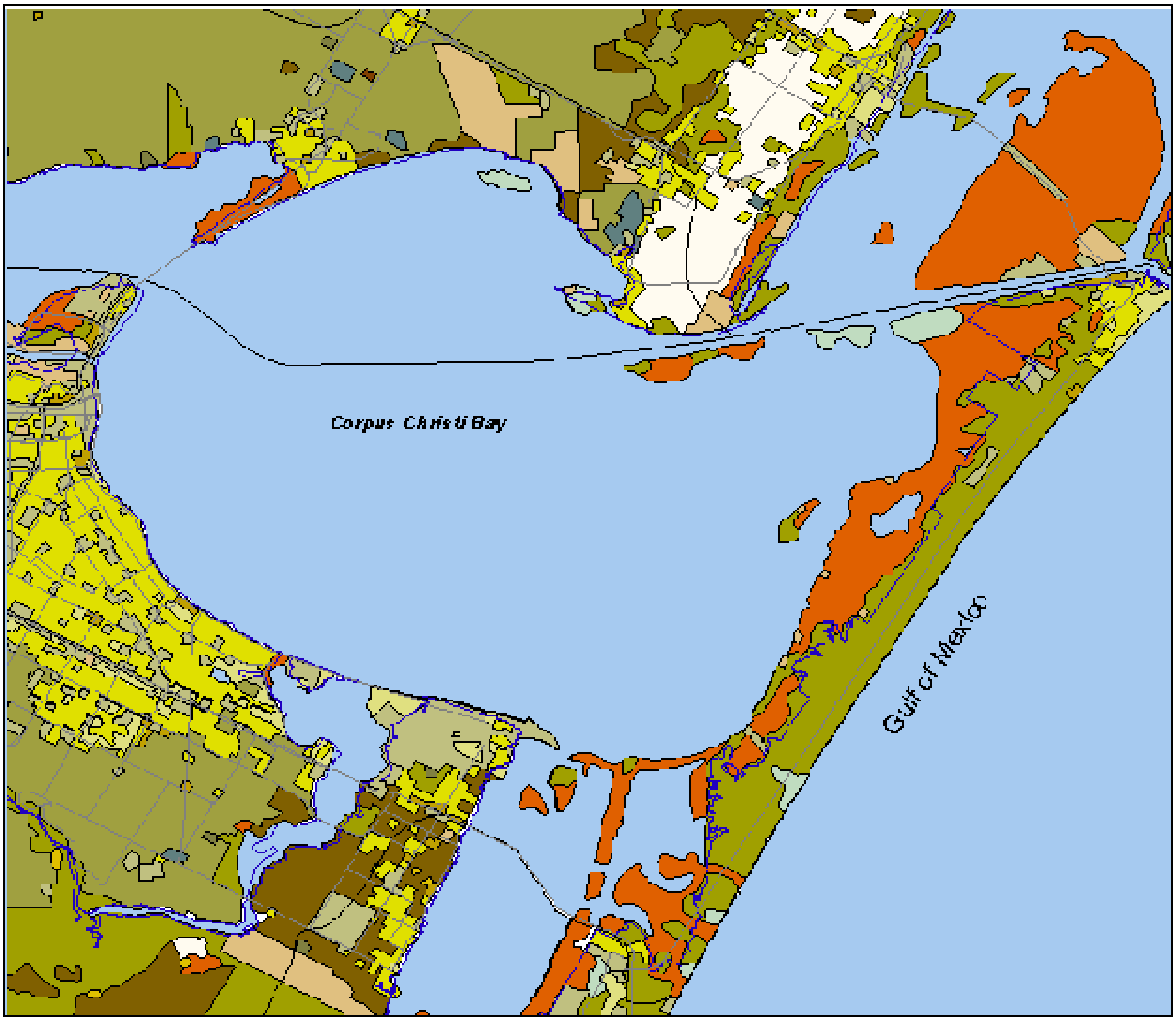
GIS Database of Hypoxia (Low Oxygen) Conditions in Corpus Christi Bay
Volume I: Technical Report

