Physical Processes Contributing to Localized, Seasonal Hypoxic Conditions in the Bottom Waters of Smithtown Bay, Long Island Sound, New York

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Abstract of the Thesis

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Summertime hypoxia regularly occurs in the bottom waters of Smithtown Bay, Long Island Sound. Hypoxia, defined in this study as <3.0 mg O_2 L^{-1}, is plaguing many of our coastal estuaries and can be detrimental to aquatic organisms. A generally accepted model for the cause of coastal hypoxia in temperate regions is the establishment of seasonal water column stratification and the introduction of anthropogenic nutrients from sewage treatment plants, combined sewer overflows, agricultural fertilizers, urban runoff, sediment remineralization, and atmospheric deposition. However, there are no major point sources of anthropogenic nitrogen that discharge directly into Smithtown Bay. Despite great efforts to reduce nitrogen loading into Long Island Sound, summertime hypoxia is a continuing occurrence in Smithtown Bay. While hypoxic conditions remain seasonally prevalent in the bay, the surrounding bottom waters have considerably higher concentrations of dissolved oxygen. This study examines the causes of hypoxia in Smithtown Bay and how the problem is more complex than the introduction of

anthropogenic nitrogen. Strong, thermally controlled stratification and mid-depth pycnoclines inhibit vertical mixing and the replenishment of dissolved oxygen to bottom waters. The two headlands, Crane Neck and Eatons Neck, may be creating a partial boundary between the bay and the rest of the Sound, preventing lateral mixing. This results in weak currents and bottom stress and a limited exchange of water masses over a tidal cycle. Furthermore, the classical headland gyre setting may increase the residence time of suspended particulate material transported from land into Smithtown Bay. The trapped particulate material inside the bay will sink and increase the consumption of bottom water dissolved oxygen. It appears, from these results, that Smithtown Bay is physically predisposed to hypoxia. For this reason, it is likely that the current management solution to hypoxia of implementing total maximum daily loads of nitrogen will not alleviate the hypoxia problem in Smithtown Bay.

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List of Abbreviations

ADCP	Acoustic Doppler Current Profiler
$\alpha\Delta T$	Alpha delta temperature
$\beta\Delta S$	Beta delta salinity
BOD	Biological oxygen demand
CTD	Conductivity, temperature, depth
CT DEEP	Connecticut Department of Energy and Environmental Protection
CT DEP	Connecticut Department of Environmental Protection
DO	Dissolved oxygen
DOb	Bottom dissolved oxygen
$\Delta\rho$	Delta rho
ΔS	Delta salinity
ΔT	Delta temperature
EPA	Environmental Protection Agency
LIS	Long Island Sound
LISICOS	Long Island Sound Integrated Coastal Observatory System
LISS	Long Island Sound Study
NOAA	National Oceanic and Atmospheric Administration
NYSDEC	New York State Department of Environmental Conservation
PSU	Practical salinity unit
TMDL	Total maximum daily load
T-S	Temperature – salinity
USGS	United States Geological Survey

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1.0 Introduction

1.1 Background of Smithtown Bay

Smithtown Bay, located on the southern side of west-central Long Island Sound (LIS), is a diverse ecosystem that contributes to the social, economic, and ecological well-being of the local community. The bay and its surrounding coast support a variety of recreational outlets for Long Islanders and visitors alike. Commercial and recreational anglers catch numerous species of fish including, bluefish, striped bass, winter flounder, fluke, scup, tautog, and weakfish (LISS, 2011). Oysters, crabs, and lobsters are also harvested (LISS, 2011). Along the southern coastline of the bay, beaches, spanning 4.8 km, invite people to enjoy a day of swimming, sunbathing, or boating. Brackish creeks and marshes provide a habitat for various marine wildlife including, ospreys, cormorants, muskrats, egrets, and turtles (NYS Parks and Recreation, 2010). As part of LIS, Smithtown Bay serves as a breeding, feeding, and nursery area for aquatic organisms and offers a home to more than 1,200 species of invertebrates, 170 fishes, and dozens of migratory birds (LISS, 2011). All the diverse uses Smithtown Bay provides to the community and ecosystem depend on the quality of its waters. If the water quality declines, the local economy will suffer, fishers could lose their jobs, recreational activities such as shellfishing may no longer be safe, and the ecological community may be faced with a loss of food sources, habitat destruction, and perhaps avoidance or even death of some species.

Smithtown Bay is situated between two headlands, Crane Neck and Eatons Neck (Figure 1). The depth of the water column in the bay is less than 20 m, whereas the center of LIS can reach 35 m (Swanson et al., in preparation). In Smithtown Bay, salinity ranges from approximately 24.5 to 29.5 PSU, while temperature ranges from approximately -1.0 to 28.0 ˚C. Both Stony Brook Harbor and the Nissequogue River flush into the bay through shallow entrance channels. The channel into Stony Brook Harbor is approximately 1.0-1.5 m in depth and 130 m wide and the Nissequogue River entrance is dredged to a depth of 2.4 m (SBEC, 2008; Swanson et al., in preparation). The Nissequogue River is 13.4 km long and encompasses a 104.0 km^2

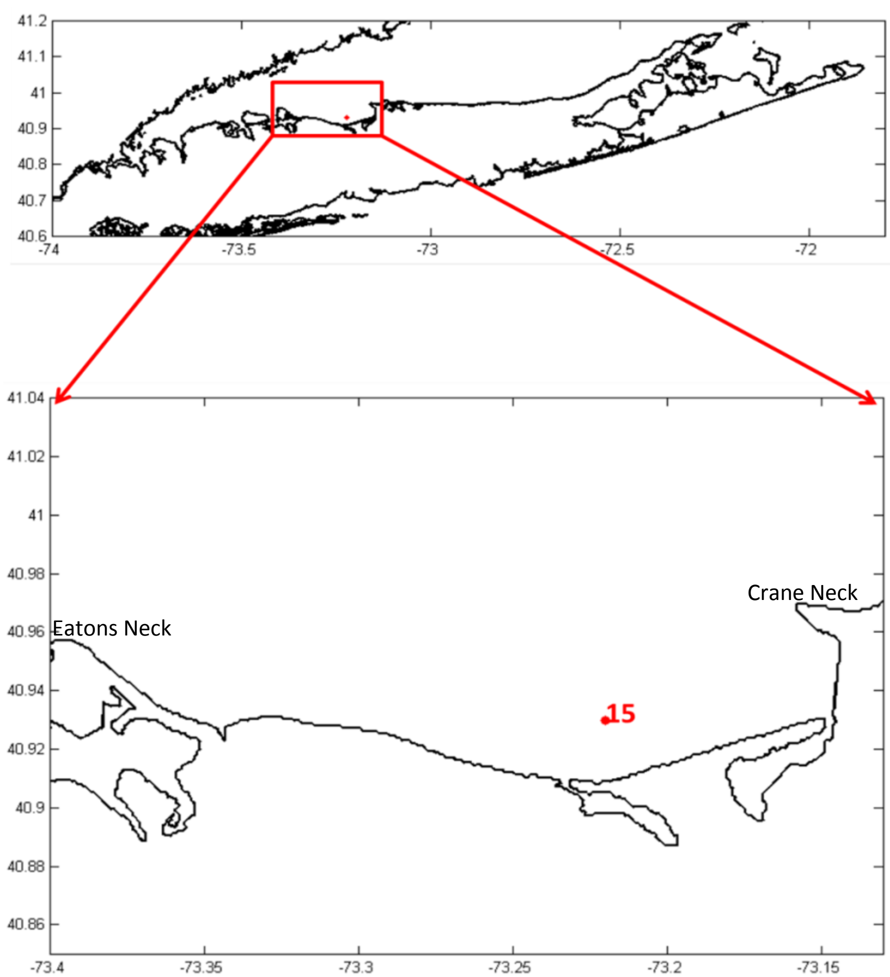

Figure 1: Map of Smithtown Bay, Long Island Sound. CT DEP station 15 is located within the confines of Smithtown Bay.

watershed discharging 1.2 m^3/s of freshwater into Smithtown Bay (Environmental Defense Fund, 2008). Stony Brook Harbor is smaller with an aerial extent of 4.8 km^2 and a watershed of only 18.0 km^2 (SBEC, 2008). Smithtown Bay experiences semidiurnal tides, two high tides and two low tides each day, with a tidal range of 2.1 m (Swanson et al., in preparation). Strong tidal currents ebb and flood through the entrances of Stony Brook Harbor and the Nissequogue River. However, compared to the center of LIS at the same longitude, the interior of the bay has weak tidal currents. The tidal currents in the center of LIS are 1.0 m/s during spring flood and 1.3 m/s during spring ebb, while the tidal currents in the bay are 0.4 m/s and 0.3 m/s, respectively (Swanson et al., in preparation).

1.2 Hypoxia Globally

One water quality problem plaguing many estuaries is hypoxia, a condition of low levels of dissolved oxygen (DO) concentrations in the water. Some scientific organizations quantify hypoxia differently. For example, the study of hypoxia in the Gulf of Mexico, led by the National Oceanic and Atmospheric Administration (NOAA), define hypoxia as < 2.0 mg O_2 L^{-1} (NOAA, 2003). The Long Island Sound Study (LISS) and, just recently, the Connecticut Department of Environmental Protection[1] (CT DEP), define hypoxia as DO concentrations <3.0 mg O_2 L^{-1} (CT DEP, 2011). However, current research suggests that concentrations of DO >3.0 mg O_2 L^{-1} may still have an adverse effect on certain species, depending upon the duration of exposure (CT DEP, 2011). For this study, the LISS and CT DEP definition of hypoxia, <3.0 mg O_2 L^{-1}, is used.

[1] On July 1st, 2011, the Connecticut Department of Environmental Protection (CT DEP) consolidated with other areas of the state government to form the Connecticut Department of Energy and Environmental Protection (CT DEEP). Since the data used in this thesis was collected prior to 2011, the former name, CT DEP, will be used.

Hypoxia has been recognized as a worldwide problem since the late 1950s (Zhang et al., 2010). Its occurrence in shallow coastal waters is increasing, most likely due to human activities (Diaz and Rosenberg, 1995). Before 1950, approximately 20 coastal sites experienced incidences of hypoxia globally; that number has now risen to over 400 (Zhang et al., 2010; Diaz and Rosenberg, 2008). Along with LIS, some other locations on the east coast of North America that experience seasonal hypoxia include Barnegat Inlet/Bay, NJ, Pamlico Sound, NC, Chesapeake Bay, MD, and Narragansett Bay, RI (World Resources Institute, 2010).

A generally accepted model for the cause of coastal hypoxia in temperate regions is the establishment of seasonal water column stratification and the introduction of anthropogenic nutrients from sewage treatment plants, combined sewer overflows, agricultural fertilizers, urban runoff, sediment remineralization, and atmospheric deposition (Driscoll, 2003; Committee on Environmental and Natural Resources, 2010). In general, freshwater runoff from snow melt initiates seasonal haline stratification in early spring. In late spring/early summer, the rate of surface heating exceeds the rate of vertical mixing and physical transport, leading to further stratification of the water column. A strong density gradient (pycnocline) develops that separates the upper and lower layers of the water column. The over-enrichment of anthropogenic nutrients along with increased sunlight and temperatures stimulates algal growth. As the algae decompose, they sink and accumulate below the pycnocline, increasing biological oxygen demand (BOD) (Song et al., 2001). Since ventilation of the bottom waters is inhibited, the oxygen supplied is exceeded by the BOD and hypoxic conditions result. In late summer/early fall surface cooling and increased wind cause the breakdown of stratification and re-ventilation of bottom waters.

The effects of hypoxia may include fish mortalities, shellfish bed losses, reductions in growth and reproductive fitness, habitat degradation, and long-term changes in species composition (Wu, 2002; Diaz and Rosenberg, 1995; Taylor and Miller, 2001; Marcus et al., 2004; White Paper, 2007). Aquatic organisms require oxygenated waters to breathe therefore, hypoxic conditions are highly unfavorable to many estuarine species. In general, mobile organisms such as fishes are able to escape hypoxic conditions by moving to areas that have higher concentrations of DO, unless the areal extent of hypoxia is too large (i.e., Gulf of Mexico) or if the concentrations of DO drop rapidly (Committee on Environment and Natural Resources, 2010). However, sessile and immobile organisms, such as mussels and oysters, are particularly vulnerable and often perish during a long duration hypoxic event (Committee on Environment and Natural Resources, 2010; Environmental Defense Fund, 2008). Dissolved oxygen concentrations <3.0 mg L^{-1} have been shown to decrease the diversity and abundance of benthic macrofauna (Ritter and Montagna, 1999).

1.3 Hypoxia in LIS

Long Island Sound is part of the National Estuary Program, established in 1984 by the U.S. Congress to improve the environmental quality of the nation's most important estuaries (Wolfe et al., 1991). In 1985, the LISS, funded by the U.S. Environmental Protection Agency (EPA), was established to conduct studies of the Sound's pollution problems as well as to develop a comprehensive plan to improve its management (Wolfe et al., 1991). Since 1991, the CT DEP has led an intensive water quality monitoring program, funded by the LISS. Monthly water samples are taken from more than 40 stations throughout LIS (CT DEP, 2004) (Figure 2).

The data collected are used to identify annual trends in hypoxia and water quality parameters such as nutrients, temperature, and chlorophyll (CT DEP, 2004).

During late summer months, up to 1,000 km^2 of LIS's bottom waters can experience hypoxic conditions (CT DEP, 2011). Historical records indicate rare occurrences of hypoxia in western LIS as early as the 1920s; however, more severe and pervasive hypoxia was not observed until the 1970s (Parker and O'Reilly, 1991; Thomas, 2000). Since 1991, the duration of seasonal hypoxia in LIS has varied between 34 and 79 days (CT DEP, 2011). The lowest concentrations of DO are found in The Narrows and western LIS; however, a unique and localized minimum is also observed in Smithtown Bay (Figure 2).

In order to alleviate hypoxia in LIS, the EPA, CT DEP and New York State Department of Environmental Conservation (NYSDEC) adopted a plan for Phase III Actions for Hypoxia Management (EPA, 1998; Lee and Lwiza, 2007). This plan aimed to reduce annual nitrogen loading by the development of total maximum daily loads (TMDLs) (EPA, 1998; Lee and Lwiza, 2007). New York State discharges approximately 45 metric tons per day of nitrogen into LIS; this is more than twice the amount being discharged from Connecticut (Fairbanks, 2004). The program's goal is to reduce by 2014 nitrogen discharges into LIS from Connecticut and New York by 58.5 percent of 1990 levels (EPA, 2012). The program plans to achieve this goal by upgrading sewage treatment plants to tertiary treatment (removing nitrogen), implementing a nitrogen credit trading program, issuing bubble permits to sewage treatment plants, reducing atmospheric deposition by controlling vehicle emissions, and controlling urban runoff through stormwater best management practices and growth management (EPA, 2012). Currently, nitrogen loading into LIS has been reduced by 25 percent from 1990 levels (EPA, 2012).

Despite these reductions, hypoxia continues to be prevalent in the Narrows, western LIS, and Smithtown Bay and the minimum concentrations of DO are declining (Wilson et al., 2008).

1.4 Hypoxia in Smithtown Bay

The physiography of Smithtown Bay leads to the natural establishment of a relatively unique circulation pattern. Relative to the main channel of LIS, Smithtown Bay's circulation is sluggish. This may be due to the existence of headland gyres restricting lateral mixing and tidal flow. It is thought that the main driver of hypoxia (DO <3.0 mg L^{-1}) is the consumption of oxygen during the aerobic microbial breakdown of excess organic matter resulting from a surplus of nitrogen loadings from point and non-point sources into LIS (Welsh and Eller, 1991; Welsh, 1995). Smithtown Bay, however, provides an important test of this hypothesis since the only point source discharging into Smithtown Bay is the Kings Park Sewage Treatment Plant, a relatively small facility that handles waste from an estimated 6,000 people and discharges only 0.4 Mm^3/yr (Figures 3-4) (Interstate Environmental Commission, 2008). Smithtown Bay is the only area in west-central LIS that experiences significant periods of hypoxia during summer months. A contour of DO during a CT DEP cruise in August 2010 is displayed in Figure 2 (CT DEP, 2010). While hypoxic conditions, as low as 1.0 mg L^{-1}, continue to be prevalent in Smithtown Bay, the surrounding bottom waters have considerably higher DO concentrations ($>$ 3.5 mg L^{-1}). This suggests that there must be something else driving the system in Smithtown Bay besides excessive nitrogen loading. Although the problem of hypoxia in The Narrows and western LIS has been extensively studied, there has yet to be an investigation focusing exclusively on the unique, seasonal occurrence of hypoxia in Smithtown Bay. This study aims to identify the physical mechanisms (i.e., circulation patterns, stratification, tides, wind) leading to hypoxia in Smithtown Bay.

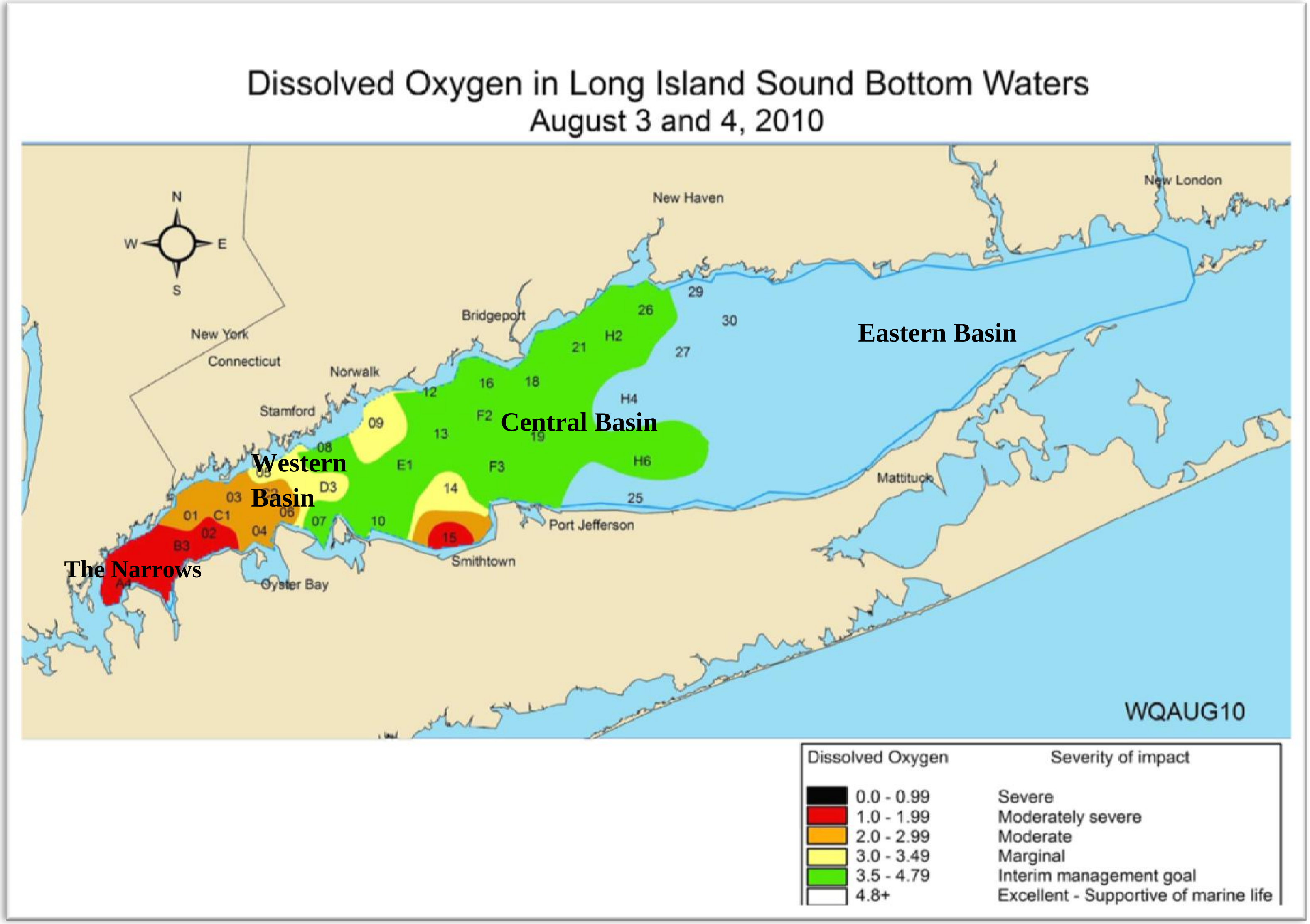

Figure 2: A contour, created by the CT DEP, of bottom dissolved oxygen concentrations in Long Island Sound during a cruise in August 2010. Smithtown Bay experienced dissolved oxygen concentrations as low as 1.0 mg L^{-1} while its surrounding bottom waters remained above 3.5 mg L^{-1} (CT DEP, 2010).

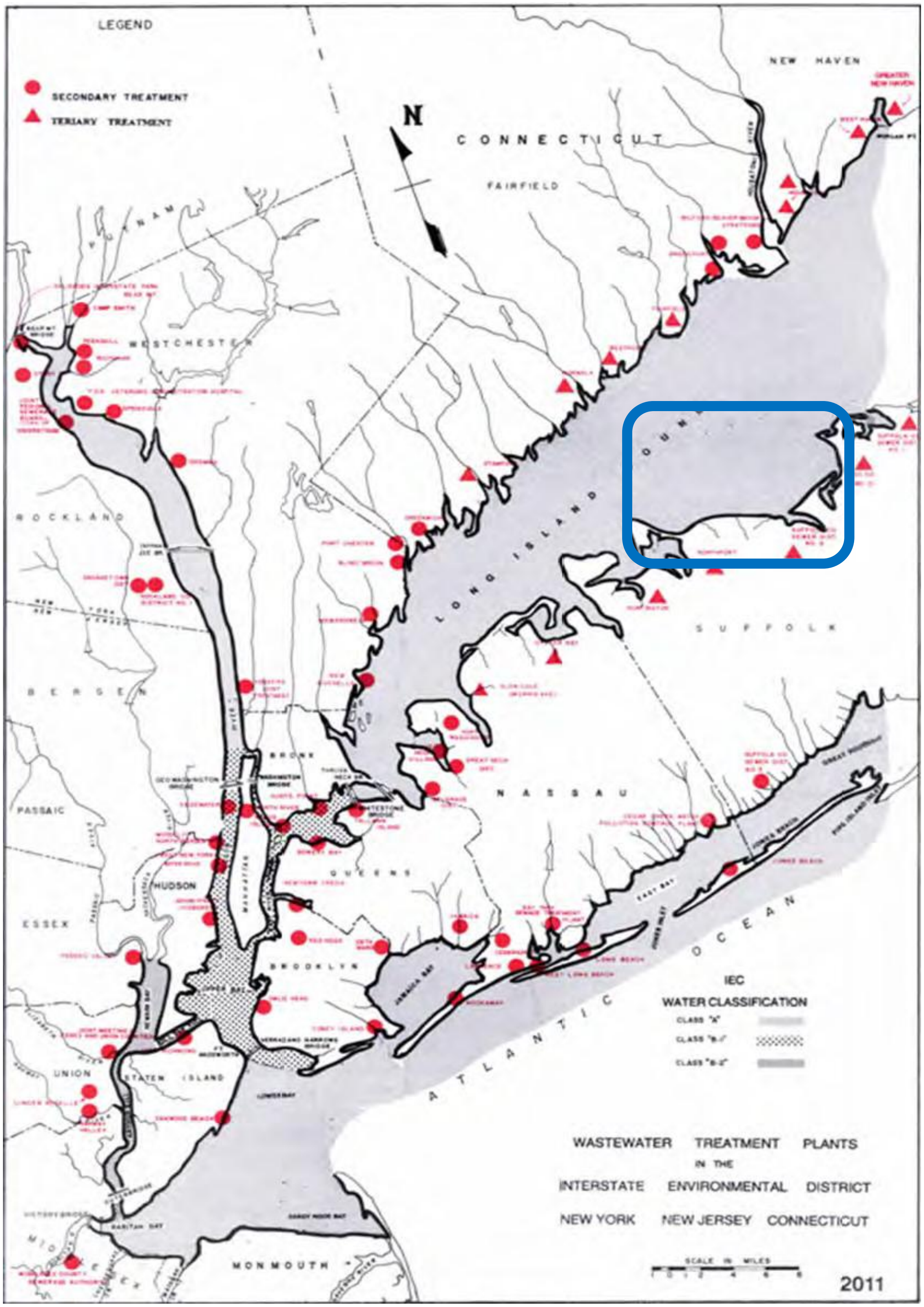

Figure 3: Map of sewage treatment plants in New York, New Jersey, and Connecticut (Interstate Environmental Commission, 2011). Only one, relatively small sewage treatment plants discharges into Smithtown Bay.

Figure 4: Location of Kings Park Sewage Treatment Plant, the only point source discharging into Smithtown Bay via the Nissequogue River (figure from google maps).

1.5 Hypothesis

Geomorphology and physical oceanographic processes, such as currents, tide, and water column density structure in Smithtown Bay, intensify the occurrence, severity, and duration of seasonal hypoxia. These processes create strong seasonal stratification and long residence times that provide ideal conditions for the development of hypoxia in this system.

2.0 Goals and Objectives

2.1 Goals

The goal of this research is to describe processes controlling stratification, circulation, and residence time leading to a "hypoxia hot spot" in Smithtown Bay. This study will ultimately help to provide resource managers of LIS with specific information about the functioning of the bay and its relationship to the greater LIS ecosystem in order to determine whether any targeted remediation measures can be taken within Smithtown Bay and its watershed to alleviate hypoxia. It will also show that the Sound does not function as a homogeneous water body and that the functioning of its bays and inlets must be understood in order to effectively manage the Sound's ecosystem.

2.2 Objectives

Objective 1: Analyze the historical data collected by the CT DEP in order to:

1) determine the relative contribution that temperature and salinity have on density stratification.
2) compare the monthly averaged DOb and delta rho ($\Delta\rho$) from a non-hypoxic year (1997) and a hypoxic year (2005).
3) determine if wind directionality and speed have an impact on the duration of hypoxia.

Objective 2: Analyze the hydrographic data collected from cruises in August 2004, May 2009 - September 2009, and May 2010 - August 2010 in order to:

1) determine the frequency of hypoxia at each station.
2) examine the structure of the water column by contouring vertical and horizontal sections of each transect and plotting Temperature-Salinity (T-S) diagrams.
3) confirm the existence of residual headland gyres and examine the structure of the tidal ellipses.
4) determine the depth of the pycnocline and relate that to the occurrence of hypoxia.

3.0 Data and Methods

3.1 Archival CT DEP Data Analysis

The CT DEP's historical data were accessed through the University of Connecticut's Long Island Sound Integrated Coastal Observatory System (LISICOS) website (http://lisicos.uconn.edu/). Hydrographic data were downloaded for CT DEP station 15 located in Smithtown Bay from 1994-2010. During each of their cruises, the CT DEP took continuous depth profiles of temperature (˚C), salinity (PSU), density (kg m^{-3}), and DO (mg L^{-1}).

Due to the use of instrumentation deployed from the water's surface and the forces of currents, it is impossible to stay in direct contact with the bottom while collecting samples. For this reason, the denotation of "bottom water" concentrations in this study refers to water samples taken from 0.5-1.5 m above the sea-water interface.

Due to the nature of the CT DEP's sampling procedures, more data is available for the months of June-September than any other time. Thus, in order to create an evenly spaced dataset, linear interpolation was applied to the data. Additionally, due to numerous gaps in the original dataset, the majority of the statistical analysis for this project only uses the data from 1996 onward. The new dataset was spaced 30.5 days apart beginning in February 1996 and ending in November 2010.

From the new interpolated dataset, the relative thermal and haline contributions to density stratification were plotted. The relative thermal and haline contributions to density structure are important to evaluate in order to determine the primary driver of summertime stratification in Smithtown Bay. Temperature and salinity data vectors were normalized for comparison. The MATLAB script, swstate.m, which can be found at the U.S. Geological Survey (USGS) Woods

Hole Coastal and Marine Science Center website, (http://woodshole.er.usgs.gov/operations/sea-mat/), was used to obtain the derivatives of temperature and salinity. The above script returns the derivatives of temperature and salinity with respect to density (dRdT and dRdS). Then, delta temperature (ΔT) and delta salinity (ΔS) (bottom-surface concentrations) were multiplied by their corresponding derivatives:

$$\boldsymbol{\alpha\Delta T = dRdT * \Delta T}$$

$$\boldsymbol{\beta\Delta S = dRdS * \Delta S}$$

The new normalized temperature and salinity concentrations are labeled alpha delta temperature (αΔT) and beta delta salinity (βΔS). Time series of αΔT and βΔS were plotted against the time series of Δρ in order to visualize their relative contribution. To quantify their contributions, a comparison of the heights of each of their annual peaks was completed.

In order to determine the influence of density structure on DOb concentrations, a comparison was made between a hypoxic year and a non-hypoxic year (Wilson et al., 2008). At station 15 from 1996-2010, the summer of 1997 experienced the highest concentrations of DOb and the summer of 2005 experienced the lowest DOb concentrations. These two years were used as representatives of a non-hypoxic year and a hypoxic year. Monthly averaged concentrations of DOb and Δρ, αΔT, and βΔS were plotted and analyzed for both years.

Climatological data were extracted from NOAA's National Climate Data Center (NCDC) website. Hourly observations of wind speed and direction at Igor Sikorsky Municipal Airport, near Bridgeport CT, were downloaded from 1996-2010. Daily observations of minimum temperature (T_{min}), maximum temperature (T_{max}), and precipitation at Igor Sikorsky Municipal Airport were also downloaded for the summers of 2004, 2009, and 2010. The daily T_{max} and T_{min}

were averaged for each month as well as for the entire summer. Monthly and seasonal precipitation totals were calculated using the daily precipitation data. The temperature and precipitation data were used to identify atmospheric differences between the three sampled years.

3.2 Sample Collection and Analysis

A total of 10 cruises aboard the R/V SEAWOLF were carried out (Table 1):

Month	Day	Year
August	**17**	**2004**
May	**18**	**2009**
June	**16**	**2009**
July	**7**	**2009**
August	**13**	**2009**
September	**30**	**2009**
May	**21**	**2010**
June	**21**	**2010**
July	**26**	**2010**
August	**11**	**2010**

Table 1: Dates of the 10 sampling cruises that took place aboard the R/V SEAWOLF.

Samples were taken from 13 stations along three transects, spaced apart by approximately 5.2 km and in the general direction of 165°T (Figure 3). Each station was sampled twice per cruise, once on a flood tide and once on an ebb tide. The times of high/low tide were determined by using the National Oceanic and Atmospheric Administration (NOAA) tidal predictions at Bridgeport, CT. At each station, a Sea-Bird 19 conductivity temperature depth (CTD) sensor with an SBE-43 probe was lowered from the surface, approximately 1.0 m depth, to approximately 1.5 m off the bottom in order to measure temperature (˚C), salinity (PSU), density (kg m^{-3}), and DO (mg L^{-1}) in the water column. An Acoustic Doppler Current Profiler (ADCP) was used to measure currents along the cruise tracks.

After every cruise, the data from each station were organized into separate Excel spreadsheets where the variables were represented in columns and depth in rows. For every cruise and at each station, the surface and bottom concentrations were calculated by averaging the top and bottom 0.5 m of recorded data. Since the vertical profiles from the CTD did not start until 1.0 m below the surface and stopped 1.5 m above the bottom, the surface concentrations are an average of the data from approximately 1.0-1.5 m and the bottom concentrations are an average of data collected from approximately 1.5-2.0 m off the bottom. Surface and bottom concentrations were used to make horizontal contours. The horizontal contours were plotted using optimal interpolation, which constructs the arbitrarily located data into a gridded data matrix with the lowest error variance. The data with standard errors less than 0.35 were used in to make the contours. The vertical profiles from each CTD cast were linearly interpolated to every 0.5 m and contoured along the three transects to make vertical sections of the water column. In addition, the bottom concentrations of DO for every cruise were used to determine the frequency of hypoxia at each station. Temperature-Salinity diagrams were made using temperature and salinities for all the stations from the surface to the bottom at half-meter intervals. Temperature-Salinity diagrams of just surface and bottom concentrations were also plotted in order to analyze their differences. Due to numerous CTD casts resulting in erroneous salinity measurements, May 2009 was not used in this analysis.

Analyses of currents, tidal ellipses, and flood and ebb bottom stress were used to determine the circulation patterns within and around Smithtown Bay. Using the data extracted from the ADCP, a model of residual currents throughout the bay as well as vectors of mean M2 depth-averaged currents along the cruise tracks were plotted (figure by R.E. Wilson, Stony Brook University). Tidal ellipses along the cruise tracks were also plotted (figure by R.E. Wilson, Stony Brook University). Ebb and flood tide bottom stress were calculated and plotted by R.E. Wilson using the ADCP data. The currents, tidal ellipses, and bottom stress were based on a composite of the data collected on all 2009 and 2010 cruises.

