

Task Order Number 35: Influence of Physical Controls on Dissolved Oxygen Variation at the Outfall Site

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Introduction

The goal of the task order is to evaluate the physical factors affecting bottom water dissolved oxygen (DO) concentrations in Massachusetts Bay, specifically in the vicinity of the MWRA bay outfall site. This is a continuation of the work initiated for the 1999 Annual Water Column Report (Libby et al., 2000), in which the relationship between bottom water dissolved oxygen fluctuations and temperature and salinity variations was first noted.

The DO level in the near-bottom waters at the outfall site reaches its annual minimum during the fall, in the range of 6-8 mg/l. During 1999, there were observations below 6 mg/l, the EPA-mandated action level for remediation. The decrease in DO during this period is presumed to be due to some combination of the following: local oxygen demand, lack of vertical ventilation due to stratification, and the advection of low-oxygen waters from elsewhere. A number of specific physical factors have previously been considered to explain the interannual variations of near-bottom DO. These include

1. low initial bottom water DO levels when stratification is established in the spring;
2. flux of organic matter following the summer phytoplankton bloom;
3. lack of reventilation events; and
4. deepening of the seasonal pycnocline.

This study is based on correlation analysis between different physical factors and DO. This analysis indicates that the interannual variations of DO at the outfall site are highly correlated with the interannual variations of DO in the deep waters of Stellwagen Basin and at the northeastern boundary of Massachusetts Bay. This suggests that the variability is not locally driven, but rather that it is a regional phenomenon, which is manifested locally due to the advection of water of varying DO into western Massachusetts Bay. These interannual variations are significantly correlated with physical variables, specifically the near-bottom salinity and temperature. The causal link between these variables and dissolved oxygen has not yet been determined, but the first finding indicates that the connection is regional, rather than local. This report summarizes the analysis that leads to these conclusions and explores the possible causal relationships between temperature, salinity, and dissolved oxygen.

Data Analysis

The inner nearfield stations N13 to N21 together characterize the conditions in the vicinity of the outfall site. Two of these stations, N18 and N19, are less than 25-m depth, whereas the other stations are between 29 and 45-m depth. The two shallower stations do not show as consistent variation of DO as the others, probably because of intermittent reventilation of these shallower stations. Thus, stations N13, N14, N15, N16, N17, N20 and N21 were aggregated to define the spatially averaged conditions in the vicinity of the outfall site. The variations between stations was small relative to the seasonal variations, and analysis using individual stations yielded similar results to using the spatial average. The analysis only considered data from the months of September and October, which included between 2 and 5 surveys, depending on the year. This time interval always corresponded to low DO conditions and a stratified water column.

The temporal variations of near-bottom DO at the outfall site are shown in Figure 1. There is a strong seasonal cycle, with high DO during the winter and declining DO during the stratified months, with minima occurring just before the fall overturn (around the end of October). This variation is controlled mainly by stratification, which inhibits vertical exchange between June and October. The interannual variations in DO are also significant, as evidenced by the variations in the minimum DO value. The levels drop below 6 mg/l during the fall of 1994 and 1999. The purpose of this technical memorandum is to investigate the causes of this interannual variability.

The simplest and most statistically robust explanation for the interannual variation of DO at the outfall site is simply that it is controlled by the offshore variation in near-bottom DO. This is demonstrated by Figures 2 and 3, which compare the annual minimum deep DO value at the outfall site to the deep DO at the boundary with the Gulf of Maine (station F27—Figure 2), and Stellwagen Basin (station F22—Figure 3). Unfortunately there are only 7 years of data available for the comparison at station F27, but for these years, 92% of the variability at the outfall site is explained by a linear regression with the boundary DO. With 9 years of data for comparison at Stellwagen Basin, 81% of the variability is explained. This analysis convincingly demonstrates that the interannual DO variations are regional in scale, rather than being dependent on local conditions at the outfall site. This finding does not in itself indicate the cause of the variations.

The dominant circulation pattern in Massachusetts Bay includes inflow from the northeast, so the correlation between the nearfield and farfield DO could simply reflect the advective pathway of the water. However there is a large difference in depth between the offshore and nearshore waters, so the bottom water would have to be raised up more than 60 m as it moved onshore. Cross-sections across the northern portion of Massachusetts Bay (Figure 4) demonstrate that during some years, there appears to be a continuity of water properties between the deep waters nearshore and offshore due to upwelling of cold water, but generally the bottom waters in the nearshore are several degrees warmer than the offshore bottom water. Thus the bottom water is not simply advected to shallow water. However the continuity of the near-bottom DO distribution

between offshore and onshore indicates a regional coherence of the process that consumes DO.

Another line of evidence that would appear to argue against a simple advective pathway is that the Stellwagen DO values are often lower than those in the nearfield (Figure 3). This is most easily explained in that the nearfield stations were sampled 2-5 times each year during the September and October period, while station F22 was only sampled during the early October (nominally) survey. Regardless of the timing of surveys, there is local oxygen consumption at both sites, and both sites share a common source of water, whose dissolved oxygen variation explains most of the interannual variability.

An examination of the interannual variations of temperature and salinity shows that these variables are statistically related to the DO variations. Figure 5 shows the variation of DO relative to temperature and salinity for all of the years of the monitoring program at the outfall site (station N21 for 1992-2000). The regression coefficients are significant for both temperature ($r^2=0.47$) and salinity ($r^2=0.50$). Surprisingly, there is insignificant correlation between interannual fluctuations of temperature and salinity ($r^2=0.06$). Thus the physical mechanism responsible for the covariation of salinity and DO is different from that associated with temperature and DO.

Dissolved oxygen was also found to be correlated with stratification ($r^2=0.26$). However, virtually all of this correlation was related to the interannual variation of temperature, which is more highly correlated with DO. The dissolved oxygen is also correlated with the “setup” DO, the value of deep DO observed in June ($r^2=0.30$). However, the “setup” DO is significantly correlated with interannual salinity variations, so it is not clear that this correlation indicates a separate physical mechanism. More on this issue is discussed below.