University of Texas at Austin, Marine Science Institute
Technical Report Number TR/02/001
March 31, 2002



Coastal Management Program Grant no.: 01-214

GIS Database of Hypoxia (Low Oxygen) Conditions in Corpus Christi Bay

Volume I. Technical Report

by:

Sally Morehead, Research Assistant

Carol Simanek, Research Assistant

and

Paul A. Montagna, Ph.D., Principal Investigator

University of Texas at Austin

Marine Science Institute

750 Channel View Drive

Port Aransas, TX 78373

Final Report to:

Coastal Coordination Council

P.O. Box 12873

1700 N. Congress Avenue, Room 617

Austin, Texas 78701-2873

Coastal Management Program Grant number: 01-214

UTMSI Technical Report Number 2002-001

March 31, 2002

Table of Contents

List of Tables iii

List of Figures iv

Acknowledgments vii

Abstract viii

Introduction 1

Methods 2

Study Location 2

Water Quality Survey 2

Continuous Oxygen Monitoring 3

Historical Data 3

Hypoxia Likelihood Index 4

Hypoxia Disturbance Index 5

Effect of Climate Change 5

Statistical Analysis 6

GIS Methods 6

Results 7

Appendices 7

2001 Hydrographic Spatial Surveys 7

2001 Water Column Profiles 8

Continuous Hydrographic Monitoring 8

Salinity Stratification Relationships 9

Nutrient Relationships 9

Hypoxia Likelihood Index 9
Effect of Climate Change 9

Discussion 10
Spatial Extent of Hypoxia 10
Temporal Extent of Hypoxia 11
Hypoxia Causes 12
Effect of Climate Change 14

Summary 14

References 15

List of Tables

Table 1. Metric definitions for HLI 17

Table 2. Threshold values for metrics in HLI 18

Table 3. Metric definitions for HDI 19

Table 4. HDI metric values for all years sampled 20

Table 5. Average bottom water dissolved oxygen values for stations 21

Table 6. Metric scores and averages for HDI 22

Table 7. Observed hypoxia events at station 24 during first deployment (7/9/01 - 7/19/01) 23

Table 8. Observed hypoxia events at station 24 during second deployment (7/24/01 - 8/7/01) 24

Table 9. Correlation values for hydrographic parameters for hypoxic station 10 and normoxic station 2 25

List of Figures

Figure 1. Map of study area 26

Figure 2. YSI mooring system 27

Figure 3. Map of stations used in climate change analysis 28

Figure 4. Mean surface water values for salinity and dissolved oxygen, 2001 29

Figure 5. Mean bottom water values for salinity and dissolved oxygen, 2001 30

Figure 6. Depth profile patterns 31

Figure 7. Rate of occurrence in percent for pattern 1, 2, and 3 during 2001 32

Figure 8. Continuous monitoring surface water parameters for station 2 during 7/9/01 - 7/19/01 deployment 33

Figure 9. Continuous monitoring bottom water parameters for station 2 during 7/9/01 - 7/19/01 deployment 34

Figure 10. Continuous monitoring surface water parameters for station 24 during 7/9/01 - 7/19/01 deployment 35

Figure 11. Continuous monitoring bottom water parameters for station 24 during 7/9/01 - 7/19/01 deployment 36

Figure 12. Continuous monitoring surface water parameters for station 2 during 7/24/01 - 8/7/01 deployment 37

Figure 13. Continuous monitoring bottom water parameters for station 2 during 7/24/01 - 8/7/01 deployment 38

Figure 14. Continuous monitoring surface water parameters for station 24 during 7/24/01 - 8/7/01 deployment 39

Figure 15. Continuous monitoring bottom water parameters for station 24 during 7/24/01 - 8/7/01 deployment 40

Figure 16. Bottom water salinity and dissolved oxygen relationship at hypoxic station 24 41