The Brunt-Väisälä frequency, or buoyancy frequency, was used to determine the depth of the pycnocline. It demonstrates the frequency at which a vertically displaced water parcel will oscillate in a stable, stratified environment. The depth at which the maximum frequency is reached is traditionally determined to be the depth of the pycnocline. The Brunt-Väisälä frequency is defined as:

$$\boldsymbol{N = \sqrt{\frac{g}{\rho}\frac{d\rho}{dz}}}$$

where g is the gravitational acceleration, ρ is the potential density, and z is the depth. In order to obtain the Brunt-Väisälä frequency for every vertical CTD cast, the MATLAB function, bvfreq(S,T,P) was used. For each cast, vectors of salinity, temperature, and depth, all interpolated to every 0.5 meters, were loaded into the function and the function returned a vector of Brunt-Väisälä frequencies at each of those points. The Brunt-Väisälä frequency was plotted with depth and the pycnocline depth was recorded as the depth at which the Brunt-Väisälä frequency reached a maximum. The pycnocline depth as a percentage relative to the total water column depth was obtained.

4.0 Results

4.1 Time Series Analysis of Historical CT DEP Data

A time series of DOb at CT DEP station 15 from 1994-2010 is presented in Figure 6. Bottom water hypoxic concentrations, defined above as <3.0 mg O_2 L^{-1}, were recorded for 15 of the 17 consecutively sampled years. Hypoxia was not recorded in Smithtown Bay by CT DEP during the years 1997 and 2009. In 1997, DOb reached a minimum of 3.3 mg L^{-1} on September 2 and a minimum of 3.1 mg L^{-1} was recorded on August 18, 2009. The lowest DOb for the entire sampling period was recorded on August 16, 2005 with a concentration of 0.9 mg L^{-1}. Overall, DOb reached its annual minimum concentration around the months of July and August. As expected, DOb in Smithtown Bay has a strong seasonal cycle, with only slight interannual variability. Monthly averages of DOb were analyzed from 1996-2010 (Figure 7). Linear regression of the data demonstrates that DOb has not significantly changed during this time period. For each month, the R^2 value did not exceed 0.3. Linear trend lines for the months of July and August, when DOb concentrations are at an annual minimum, resulted in R^2 values of 0.2 and 0.0, respectively.

Month	R^2
January	0.04
February	0.01
March	0.02
April	0.09
May	0.30
June	0.33
July	0.23
August	0.00
September	0.20
October	0.09
November	0.06
December	0.04

Table 2: Corresponding R^2 values for monthly averaged DOb concentrations from 1996-2010. Based on the R^2 values, DOb concentrations have not significantly changed for any given month over this time period.

A time series of DOb, $\Delta\rho$, $\alpha\Delta T$, and $\beta\Delta S$ (the new variables of ΔT and ΔS normalized to density) from 1996-2010 is presented in Figure 8. As DOb decreased during summer months, $\Delta\rho$, $\alpha\Delta T$, and $\beta\Delta S$ all increased. This demonstrates the well-known relationship between DOb and stratification of the water column. The figure also allows for a visualization of the contribution that temperature and salinity make on density structure. In late winter/early spring, a slight peak in $\beta\Delta S$ was exhibited, while $\alpha\Delta T$ remained low. This is a result of increased freshwater runoff due to excess snowmelt. Early season surface to bottom salinity differences initiate the process of density stratification. However, salinity controlled stratification in Smithtown Bay is of minimal duration and strength (Figure 8). Therefore, it likely does not contribute greatly to the drawdown DOb in the later months. On the other hand, stratification that develops later in the spring, which lasts considerably longer and reaches a greater magnitude, is critical to the drop in concentrations of DOb during the summer. For 13 of the 15 sampled years, the peaks of $\alpha\Delta T$ were higher than those of $\beta\Delta S$ during the summer (Figure 8). In order to quantify these results, Table 2 illustrates the maximum annual peak height of $\alpha\Delta T$ and $\beta\Delta S$ as measured from Figure 8. Over the 15-year dataset, the thermal contribution to density ranged from 43.6 to 81.1 percent. On average, the maximum annual peak height of $\alpha\Delta T$ accounts for 67.5 percent of the water column density structure, while $\beta\Delta S$ accounts for only 32.5 percent. Temperature contributes more than twice as much to summertime density stratification than salinity does.

Year	Peak Height $\beta\Delta S$	Peak Height $\alpha\Delta T$	Thermal Contribution to Density (%)	Haline Contribution to Density (%)
1996	0.7	1.0	58.9	41.1
1997	0.3	0.7	69.9	30.1
1998	0.5	0.5	49.8	50.2
1999	0.3	0.6	64.7	35.3
2000	0.2	0.8	76.8	23.2
2001	0.5	0.5	51.0	49.0
2002	0.2	0.9	81.1	18.9
2003	0.3	1.0	76.6	23.4
2004	0.3	0.8	76.1	23.9
2005	0.2	0.8	78.8	21.2
2006	0.7	1.7	70.8	29.2
2007	0.6	0.5	43.6	56.4
2008	0.4	1.0	74.0	26.0
2009	0.5	1.0	65.4	34.6
2010	0.4	1.3	75.0	25.0
Average	0.4	0.9	67.5	32.5

Table 3: The maximum annual peak heights of $\alpha\Delta T$ and $\beta\Delta S$ (the normalized variables of ΔT and ΔS) are shown in columns 2 and 3. Columns 4 and 5 represent the percentages that temperature and salinity contribute to overall density stratification.

Using the linearly interpolated dataset[2], the results of a comparison of $\Delta\rho$, $\beta\Delta S$, $\alpha\Delta T$, and DOb for a hypoxic year (2005) versus a non-hypoxic year (1997) are shown in Figures 9a-b. One significant difference in 1997 compared to that of 2005 was the duration of density stratification. Figures 9a-b emphasize the influence that duration of density stratification has on DOb concentrations. During the non-hypoxic year, $\Delta\rho$ exceeded 0.5 kg m^{-3} in mid-June, reached a maximum in July with 0.9 kg m^{-3}, and dropped below 0.5 kg m^{-3} at the end of August (Figure 9a). Dissolved oxygen reached a minimum in August with a concentration of approximately 3.9 mg L^{-1} (Figure 9a). During the hypoxic year, $\Delta\rho$ exceeded 0.5 kg m^{-3} in mid-April, reached a maximum in July with 1.0 kg m^{-3}, and dropped below 0.5 kg m^{-3} at the end of August (Figure 9b). Dissolved oxygen reached a minimum in August with a concentration of approximately 1.0 mg L^{-1} (Figure 9b). Both years experienced water column stratification during summer months; however, total stratification was greater (by approximately 0.1 kg m^{-3}) with a greater thermal contribution during the hypoxic year (Figures 9a-b). Also, stratification developed approximately two months earlier during the hypoxic year compared to the non-hypoxic year. Similar results observed in the years 2009 and 2010 are presented in Figure 10. In 2009, density stratification did not develop until mid-June and DOb concentrations recorded by the CT DEP at station 15 remained above the hypoxic threshold the entire season. In contrast, density stratification in 2010 developed in early May and the CT DEP recorded DOb concentrations below 3 mg L^{-1} during three sampling cruises that summer.

[2] The concentrations of DO using the linearly interpolated dataset are slightly different than the raw data shown in Figure 4, but the general trend remains the same. The interpolated dataset was needed for this particular analysis because the different variables, $\Delta\rho$, $\beta\Delta S$, $\alpha\Delta T$ and DOb, were taken on different days.

4.2 Wind Direction vs. Duration of Hypoxia

In order to determine any significance that the directionality and speed of wind have on DOb concentrations, the duration hypoxia was correlated to summer wind direction when speeds were greater than 2.5 m/s. The duration of hypoxia (in days) from 1996-2010 is presented in Figure 11. During the 15-year dataset, the duration of hypoxia was the greatest during the summer of 1998, with 52 days. The average duration of hypoxia in at CT DEP station 15 in Smithtown Bay during this time period was 25 days.

The results of the correlation of wind direction from July 1 to Sept 1 for each year with the duration of hypoxia are presented in Figure 12. Based on the 15-year dataset, the directionality of wind was correlated to the duration of hypoxia when wind came from 270˚T, 320˚T, and 330˚T. The corresponding p-values were 0.04, 0.03, and 0.007, respectively (Figure 13). Therefore, winds from the west and northwest are significantly correlated with long durations of hypoxia.

4.3 Frequency and Location of Hypoxia

Concentrations of DOb were analyzed for each station and isolated relative to years, months, and stages of tide (Figures 14-19). In August 2004, hypoxic concentrations were observed at stations 4, 5, 6, 7, and 8 during flood (Figure 14). On the ebb tide, stations 4, 5, 6, 7, 8, and 9 were recorded as hypoxic (Figure 15). The lowest DOb concentration of 1.9 mg L^{-1} was observed during ebb at station 5, closest to Stony Brook Harbor. In 2009, DOb concentrations were recorded from May-September (Figures 16-17). In May, the concentrations of DOb varied between 8.0 and 9.0 mg L^{-1} and gradually declined each month until reaching a minimum in

August. Observed DOb concentrations did not fall below 3.0 mg L^{-1} until the August 2009 cruise. Stations 5, 6, 7, and 8 were hypoxic during the flood tide, and stations 5 and 8 were hypoxic during the ebb tide. The lowest concentration of DOb in 2009 was recorded at station 5 during a flood tide with 2.6 mg L^{-1}. By the September cruise, DOb concentrations rebounded with the lowest DOb concentrations just below 6 mg L^{-1}. In 2010, DOb concentrations were recorded from May-August (Figures 18-19). Similar to May 2009, observed concentrations of DOb in May 2010 fell between 8.0 and 9.0 mg L^{-1} at every station. In June, DOb concentrations declined but remained above 5.0 mg L^{-1}. By July, hypoxia was recorded at stations 6 and 7 during both ebb and flood. Concentrations of DOb remained low during the August cruise with observed hypoxia at stations 7 and 13 during flood and station 13 during the ebb tide. In 2010, the lowest DOb concentration of 2.1 mg L^{-1} was recorded at station 6, closest to the Nissequogue River, during an ebb tide. From the observations over the three years, it appears that the lowest concentrations of DOb occur near shore, close to the two embayments. Also, the stage of tide does not seem to have a great effect on the concentration of DOb in Smithtown Bay.

A histogram of the frequency of hypoxia at different stations of all the cruises combined is displayed in Figure 20. Stations 6 and 7 experienced the highest number of observed hypoxic conditions. From the 10 cruises, hypoxic conditions were never observed at stations 1, 2, 3, 10, 11, 14, and 15. Stations 1, 2, 3, 10, and 11 are just outside the confines of Smithtown Bay. Stations 14 and 15 are the only stations within the bay with no recorded concentrations below 3.0 mg L^{-1}. Overall, the frequency of hypoxia is greater at stations in the center of the bay and those closest to the two embayments, Stony Brook Harbor and the Nissequogue River.

"Bottom water" hypoxic concentrations were recorded during four of the 10 sampling cruises: August 2004, August 2009, July 2010, and August 2010. Horizontal contours of DOb during ebb and flood tides were completed for the four cruises (Figures 21a-h). During each August, similar spatial patterns of DOb concentrations were observed. The lowest DO concentrations generally extended diagonally across the three transects from station 5 to station 11. The highest DOb concentrations are found at station 15, a shallow well-mixed station, and station 1, a deep, strongly stratified station just outside of Smithtown Bay's boundaries. A similar pattern was also observed in July 2010 during an ebb tide. The contour during the flood tide in July 2010 looks slightly different, with the lowest DO concentrations observed along the southern shoreline. This contour may have been slightly skewed due to a lack of data at the well-mixed, non-hypoxic station 15.

4.4 Circulation Patterns: Currents and Tides

Mean, depth-averaged currents along the cruise tracks are presented in Figure 22 and a model of summertime residual currents at mid-depth is displayed in Figure 23. The currents inside the bay tend to be weak relative to the center of LIS at the same longitude (Figures 22-23). The currents around Eatons Neck and Crane Neck are much stronger with varying directions. The model confirms the existence of a large counterclockwise gyre located outside of Smithtown Bay as well as two smaller gyres on either end of Smithtown Bay, created by the headlands. A classical headland eddy setting can be observed (Figure 23). The two headlands appear to create a partial barrier for lateral mixing of water between Smithtown Bay and the rest of LIS.

Tidal ellipses along the cruise tracks are presented in Figure 24. The structure of the tidal ellipses demonstrates weaker tidal currents inside Smithtown Bay and stronger tidal influence in the center of LIS. The weakest tidal currents occur at station 5, near the entrance to Stony Brook Harbor. The strongest tidal current was observed outside of Smithtown Bay, just north of

Cranes Neck. Weak residual currents and limited tidal influence in Smithtown Bay likely contributes to increased residence time of particulate matter.

Bottom stress on both the ebb and flood is presented in Figures 25a-b. Relative to the bottom stress in adjacent waters, the bottom stress inside Smithtown Bay is weaker. Also, the magnitude of the bottom stress inside Smithtown Bay on the ebb and flood is relatively the same.

4.5 Vertical Structure of the Water Column

A T-S diagram of transect 1 during the August 2009 cruise is presented in Figure 26. The warmest and freshest concentrations were found in the surface waters at offshore stations 1 and 2. The surface waters at stations 3, 4, and 5, located inside Smithtown Bay, were up to 1.5˚C cooler and nearly 0.5 PSU saltier than the surface waters at stations 1 and 2. Station 3 is nearly 10 m shallower than stations 1 and 2; however the "bottom water" temperature and salinities for all three stations were similar. This is characteristic of a bottom front, with LIS bottom water being brought into Smithtown Bay.

A T-S diagram of the entire water column for June- September of 2009 is shown in Figure 27a. A separate T-S diagram of just surface and bottom temperature and salinity concentrations for the same months is shown in Figure 27b. During the summer months, the surface and bottom values for temperature and salinity fall into two distinct groups. The surface waters are warmer and fresher, and the bottom waters are colder and saltier. As expected, the surface waters in June are the coolest and freshest, and as the season progresses, the water gets warmer and saltier. In September, the surface and bottom concentrations of temperature and salinity do not have this pronounced distinction. Both surface and bottom waters are relatively isothermal with varying salinities, not distinguished by depth, but by station (Figure 27b).

In June 2009, the temperature ranged from 12.0-19.3 ˚C and salinity from 24.0-27.2 PSU. In July 2009, the temperature was slightly warmer with a range between 14.6-22.0 ˚C and salinity 24.9-27.0 PSU. August 2009 temperatures ranged between 18.6-22.6 ˚C and salinity between 25.9 and 27.1 PSU. The bottom water temperature increased as the season progressed but the salinity remained around the same (Figure 27a). The plots of temperature and salinity for 2009 summer months cross many lines of constant density, which demonstrate strong stratification. The water columns for June 2009, July 2009, and August 2009 were strongly stratified; therefore, vertical mixing of DO from the surface to the bottom was restricted. Also, for June, July, and August there was little variation in density structure, temperature, and salinity among stations and both stages of the tide. In September, the density gradient between surface and bottom concentrations of temperature and salinity disappeared. The water column became well-mixed and ventilation of DO to the bottom waters was restored.

A T-S diagram of the entire water column for May-August of 2010 is displayed in Figure 28a. A T-S diagram of only surface and bottom concentrations of temperature and salinity for the same months was also plotted (Figure 28b). Similar to Figure 27a, the surface waters for all four months were warmer and fresher; further down in the water column the water temperatures decreased and the salinity increased. As expected, the waters in May 2010 were the coolest and freshest, and as the season progressed the water became warmer and saltier. In May, temperature ranged from 10.0-15.5 ˚C and salinity ranged from 25.1-26.9 PSU. June temperatures ranged from 13.9-21.6 ˚C, while salinity ranged from 25.8-27.7 PSU. In July, the temperatures fell between 19.0 and 25.4˚C and salinity in between 26.4 and 28.1 PSU. In August, temperature and salinity reached their maximum with temperatures from 20.9-25.3 ˚C and salinities from 27.2-28.5 PSU. The plots of temperature and salinity for each cruise run across isopycnals; therefore, the water column from May-August 2010 was stratified and DO was not mixed from the surface to the bottom waters. Similar to 2009, there was little variation in density structure, temperature, and salinity among stations and both stages of the tide. However, unlike the T-S diagram for the summer of 2009, in 2010 the temperature and salinity plots are not directly perpendicular to the isopycnal lines. The surface waters display isohaline properties with rapidly changing temperature, and the bottom waters display the opposite pattern, isothermal with rapidly changing salinity. This pattern is displayed in the T-S diagram for all four months of 2010 that were plotted. Also, in the T-S diagram, for the summer of 2009, the bottom salinities throughout the season remained approximately the same. However, in the 2010 T-S diagram the bottom salinities increased from May to August by more than 2.0 PSU.

The August 2004, 2009, and 2010 temperatures and salinities are compared with one another in Figure 29. The August water column for each year was strongly stratified; therefore, mixing of DO from the surface to the bottom was inhibited. The figure also shows the interannual variability in temperature and salinity. August 2009 was the coolest and freshest of the three, with temperatures ranging from approximately 18.6-22.6˚C and salinity ranging from approximately 25.9-27.1 PSU. August 2010 was the warmest and saltiest, with temperatures ranging from approximately 20.9-25.3˚C and salinities in the range of 27.2-28.5 PSU. August 2004 was in the middle, with temperatures between 19.5-23.5˚C and recorded salinities between 26.8-28.4 PSU. The T-S diagrams for each August are consistent with the atmospheric conditions during that summer. The summer of 2009 can be characterized as cool and wet with temperatures ranging from 16.9°C to 25.5°C and rainfall totaling 36.5 cm (Tables 3-5). The summer of 2010 can be characterized as hot and dry with temperatures ranging between18.9°C and 28.4°C and only 15.8 cm of rainfall (Tables 3-5). The temperatures and precipitation totals for the summer of 2004 fell in the middle of 2009 and 2010 conditions. The atmospheric temperatures varied between 17.5°C and 25.9°C, and rainfall reached a total of 35.0 cm (Tables 3-5).

Month	2004	2009	2010
June	6.6	15.7*	7.4
July	19.3	11.9*	4.1
August	9.1	8.9	4.3
Summer Totals	35.0	36.5	15.8

Table 4: Total precipitation (cm) at the Igor Sikorsky Municipal Airport. Due to lack of data at the airport, the data marked with an asterisk (*) were obtained from a NOAA station in Setauket, NY.

Month	2004	2009	2010
June	25.0	22.1*	26.9
July	26.6	26.7*	30.5
August	26.2	27.6	27.9
Summer Average	25.9	25.5	28.4

Table 5: T_{max} (˚C) at the Igor Sikorsky Municipal Airport. Due to lack of data at the airport, the data marked with an asterisk (*) were obtained from a NOAA station in Setauket, NY.

Month	2004	2009	2010
June	15.7	14.4*	17.1
July	18.5	16.9*	20.6
August	18.4	19.6	19.0
Summer Average	17.5	16.9	18.9

Table 6: T_{min} (˚C) at the Igor Sikorsky Municipal Airport. Due to lack of data at the airport, the data marked with an asterisk (*) were obtained from a NOAA station in Setauket, NY.

Seasonal progressions of temperature, salinity, density, and DO with depth of transect 1 for 2009 and 2010 are presented in Figures 30-37. In June 2009, seasonal stratification was initiated; a gradual change in temperature, salinity, density, and DO with depth is observed. By July, a distinct mixed layer depth was developed that extended to a depth of approximately 9.0 m offshore and 12.0 m at near shore stations. Dissolved oxygen reached its minimum in the bottom waters of station 5 (the near shore station) with a concentration of approximately 4.0 mg L^{-1}. In August 2009, the water column was strongly stratified, especially at off shore stations. Hypoxic conditions were observed in the bottom waters and were the lowest at station 5. In September 2009, the entire water column was vertically homogeneous at all stations. Seasonal stratification was overcome by vertical mixing and surface cooling, and hypoxic conditions ended.

Figures 33-37 show that, for May 2010, stratification was in its developing stage. There was a gradual change of temperature, salinity, and density with depth, with no distinct pycnocline. Dissolved oxygen was high, ranging from 8.0-11.0 mg L^{-1} (Figure 37). Temperatures throughout the water column were relatively cool and the salinities were low. In June, the water column was stratified with increasing temperatures and salinities. A DO minimum of approximately 5.0 mg L^{-1} was observed in the bottom waters. In July and August, the water column was strongly stratified. Hypoxic conditions were observed not only in bottom waters, but also at mid-depth. A DO minimum was recorded in July and August at stations 1 and 2 between 10.0 and 15.0 m, near the base of the pycnocline (Figure 37).

Vertical profiles of temperature, salinity, density, and DO for August 2009 are presented in Figures 38-45. As expected, the temperature, salinity, and density profiles followed a similar pattern (Figures 35-40). The pycnocline depth at the nearshore stations (5, 6 and 15) ranged from 5 to 7m (Figures 40, 42, and 44). The depth of the pycnocline increased in deeper, offshore waters. The deepest stations of each transect (stations 1, 10, and 11) had pycnocline depths extending from 11-14 m (Figures 40, 42, and 44). Also, at each transect, there appears to be a lens of slightly more dense surface water at the nearshore stations compared with those stations offshore and in the center of the bay. The bottom waters at each transect are denser in the deeper waters offshore and a bottom front can be observed bringing in denser bottom water to the shallower stations inside Smithtown Bay.

The structure of DO in the water column is practically identical to the corresponding density structure. For all three transects, the depth of the oxygen was the same as the pycnocline depth. In 2009, DO at station 5 ranges from 2.3 mg L^{-1} to 4.0 mg L^{-1} and hypoxic concentrations were observed in the bottom two-thirds of the water column (Figure 41). Hypoxic conditions began just below the pycnocline. Smaller percentages of the water column were hypoxic at the further offshore and deeper stations.

4.6 Brunt-Väisälä Frequency

The Brunt-Väisälä frequency was used to determine the depth of the pycnocline. In order to demonstrate the accuracy of the Brunt-Väisälä Frequency in determining the pycnocline depth, a comparison was made between the vertical profiles of density and the Brunt-Väisälä Frequency (Figures 46a-c). Vertical profiles of density, DO, and Brunt-Väisälä Frequency August 2009, station 6, July 2010, station 7 and August 2010, station 1 were used as representatives of all sampling stations. Station 6 is relatively shallow with a depth of 14 m and had a sharp pycnocline in August 2009 at approximately 7 m (Figure 46a). Station 7 is deeper at roughly 19 m with a more gradual pycnocline in July 2010, the most rapid change occurring at 7.5 m (Figure 46b). Station 1 is the deepest of the three stations, with a depth of 35 m. In

August 2010, the pycnocline at station 1 was approximately 9 m (Figure 46c). There was a strong negative correlation between DO and density during all three times. Also, for all three examples, the peak in the Brunt-Väisälä Frequency coincided with the depth in the water column where the greatest change in density was observed. This demonstrates that the Brunt-Väisälä equation is an accurate representation of the pycnocline depth.

Figure 47 is a histogram of the number of occurrences of hypoxia when the pycnocline was at different percentages of the water column. There were 25 observations of hypoxia during the three sampled years. All hypoxic observations occurred when the pycnocline was between 24.9-61.7 percent of the water column. Approximately 80.0 percent of hypoxic conditions were observed when the pycnocline depth was between 31.0-60.0 percent of the water column.

Based on the samples for all three years at every station, the average pycnocline depth relative to the water column depth during an ebb versus a flood tide was calculated. On the ebb tides, the average pycnocline depth was 44.1 percent of the total water column depth (Table 5). On the flood, the average pycnocline depth was 44.6 percent of the total water column depth (Table 5).

Tide	Pycnocline Depth as a Percentage of Total Water Column Depth
Ebb	**44.1 %**
Flood	**44.6 %**

Table 7: The percentage of the pycnocline depth relative to the total water column depth for both stages of tide.

5.0 Discussion

Based on the statistical analysis of the time series data collected by the CT DEP, there has been no change in monthly DOb concentrations at CT DEP station 15 since 1996. Therefore, despite the efforts of the LISS to reduce nitrogen loadings into LIS, summertime bottom water hypoxia in Smithtown Bay has not improved. A strong seasonal cycle dominates the concentration of DOb with an annual minimum occurring around the months of July and August each year. Hypoxic conditions were observed for all but two sampled years. Therefore, localized "bottom water" hypoxia can be expected almost any summer in Smithtown Bay.

It is well known that the development of seasonal stratification is closely coupled with the depletion of bottom water DO concentrations in most estuarine systems, which accounts for the seasonal consistency of hypoxia (Welsh, 1995; Diaz and Rosenberg, 2008). What changes between systems is whether the stratification is thermally or salinity controlled (Welsh and Eller, 1991). In Chesapeake Bay and the Gulf of Mexico, salinity is the driving force behind the vertical density gradient (Welsh and Eller, 1991). In western LIS, summer density stratification is thermally controlled (Welsh and Eller, 1991; Wilson et al., 2008). Freshwater input has less of an impact on LIS compared to Chesapeake Bay because though their volumes are comparable, Chesapeake Bay has a watershed four times as large (Gay and O'Donnell, 2009).

Based on the results of this study, the summer density structure in Smithtown Bay appears to be controlled heavily by thermal stratification, similar to western LIS. In LIS, slight salinity stratification generally persists throughout the year with changes in surface and bottom salinity ranging from 0.5 to 1.0 ppt (Signell et al., 2000). High freshwater discharge from snow melt and precipitation may create a thin freshwater film in the surface waters, briefly enhancing salinity stratification in early spring (Signell et al., 2000; Gay and O'Donnell, 2009). The results of this study displayed haline control of stratification during early spring but it quickly disappeared as the season progressed. In late spring and throughout the summer, thermal stratification exceeded that of haline stratification for 13 of the 15 sampled years. On average, the thermal contribution to summer density stratification was twice that of the haline contribution. This suggests that surface heating is the predominant factor in determining the degree of summertime stratification in Smithtown Bay. In western LIS, Wilson et al. (2008) found the haline contribution to density structure to dominate in the spring and late summer and the thermal contribution to dominate in mid-summer. In Smithtown Bay, slightly different results were observed. Salinity stratification dominated during early spring and temperature dominated in late spring and throughout the entire summer. The continual summertime dominance in the thermal contribution to density in Smithtown Bay as opposed to the increase of haline contributions to density structure in western LIS may be attributed to greater influence of freshwater sources from the Hudson River and discharges of New York City sewer systems through the East River into western LIS (Gay and O'Donnell, 2004). Most of the freshwater comes from the north; thus, freshwater sources to Smithtown Bay are minor (Gay and O'Donnell, 2004). Overall, vertical salinity gradients in LIS are weak and the seasonal thermocline, once established, is strong (Welsh, 1995).

When time series of density, thermal, and salinity stratification for a hypoxic year and a non-hypoxic year were compared, differences in duration and strength of stratification were observed. Both years experienced water column stratification during summer months; however, total stratification was greater with a greater thermal contribution during the hypoxic year. Also, this analysis suggests that hypoxic years can be characterized as having an earlier onset of seasonal stratification than non-hypoxic years. Based on our results, the hypoxic year experienced stratification two months earlier than the non-hypoxic year. Therefore, the duration of water column stratification has an impact on the concentration of DOb in Smithtown Bay. Similar results were found in western LIS when the years of 1988 and 1992 were compared (Wilson et al., 2008). In western LIS, the persistence of stratification was the predominant factor between a hypoxic and non-hypoxic year. They found that the non-hypoxic year could be characterized by frequent destratifying events, while stratification was more stable during the hypoxic year. Density stratification is variable and can fluctuate in as little as two weeks (Wilson et al., 2008). Due to our relatively long sampling period of one month, any destratifying events that occurred could have been missed.

Previous studies conducted in western LIS have suggested that the directionality and speed of winds can contribute to the concentrations of DO in the bottom waters (Wilson et al., 2008; Valle-Levinson et al., 1995). Winds can create significant surface mixing that may deepen or destroy the pycnocline (Valle-Levinson et al., 1995). Winds are generally from the southwest during the summer (Signell et al., 2000). However, interannual variability of wind speed and direction is common. Based on the correlation analysis between wind direction and the duration of hypoxia, westerly and northwesterly winds are highly coupled with long-term durations of hypoxia in Smithtown Bay. Generally, up-estuary winds bring in saltier surface water and break up stratification; down-estuary winds bring in fresher surface water, increasing stratification (Scully, 2005). Since most freshwater sources to LIS come from the north from rivers and from the west from sewage discharges and the Hudson River via the East River, west and northwesterly winds might act similar to down-estuary winds in the case of Smithtown Bay. Westerly and northwesterly winds may bring in fresher surface water and therefore increase stratification. Since it was previously shown that stratification is highly coupled with DOb concentrations, it is likely that increased stratification would lead to greater durations of hypoxia. It appears that the directionality of wind and its effect on hypoxia and stratification is a basin wide phenomenon. Previous studies have shown that in western LIS westerly winds intensify stratification and hypoxic conditions while easterly winds break it up (Wilson et al. 2008). Winds blowing parallel to LIS can either strengthen or weaken estuarine flow.

Based on the histograms and contours of DOb concentrations in Smithtown Bay, stations 5, 6, and 7 experienced the most frequent and the most severe hypoxia while stations 14 and 15 were the only ones inside the bay that never experienced hypoxic conditions. Station 15 is the shallowest station, approximately 9 m, and the water column at that station was always well mixed. It is likely that station 15 never experiences bottom water hypoxia. Station 14 is much deeper, approximately 21 m. Concentrations of DOb at station 14 were recorded as low as 3.2 mg L^{-1}. Unlike station 15, station 14 does become stratified. It is likely that station 14 does experience hypoxia, but was not detected during our field sampling. It appears that stations near shore, closest to the Nissequogue River and Stony Brook Harbor, experience the lowest concentrations of DOb. Since this may be the case, the shallow sill separating the bay from the two embayments acts as an important geological feature restricting the low DO from entering Stony Brook Harbor or the Nissequogue River. Therefore, dredging the entrance channel to Stony Brook Harbor and deepening the presently dredged entrance channel to the Nissequogue River may be ecologically damaging (Swanson et al., in preparation).

The low DOb concentrations at nearshore stations occurred at the same time a thin film of dense surface water was observed hugging the shore (Swanson et al., in preparation). Despite being the closest to the entrances of Stony Brook Harbor and the Nissequogue River, the surface temperatures and salinities at stations 5 and 6 do not appear to be warmer and fresher than stations offshore. In fact, several times the surface waters were slightly cooler and saltier than the offshore waters. These findings support the idea of the importance of topographically controlled circulation in Smithtown Bay. The counterclockwise gyre may be transporting dense surface water from the center of LIS to the coast. Once in the bay, the currents are sluggish, trapping this dense water mass for many tidal cycles.

The model of residual currents revealed the existence of a large counterclockwise gyre outside Smithtown Bay and two smaller gyres inside Smithtown Bay, near the two headlands. The weak surface currents within Smithtown Bay appear to be topographically controlled by the two headlands, Crane Neck and Eatons Neck, creating a boundary between the bay and the rest of the Sound, limiting flushing, lateral mixing, and circulation. Topographically controlled circulation is likely a major contributing factor in the creation of a “hypoxia hot spot” in Smithtown Bay (Swanson et al., in preparation). The residual currents close to the headlands are cyclonic and strong. Once away from the headlands, the circulation inside Smithtown Bay is sluggish; the time it takes a water parcel to get to the east end of the Sound from Smithtown Bay is on the order of 100 days (Swanson et al., in preparation; Hao, 2008). These conditions may increase the residence time of suspended particulate material within the confines of Smithtown Bay. The entrances to the two embayments, Stony Brook Harbor and the Nissequogue River, have very strong tidal currents, while the currents within Smithtown Bay are relatively weak (Swanson et al., in preparation). Because of this, decaying wetland and other organic material inside the embayments may be transported to and trapped inside Smithtown Bay (Swanson et al., in preparation). An excess of particulate matter would increase the consumption of DOb, and with stratification limiting vertical exchange and circulation patterns limiting horizontal exchange, hypoxic conditions are inevitable. The calculated bottom stress inside the bay is weak relative to the main channel of the LIS. The sluggish surface currents may trap organic material originating on land inside the bay. Once it sinks, weak bottom stress may increase deposition and prevent resuspension. The organic matter will build up below the pycnocline and oxygen will be consumed. In the summer, stratification will inhibit the resupply of oxygen and hypoxic conditions will arise. Therefore, topographically controlled circulation is likely a major contributing factor in the seasonal reoccurrence of hypoxia in Smithtown Bay. A model study off the New Jersey coast has shown that recurrent hypoxia can be attributed to circulation as a result of bottom topography (Song et al., 2001).

In estuaries, tidal stirring will generally assist in the development of stratification on the ebb and promote its breakdown on the flood (Simpson et al., 1990). However, in Smithtown Bay, stratification was persistent with little to no changes in the concentration of surface temperatures and salinities throughout the tidal cycle. Based on the results from the horizontal contours and the T-S diagrams, the stage of tide does not appear to greatly affect the concentration of DOb, temperature, or salinity in Smithtown Bay. Also, the strength of stratification did not appear to differ between ebb and flood tide. The tidal ellipses demonstrated that the tidal currents inside Smithtown Bay are weak relative to the center of LIS. Weaker tidal mixing results in greater stratification, thus contributing to low DOb concentrations (Gay and O'Donnell, 2004). This further suggests that circulation is sluggish inside the bay or perhaps there is a large uniform water mass within the central Sound extending throughout Smithtown Bay (Swanson et al., in preparation). In either case, an exchange of water masses in Smithtown Bay over a tidal cycle is not occurring (Swanson et al., in preparation).