A Statistical Model

Based on the high correlations between temperature and DO and salinity and DO, a statistical model for the deep dissolved oxygen variations was constructed according to the formula

$$DO = A - B \times T' - C \times S'$$

where T' and S' are the near-bottom temperature and salinity anomalies (relative to the 9-year mean for Sept.-Oct., $A=7.46$ mg/l, $B=1.9$, and $C=0.22$). These coefficients were obtained by least-square analysis of the dissolved oxygen variations with respect to salinity and temperature. The model explains 77% of the variance of autumn DO over the 9-year period and is significant at the 95% level. The timeseries of model predictions are shown for the 9-year period in Figure 6. Only in 2 years, 1998, and 2000, are there significant deviations between model predictions and the observations. The lower panel in Figure 6 indicates which of the factors, salinity or temperature, contributed more to the predicted anomaly in a given year. For example in 1994, the low dissolved oxygen was related to both salinity and temperature anomalies, whereas in 1999 it was due principally to the salinity effect.

Because of the observed correlation with “setup” DO, a modified model was constructed with “setup” DO as a third forcing variable. This inclusion increased the regression coefficient from $r^2=0.77$ to 0.80, which is not a large enough improvement to indicate that the “setup” dissolved oxygen is a dominant forcing variable.

This analysis suggests that both temperature and salinity have significant and independent effects on the fall DO values. If the causality of these correlations could be determined, that would be of considerable value in understanding and predicting future variations of dissolved oxygen.

This local model appears somewhat inconsistent with the first result, that the best predictor of nearfield DO is the boundary DO. An analysis of the variation of offshore temperature and salinity relative to DO was conducted to determine whether the same relationship between water properties and DO occurs regionally. This analysis indicates that the deep salinity at F27 is highly correlated with deep DO (high salinity occurring with low DO), with $r^2=0.69$. Temperature shows weak correlation, however. The strong correlation with salinity supports the hypothesis of a regional control. The weak temperature signal offshore is probably explained by the lack of temperature gradients in the deep water compared to the waters around 30-m depth (cf. Figure 4). The temperature variability near the outfall site is highly sensitive to upwelling and downwelling of the thermocline and these variations in water temperature in turn has a direct affect on DO levels. This signal is not evident in the temperature signal at 90-m depth, however the upwelling-downwelling conditions still appear to influence the deep DO levels.

Causal Mechanisms

1. The Role of Horizontal Advection

A model for the influence of horizontal advection on the DO is constructed by first defining a volume in which both sediment oxygen demand and deep water respiration influence the DO. Based on observed vertical extent of DO anomalies, a layer of 5-10 m thickness above the bottom is considered, in water depths of 30-35 m. The physical factors responsible for replenishing DO are assumed to be vertical mixing and horizontal advection. The vertical mixing rate is determined based on the observed seasonal increase in temperature of the deep water, leading to an average vertical diffusivity of approximately $10^{-5} \text{ m}^2 \text{ s}^{-1}$. The estimated contribution of advection is determined as a residual, based on knowledge of the other terms in the equation for time-variation of DO:

$$\partial O_2 / \partial t = C + I / h_b (K \partial O_2 / \partial z) - u \partial O_2 / \partial x$$

where the first term on the right is the local consumption term, the second term is the vertical diffusive flux term (with diffusivity K and the thickness of the bottom layer represented by h_b), and the third term is the horizontal advective term. The magnitude of the time-dependent term is approximately -0.04 mg/l per day (average July to October). The value of C is determined by summing the contributions of the benthic oxygen

demand and the water-column respiration. The observed sediment oxygen demand for late summer for western Massachusetts Bay is 20 mmol O₂/ m²/day (Hopkinson *et al.*, 2001). For a 5-10 m thickness water, this represents a sink of 0.06-0.12 mg/l O₂/day. The local water-column respiration contributes another 0.03-0.12 mg/l/d (Kelly and Doering, 1999). Summing these two contributions yields a value of C of 0.09-0.24 mg/l/day.

The average vertical gradient in DO is 0.1-0.2 mg/l/m (e.g., Figure 4). This yields an average diffusive increase in DO in the bottom layer of 0.01-0.03 mg/l/day.

These estimates indicate that the vertical diffusive flux has a minor mitigative influence on the local consumption rate, amounting to at most only one third of the consumption rate. However, the observed decrease in DO is substantially less than that due to the difference between local consumption and vertical diffusion: 0.04 mg/l/day compared with 0.06-0.23 mg/l/day. This suggests that there must be an advective contribution that provides an effective source of 0.02-0.19 mg/l/day. An effective average near- bottom velocity of 1-2 cm/s would yield a transit time of 15 to 30 days for northern Massachusetts Bay, which is consistent with observations and model results. This leads to a gradient between the source waters in the Gulf of Maine and western Massachusetts Bay of 0.3-6 mg/l, depending on the advection rate and the magnitude of consumption. Figure 4 suggests that the difference may be around 0.5 mg/l, but there is no indication that it could reach the upper end of that range.

This analysis suggests that the observations are potentially consistent with a model in which advective supply of dissolved oxygen partially compensates for the local consumption. However, the model could not explain a consumption rate at the high end of the estimates. These calculations should be interpreted as providing support for the assertion that advection *could* be a controlling variable. In combination with the empirical results described above, the influence of advection in the interannual variation of DO should be carefully considered.

2. The Influence of Temperature Variations

The variation of DO with temperature might be explained by the temperature dependence of the consumption rate C. Both the water column and sediment oxygen demand rates are functions of deep-water temperature—the temperature of the biologically active sediment is virtually the same as that of the overlying water. Higher temperature results in more rapid consumption and thus greater depression of DO. With a Q₁₀ of 2, (i.e., a factor of 2 for each 10 degrees C), the temperature variations of up to 6 degrees, should produce 50% variations in the dissolved oxygen consumption. This is close to what is observed, i.e., of 2 mg/l DO variations correlated with temperature, compared to an overall DO decrease of about 4 mg/l.