Figure 17. Salinity stratification and wind speed relationship at station 2 and 24 during 7/9/01 - 7/19/01 deployment 42

Figure 18. Salinity stratification and wind speed relationship at station 2 and 24 during 7/24/01 - 8/7/01 deployment 43

Figure 19. Hydrographic relationships with salinity at hypoxic station 10 44

Figure 20. Hydrographic relationships with chlorophyll at hypoxic station 10. Values are averages or surface and bottom water parameters 45

Figure 21. Hydrographic relationships with salinity at normoxic station 2 46

Figure 22. Hypoxia likelihood index for 2001 47

Figure 23. HDI average ranks for 1994, 1997, 1999, 2000 and 2001 48

Figure 24. Monthly values for temperature, salinity and dissolved oxygen from combined UTMSI, TNRCC, and TPWD data 49

Figure 25. Annual variations in temperature, salinity and dissolved oxygen from combined UTMSI, TNRCC, and TPWD data 50

Figure 26. Annual variations in temperature, dissolved inorganic nitrogen, and phosphate from long term UTMSI stations 2 and 10 51

Figure 27. Annual variations in temperature, salinity and dissolved oxygen for the month of July from combined UTMSI, TNRCC, and TPWD data 52

Acknowledgments

This report is the result of research funded by a grant (number 01-214) from the Texas General Land Office, Texas Coastal Management Program to Paul A. Montagna, Principal Investigator. This grant is funded via the Coastal Coordination Council by a cooperative agreement from the National Oceanic and Atmospheric Administration award number NA97OZ0179. The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its sub-agencies. Many people contributed to the successful completion of this project. From the University of Texas Marine Science Institute we thank, Rick Kalke and Kristi Jones for help in sampling, Carol Simanek for data management, Christopher Kalke and Terry Palmer for hydrographic data collection. The Texas Natural Resource Conservation Commission and Texas Parks and Wildlife Department provided historical dissolved oxygen data for Corpus Christi Bay. From the Coastal Management Program, Melissa Porter helped in administrating the grant, facilitating approval of changes in the plan, and reminding the PI when progress reports were due. The original observations of hypoxia in Corpus Christi Bay were made during a project funded by the Texas Water Development Board (Interagency cooperative agreements: 9-483-706 and 9-483-705). University of Texas Marine Science Institute Technical Report 2002-01.

Abstract

Hypoxia (low oxygen conditions) has been documented in the southeastern region of Corpus Christi Bay, Texas every summer since 1988. Hypoxia is a serious water quality condition because all aerobic organisms require oxygen to live. Hypoxia in Corpus Christi Bay occurs only in bottom waters, within 1 - 2 meters above bottom, so effects are mostly on benthic organisms. The objectives of the current study were to determine the spatial and temporal extent of hypoxia in Corpus Christi Bay, Texas, as well as to generate a GIS database for existing data to aid in management. Continuous oxygen recorders were deployed and water quality was surveyed during summer to measure the extent of hypoxia. Water column profiles measured during spatial surveys revealed benthic oxygen depletion with and without salinity stratification. Continuous oxygen monitoring captured numerous hypoxic events, many of which were of short duration (less than 1 hr) and high intensity (between 1 and 2 mg l^{-1}). Other archival data from resource agencies was also obtained for analysis. The trends in the hydrographic data indicate that hypoxia in Corpus Christi Bay is a transient event in the southeastern region and is caused by a combination of biotic processes (i.e., respiration) and abiotic processes (i.e., low mixing potential because of sluggish currents, a small tidal range, and high temperatures). Temperature has increased in this region of Corpus Christi Bay over the last 20 years, presumably due to global warming. Trends in the data indicate that extent and intensity of hypoxia is increasing over time. This increase in hypoxia is primarily due to increases in temperature, because nutrients have not increased.