The T-S diagram for the three Augusts suggests that the temperatures and salinities for any given year are variable. This interannual variability in water column temperatures and salinities are highly dependent upon the atmospheric conditions such as air temperature and precipitation during any given summer. Based on the T-S diagrams and the vertical sections, the water column was strongly stratified during the summers of 2009 and 2010. The vertical sections demonstrated the importance that stratification had on the DO structure. For both years, a relationship between the depth of the pycnocline and depth of the oxycline was clearly displayed. Lee and Lwiza (2008) also found that the variability in summer bottom DO (DOb) at station 15, located within Smithtown Bay, exhibited a strong relationship with stratification. As the season progressed and stratification developed, ventilation of the bottom waters through vertical dispersion was restricted (Welsh and Eller, 1991). Low DO concentrations were observed from the base of the pycnocline to the bottom. This demonstrates the expected physical control of the oxycline by the pycnocline (Welsh and Eller, 1991). This also suggests that vertical mixing is more important in distributing oxygen to depth than lateral advection. Therefore, once stratification develops, a barrier is created and DO concentrations in the bottom waters will not be replenished until stratification subsides.

The results using the Brunt-Väisälä frequency suggest that there is a relationship between the size of the bottom layer, beneath the base of the pycnocline and the concentration of DOb in Smithtown Bay. Also, the similarities between the average pycnocline depth for ebb and flood further suggest that the tide is not a determining factor to stratification in Smithtown Bay. When hypoxic concentrations were observed, the pycnocline was in the middle of the water column, between 24.9-61.7 percent of the total water column depth. However, the opposite does not hold true. When the pycnocline is in the middle of the water column, it does not necessarily mean that the bottom waters will by hypoxic. Higher DOb concentrations were observed when the pycnocline was at all percentages of the water column. This has been seen before in the New

York Bight area (Swanson and Parker, 1988). Swanson and Parker (1988) determined that the likelihood of having hypoxic conditions in the bottom waters of the New York Bight area was greater when the pycnocline was between 30-70 percent of the total depth of the water column. When the pycnocline is shallow, a large reservoir of oxygenated water is below the pycnocline supplying DO to the bottom waters. When the pycnocline is deep, it may occasionally reach the bottom, destratifying the water column and hence replenishing DOb concentrations. Mid-depth pycnoclines restrict saturated surface waters from mixing with the bottom waters and do not allow a large enough reservoir of oxygenated waters below the pycnocline to develop. Therefore, pycnoclines at mid-depth create ideal conditions for the development and persistence of bottom water hypoxic conditions. .

6.0 Conclusions

So far, solutions for hypoxia management in LIS have been designed on the assumption that the entire Sound can be characterized the same way: a relatively free exchanging body of water that receives large loads of anthropogenic nitrogen. However, physical characteristics of the shoreline make certain regions of the Sound unique and functionally very differently from the rest of it. Smithtown Bay is an example of such a place where there is not a major source of nitrogen discharging directly into the bay yet seasonal hypoxia is a regular occurrence. Physical processes including stratification, depth of the pycnocline, winds, and most importantly topographically controlled circulation are major contributing factors to reoccurring bottom water hypoxia in Smithtown Bay. It appears from these results that Smithtown Bay, like western LIS itself, is physically predisposed to hypoxia. For this reason, it is likely that the current management solution to hypoxia, implementing total maximum daily loads of nitrogen, will not alleviate the reoccurring summertime bottom water hypoxic problem in Smithtown Bay.

7.0 Summary of Major Findings

- Bottom water hypoxic conditions have not improved and can be expected almost any summer in Smithtown Bay.
- Summer density stratification in Smithtown Bay is largely thermally controlled.
- The duration of stratification is a predominant factor in the difference between a hypoxic and non-hypoxic year.
- West and Northwest winds are positively correlated with the duration of hypoxia in Smithtown Bay.
- Concentrations of DOb are the lowest in the center of Smithtown Bay and along its eastern coast.
- The stage of tide is not a major factor in the concentrations of DOb, temperature, and salinity or the degree of stratification in Smithtown Bay.
- Relative to the central Sound at the same longitude, Smithtown Bay has weak currents and bottom stress.
- A classical headland gyre system is observed creating a partial barrier between Smithtown Bay and the rest of the LIS.
- Hypoxic conditions were only observed when the pycnocline was between 24.9-61.7 percent of the total water column depth.

7.0 References

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9.0 Apendix A: Figures

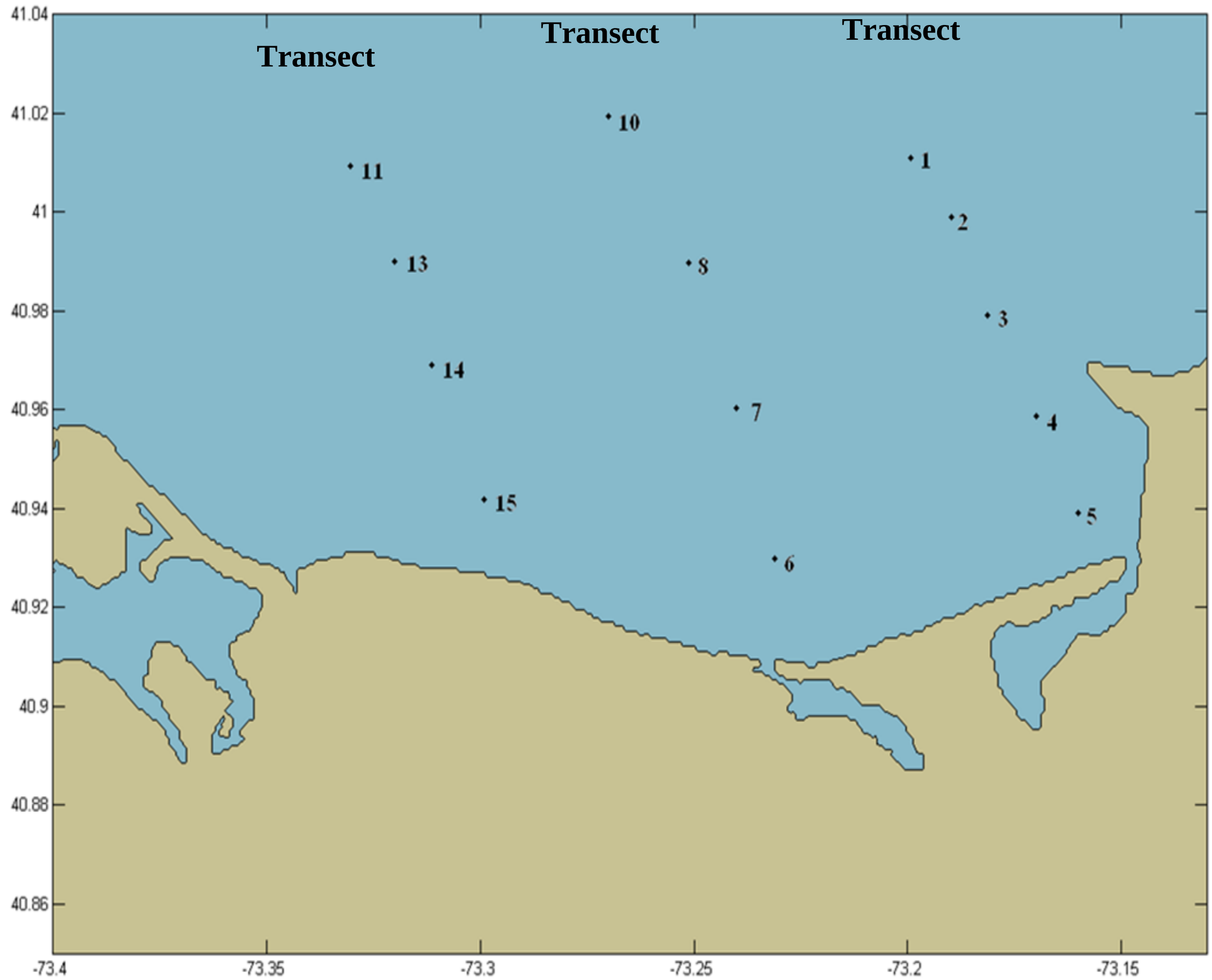

Figure 5: Map of the 13 station locations in Smithtown Bay. Stations 9 and 12 were not sampled due to close proximity to other stations.

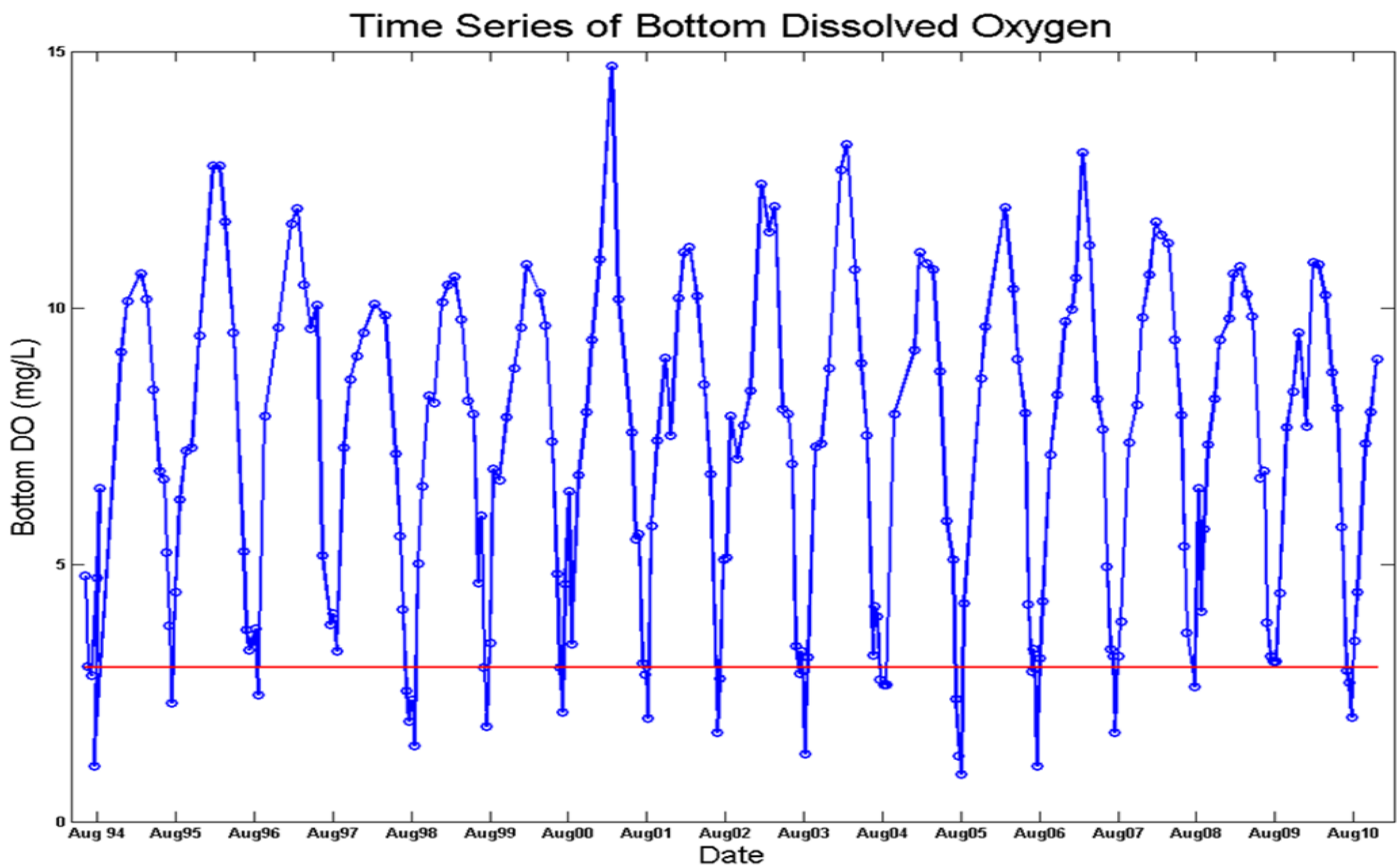

Figure 6: Time Series of bottom dissolved oxygen at CT DEP station 15 from 1994–2010. The red line indicates the hypoxic threshold of 3.0 mg L^{-1}.

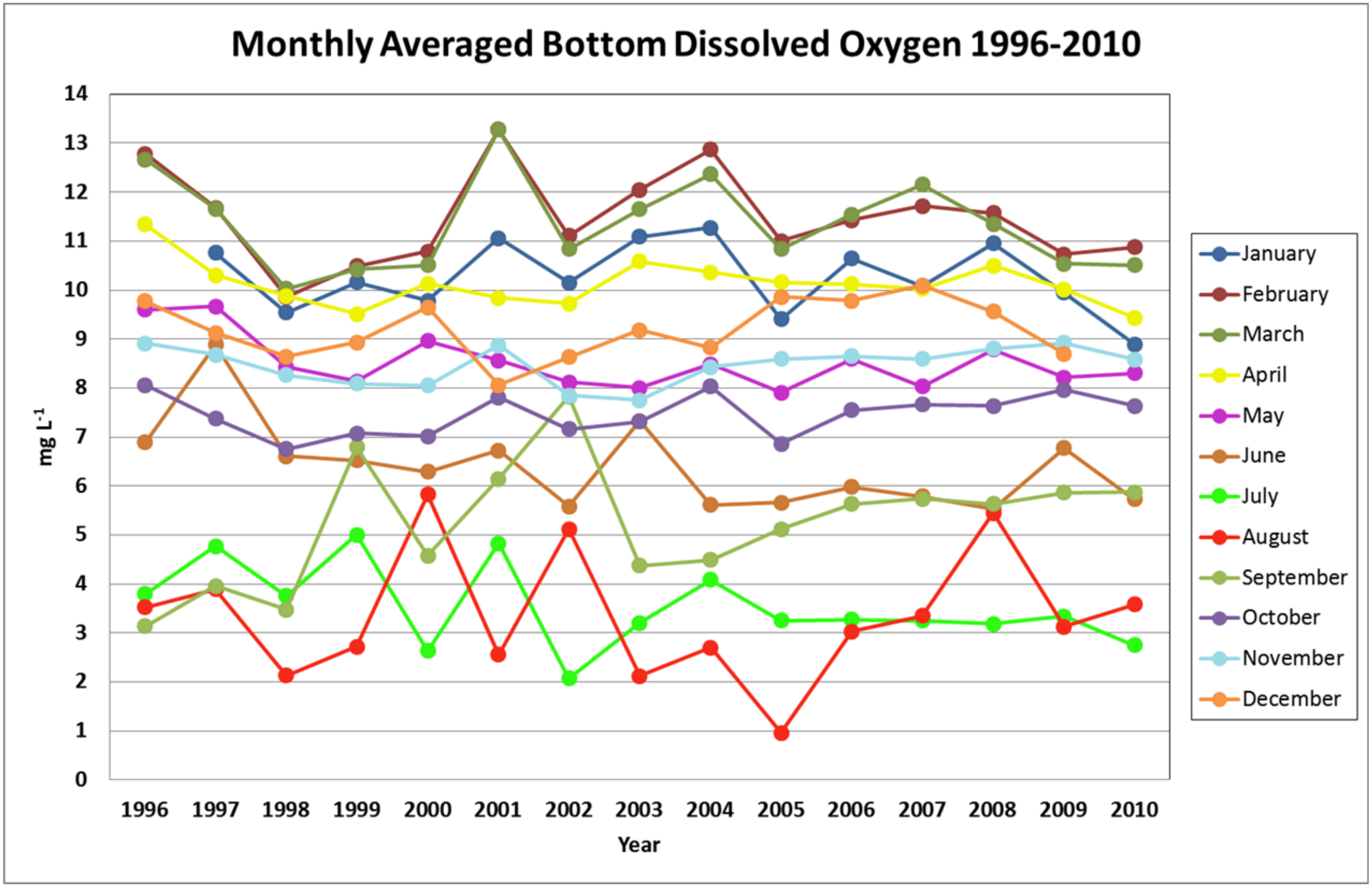

Figure 7: Time series of Monthly Averaged DOb from 1996-2010. There was no significant change in DOb for any month.

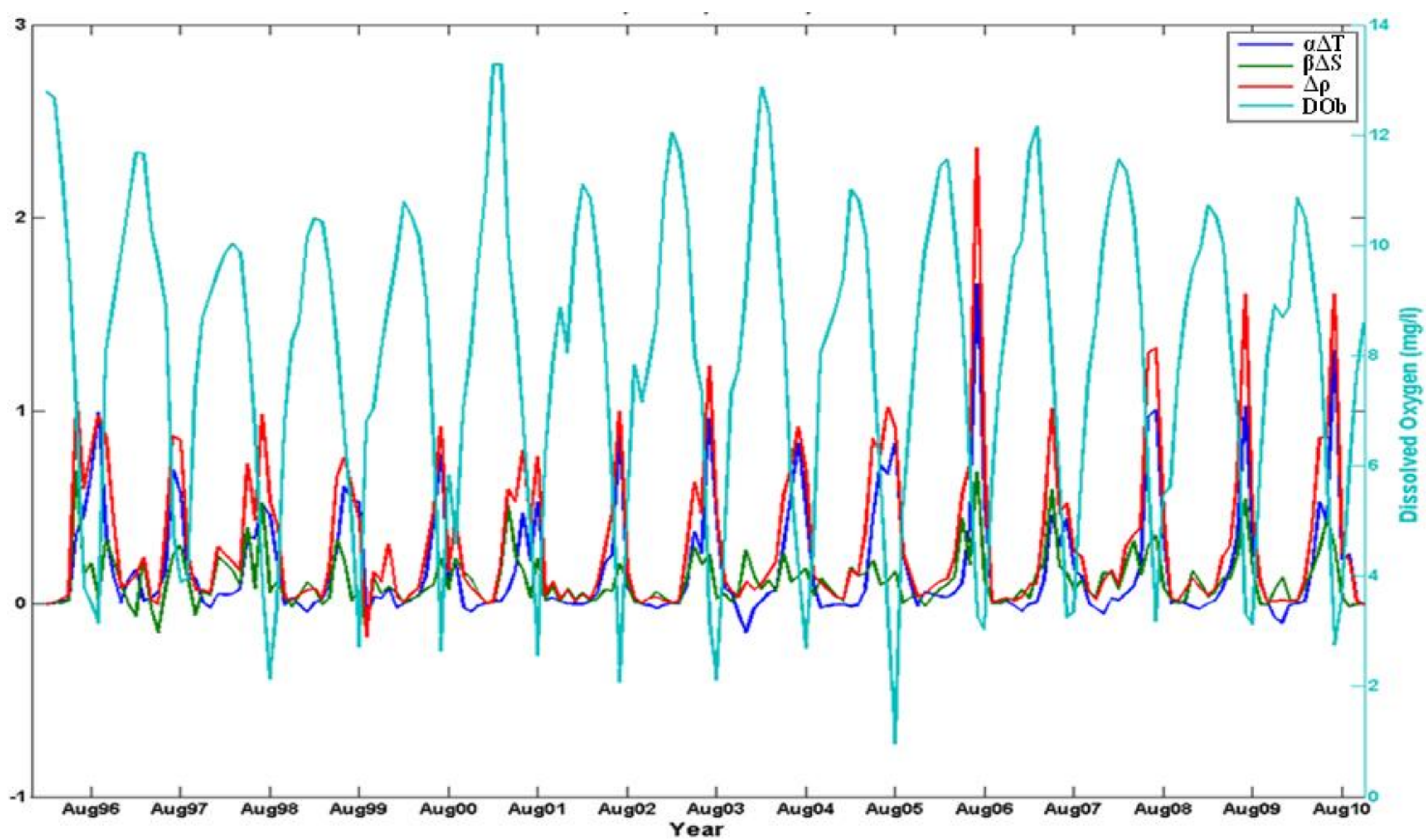

Figure 8: Time series of bottom dissolved oxygen, Δρ, αΔT, and βΔS (the standardized variables of ΔT and ΔS) and CT DEP station 15.

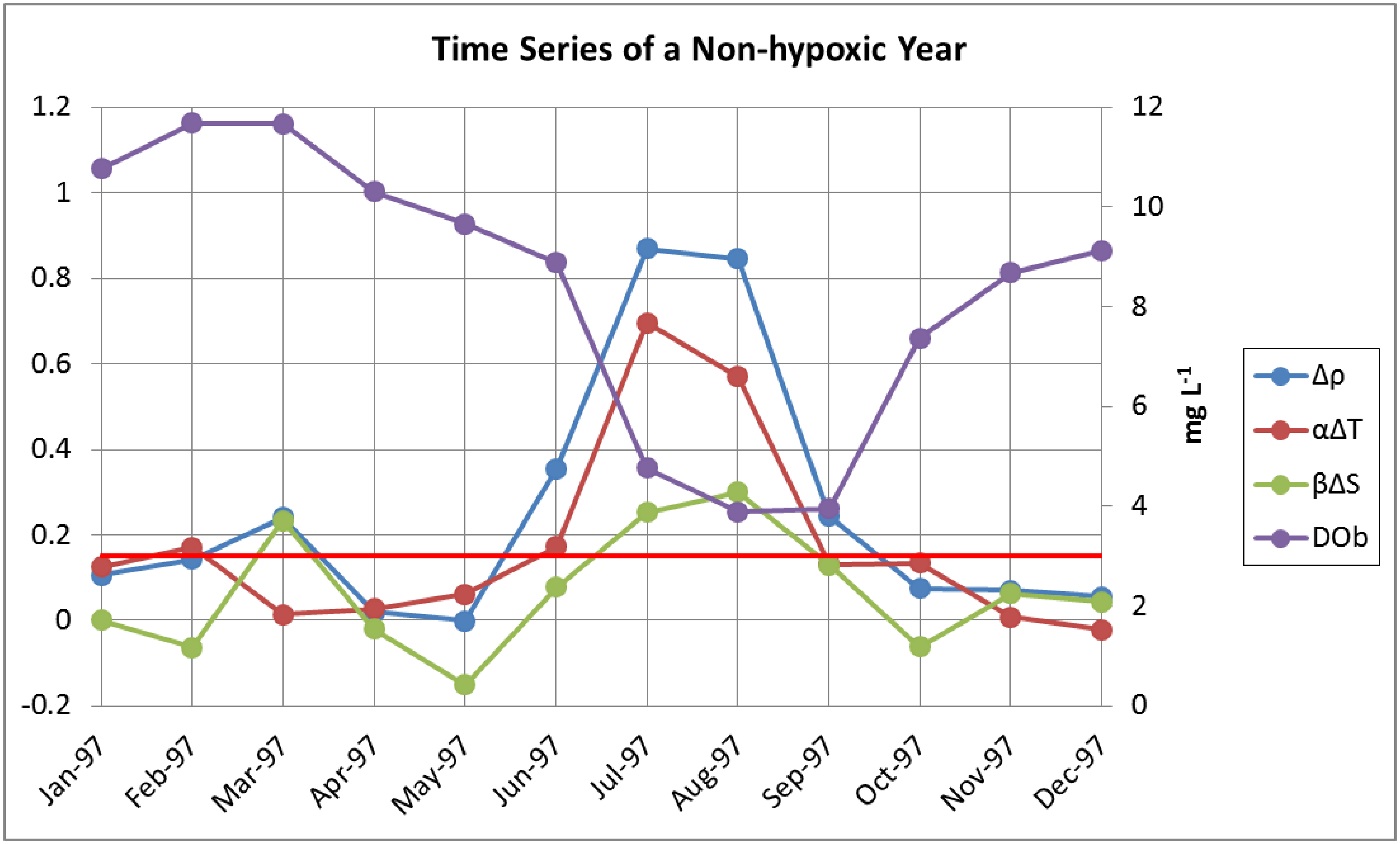

Figure 9a: Monthly averaged concentrations of DOb, Δρ, αΔT, and βΔS for 1997, a non-hypoxic year at CT DEP station 15.

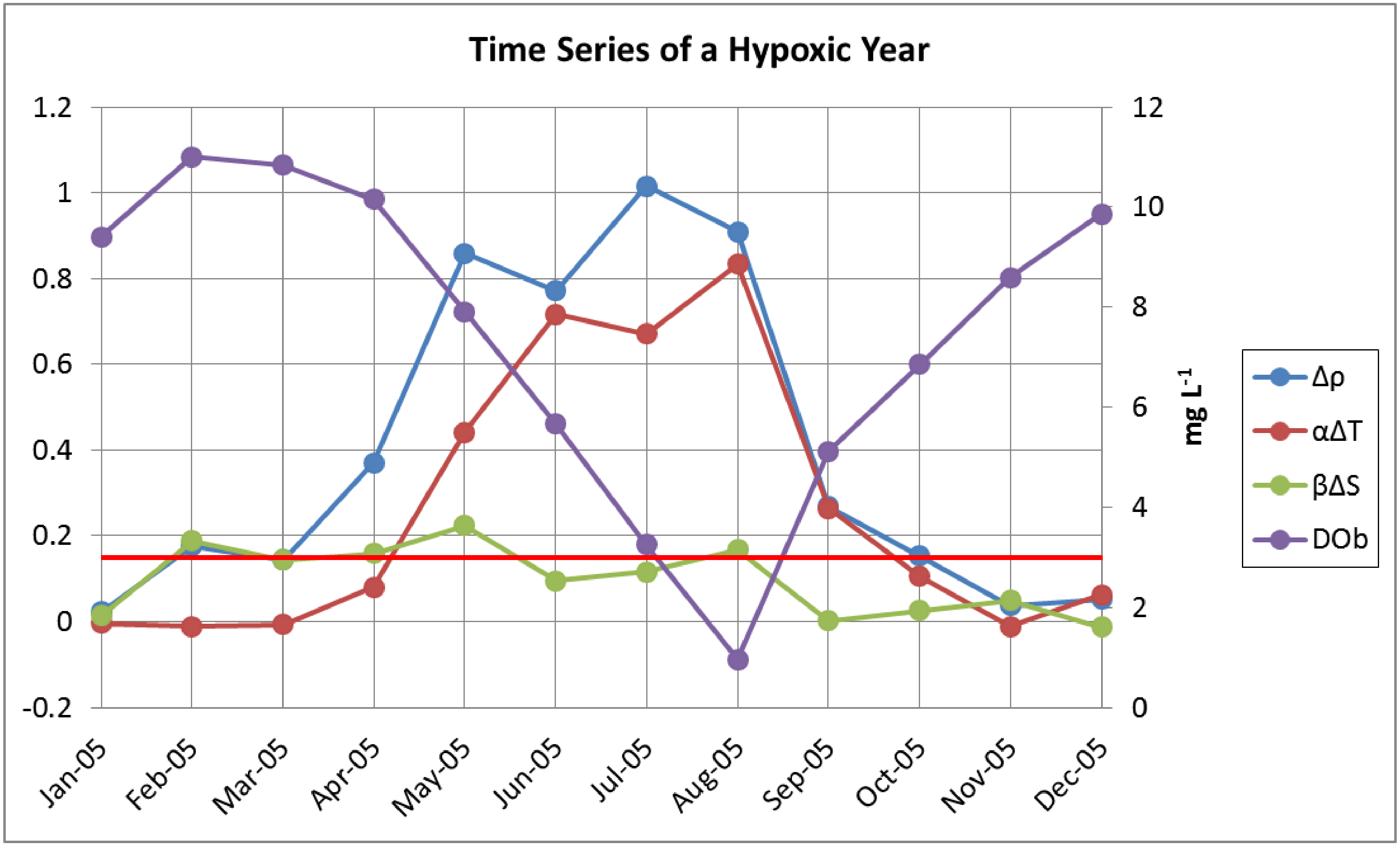

Figure 9b: Monthly averaged concentrations of DOb, Δρ, αΔT, and βΔS for 2005, a hypoxic year at CT DEP station 15.

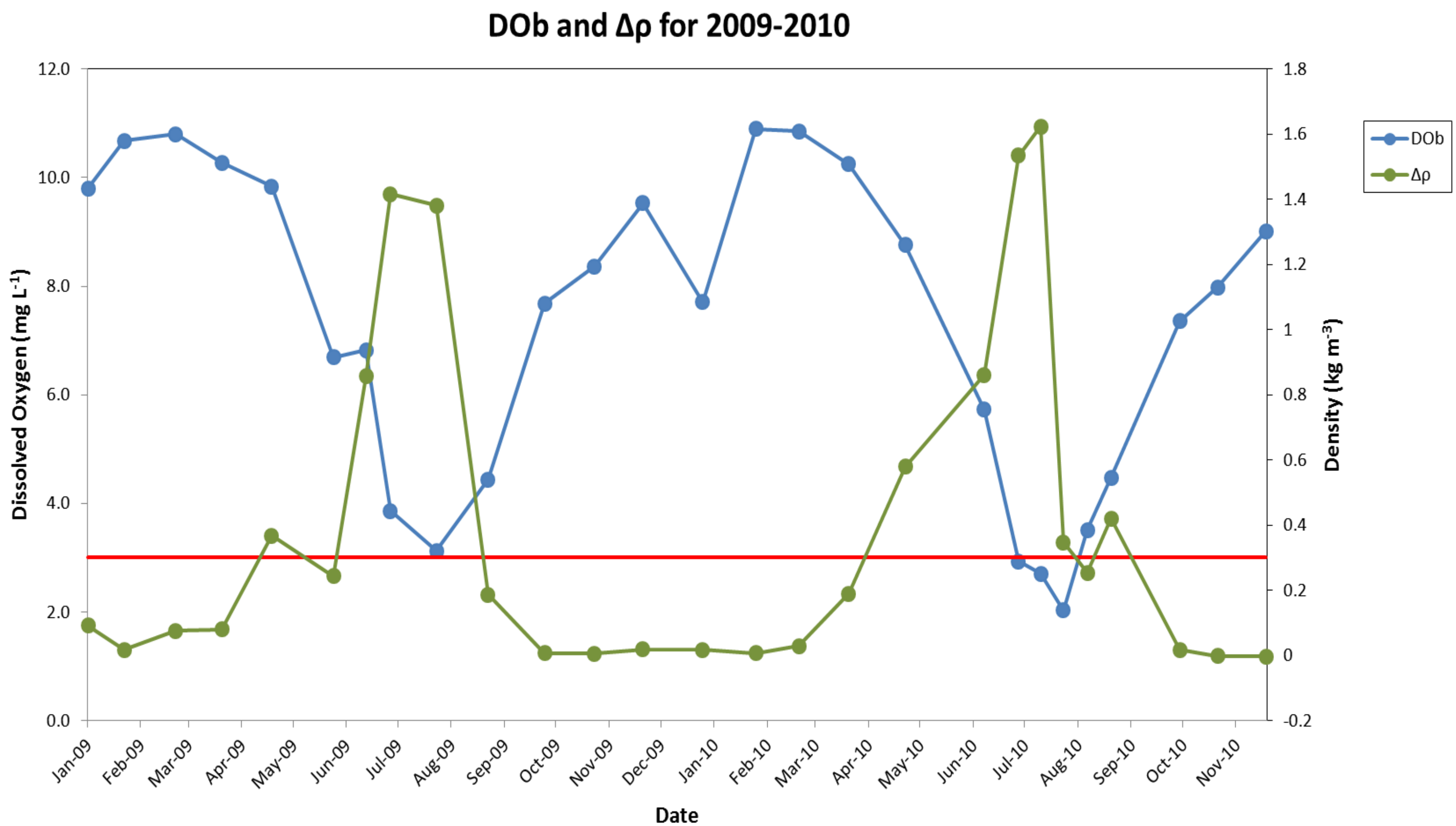

Figure 10: Monthly averaged concentrations of DOb and Δρ for 2009-2010 at CT DEP station 15.