3. Salinity Effect

The influence of salinity is not as easy to explain as temperature. It is most likely related to the rate of horizontal advection. During years in which there is more freshwater input, the near-bottom salinity is lower. Greater freshwater input leads to a more vigorous coastal current (Geyer et al., submitted). At the regional scale of the western Gulf of Maine, this more vigorous circulation leads to shorter residence time of water in the coastal current. This shorter residence time might in turn result in less depletion of dissolved oxygen due to local respiration of organic matter. There also may be increased ventilation of the deep waters during years with more freshwater inflow due to mechanisms that are yet to be determined. At the local scale of western Massachusetts Bay, the more vigorous coastal circulation may result in more rapid through-flow and more effective flushing of the bottom waters, causing less reduction in DO. Another possible explanation for the salinity signal is that higher salinities correspond to “older” water, which has spent more time away from the surface waters where it would be reventilated. This hypothesis could be tested with a detailed analysis of the T-S-DO characteristics of the Gulf of Maine, but it has not been accomplished in this study.

These explanations are speculative, however. Further data analysis and modeling is required to clarify the causality of the correlation between salinity and dissolved oxygen.

Summary and Conclusions

The main conclusion of this analysis is that the DO is regionally controlled, with a spatial correlation scale at least comparable to the lateral dimensions of Massachusetts Bay. The deep DO at the boundary between Massachusetts Bay and the Gulf of Maine is a good predictor of the deep DO at the outfall site. This high correlation indicates 1) that the processes affecting DO occur on a regional scale, and 2) that the advection of water from the Gulf of Maine influences the DO levels in the nearfield.

These findings are in agreement with recent model results from the Bays Eutrophication Model (BEM; HydroQual, 2001). Boundary sensitivity tests were run on the BEM to evaluate the relationship between DO conditions at the boundary and nearfield stations. The results of the evaluation indicated that there was a strong correlation in DO between the boundary and nearfield stations and that model results for DO levels in the nearfield were highly dependent on boundary conditions.

The DO variability in the nearfield is linked to variations in temperature and salinity. The temperature dependence is most likely explained by the influence of bottom temperature on metabolism, which in turn affects the seasonal drawdown of DO. The salinity dependence of DO concentrations appears to be related to the connection between freshwater inflow, salinity and the through-flow rate of the Western Maine Coastal Current. When the freshwater inflow rate increases, the salinity drops, and the coastal current speeds up. This increases the advection rate and reduces the drawdown of DO.

These observations are consistent with a simple model that includes advection and temperature-dependent depletion due to water column and sediment oxygen demand. Such a model provides a conceptual view of the processes and a rough, quantitative check on the rates. A more accurate treatment would require consideration of the variations of BOD across the domain and a more detailed examination of the advective trajectory of the water. These more detailed calculations should be done in context with the 3-d numerical model.

Our analysis suggests that the “setup” DO condition in June plays a minor role in determining September-October DO minima in the nearfield, but we do not directly evaluate the localized physical and biological processes that contribute to the seasonal decline in near-bottom DO that is observed each year as was done by Kelly and Doering (1999). Our focus is on the physical factors contributing to the interannual variability in annual DO minima in the nearfield. An integration of the two approaches may yield a more robust explanation of the physical and biological forcing factors affecting near-bottom water DO in the nearfield.

The most obvious recommendation based on this analysis is to make sure to obtain high quality DO measurements at the boundary of the domain during the late summer and fall, and to try to document the spatial gradients of DO in the seaward direction from the outfall site at scales of 10's of kilometers. In conjunction with continued collection of high quality survey data, we recommend that additional efforts should be undertaken to obtain continuous oxygen measurements in bottom water during the stratified season (August through October at a minimum).

Currently there are three mooring platforms that could provide excellent placement for such measurements. The USGS has a mooring and instrument array that is located within the nearfield approximately 1 km south of the outfall that provides current, temperature, and salinity data from ~6 m to 1 m above bottom. NOAA weather buoy #44013 is located just to the southeast of the nearfield and may provide an opportunity for sensor deployment. Deployment of moorings specifically for MWRA data collection is also an option. Further afield, the Gulf of Maine Ocean Observing System (GoMOOS) deployed a mooring in 2001 in northeastern Massachusetts Bay at a location approximately halfway between MWRA stations F22 and F27 discussed in this report. A dissolved oxygen sensor has since been added to this GoMOOS mooring in 2002. The high resolution data from this mooring on temperature, salinity, current speed and direction, and dissolved oxygen concentrations (DO from 40 m only) will provide a more complete picture of DO variability of the water entering Massachusetts Bay from the Gulf of Maine. The availability of high resolution DO data during the stratified period both within the nearfield and upstream near the entrance to Massachusetts Bay would provide valuable information for both model development and to distinguish between local and regional factors affecting nearfield DO levels.