Introduction

Hypoxia is a common estuarine phenomenon defined as low dissolved oxygen (DO) concentrations; below 2 mg l^{-1} (Dauer et al. 1992). Hypoxia is a coastal environmental issue that has attracted national and international attention (Rabalais and Turner, 2001). Large "dead zones" in the Northwestern Gulf of Mexico receive national media attention every summer (Rabalais et al. 2001). The National Sea Grant Program and the White House Committee on Environment and Natural Resources sponsored an international workshop in March, 1998 to consider the causes and effects of this event in the Gulf of Mexico. Hypoxia has been reported and studied in at least 44 systems around the world (Diaz and Rosenberg 1998), and three Texas coastal systems: Corpus Christi Bay (Montagna and Kalke 1992; Martin and Montagna 1995; Ritter and Montagna 1999, 2001), Offats Bayou (Gunter 1942), and the Gulf of Mexico (McKinney and Harper 1980). Hypoxia also occurs in parts of Galveston Bay (Don Harper, personal communication), and other parts of Texas estuaries (Montagna unpublished data, TWDB 2001).

Hypoxia is a serious disturbance because few animals can tolerate the physiological stress of extended exposure to low oxygen concentrations (Diaz and Rosenberg 1995). For example, hypoxia in Corpus Christi Bay, Texas is correlated to about a 10 fold reduction in benthic standing stock and diversity (Ritter and Montagna 1999). Direct effects of hypoxia include reduced benthic abundance and biomass (Dauer et al. 1992), avoidance by mobile epifauna, emergence of infauna, physical inactivity and death (Tyson and Pearson 1991; Diaz et al. 1992). Indirect benthic effects may occur through predation of benthic fauna emerging from sediment even though they could survive temporary exposure to low oxygen. Increased prey availability to predators because of hypoxia can alter energy flow in the system (Pihl et al. 1992). Thus, hypoxia may affect higher trophic levels, including commercial and recreational fish species, by reducing available benthic prey.

Hypoxia in Corpus Christi Bay was first documented in 1988 (Montagna and Kalke 1992) and later confirmed to reoccur every summer (Martin and Montagna 1995; Ritter and Montagna 1999, 2001). During initial study, presence of hypoxia was found during summers when water temperatures were high (>28 °C) and salinities were high (> 31 ppt) indicating the low DO concentrations may simply be the result of lowered DO saturation in hot, salty water. Later, an additional correlate was found; that hypoxia occurred primarily when the water column was stratified and the bottom salinity was between 4.1 and 7.2 ppt greater than surface salinity. However, Corpus Christi Bay is shallow ($\leq$ 4 m), far from freshwater sources, and thought to be well mixed due to winds and tide. The high bottom salinities in a well-mixed system led to speculation that there might be a source of salt water intrusion from either the hypersaline Laguna Madre south of the hypoxic area, or from brines discharged from hydrocarbon production facilities north of the hypoxic area. Later surveys did not find any potential sources of salty water, but did document strange stratification patterns indicating stagnation, ground water intrusion, or high evaporation rates could be contributing factors to causing water column stratification. The relative roles of abiotic and biotic processes in causing hypoxia in Corpus Christi Bay are still uncertain.

Given the present state of knowledge in Corpus Christi Bay, the current study has three objectives: 1) conduct new field work that will extend existing data set and generate new data by deploying hydrographic sondes in the surface and bottom water at one hypoxic and one normoxic station, 2) organize and analyze historical data from UTMSI, TNRCC, TPWD, and Conrad Blucher Institute, and 3) create a GIS database for existing data. The objectives of this study were conducted in attempt to reach two goals: 1) to determine the causes, spatial, and temporal extent of hypoxia, and 2) to aid in management of this problem and protect coastal resources.