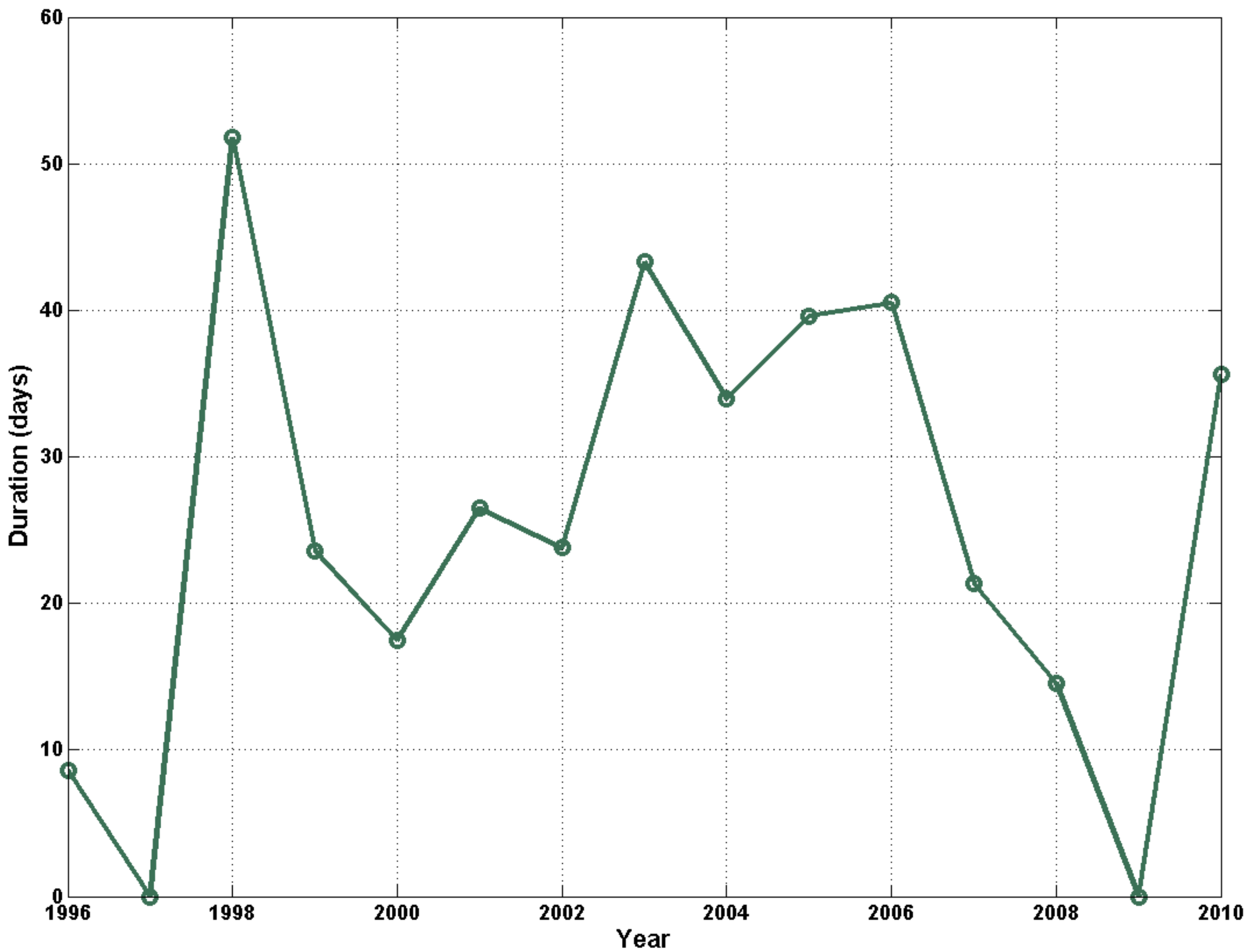

Figure 11: Duration (in days) that DOb concentrations were <3.5 mg L^{-1} from 1996-2010.

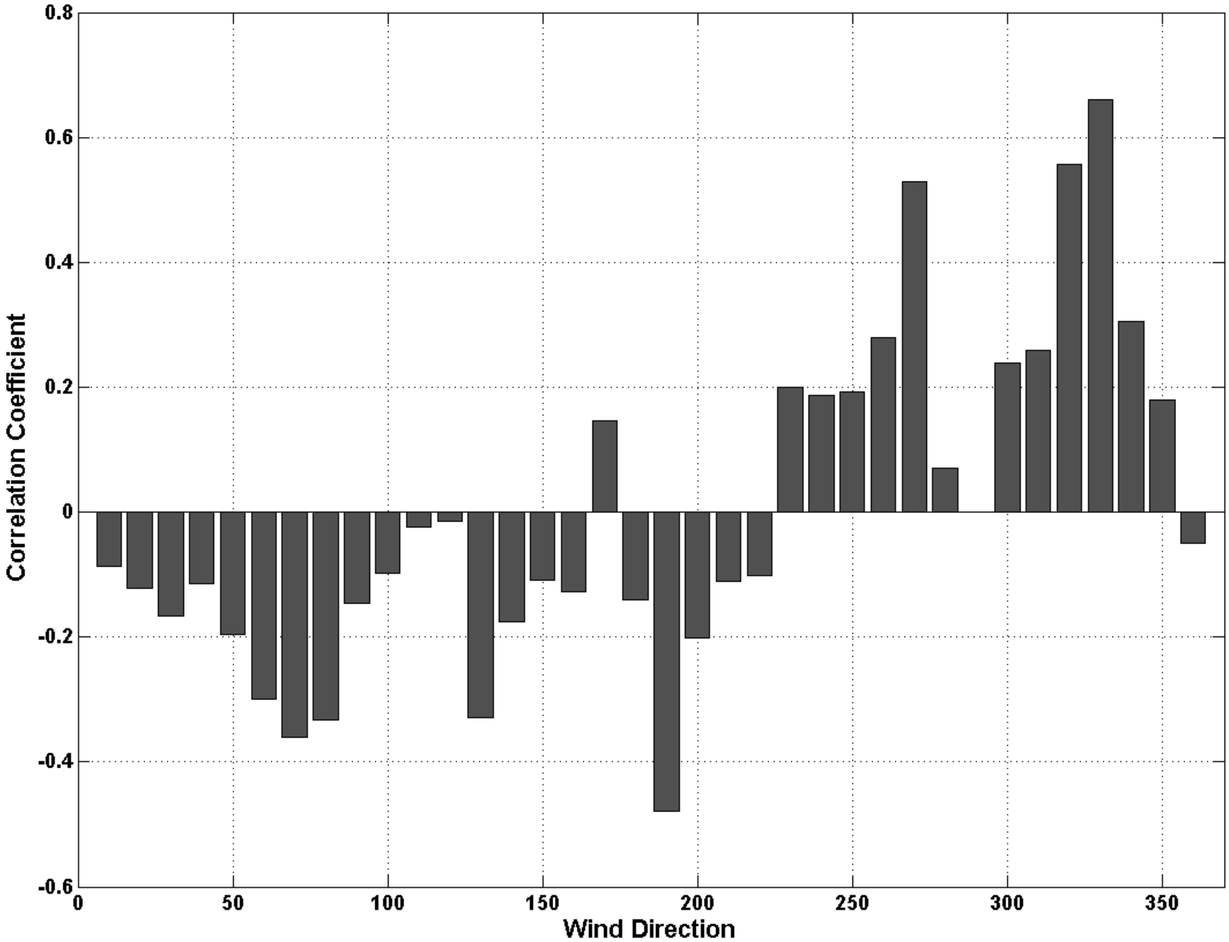

Figure 12: Correlation coefficients of hourly wind data from 6/01 – 9/01 of each year with the duration of hypoxia.

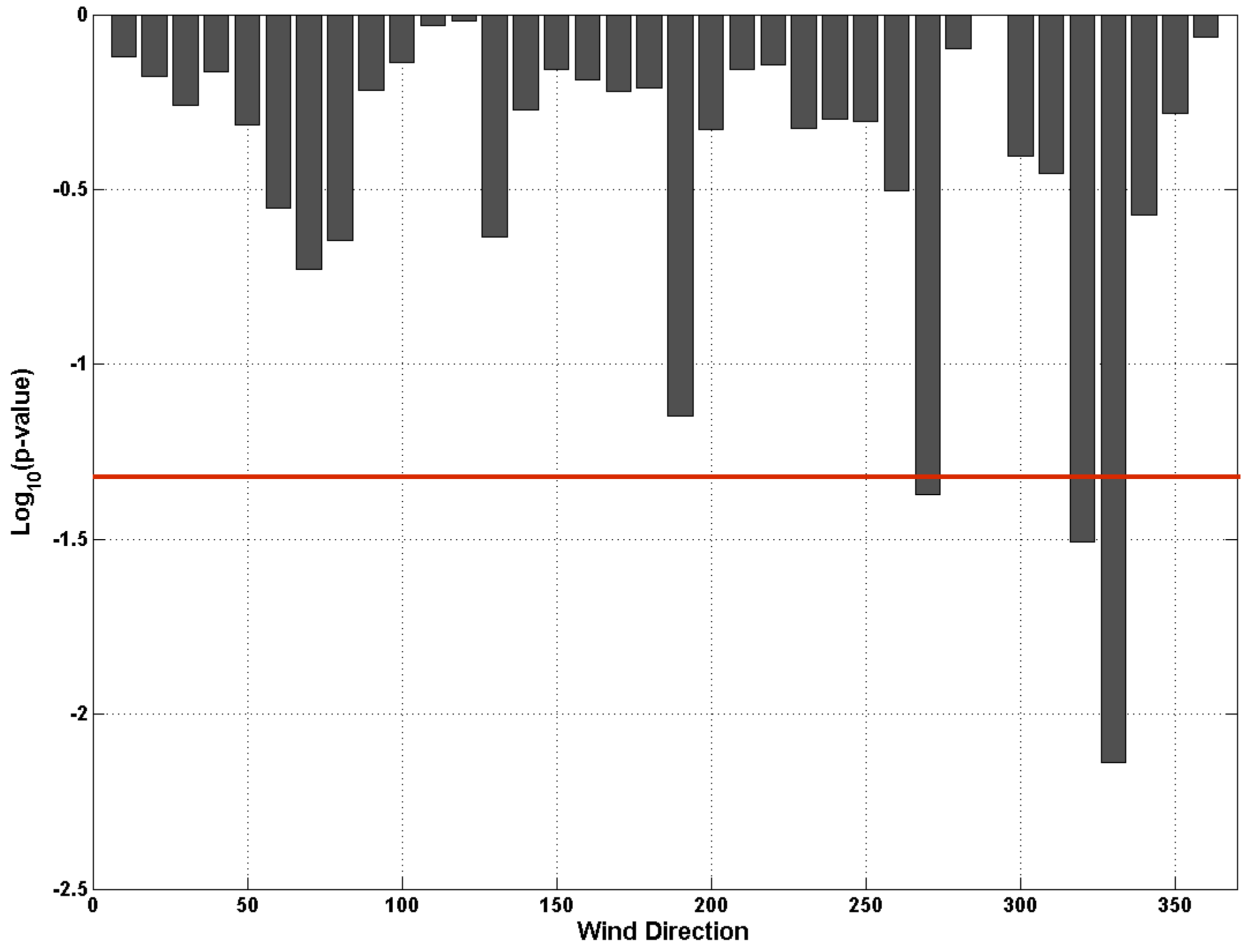

Figure 13: P-values from the correlation of hourly wind data from 6/01 – 9/15 of each year with the duration of hypoxia. The red line represents p-values of 0.05. Any bar the extends past the red line was considered significant.

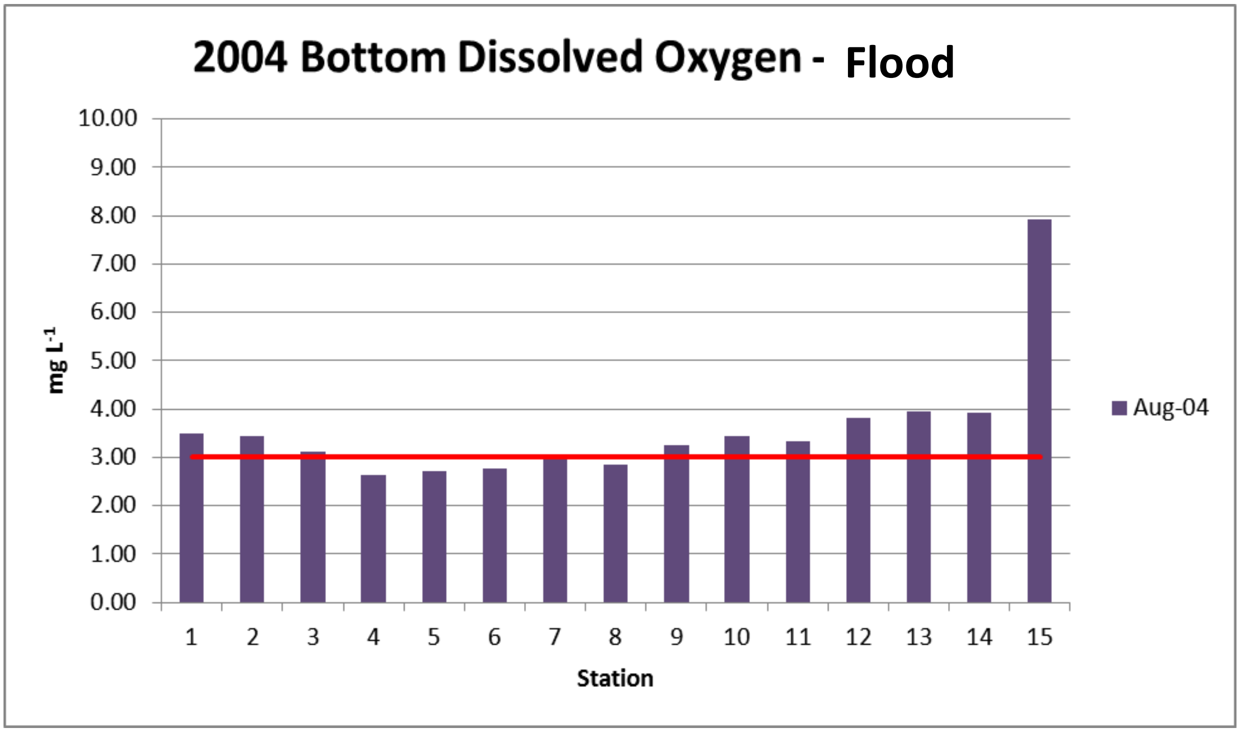

Figure 14: Histogram of the DOb concentrations at each Smithtown Bay station on the flood tide during the August 2004 cruise.

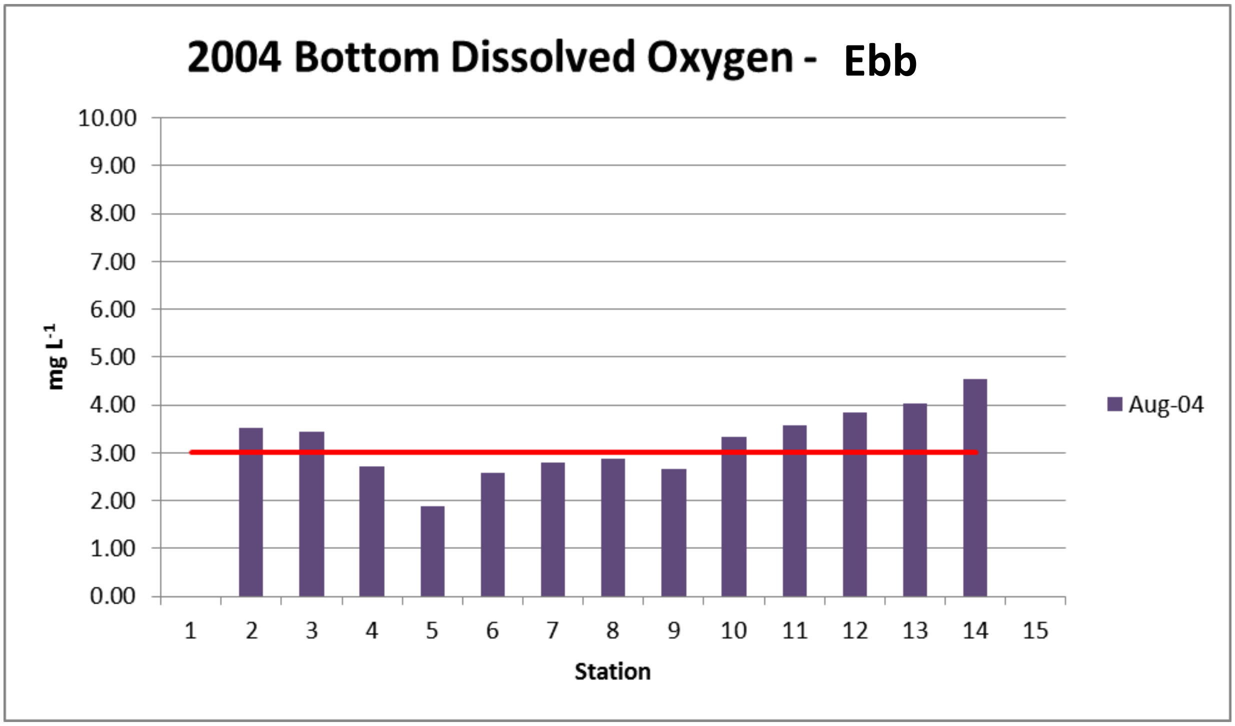

Figure 15: Histogram of the DOb concentrations at each Smithtown Bay station on the ebb tide during the August 2004 cruise.

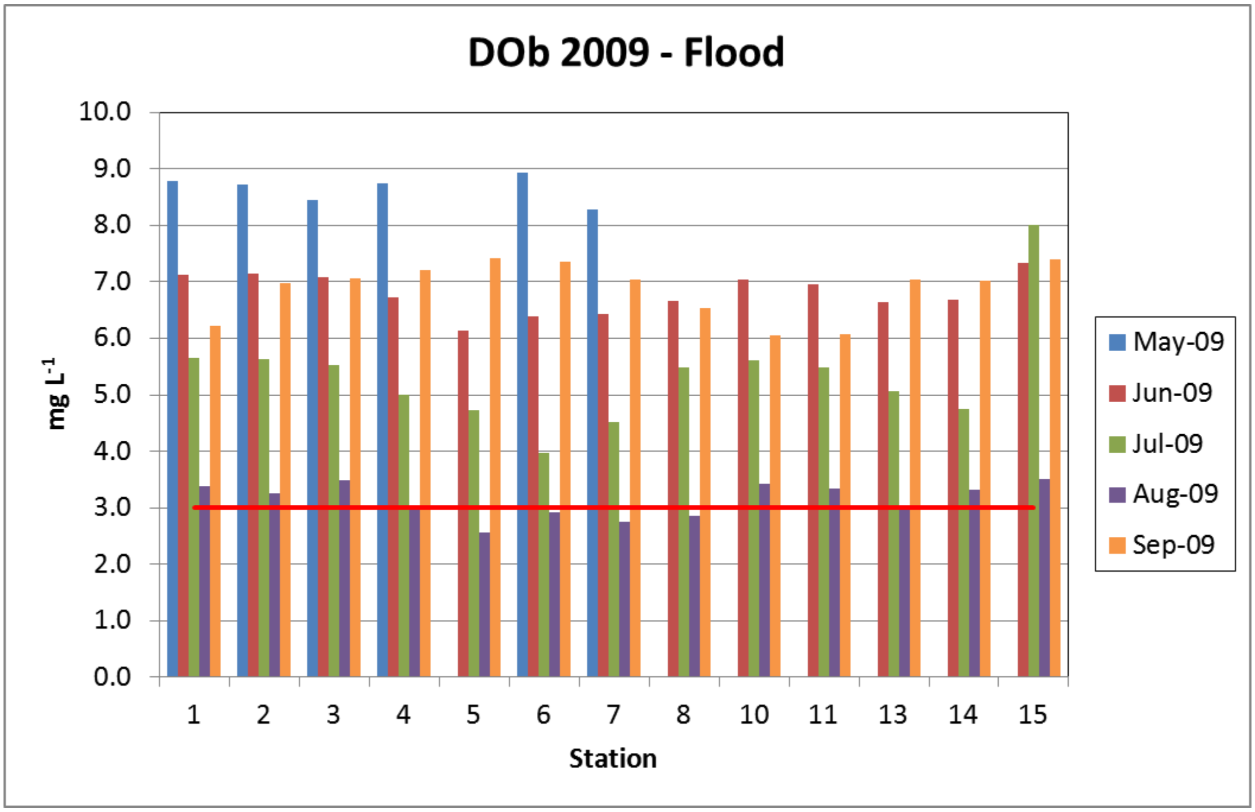

Figure 16: Histogram of the DOb concentrations at each Smithtown Bay station on the flood tide during the 2009 cruise.

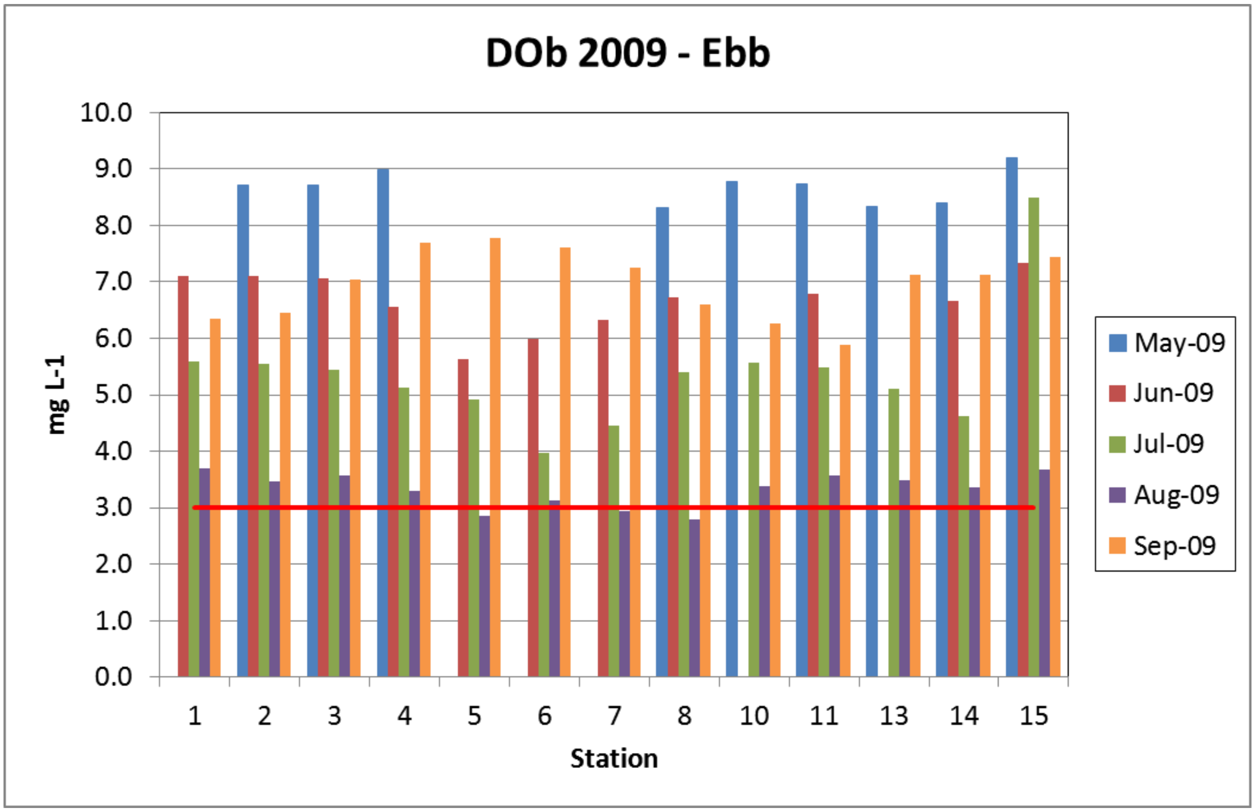

Figure 17: Histogram of the DOb concentrations at each Smithtown Bay station on the ebb tide during the 2009 cruise.

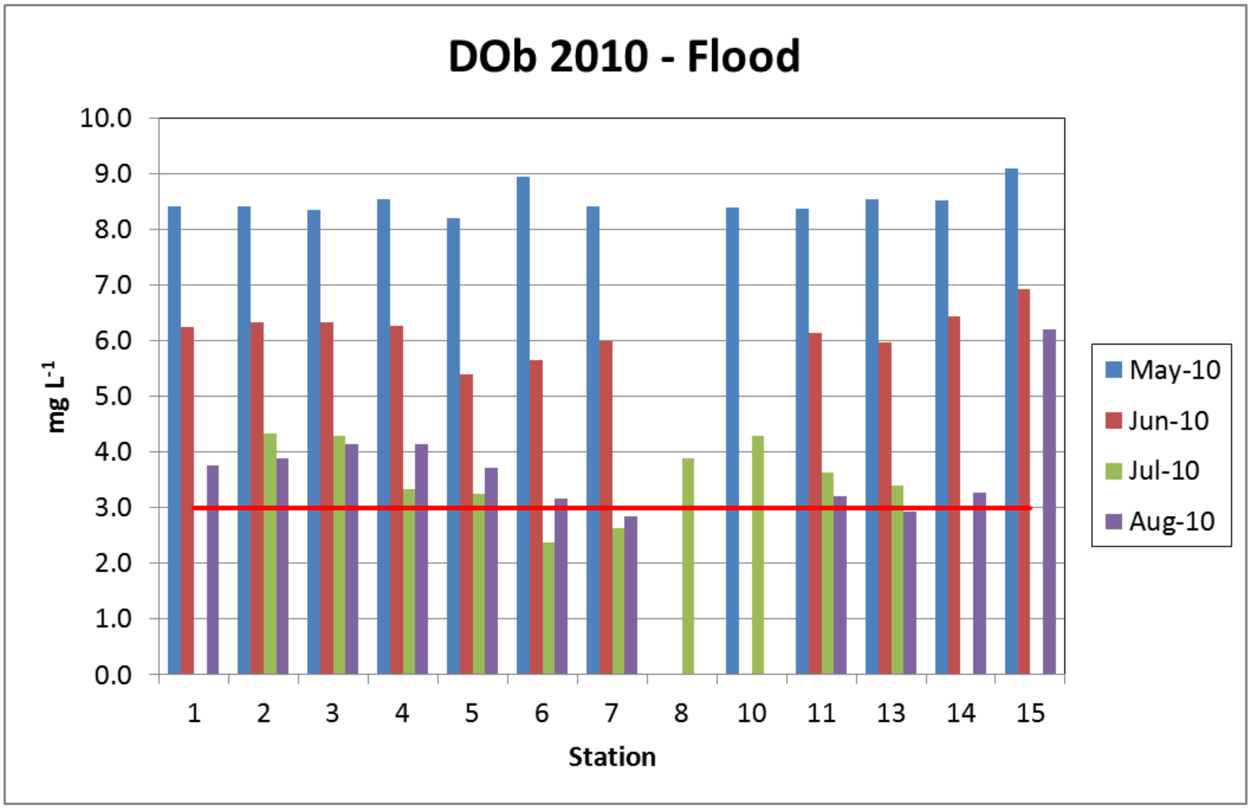

Figure 18: Histogram of the DOb concentrations at each Smithtown Bay station on the flood tide during the 2010 cruise.

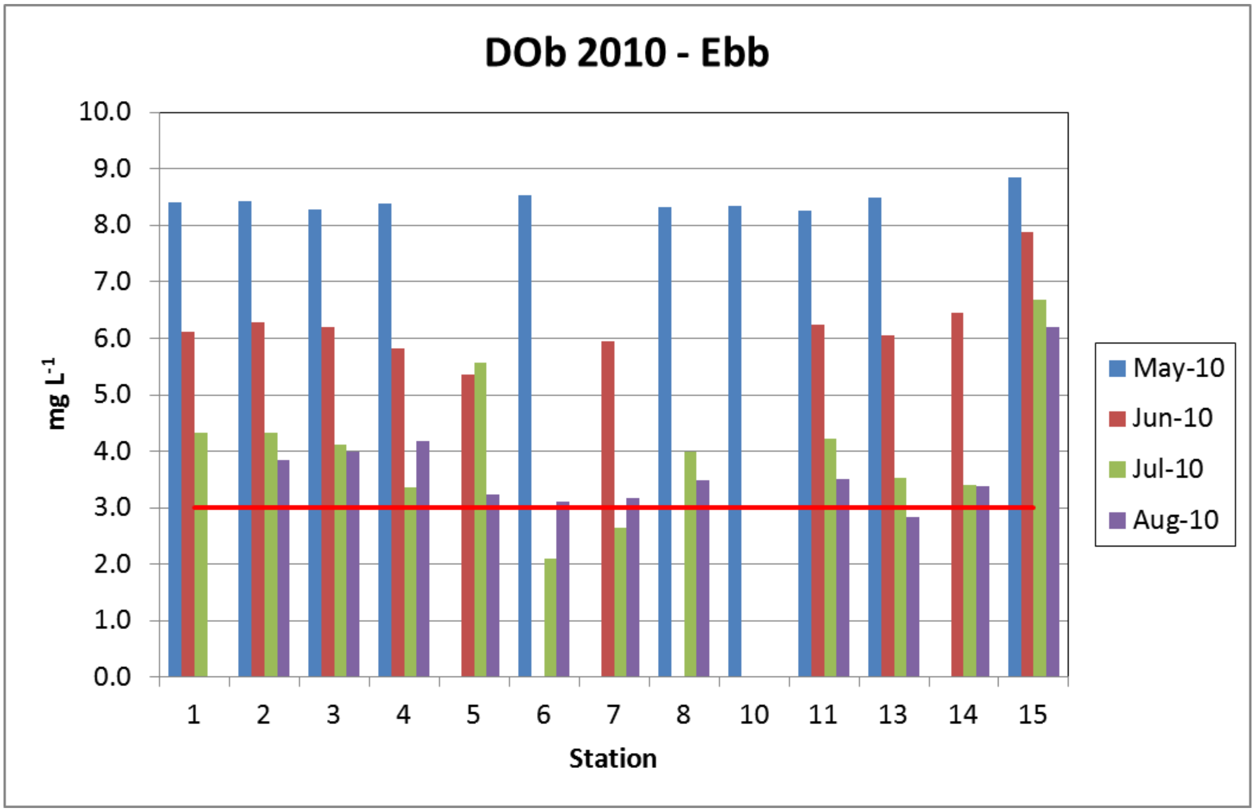

Figure 19: Histogram of the DOb concentrations at each Smithtown Bay station on the ebb tide during the 2010 cruise.

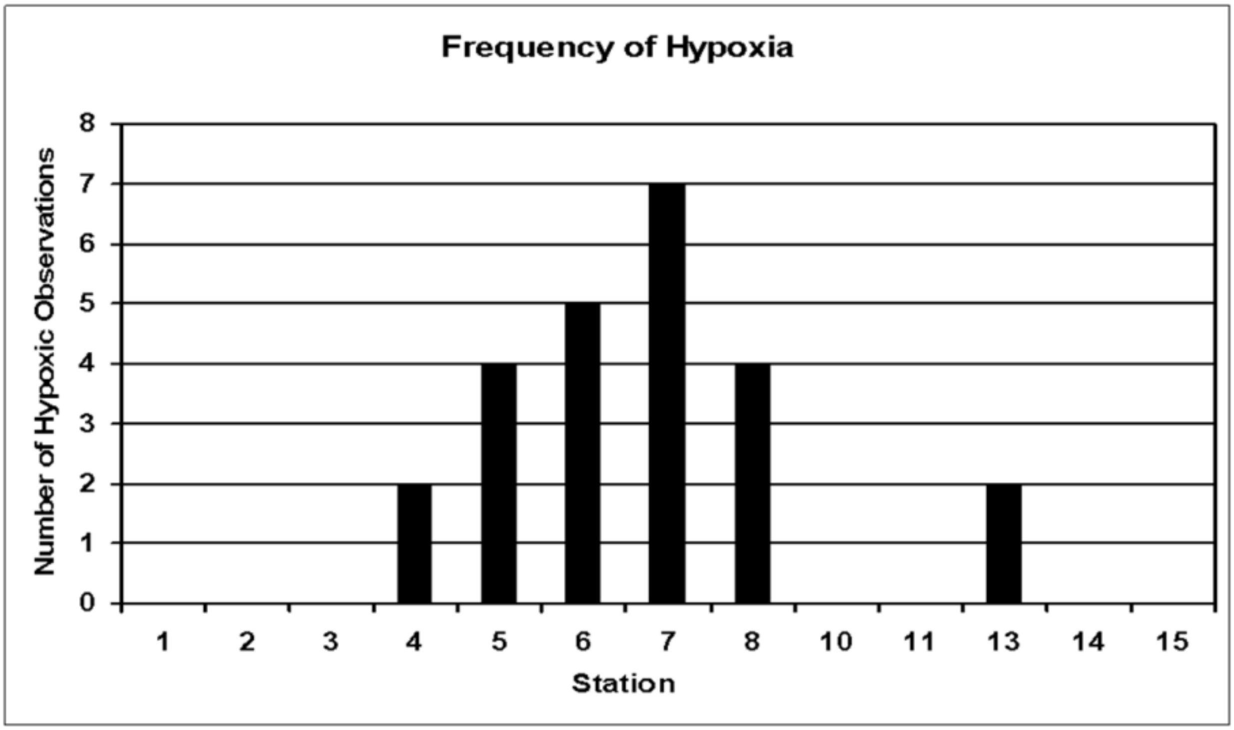

Figure 20: Histogram of the frequency of hypoxia at each Smithtown Bay station from 2004, 2009, and 2010.