References

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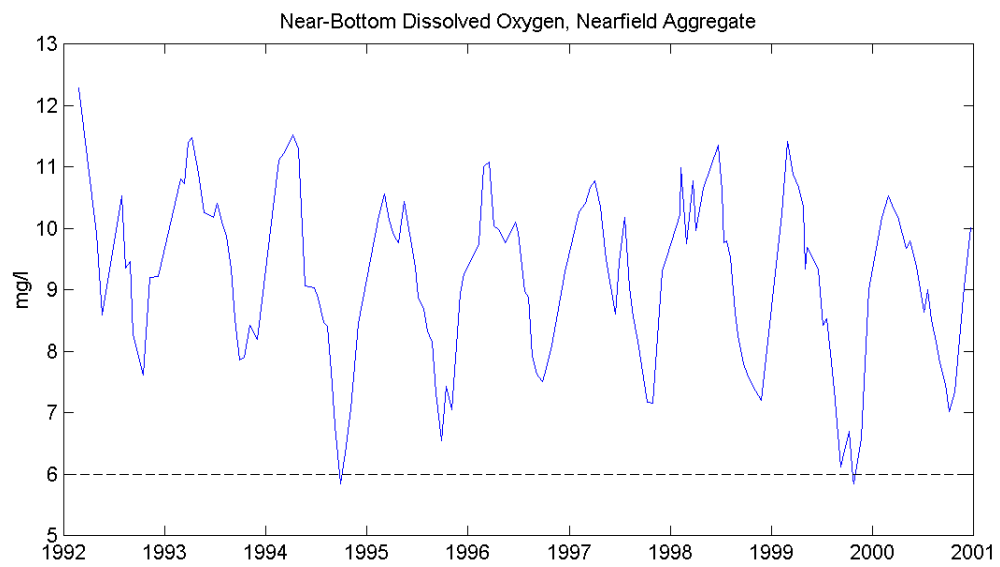


Figure 1. Timeseries of near-bottom DO aggregated over nearfield stations N13, N14, N15, N16, N17, N20 and N21.

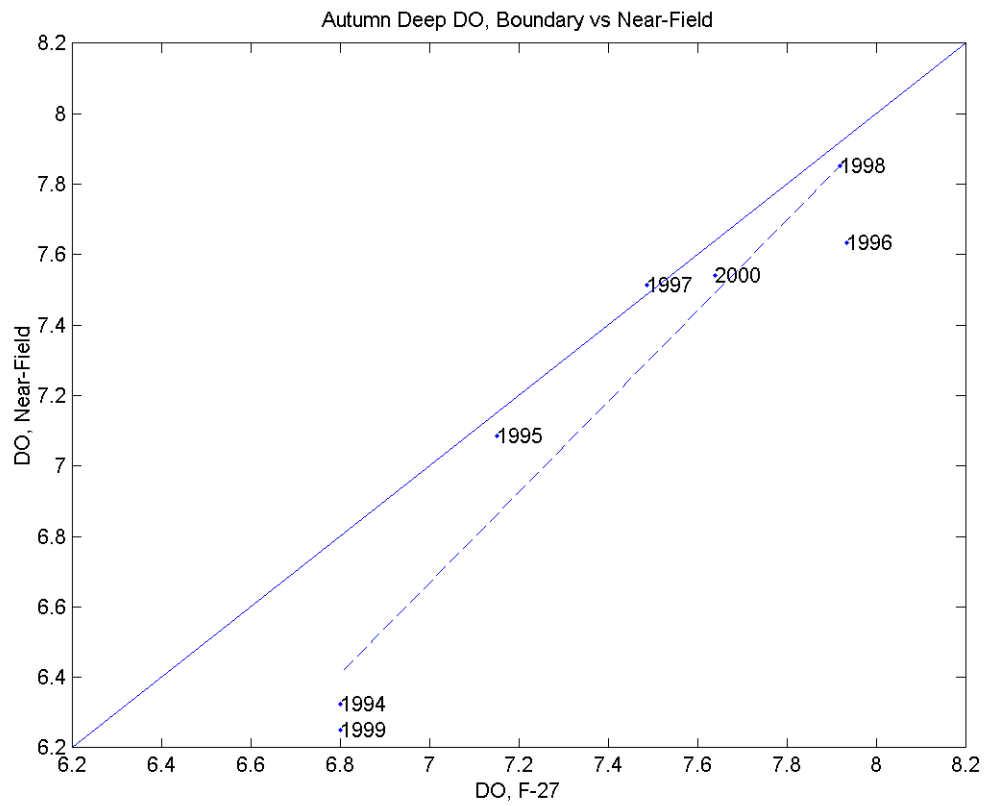


Figure 2. Comparison of boundary deep DO to nearfield DO, for autumn minimum conditions. The solid line indicates the 1:1 line, and the dashed line indicates the best linear fit, which explains 92% of the interannual variability of nearfield DO.

