (Figure 3.25). Primary production did not show typical peaks for spring and fall blooms, but rather remained at a relatively high level throughout the summer season. Primary production at the aforementioned near-field station N18 was not particularly lower than that at other stations, but it decreased to a low level during the fall season at all the stations.

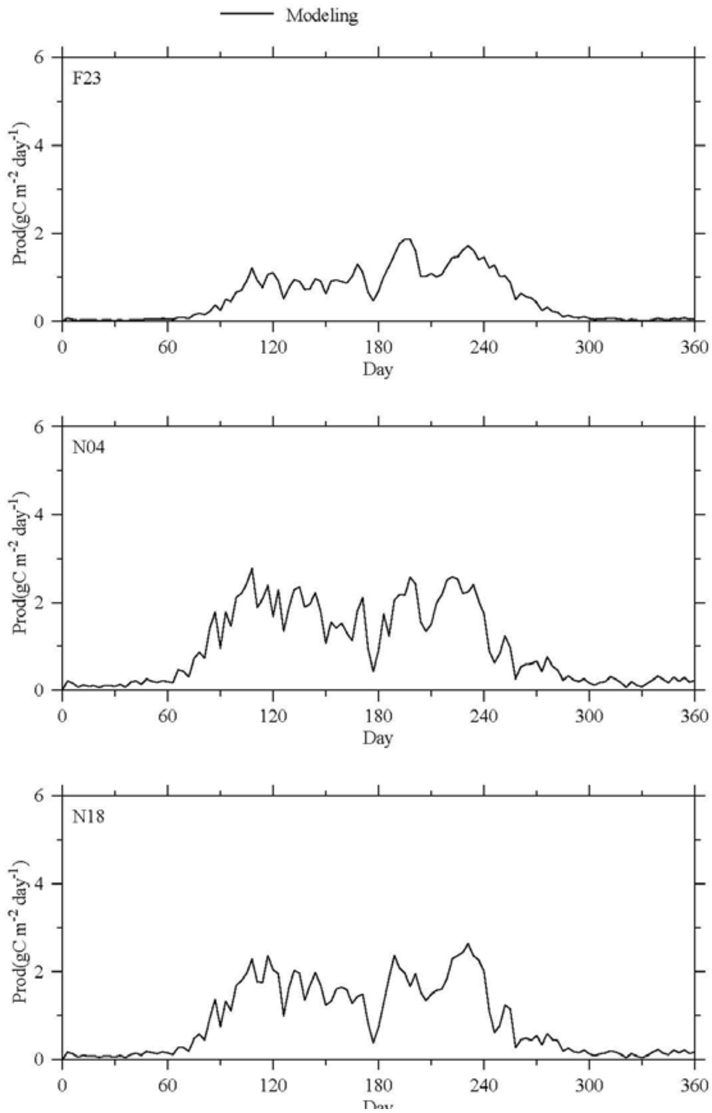


Figure 3.25 Model-simulated vertically integrated primary production at the MWRA monitoring stations. [Figure from Tian et al. (2010)]

2009, 2010 Zhao et al. (2011)

From Zhao et al. (2011): Section **3.2.1 Model-data comparisons**

Model-simulated primary production was depicted at three monitoring stations where field observations were conducted (Figure 3.28). Except perhaps for station N04 in 2009, modeled primary production did not show typical peaks for spring and fall blooms, but rather remained at a relatively high level throughout the summer season. Primary production at the near-field station N18 close to the MWRA outfall was not particularly higher than that at other stations. At all three stations, modeled primary production increased gradually in spring and dropped abruptly in late fall.

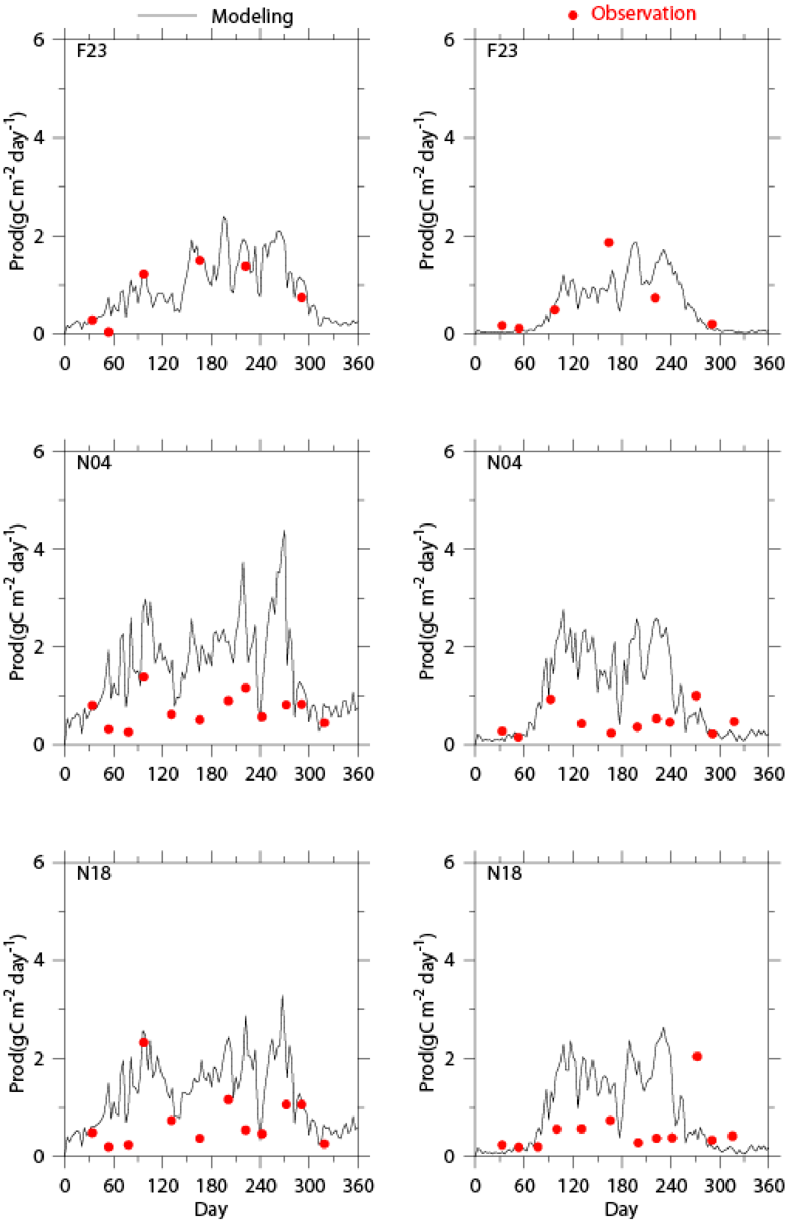


Figure 3.28 Comparison of vertically integrated primary production observed (dots) and modeled (lines) time series at the MWRA monitoring stations in 2010 (left panels) and 2009 (right panels.)

[Figure from Zhao et al. (2011)]

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Massachusetts Water Resources Authority
Charlestown Navy Yard
100 First Avenue
Boston, MA 02129
(617) 242-6000
http://www.mwra.state.ma.us