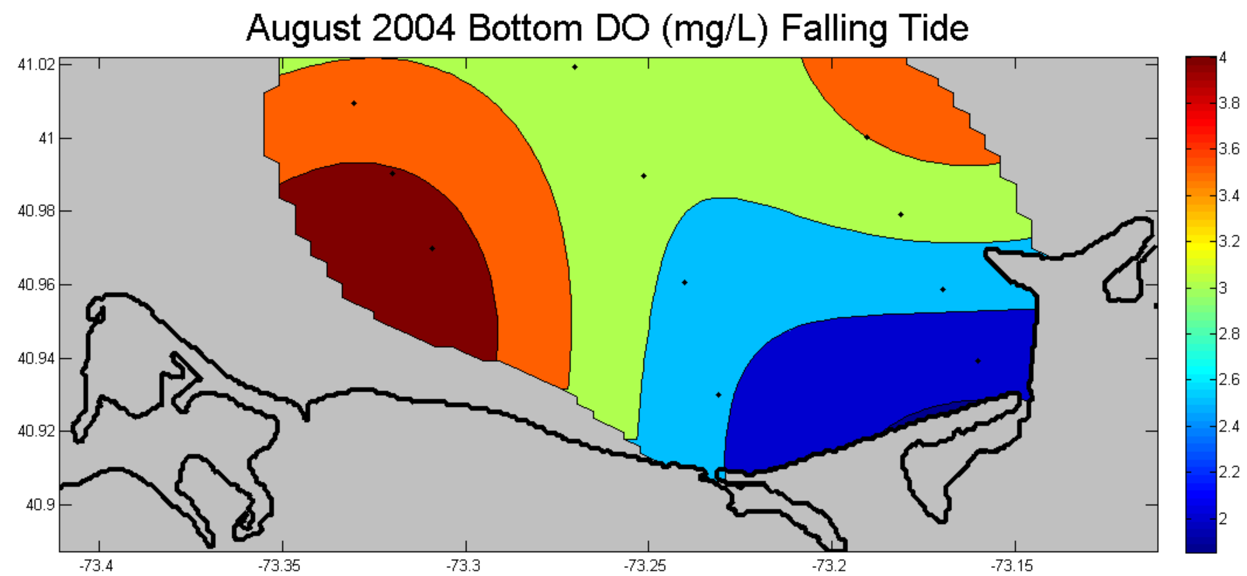

Figure 21a: A contour of August 2004 bottom DO during an ebb tide.

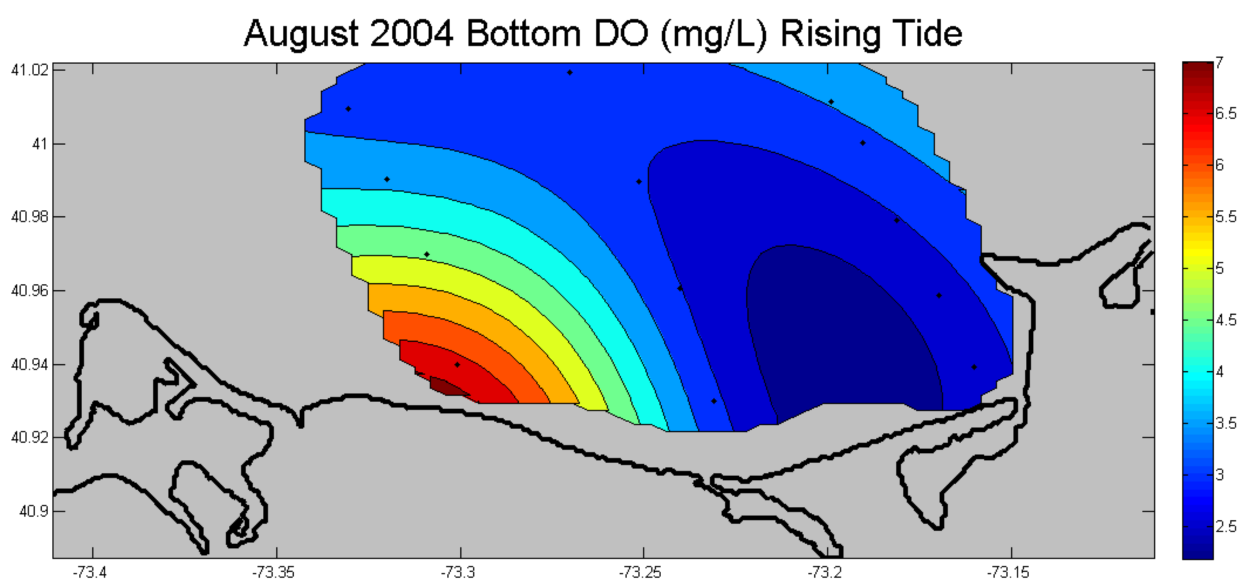

Figure 21b: A contour of August 2004 bottom DO during a flood tide.

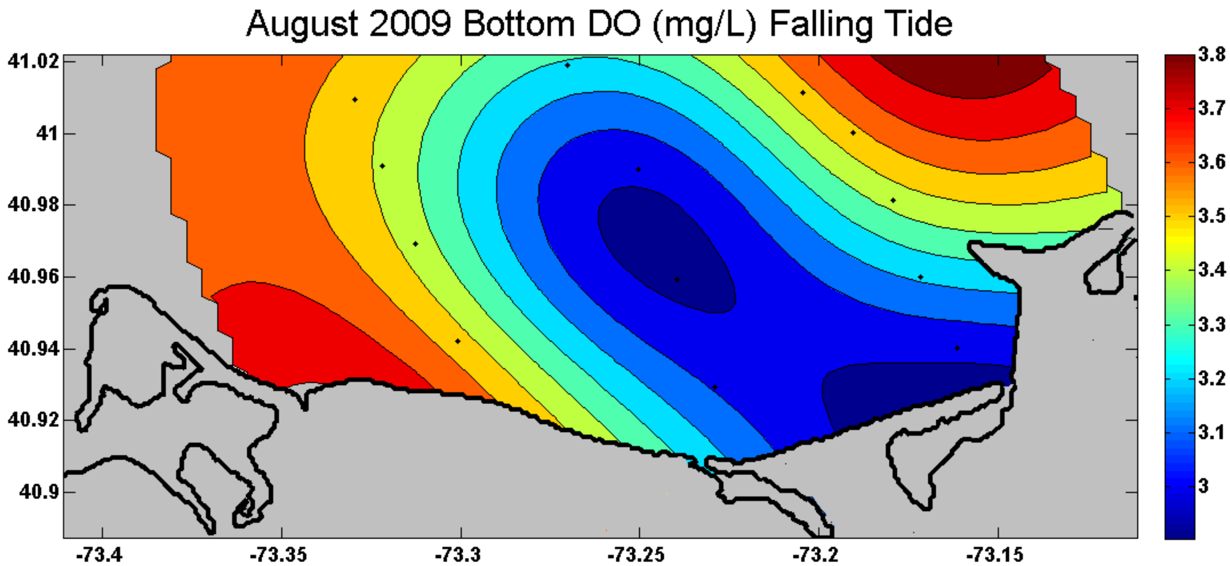

Figure 21c: A contour of August 2009 bottom DO during an ebb tide.

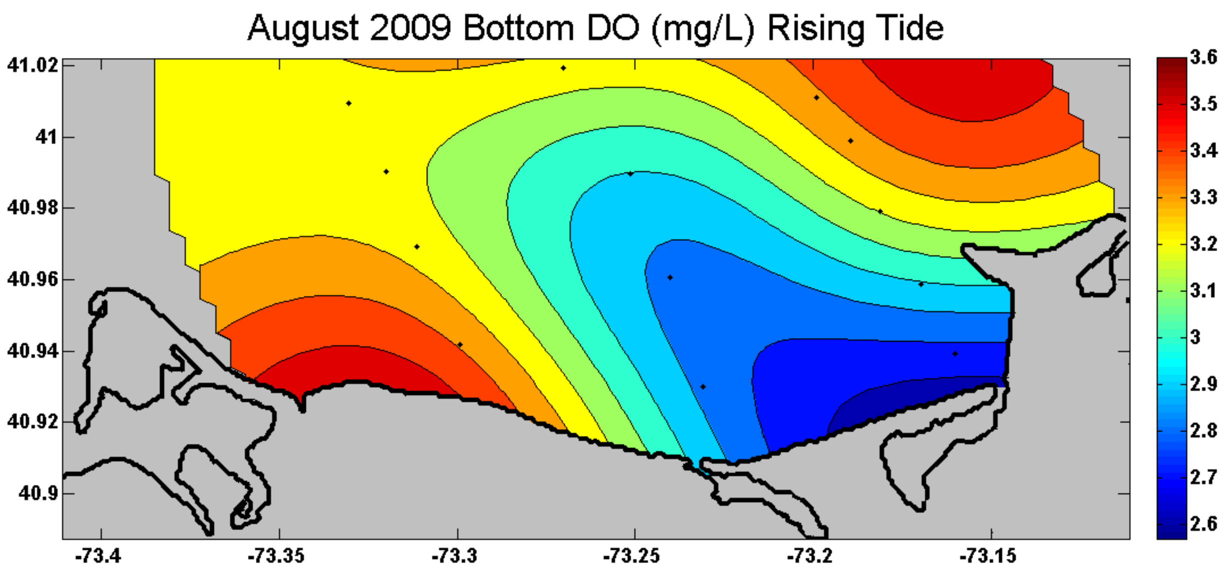

Figure 21d: A contour of August 2009 bottom DO during a flood tide.

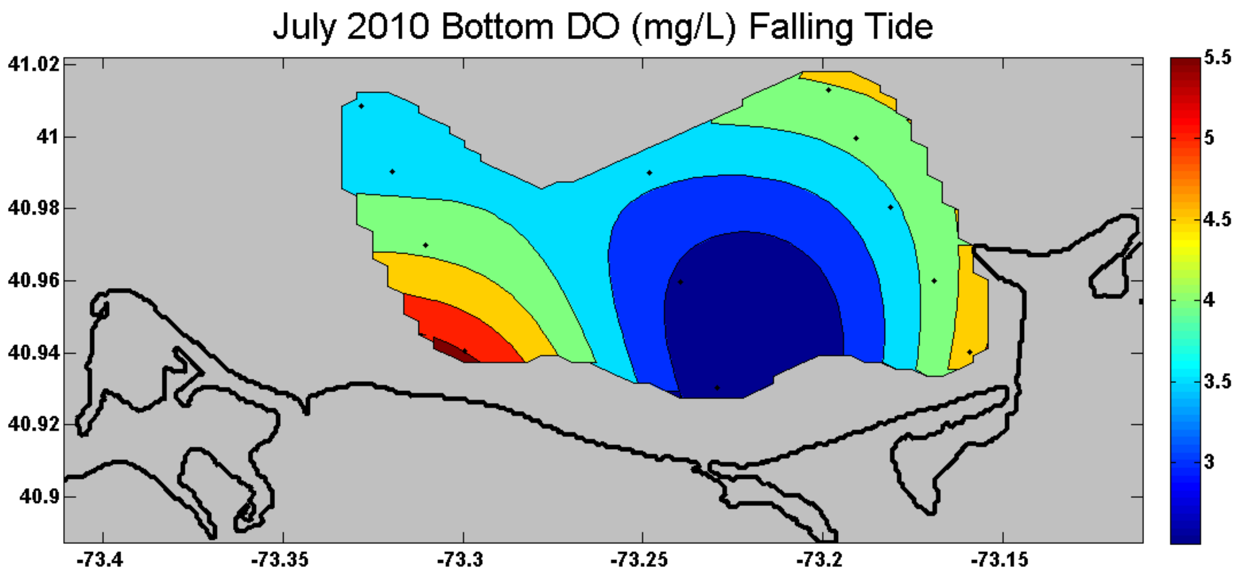

Figure 21e: A contour of July 2010 bottom DO during an ebb tide.

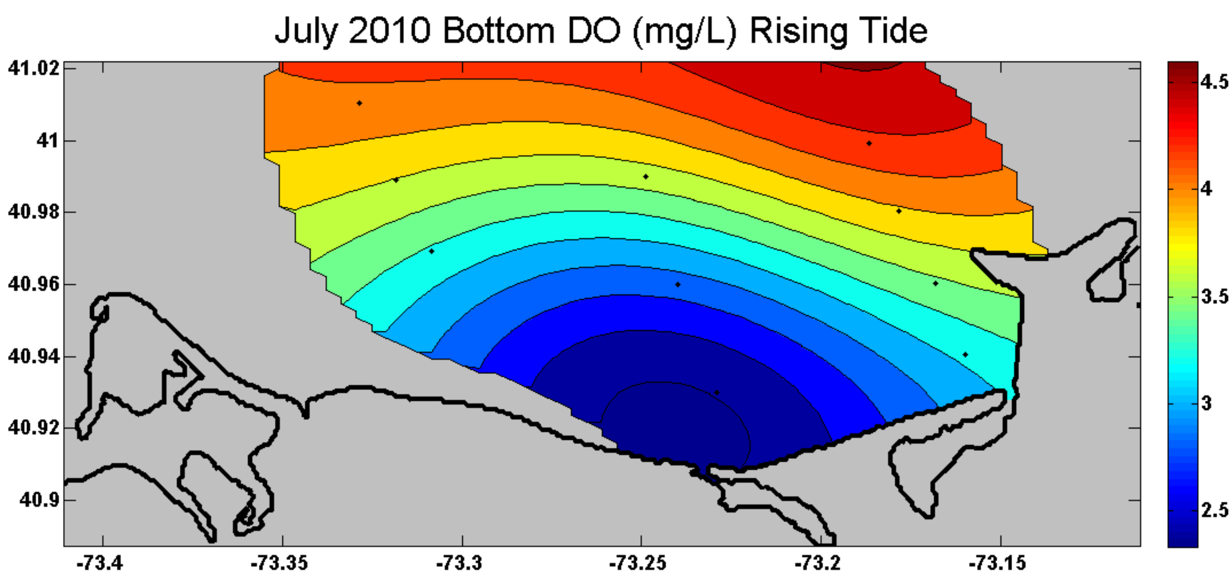

Figure 21f: A contour of July 2010 bottom DO during a flood tide.

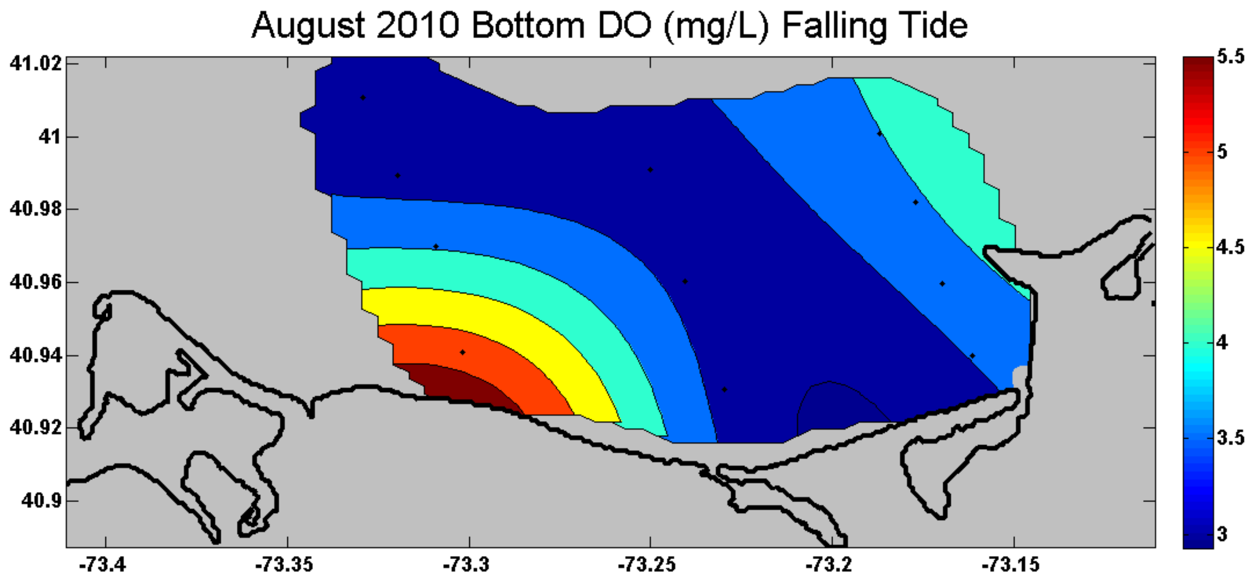

Figure 21g: A contour of August 2010 bottom DO during a ebb tide.

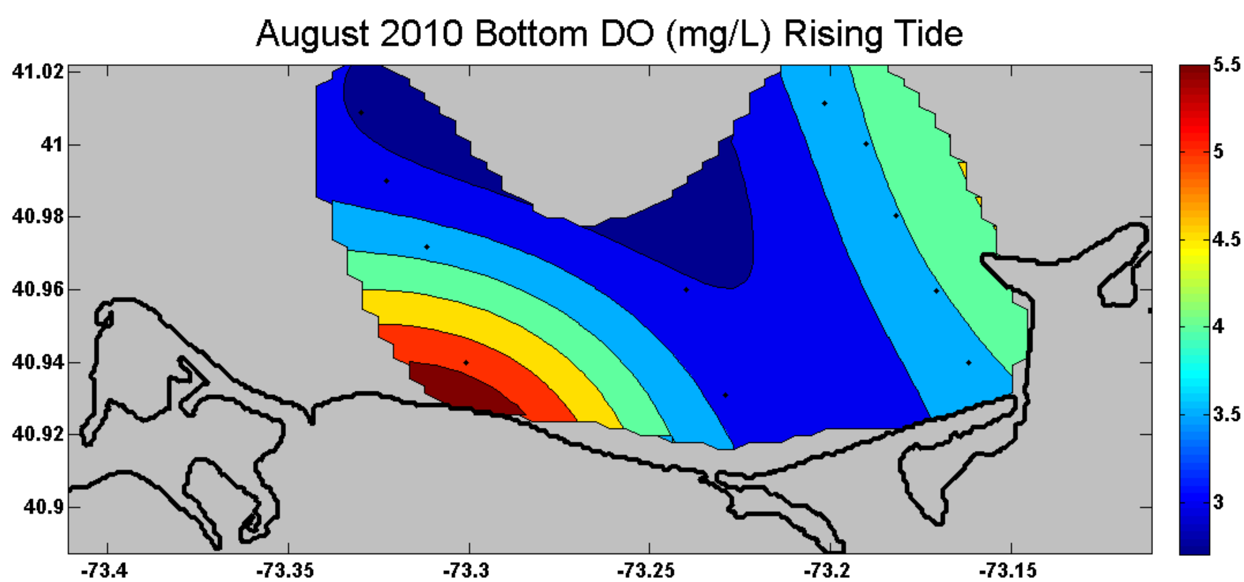

Figure 21h: A contour of August 2010 bottom DO during a flood tide.

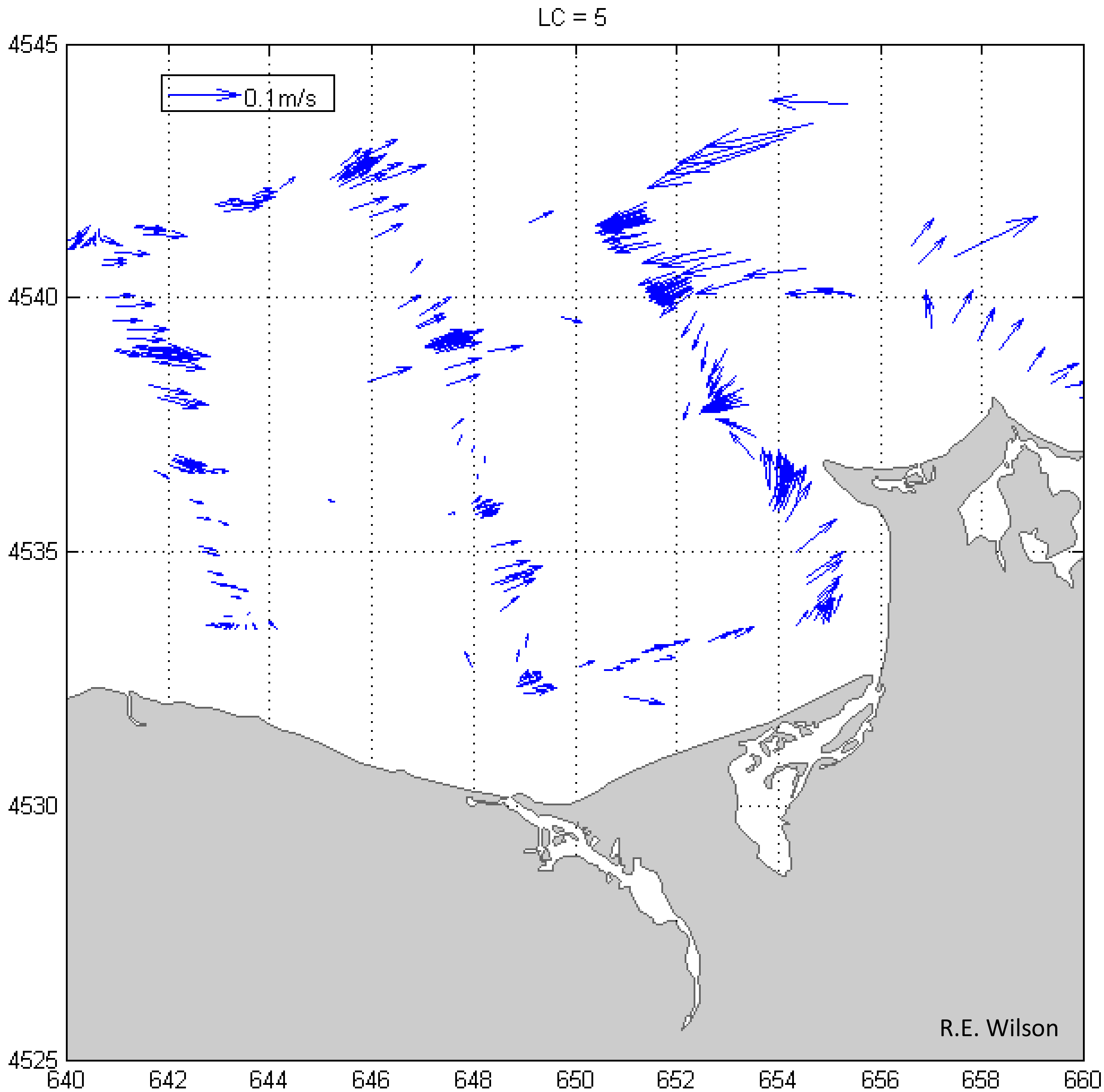

Figure 22: Mean, depth avergaed currents along the cruise tracks made from a composite of the data collected during the 2009 and 2010 cruises.

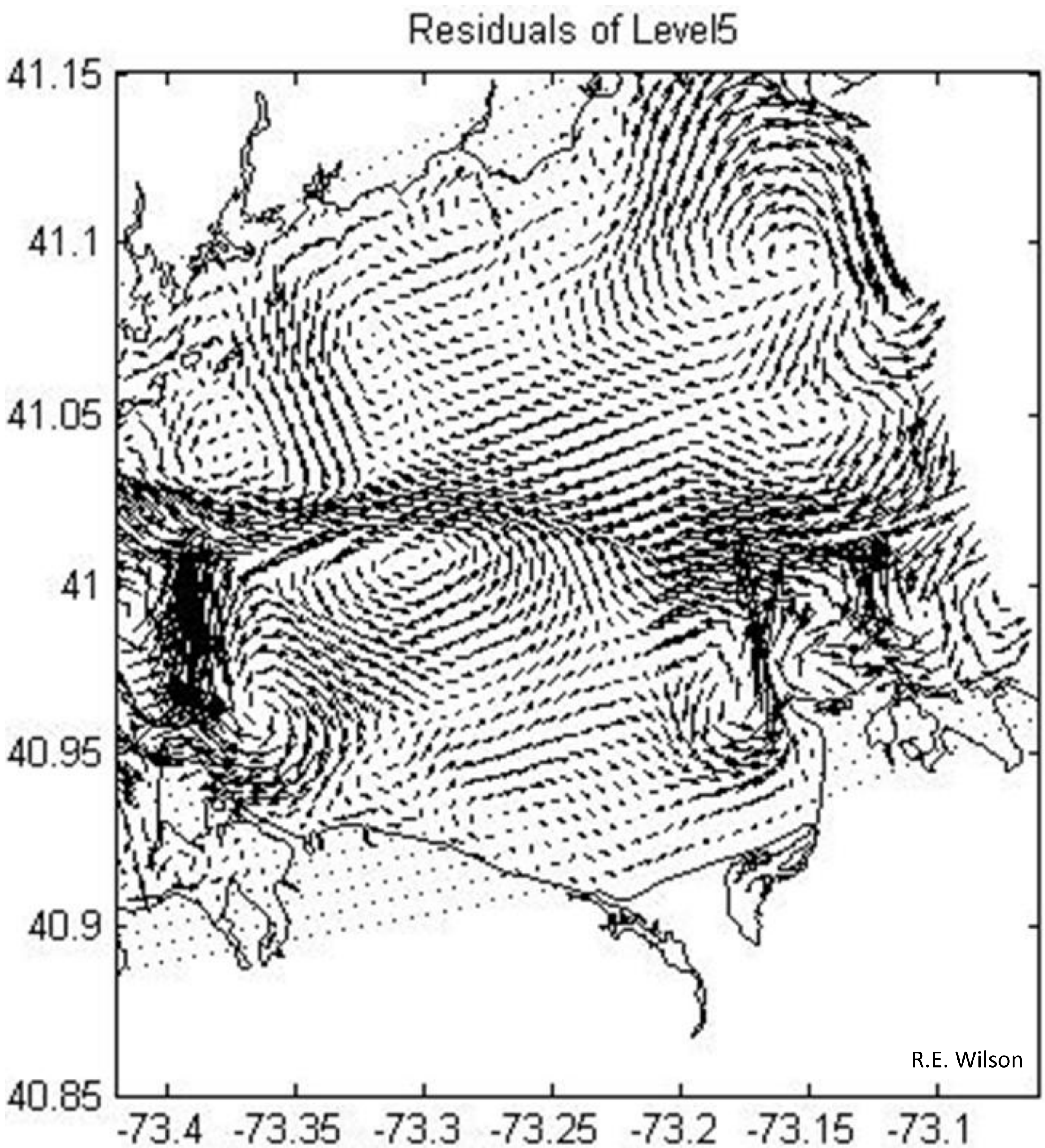

Figure 23: Model of summertime residual currents at mid-depth.

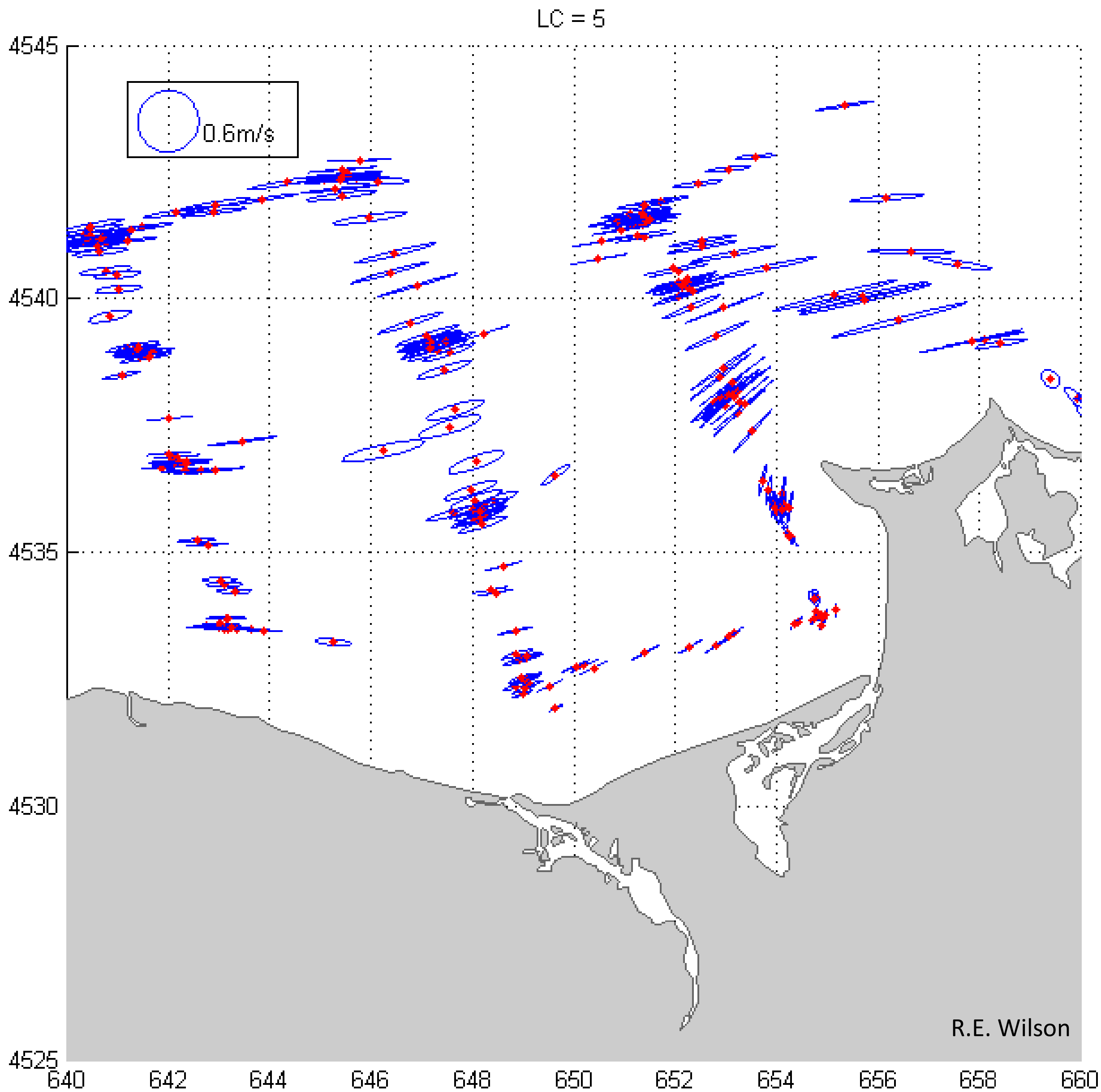

Figure 24: Mean, M2 depth-averaged tidal ellipses along the cruise tracks.

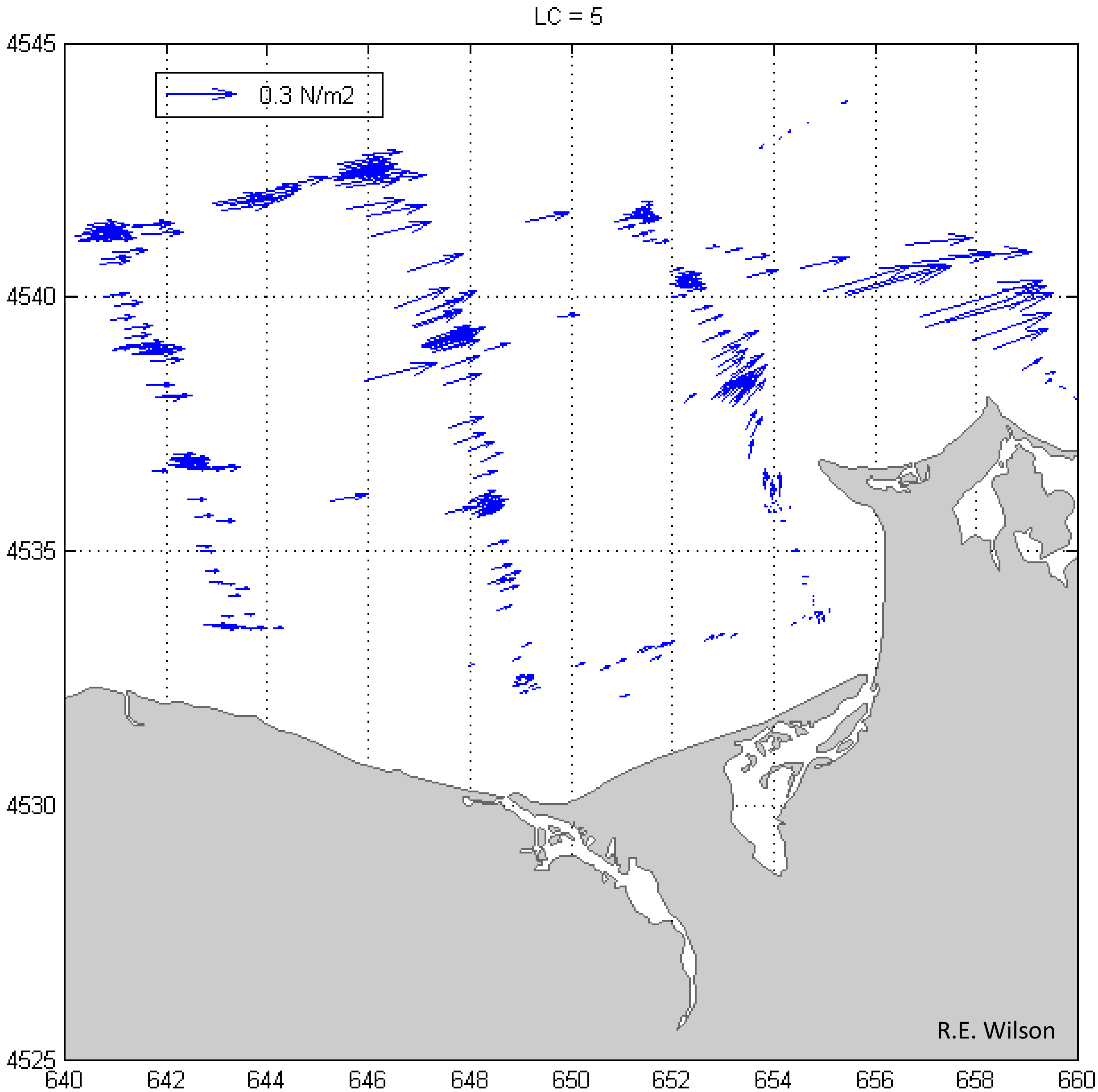

Figure 25a: Bottom stress measured along the cruise tracks on an ebb tide.