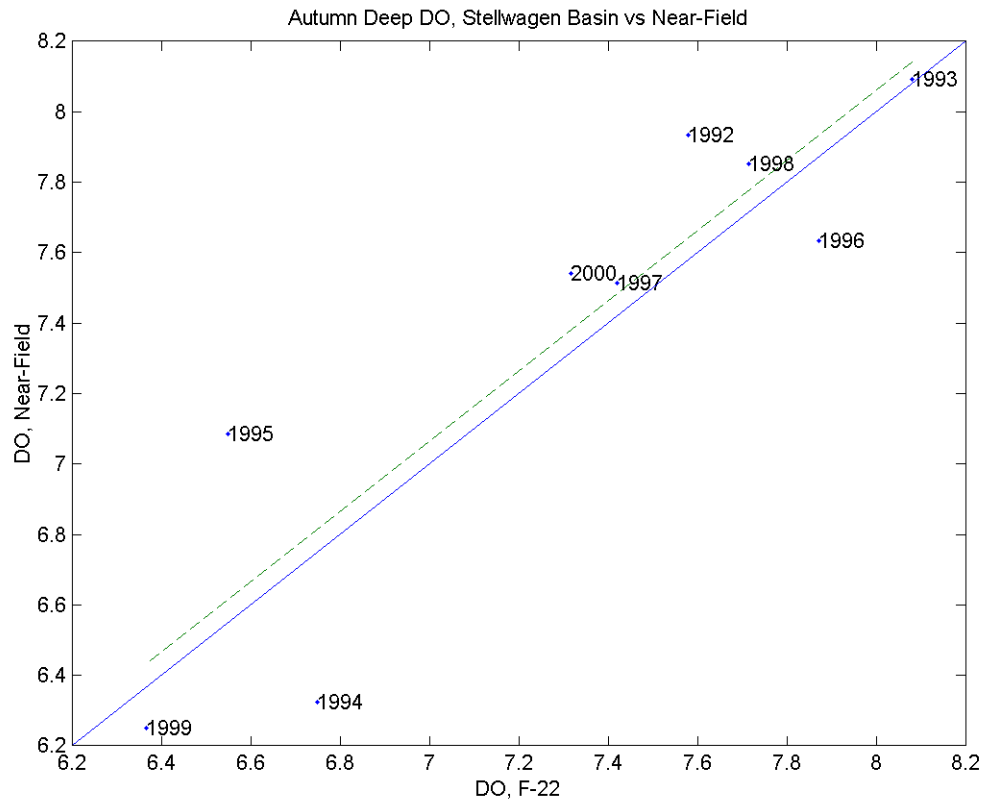


Figure 3. Comparison of Stellwagen Basin deep DO to nearfield DO, for autumn minimum conditions. The solid line indicates 1:1 line, and the dashed line indicates the best linear fit, which explains 81% of the interannual variability of nearfield DO. Note that there are two more years of data in this plot than Figure 2. Also note that the near-field DO is often higher than the Stellwagen Basin DO, but this is primarily due to the averaging used for September – October data for the nearfield.

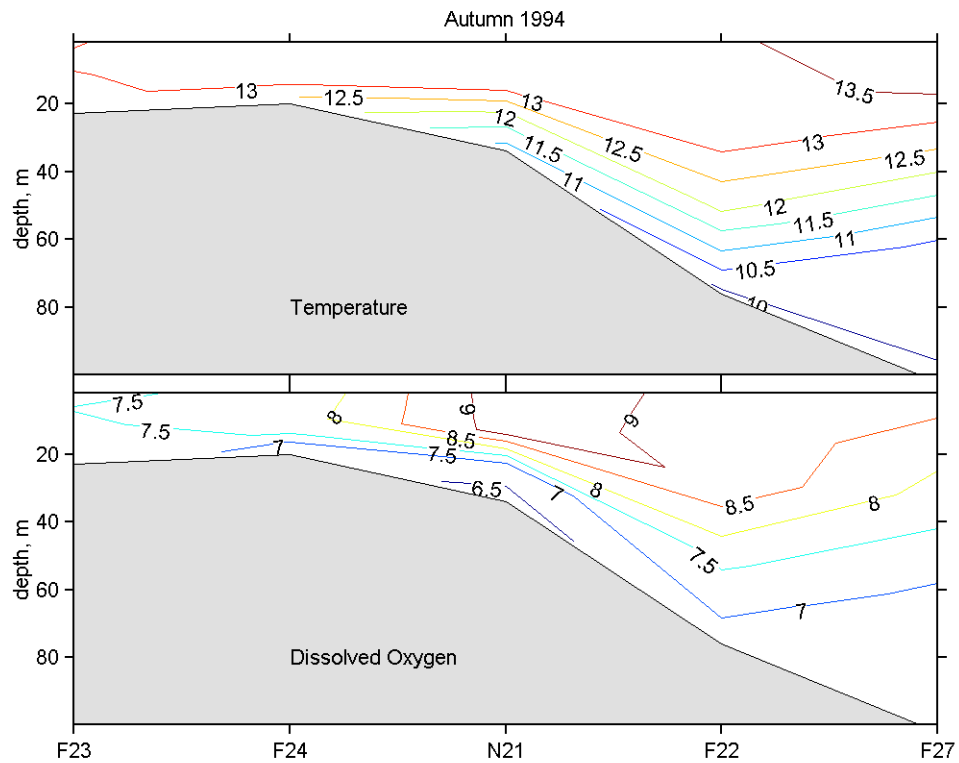


Figure 4a. Cross-sections of temperature and dissolved oxygen across northern Massachusetts Bay, from the entrance to Boston Harbor (station F23) to the northeast boundary with the Gulf of Maine (station F27) during October 1994. Note the apparent continuity of the low DO zone in the deep water.

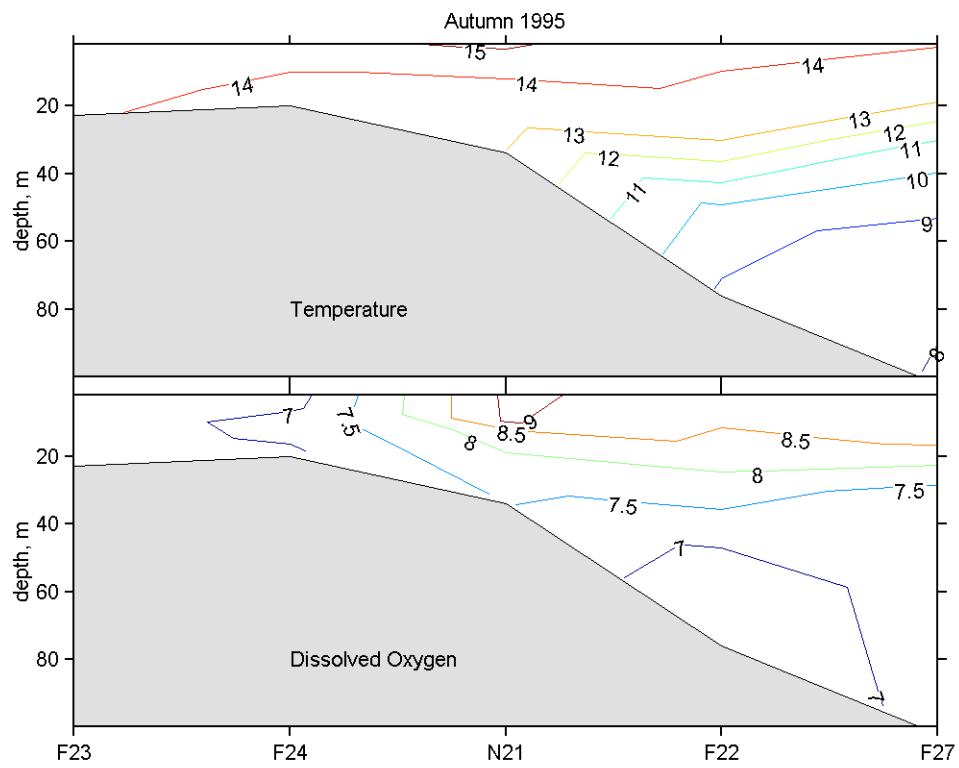


Figure 4b. Same as 4a, but for October 1995.

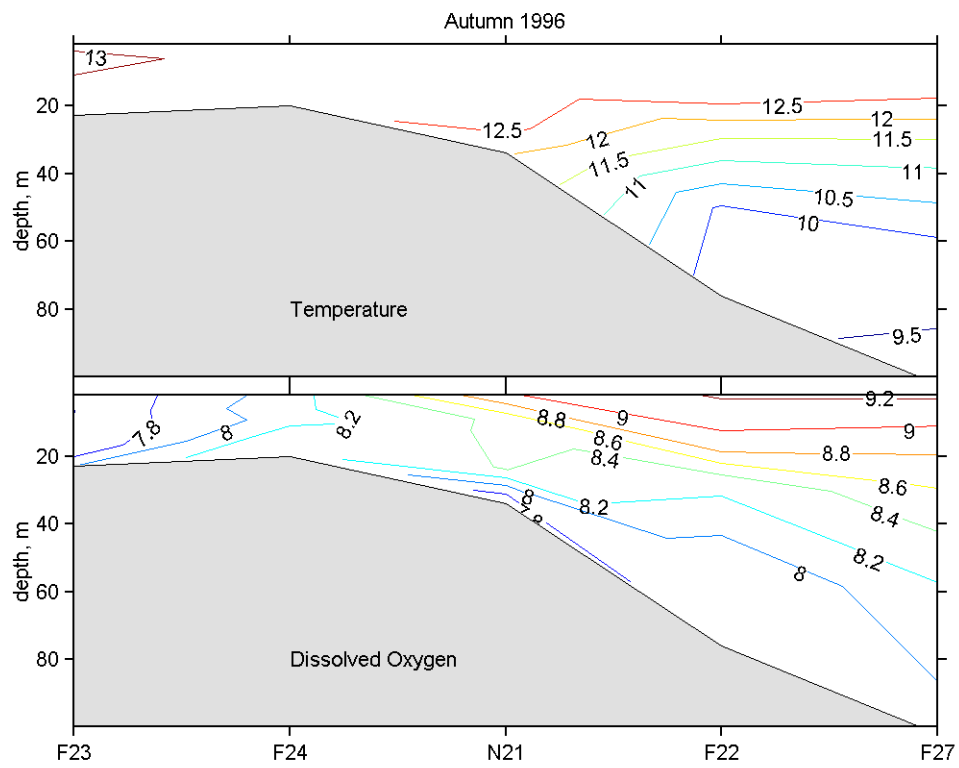


Figure 4c. Same as 4a, but for October 1996.

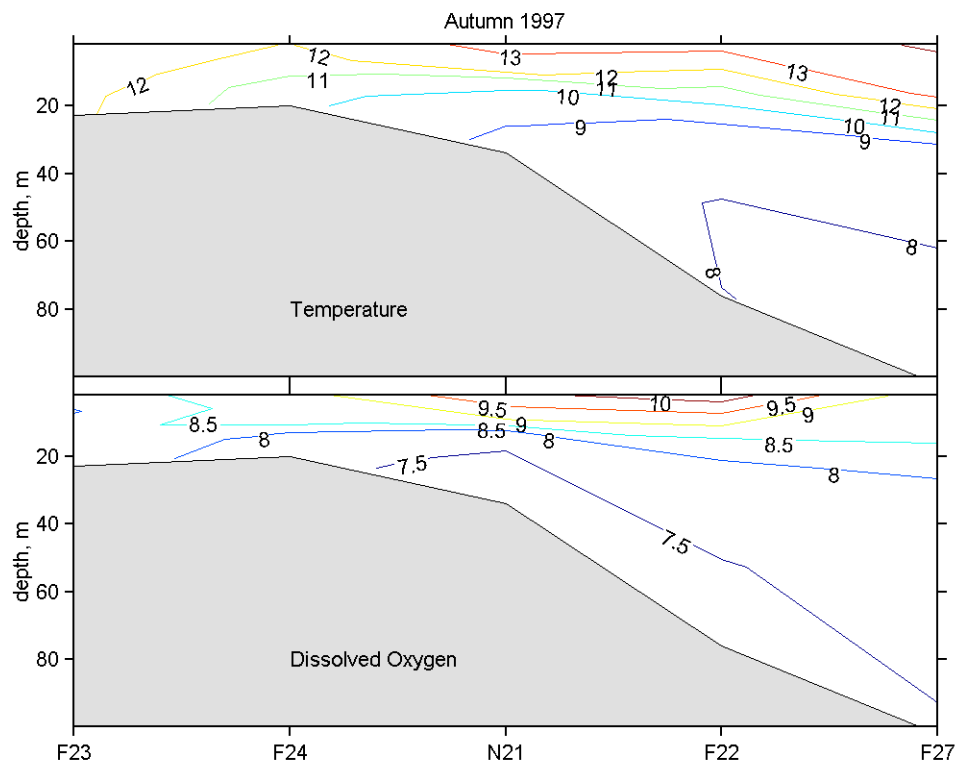


Figure 4d. Same as 4a, but for October 1997.