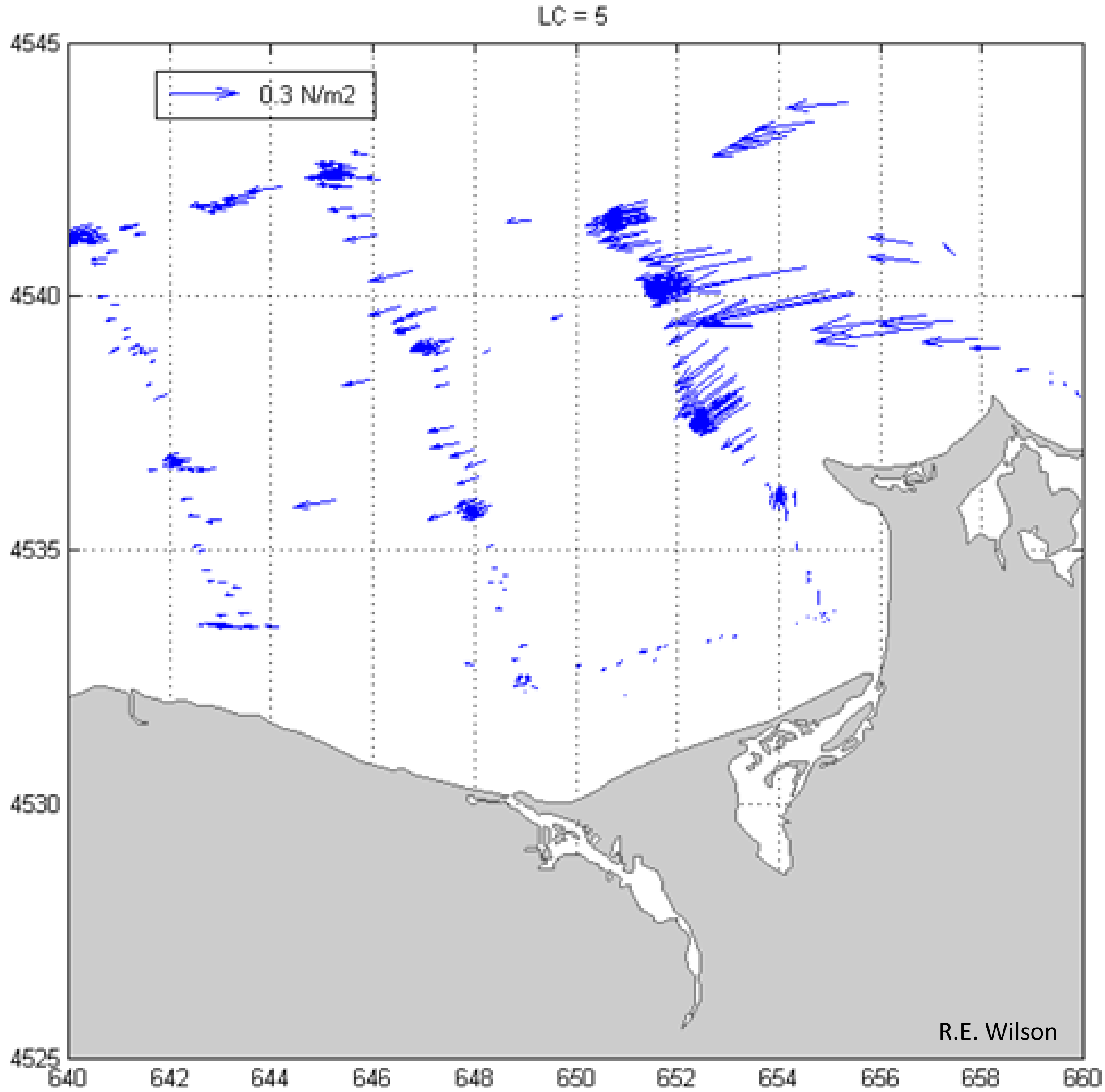

Figure 25b: Bottom stress measured along the cruise tracks on a flood tide.

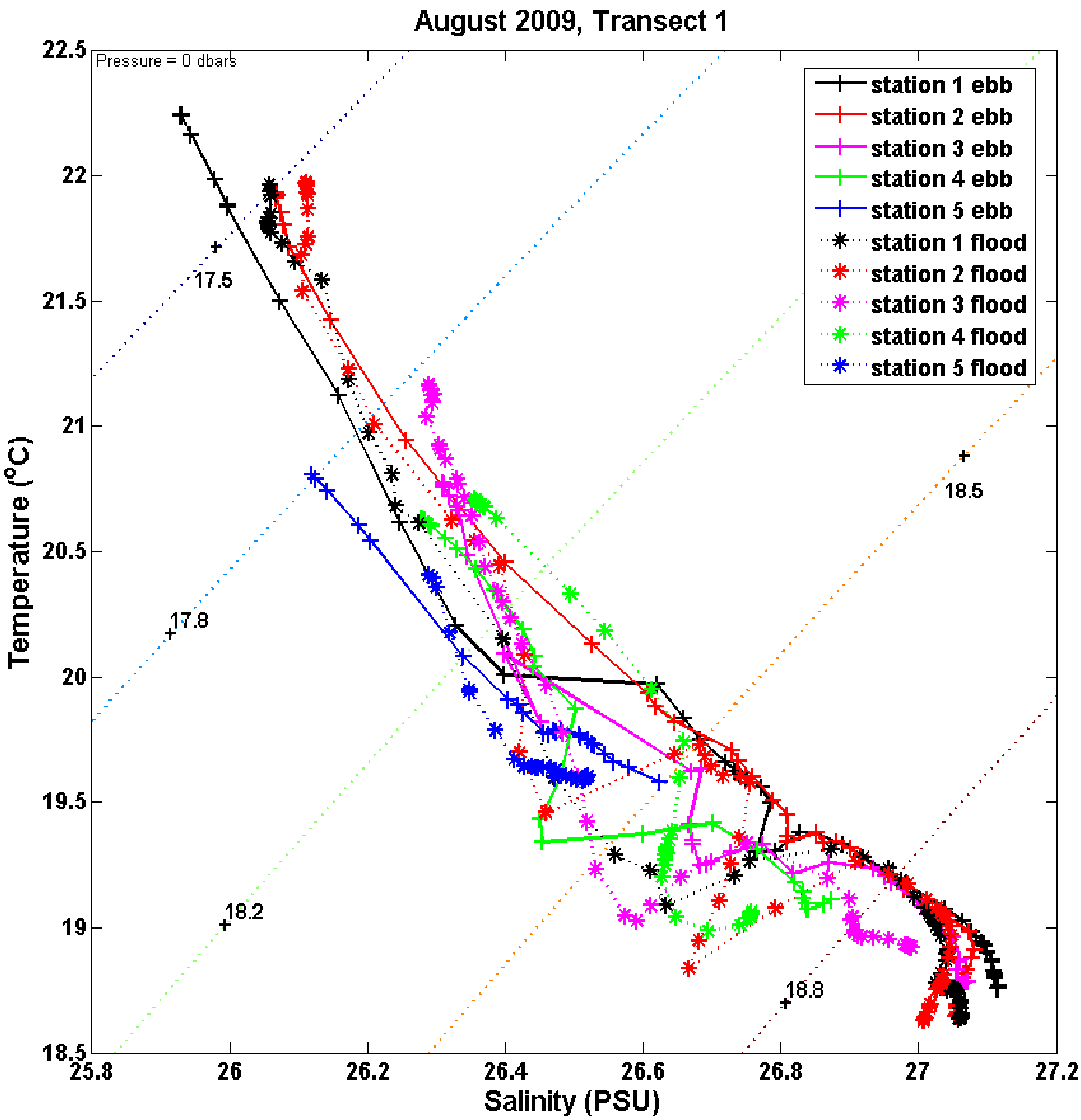

Figure 26: T-S diagram of transect 1 during ebb and flood in August 2009. The slanted dotted lines represent lines of constant density.

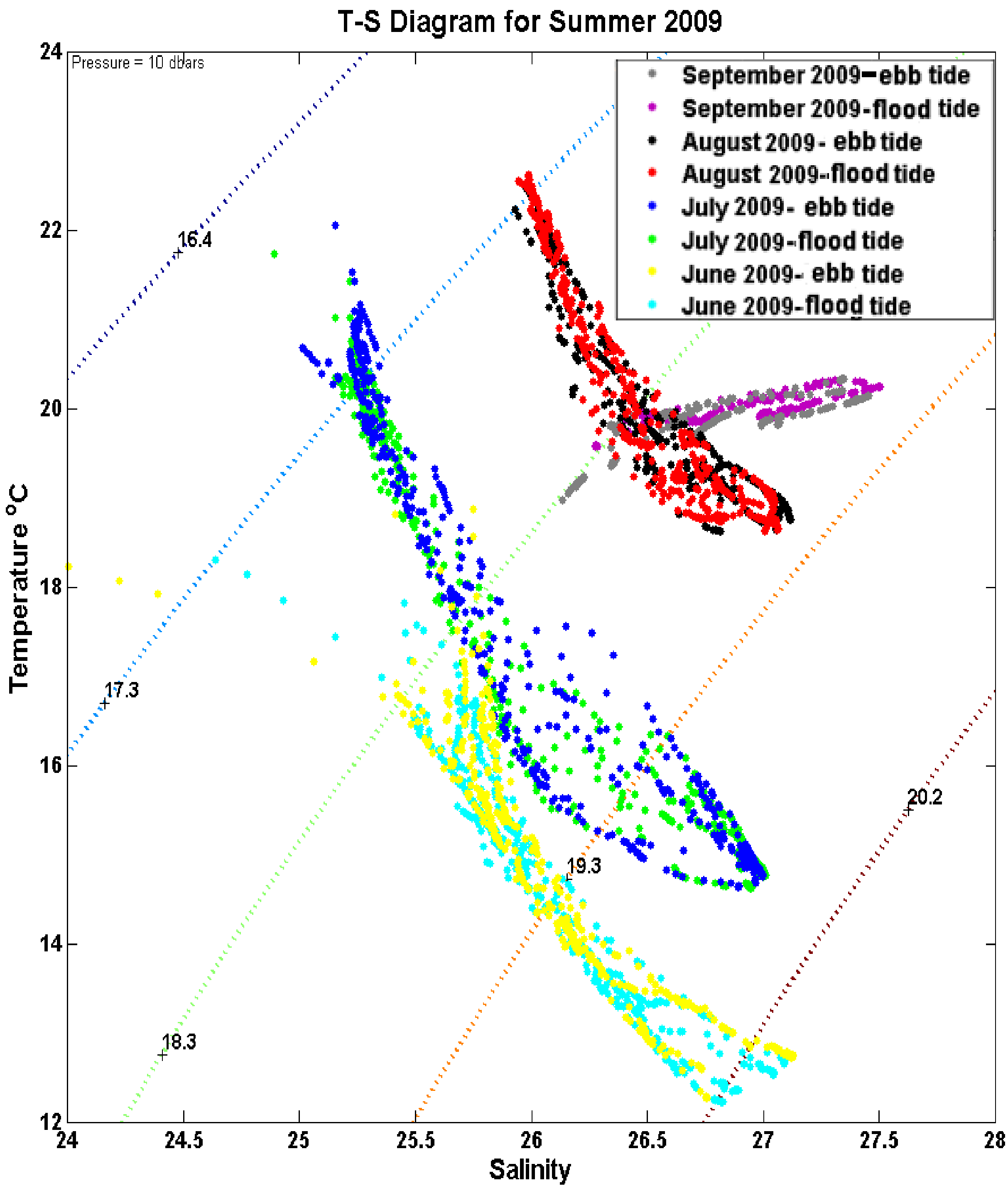

Figure 27a: T-S diagram of the entire water column during June, July, August, and September of 2009. The slanted dotted lines represent density lines.

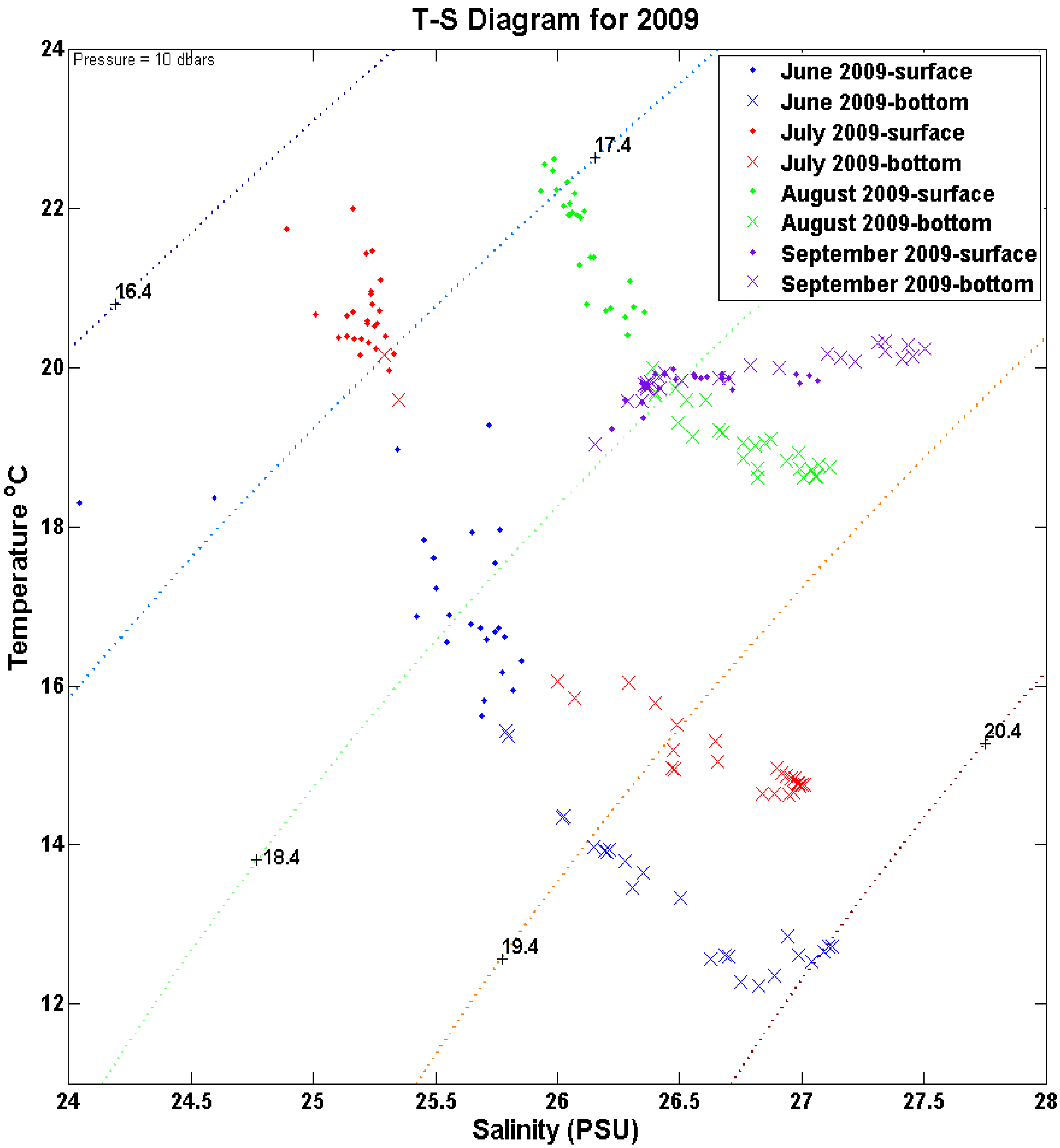

Figure 27b: T-S diagram of June, July, August, and September surface and bottom concentrations for 2009. The slanted dotted lines represent lines of constant density.

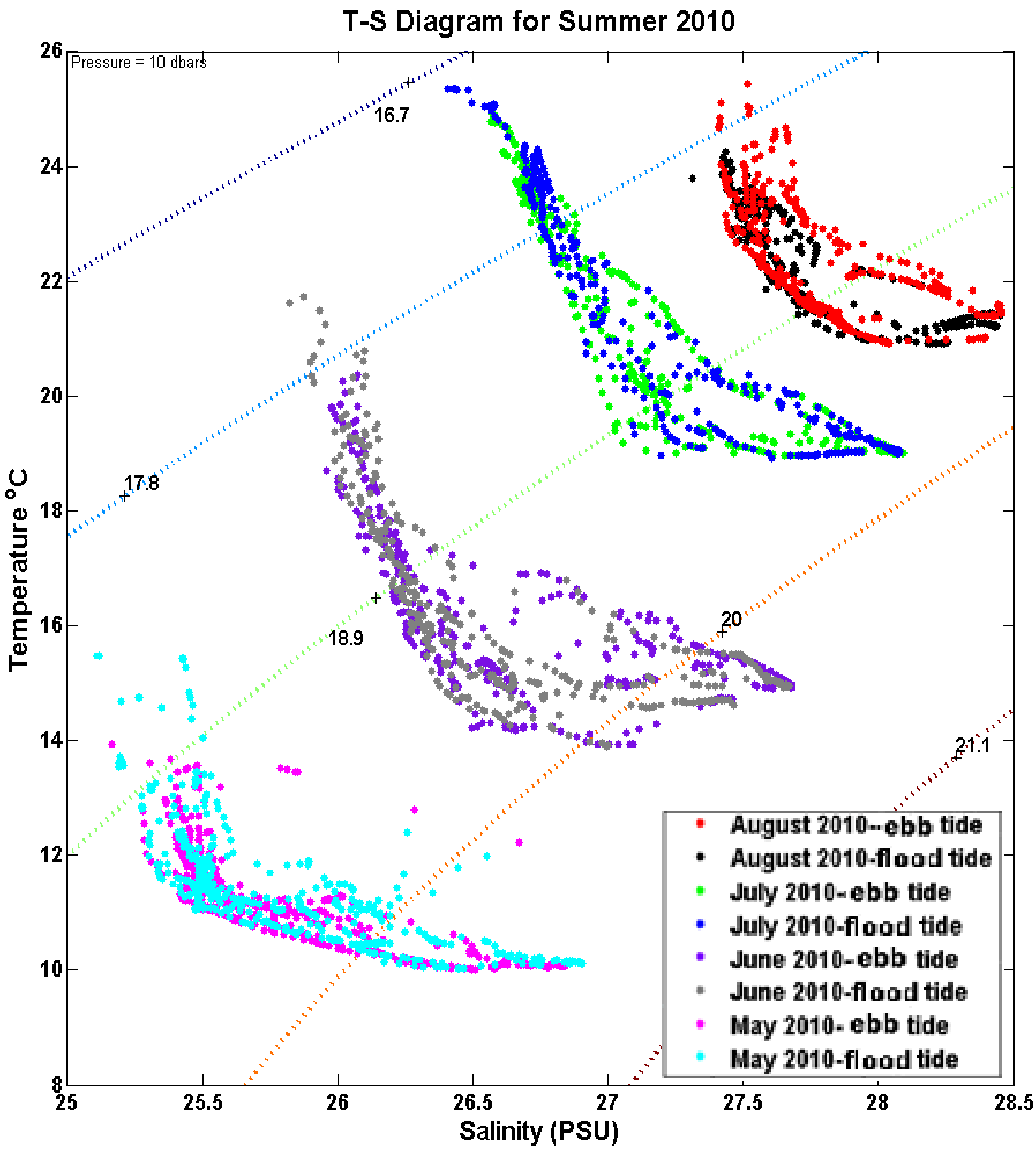

Figure 28a: T-S diagram of the entire water column during May, June, July, and August 2010. The slanted dotted lines represent lines of constant density.

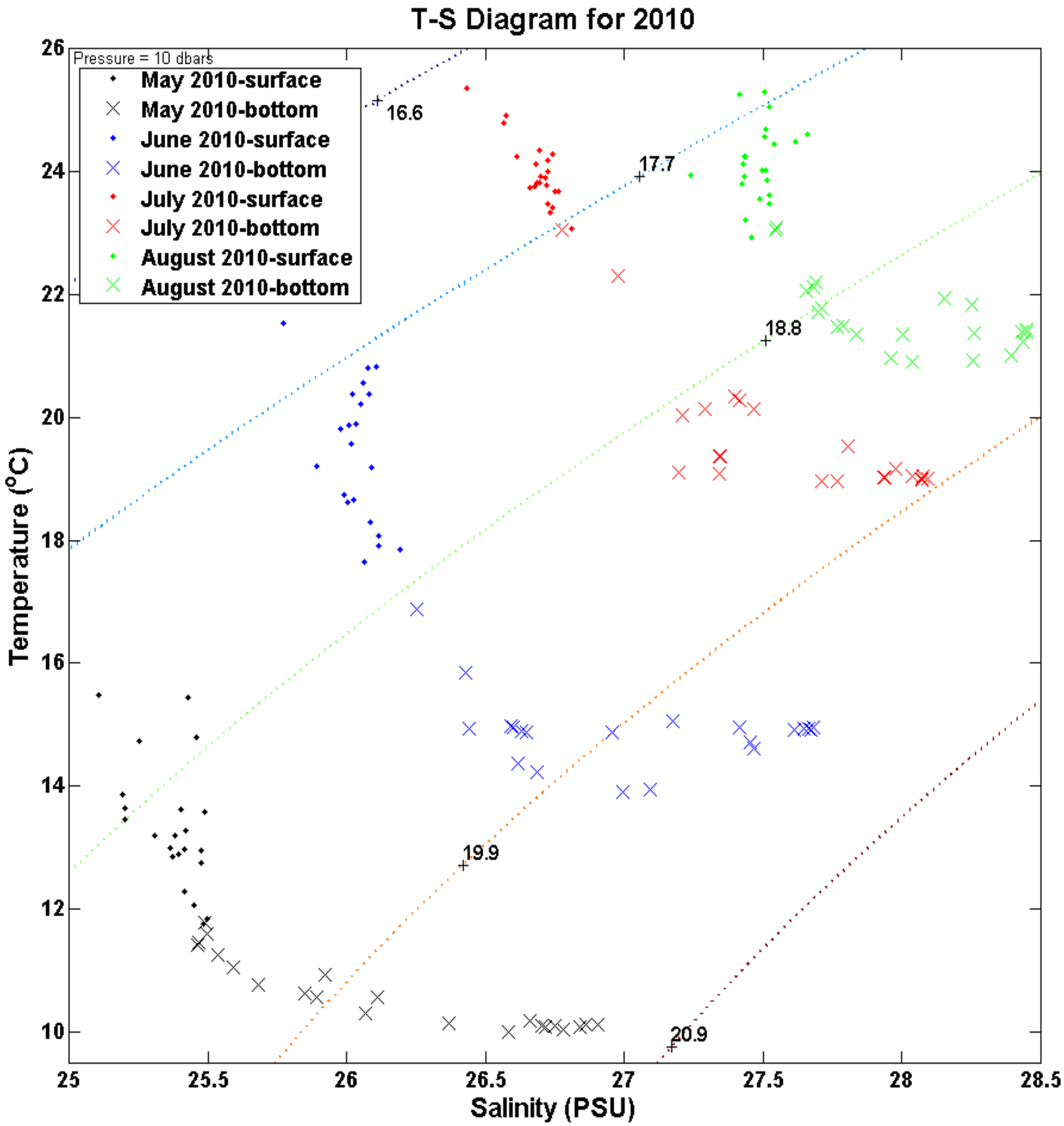

Figure 28b: T-S diagram of May, June, July, and August surface and bottom concentrations for 2010. The slanted dotted lines represent lines of constant density.

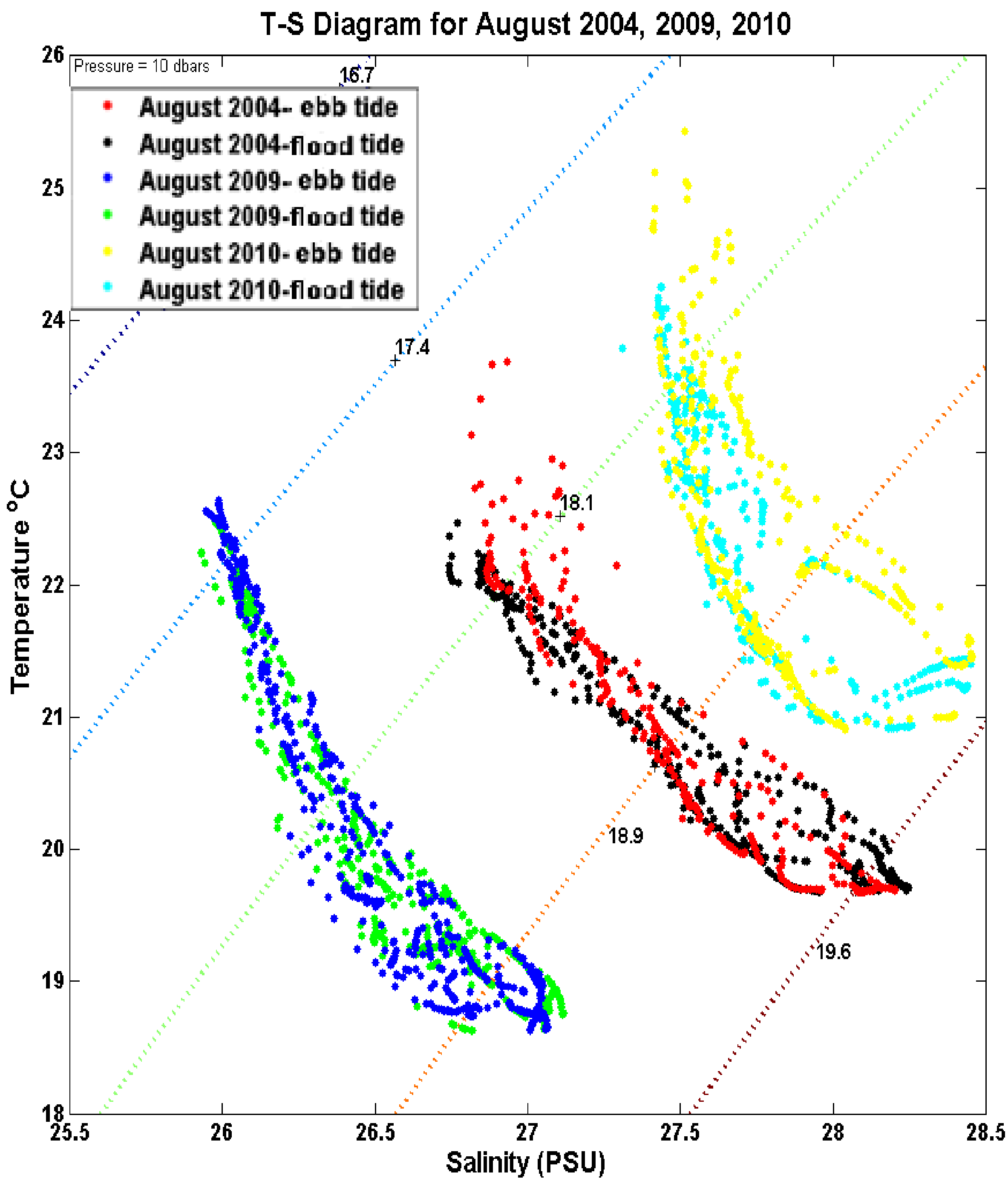

Figure 29: T-S diagram of the entire water column during August 2004, 2009, and 2010. The slanted dotted lines represent lines of constant density.

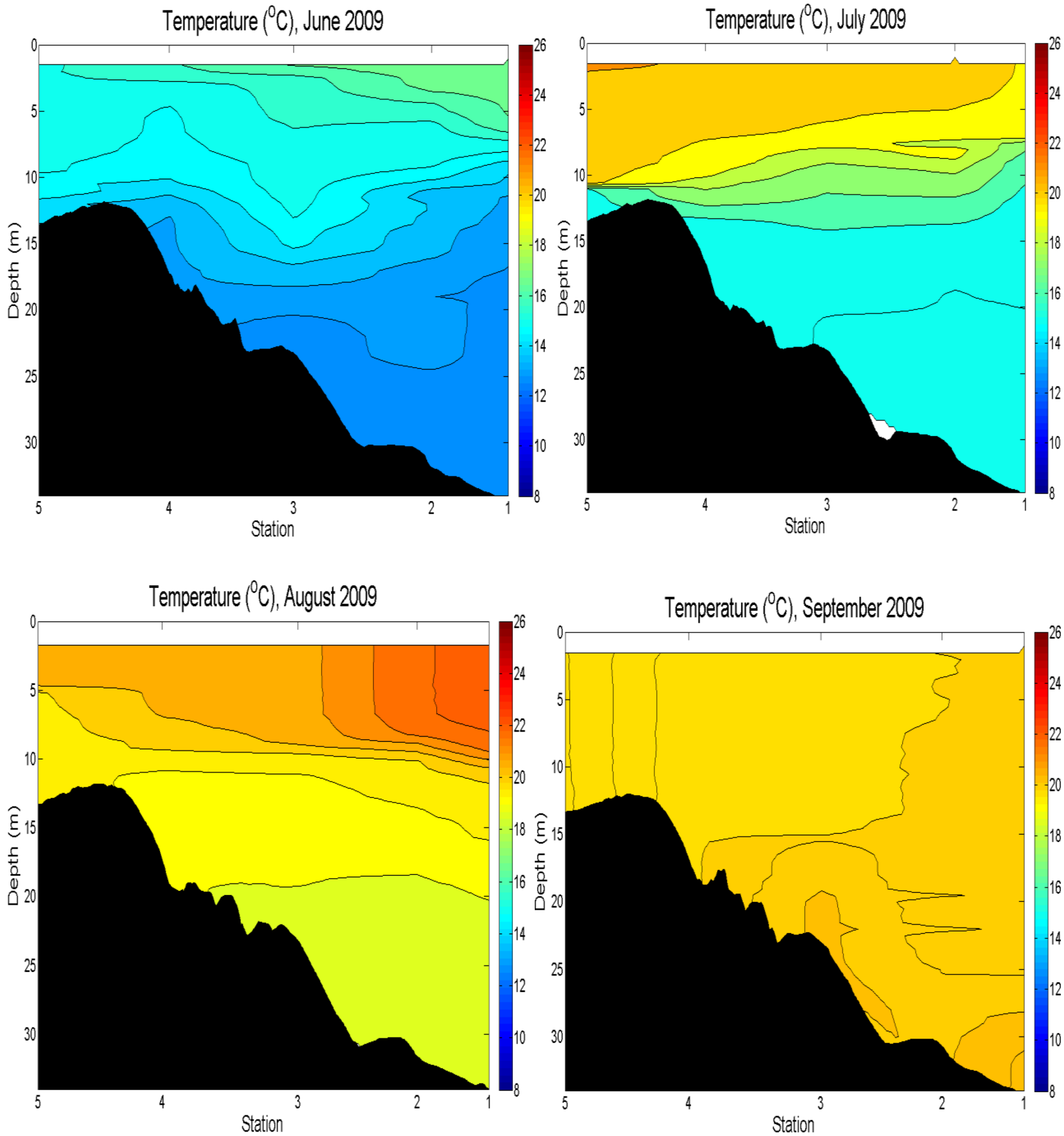

Figure 30: Vertical profiles of temperature (˚C) at transect 1 from June-September 2009.

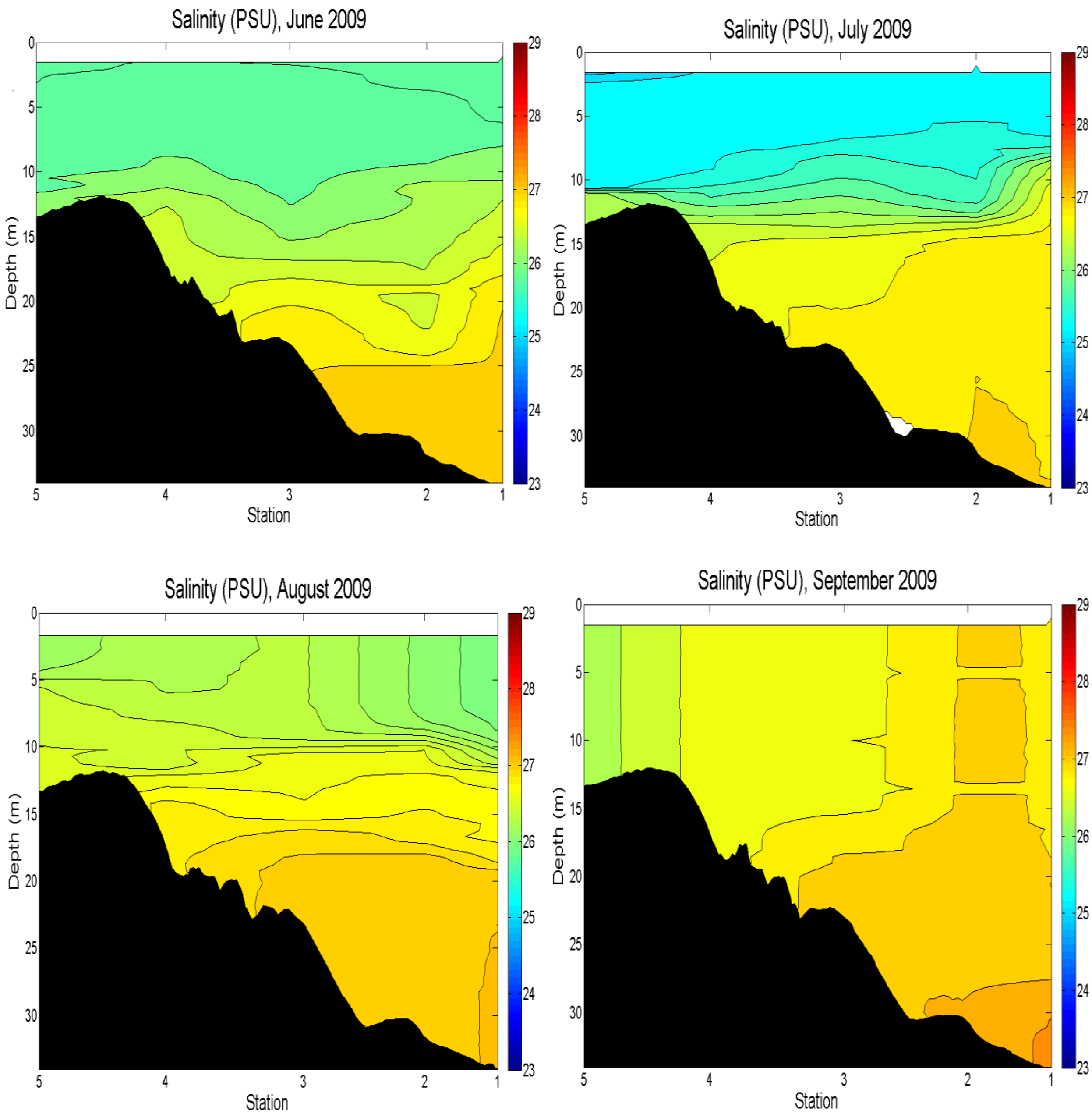

Figure 31: Vertical profiles of salinity (PSU) at transect 1 from June-September 2009.

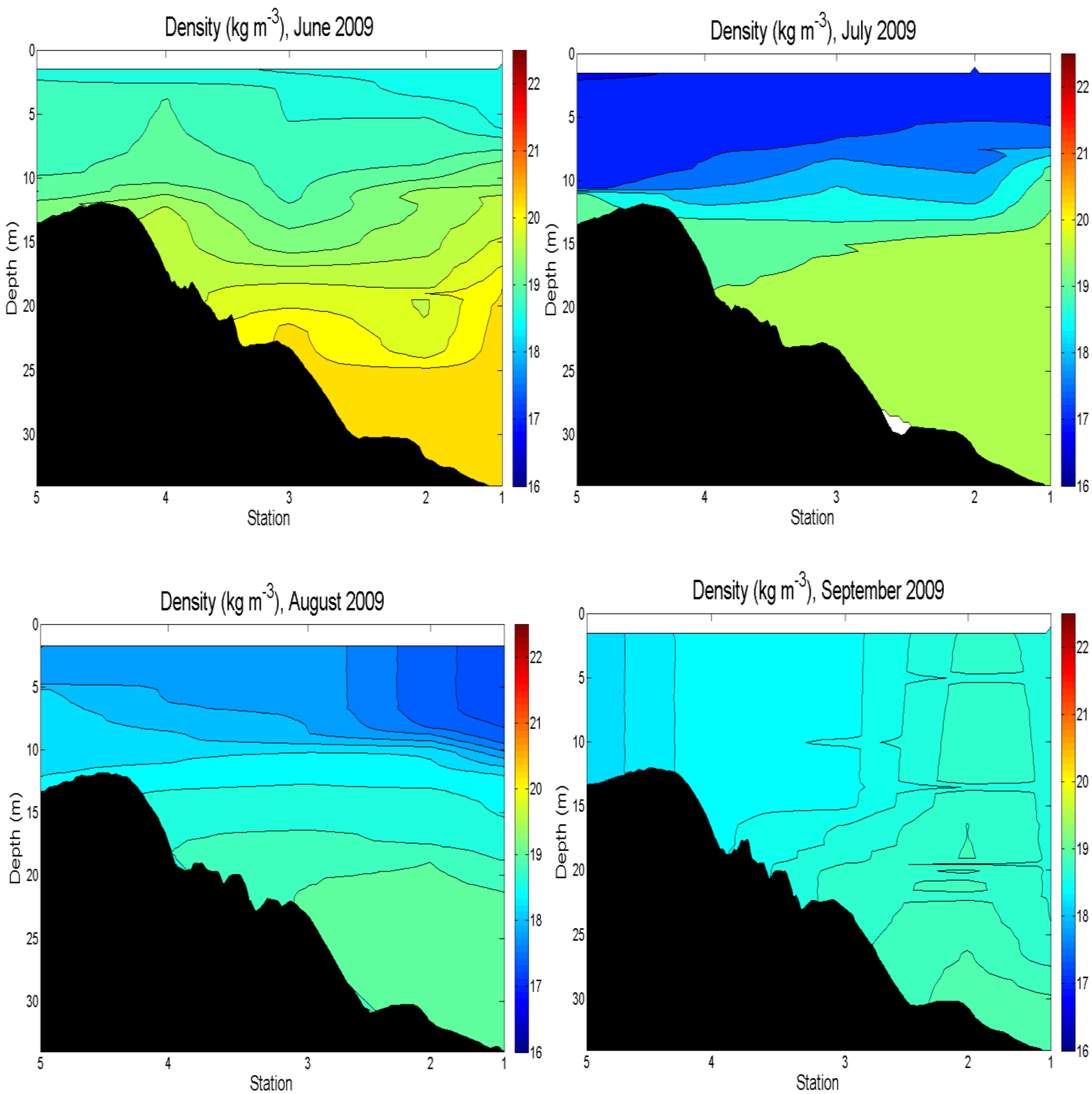

Figure 32: Vertical profiles of density (kg m^{-3}) at transect 1 from June-September 2009.

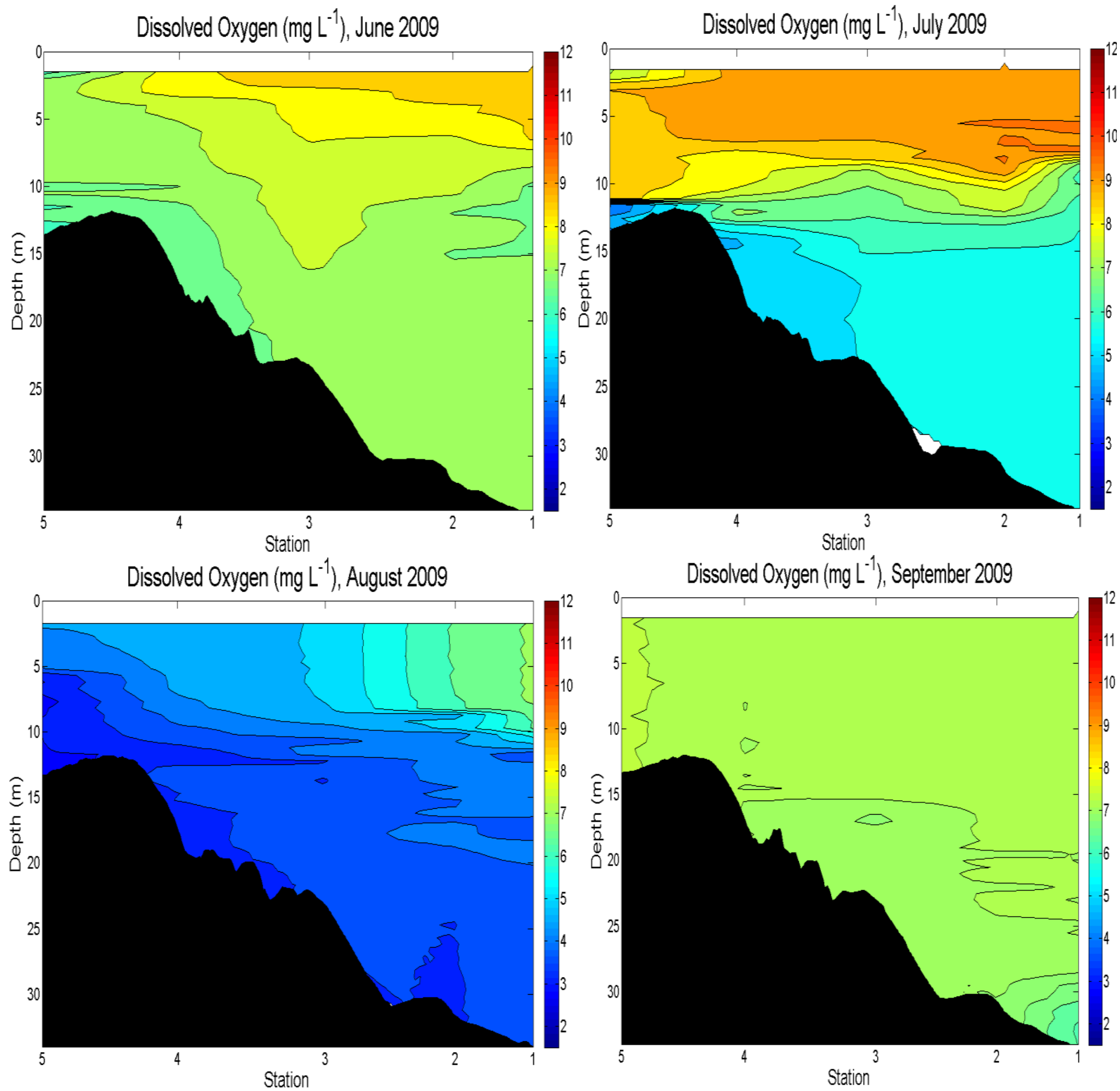

Figure 33: Vertical profiles of dissolved oxygen (mg L^{-1}) at transect 1 from June-September 2009.

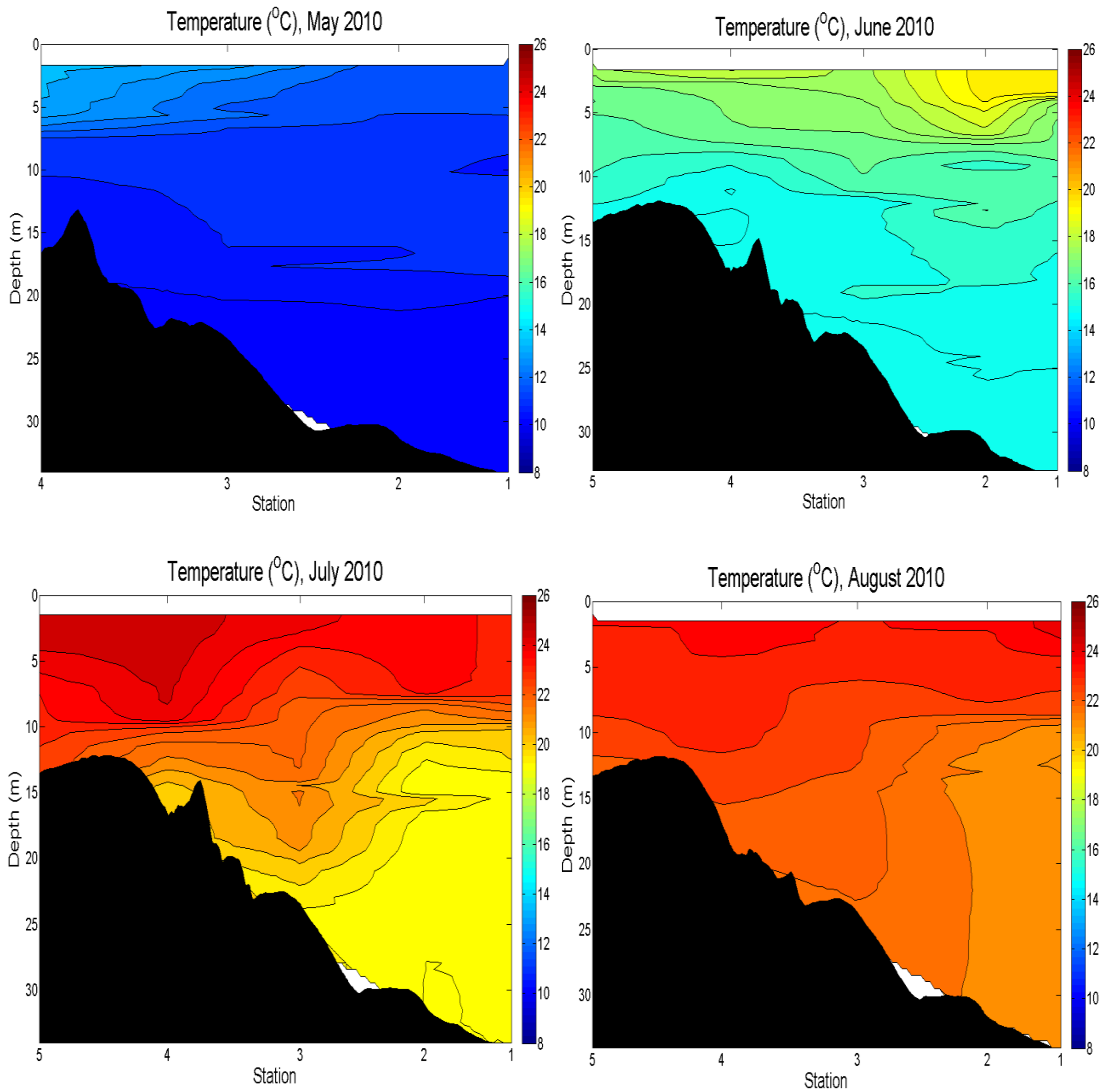

Figure 34: Vertical profiles of temperature (˚C) at transect 1 from May-August 2010.

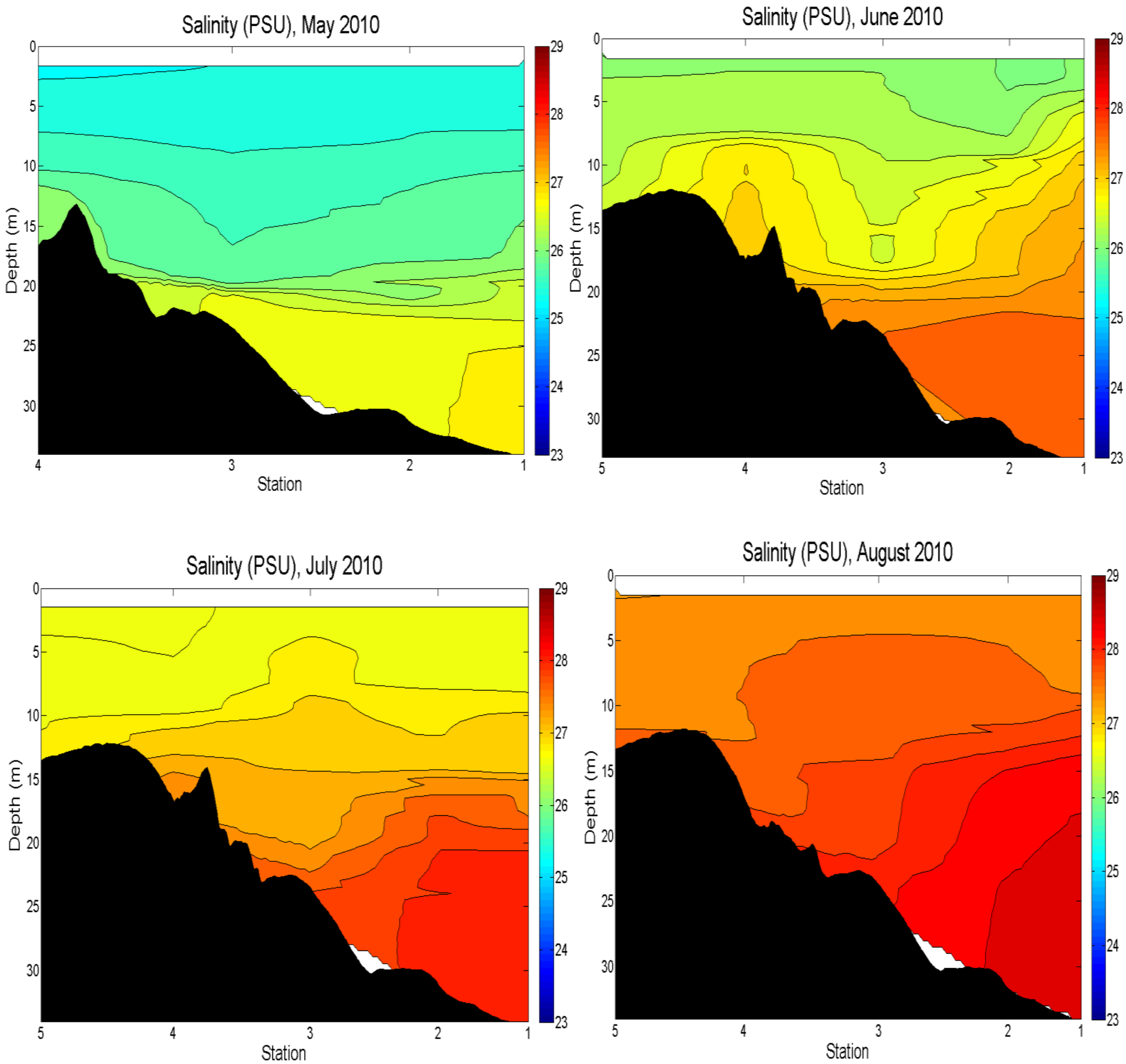

Figure 35: Vertical profiles of salinity (PSU) at transect 1 from May-August 2010.

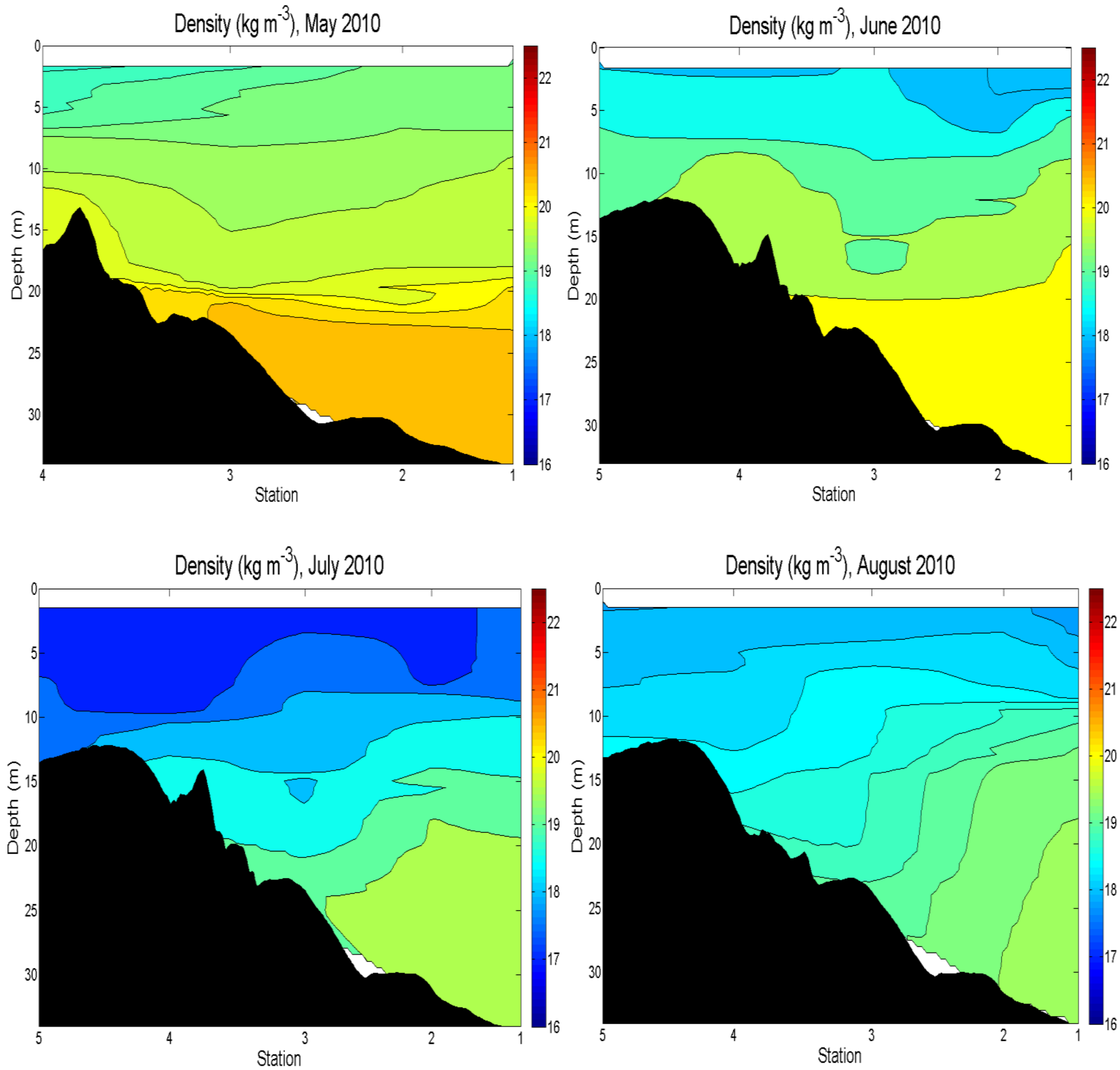

Figure 36: Vertical profiles of density (kg m^{-3}) at transect 1 from May-August 2010.

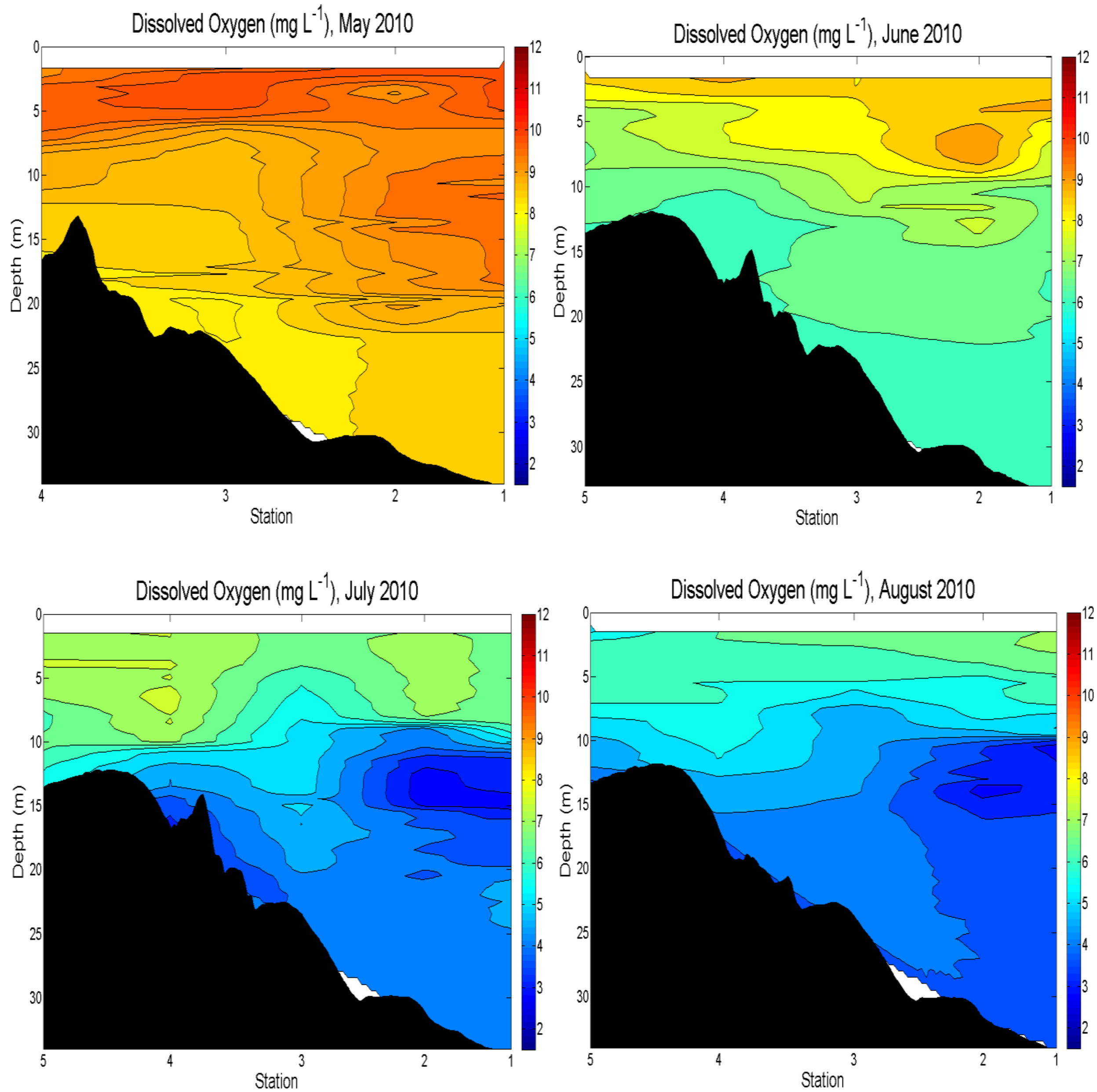

Figure 37: Vertical profiles of dissolved oxygen (mg L^{-1}) at transect 1 from May-August 2010.

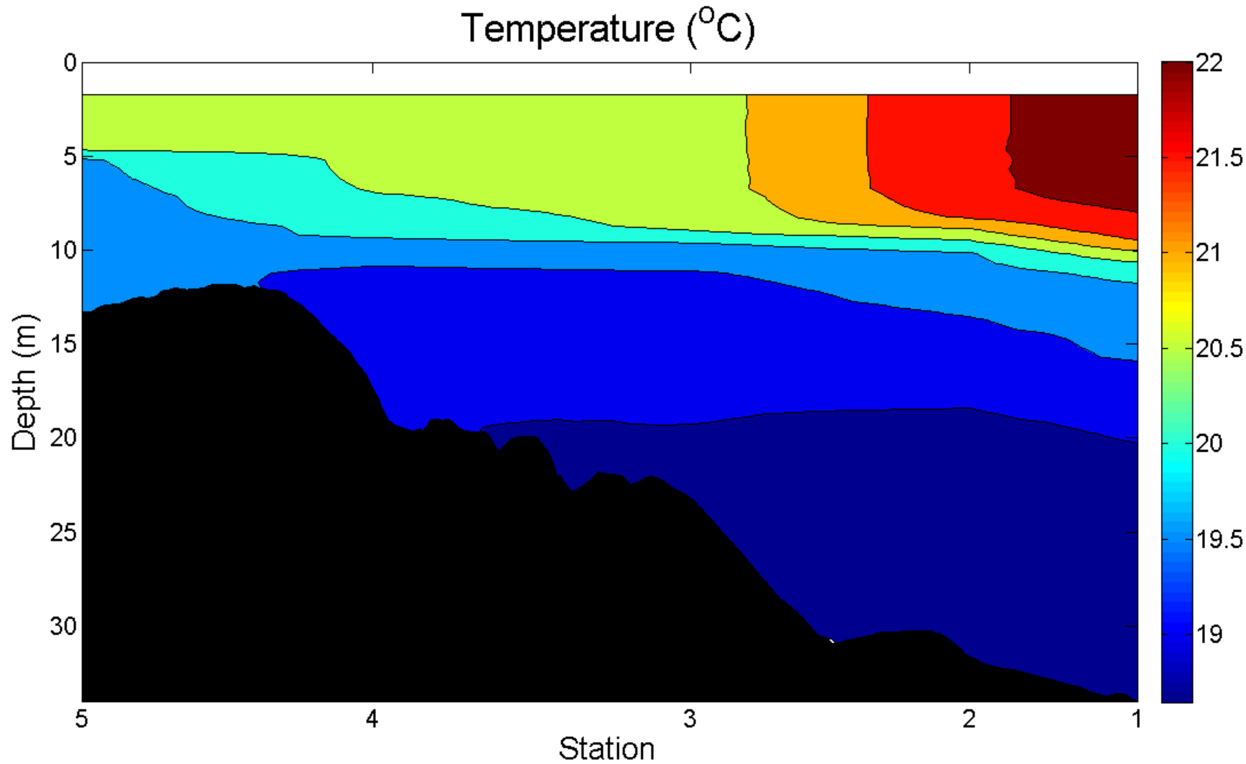

Figure 38: A vertical profile of temperature at transect 1 during August 2009.

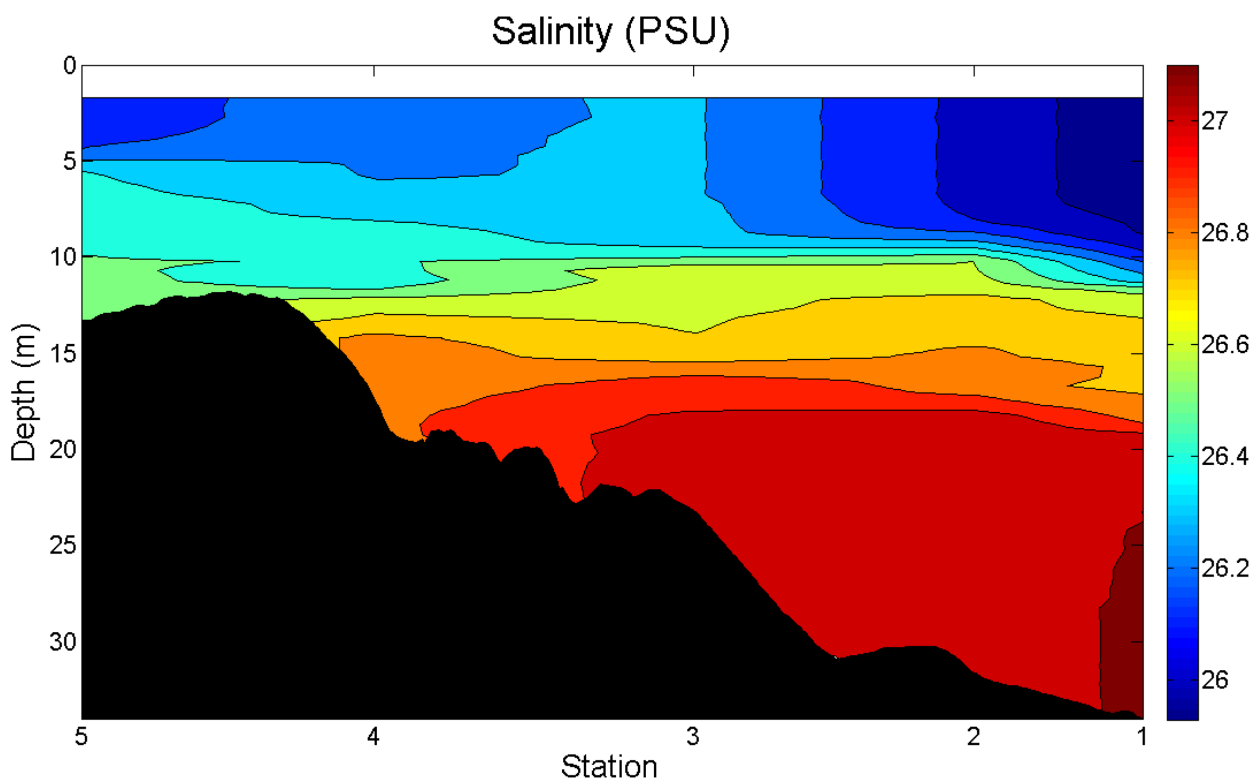

Figure 39: A vertical profile of salinity at transect 1 during August 2009.