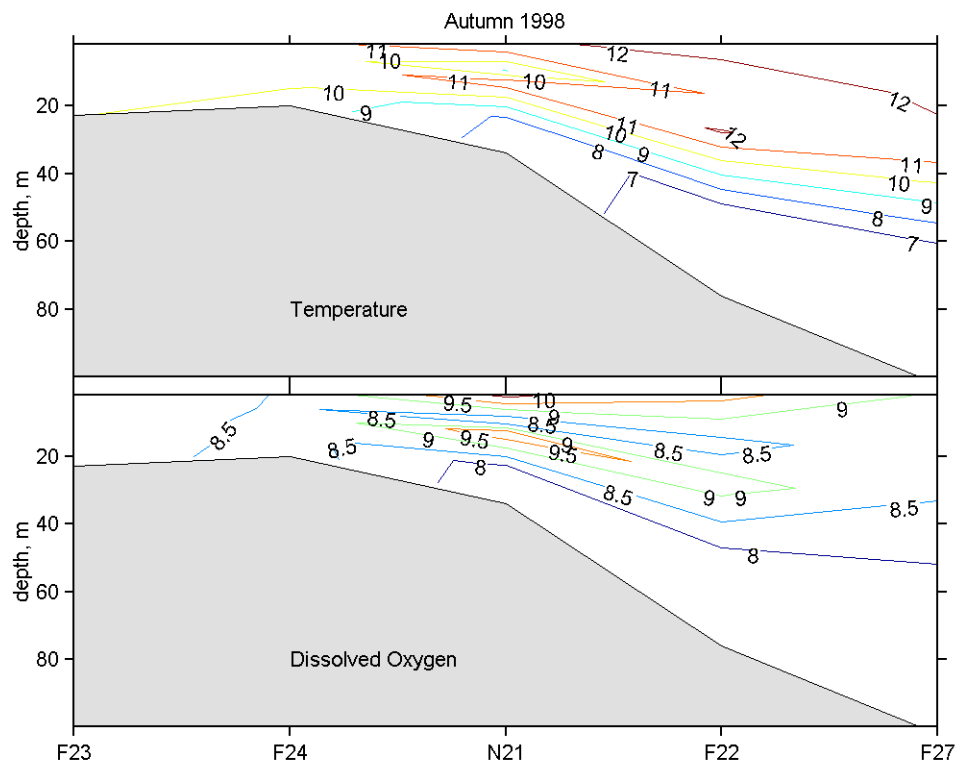


Figure 4e. Same as 4a, but for October 1998.

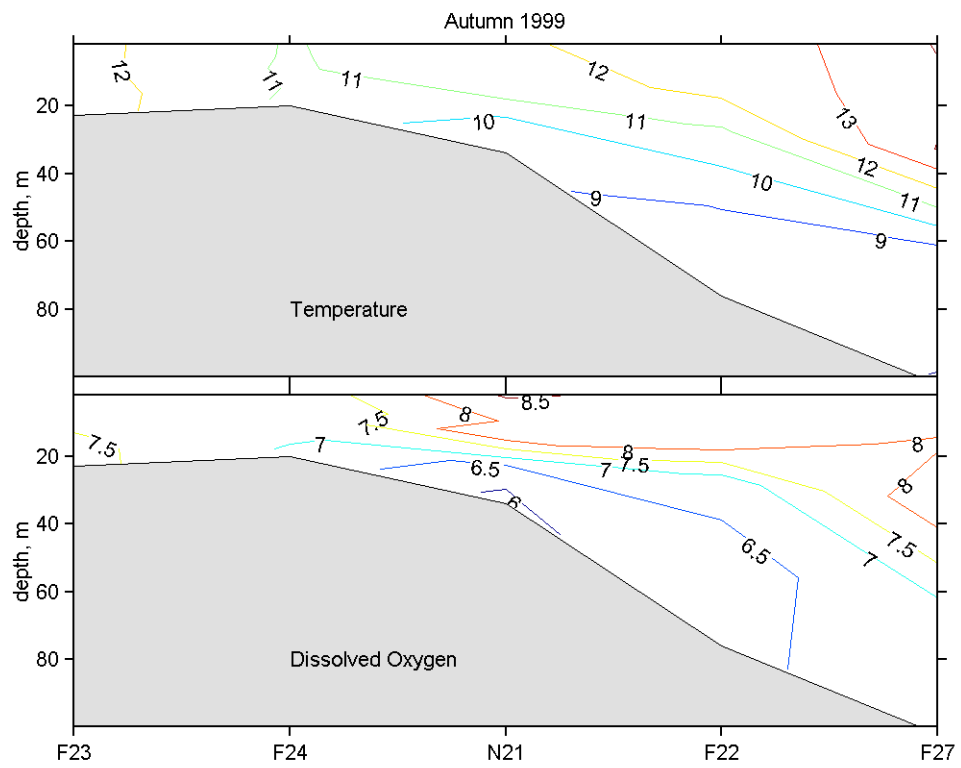


Figure 4f. Same as 4a, but for October 1999.