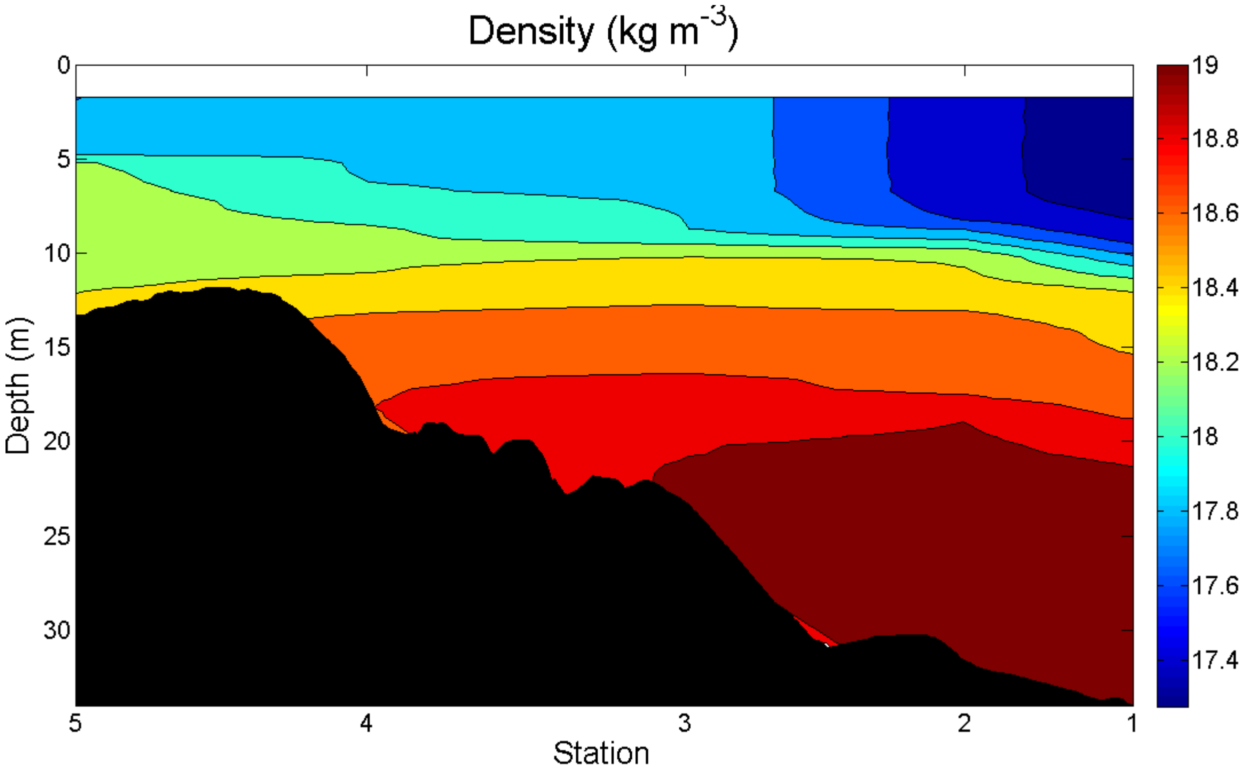

Figure 40: A vertical profile of density at transect 1 during August 2009.

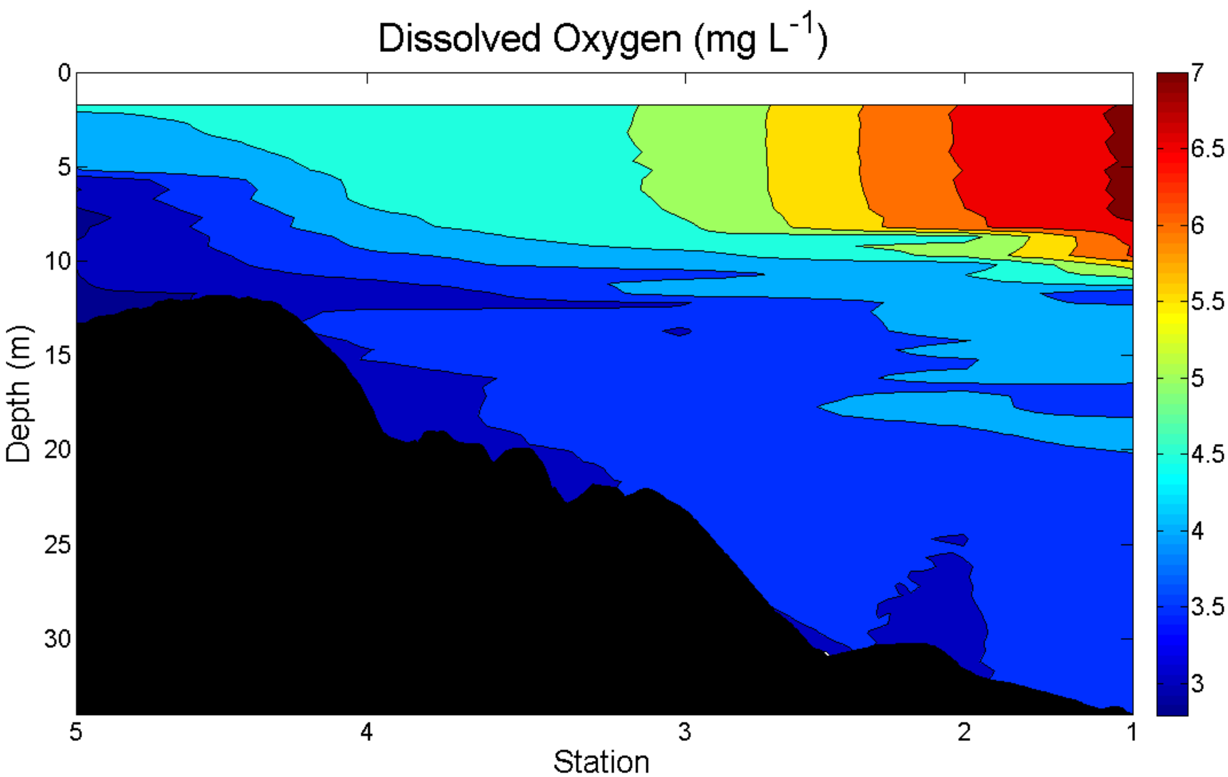

Figure 41: A vertical profile of dissolved oxygen at transect 1 during August 2009.

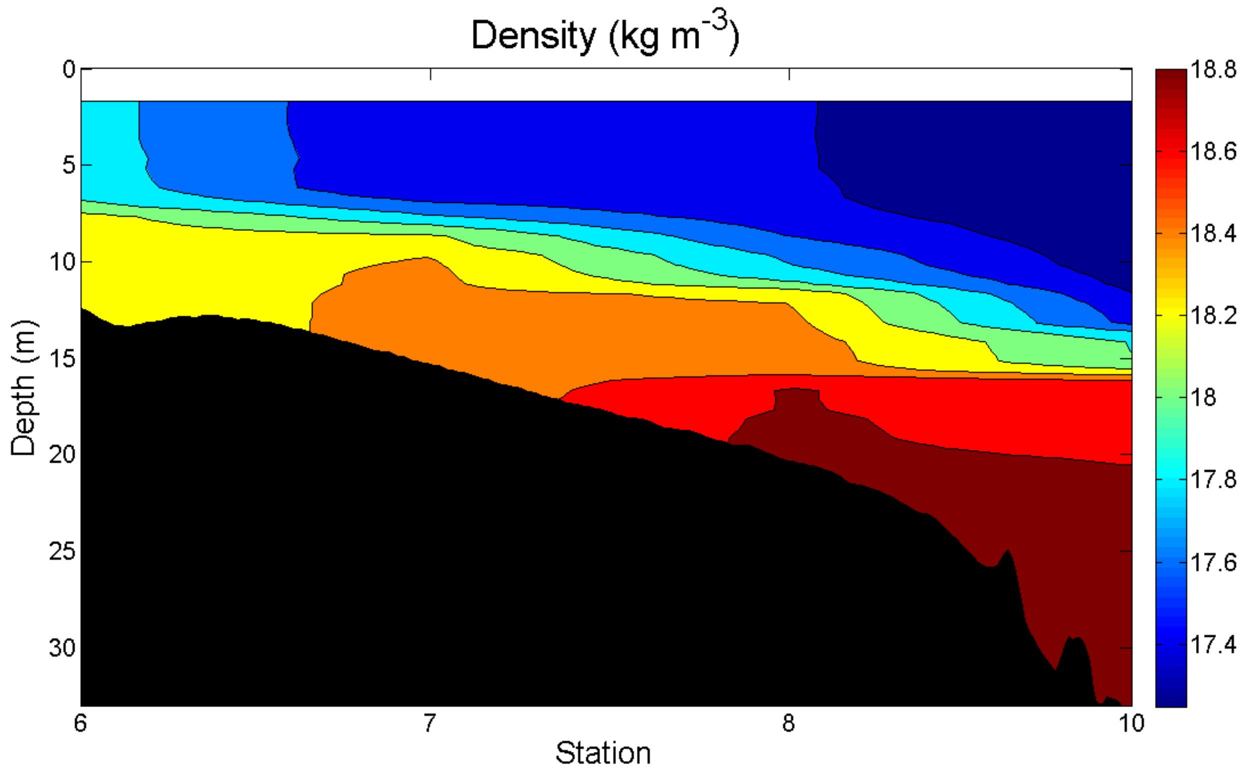

Figure 42: A vertical profile of density at transect 2 during August 2009.

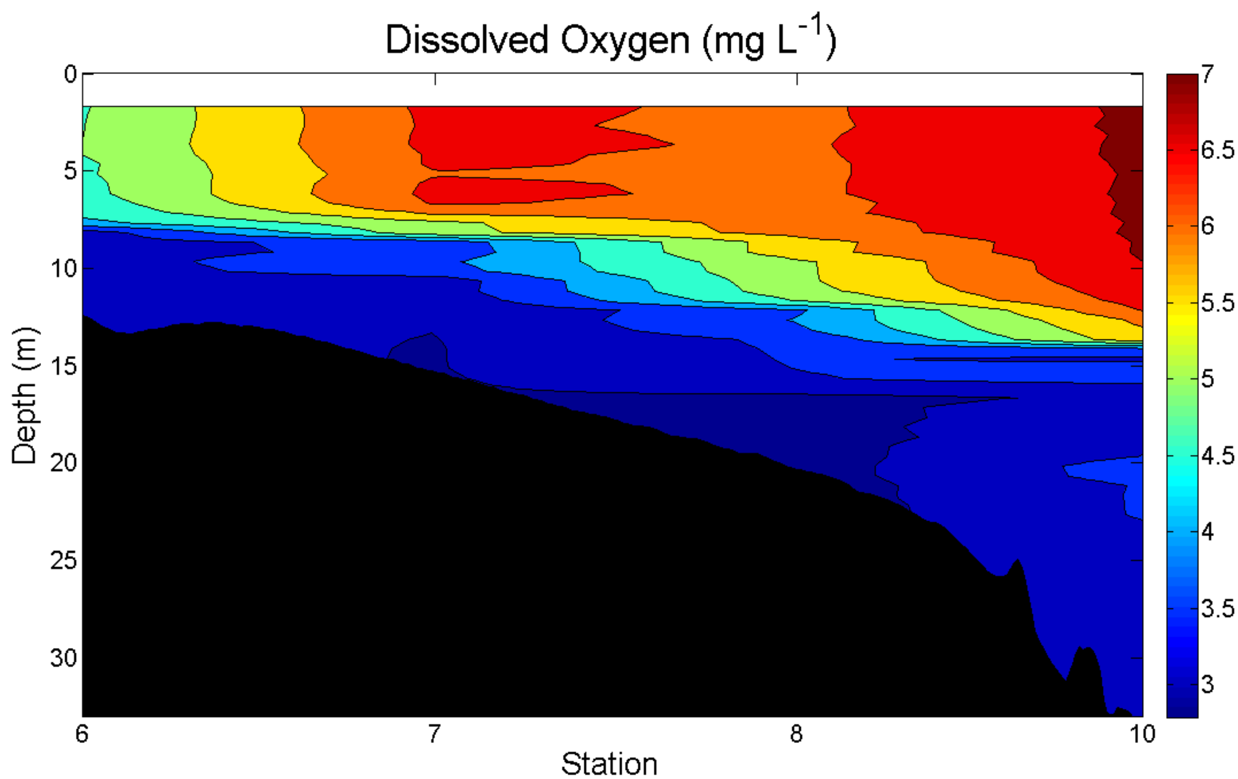

Figure 43: A vertical profile of dissolved oxygen at transect 2 during August 2009.

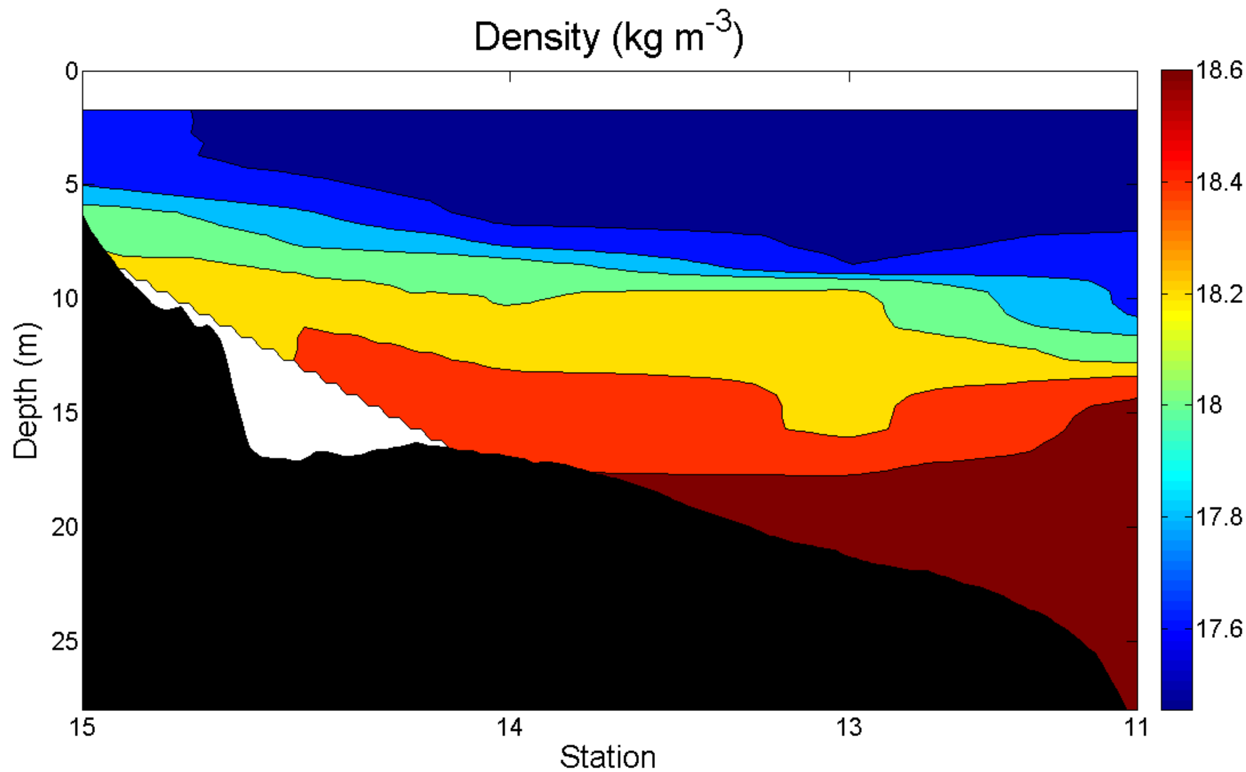

Figure 44: A vertical profile of density at transect 3 during August 2009.

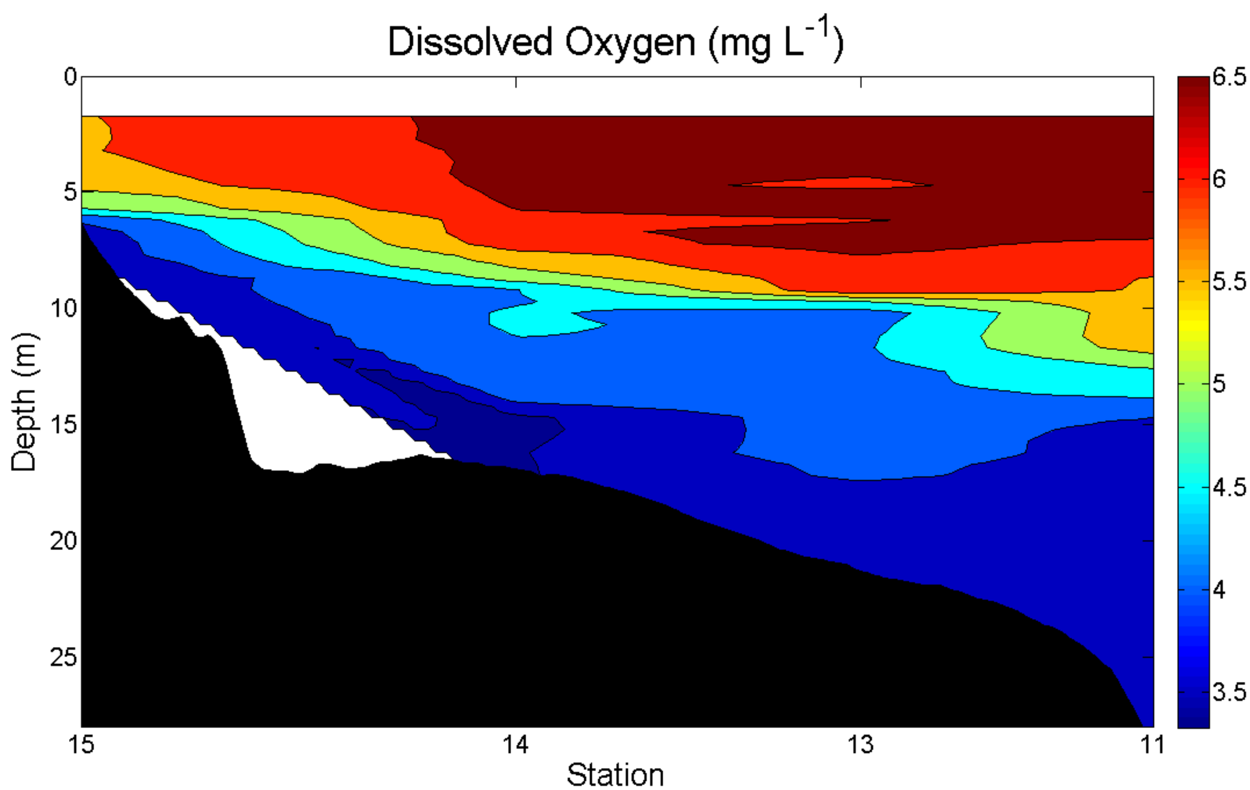

Figure 45: A vertical profile of dissolved oxygen at transect 3 during August 2009.

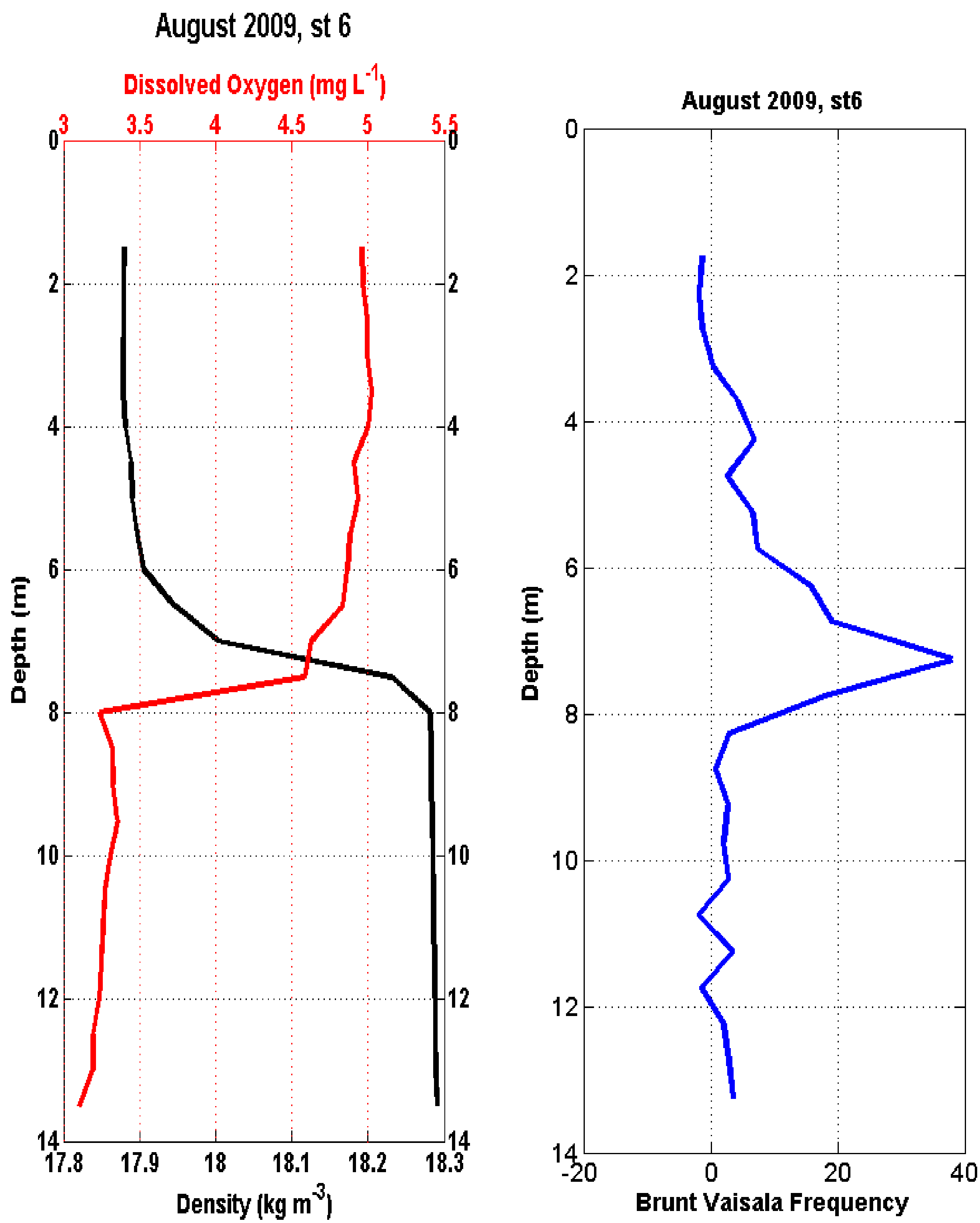

Figure 46a: Vertical profiles of DO, density, and Brunt-Väisälä Frequency at station 6 in August 2009.

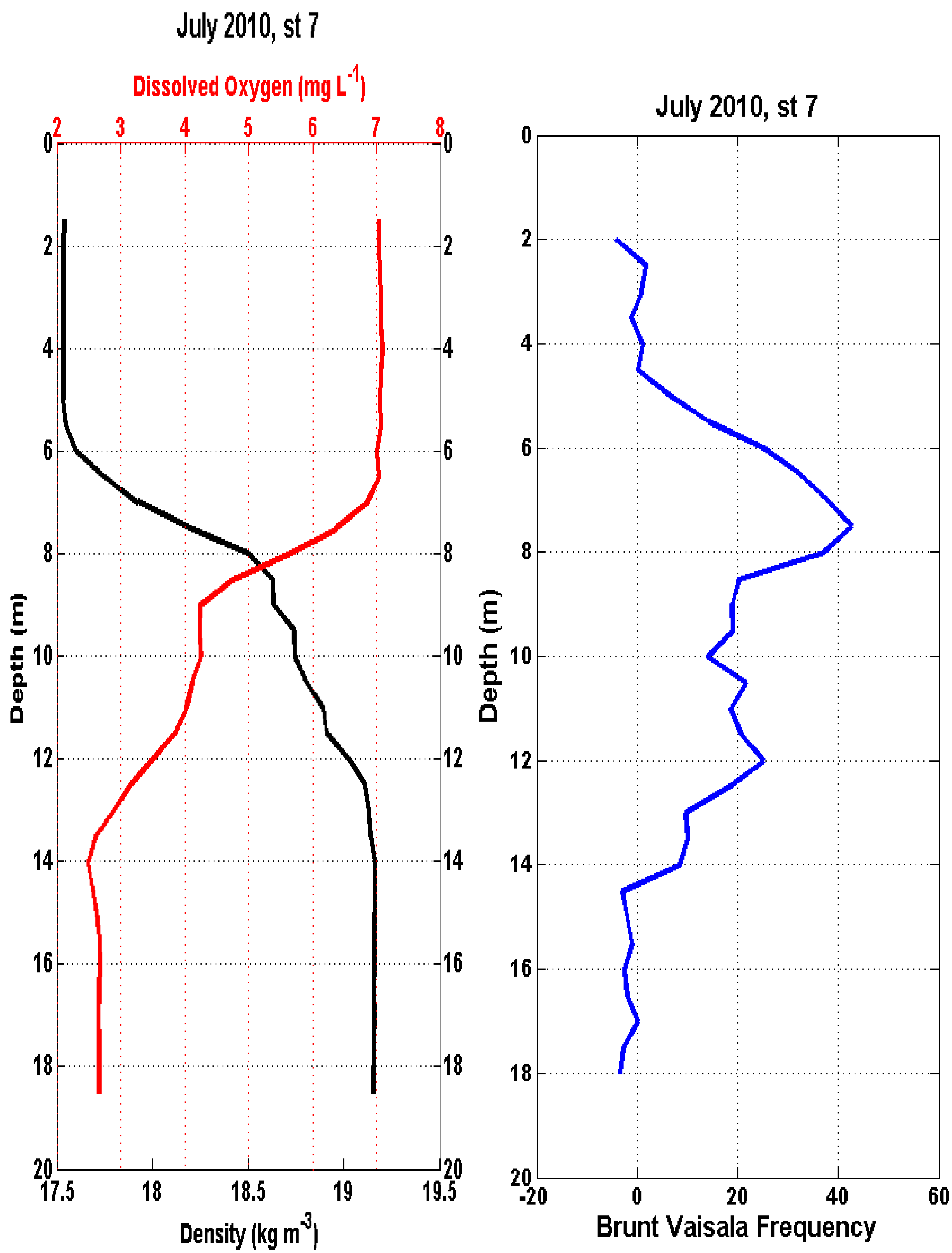

Figure 46b: Vertical profiles of DO, density, and Brunt-Väisälä Frequency at station 7 in July 2010.

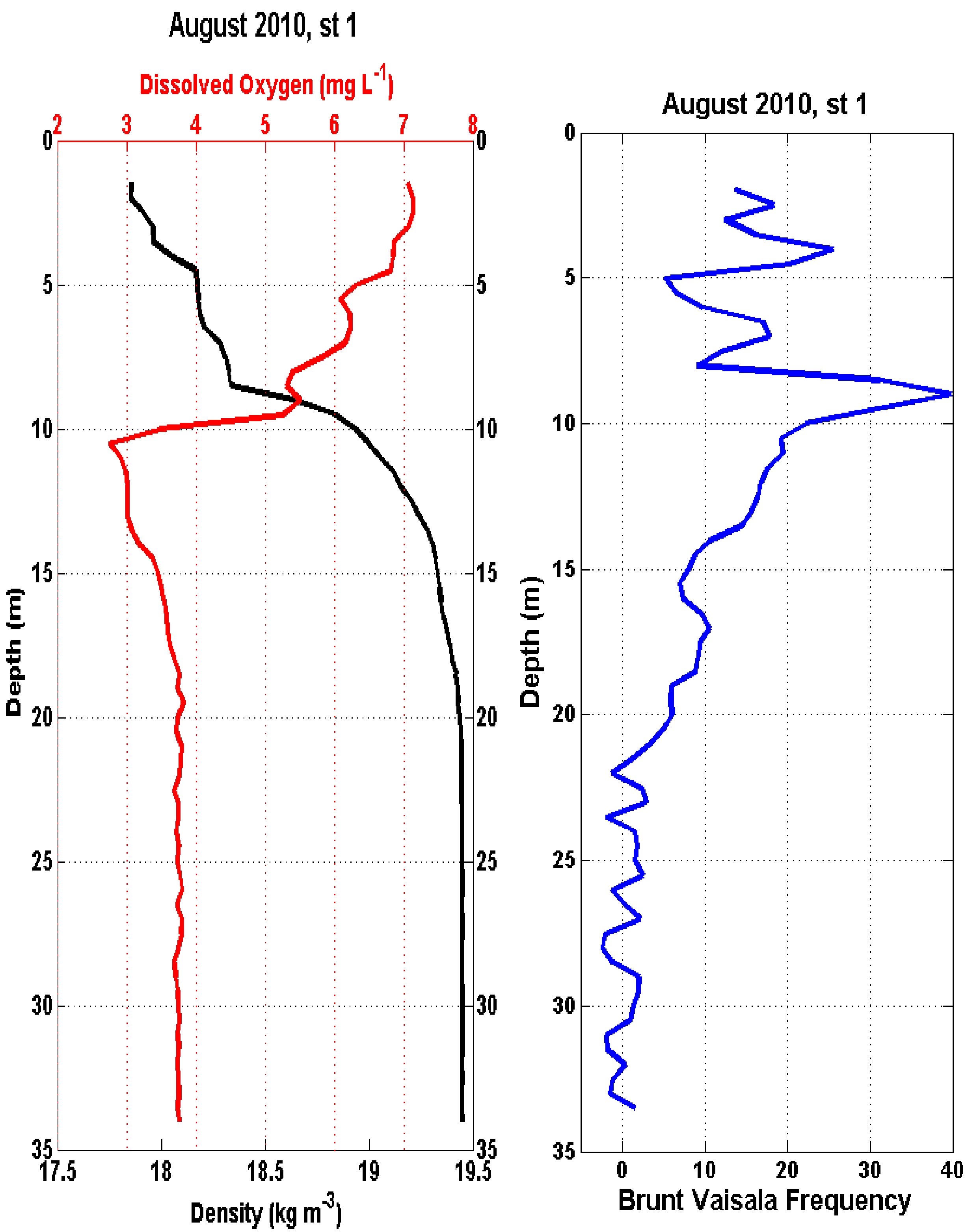

Figure 46c: Vertical profiles of DO, density, and Brunt-Väisälä Frequency at station 1 in August 2010.

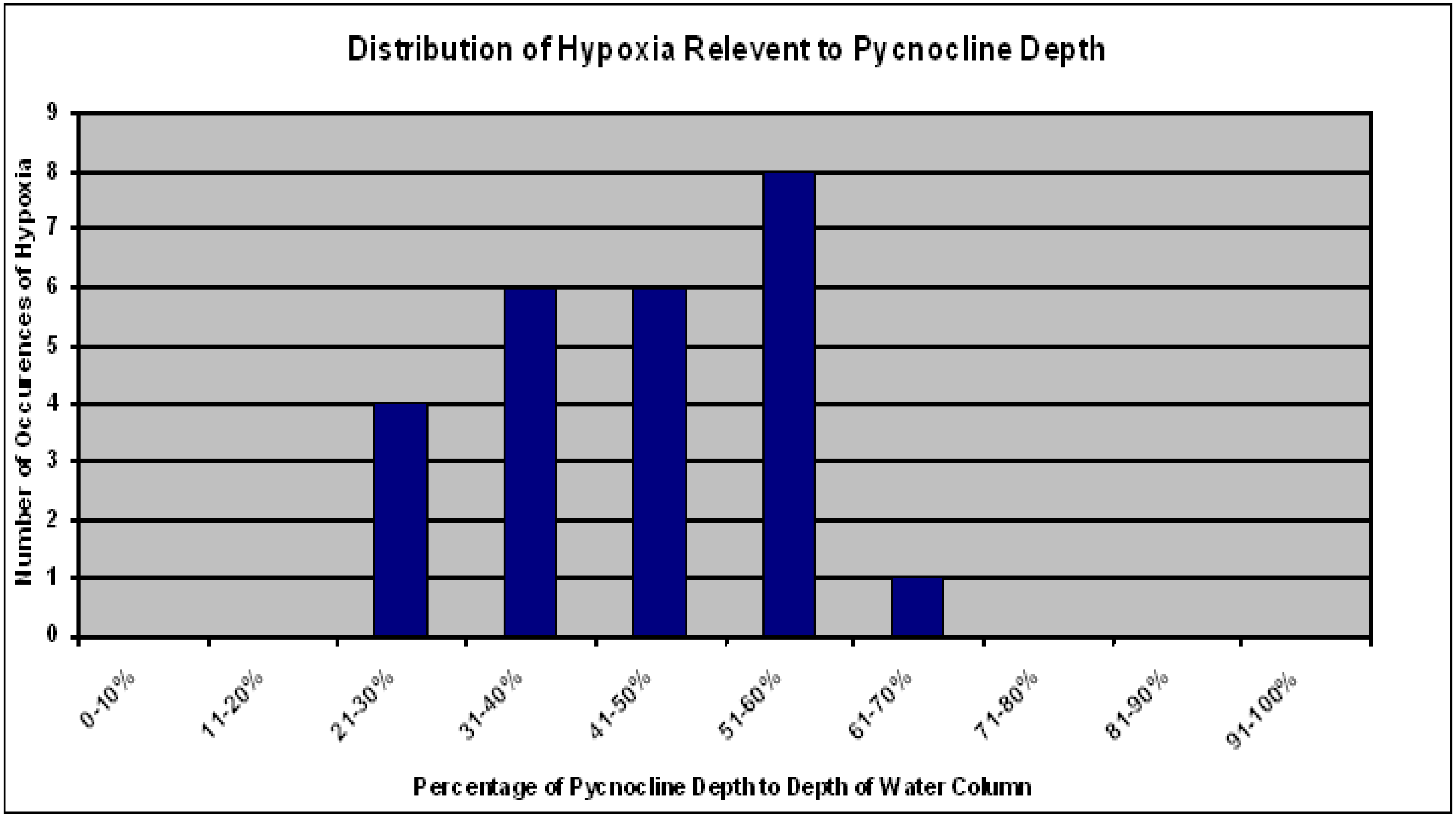

Figure 47: Histogram of the distribution of hypoxia relevant to the pycnocline depth.