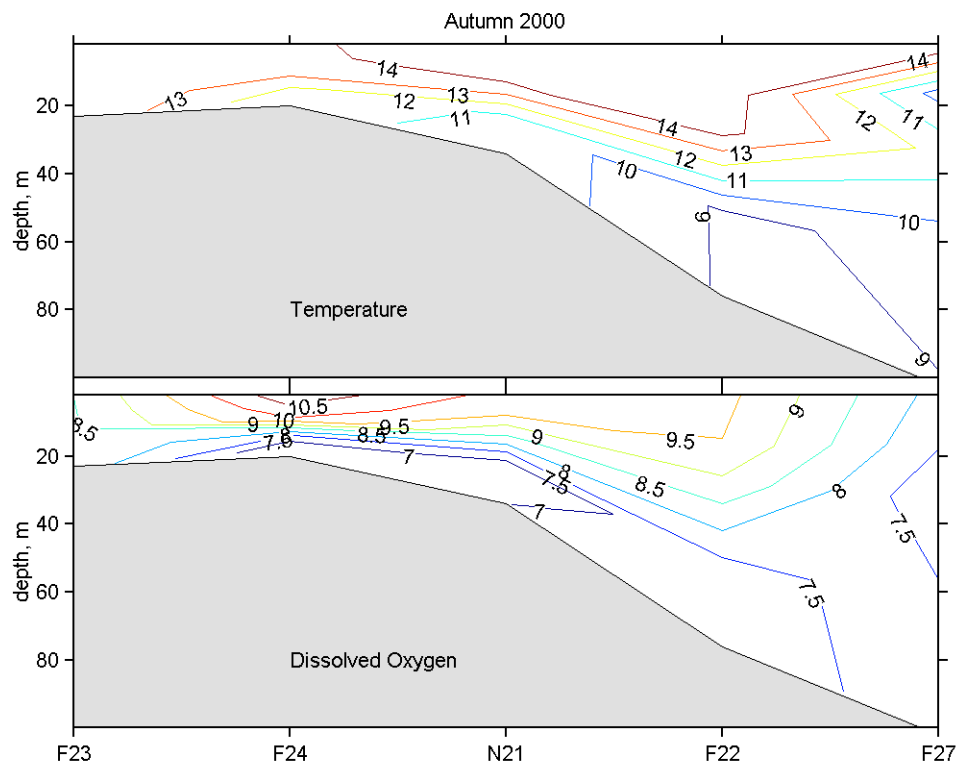


Figure 4g. Same as 4a, but for October 2000.

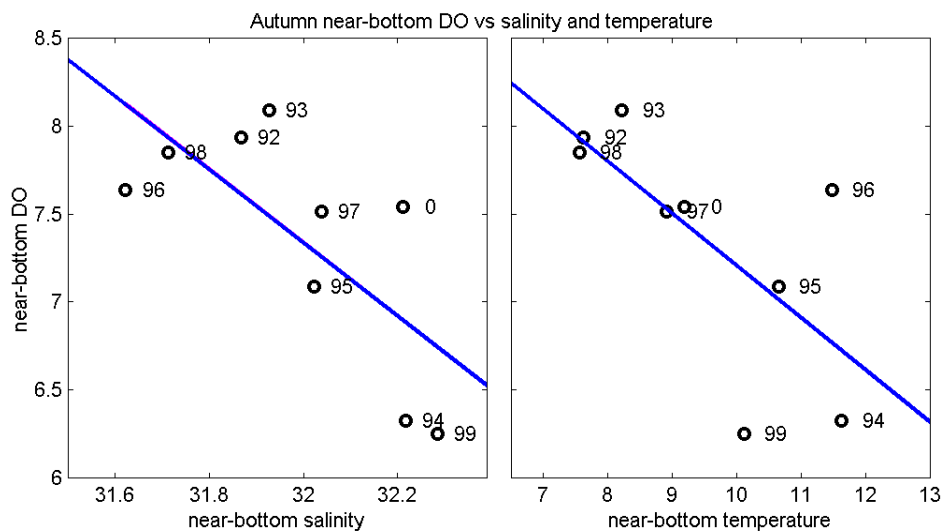
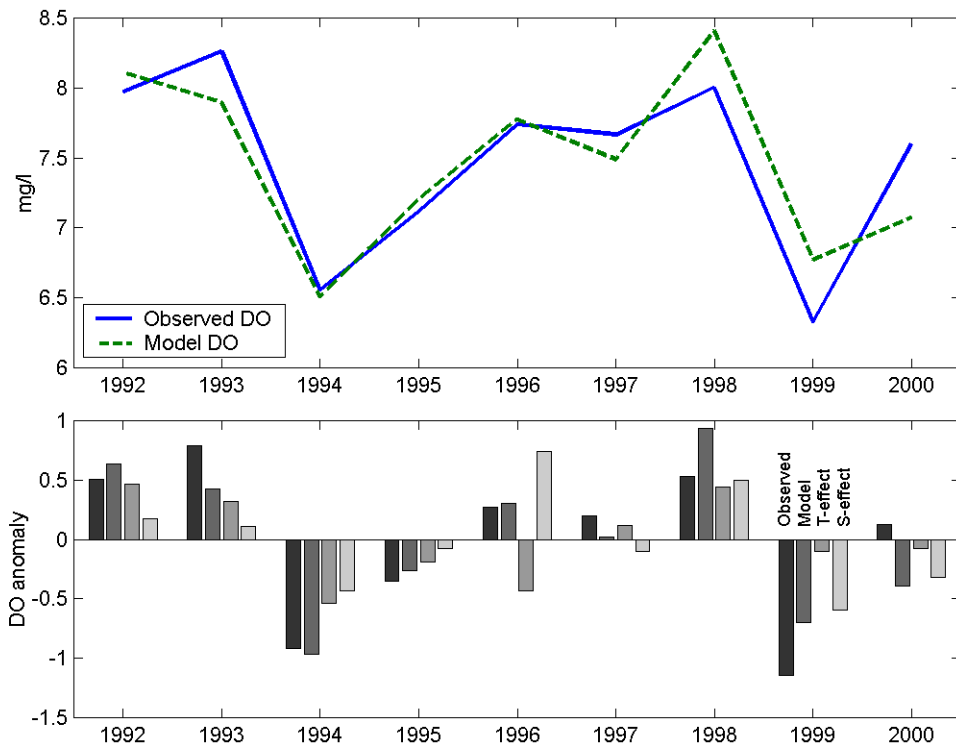


Figure 5. Near-bottom salinity and temperature compared to near-bottom DO at the outfall site (station N21), showing significant correlation between both salinity and temperature and DO. (The year 2000 is indicated by “0”; the other years by 2 digits.)



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Figure 6. Average near-bottom dissolved oxygen during September-October, compared with linear regression model based on temperature and salinity variation:

$$DO = A - B \times T' - C \times S'$$

where T' and S' are the near-bottom temperature and salinity anomalies (relative to the 9-year mean for Sept.-Oct., $A=7.46$, $B=1.9$, and $C=0.22$). The model explains 78% of the variance of autumn DO over the 9-year period and is significant at the 95% level. The bar plot in lower panel shows the individual contributions due to temperature and salinity for each of the years.