Methods

Study Location

Corpus Christi Bay is a shallow (~3.2 m; Orlando et al. 1991), almost enclosed bay with a level bottom (see maps in Montagna and Kalke 1992; Martin and Montagna 1995; Ritter and Montagna 1999). Corpus Christi Bay is microtidal and is subjected to strong meteorological forcing (Ward 1980). Average monthly wind speeds range from 17 km h^{-1} to 28 km h^{-1}. Wind direction is consistently from the southeast between April and September (Port of Corpus Christi Authority 1993). It receives an average of 74 cm yr^{-1} of rainfall and 25 m^3 s^{-1} inflow (Orlando et al. 1991). The average evaporation rate is 151 cm yr^{-1}. South Texas bays are characterized by broad climate variations that alternate between wet and dry cycles (Montagna and Kalke 1995). Stations for temporal and spatial surveys were located in the southern region of Corpus Christi Bay, and were chosen based on historical data from TPWD.

Water Quality Survey

The spatial and temporal extent of summer hypoxia in Corpus Christi Bay was determined by collecting hydrographic profiles from the surface to bottom at 0.5 m intervals using a multiparameter data sonde. From 1987 through 1999, a Hydrolab sonde was used, and from 2000 through 2001 a YSI sonde was used. Hydrographic data collected include: salinity, temperature, dissolved oxygen, oxidation reduction potential, conductivity, depth and pH.

The Hydrolab Surveyor II has a digital meter from which water quality parameters are read. The parameters have the following accuracy and units: temperature (± 0.15 °C), pH (± 0.1 units), dissolved oxygen (mg/l ± 0.2), specific conductivity (± 0.015 - 1.5 mmhos/cm depending on range), redox potential (± 0.05 mV), depth (± 1 m), and salinity (ppt). Salinity is automatically corrected to 25°C.

YSI 6-series Multi-parameter Water Quality Monitors. Models used are 6920-S and 600XLM data sondes with 610-DM and 650 MDS display loggers. The series 6 parameters have the following accuracy and units: temperature (± 0.15 °C), pH (± 0.2 units), dissolved oxygen (mg/l ± 0.2), dissolved oxygen saturation (% ± 2%), specific conductivity (± 0.5% of reading depending on range), redox potential (± 20 mV), depth (± 0.2 m), and salinity (± 1% of reading or 0.1 ppt, whichever is greater). Salinity is automatically corrected to 25°C.

A large-scale water quality survey was conducted. Stations 1, 2, 7, 8, 9, 10, 11, 12, 14, 18, and 30 were samples roughly every two weeks during the summer of 2001 (Figure 1).

Continuous Oxygen Monitoring

Dissolved oxygen concentration, dissolved oxygen percent, salinity, conductivity, depth, pH, and temperature data were collected continuously at two stations: one hypoxic (station 24) and one normoxic (station 2). Surface and bottom water hydrographic data were collected via two YSI 600XLM monitors attached to semi-permanent, low-relief moorings (Figure 2). Monitors attached in bottom water were 2.7 m below the surface at station 2 and 2.8 m below the surface at station 24. Stations were located using differential global positioning system equipment (Garmin 215 model) with an accuracy of ± 4.572 m. YSI monitors were deployed and retrieved by divers, and data downloaded back in the laboratory. Continuous data was collected during two separate deployments, 9 July 2001 thru 19 July 2001 and 24 July 2001 thru 7 August 2001.

Historical Data

Historical data was collected for analysis from four different sources. University of Texas Marine Science Institute (UTMSI) provided data from long term stations 2 and 10 from 1987 through 2001 for the following parameters: salinity, temp, dissolved oxygen, dissolved inorganic nitrogen, and phosphate. Chlorophyll data was also provided from 1998 through 2001. Texas Natural Resource Conservation Commission (TNRCC) provided monthly dissolved oxygen, temperature, and salinity data from Corpus Christi Bay from 1969 through 2001. Texas Parks and Wildlife Department (TPWD) provided monthly dissolved oxygen, temperature, and salinity data from random stations within the bay from 1980 through 2001. Conrad Blucher Institute (www.cbi.tamucc.edu) provided hourly wind speed data for time periods during continuous sonde deployment.

Hypoxia Likelihood Index

A hypoxia likelihood index (HLI) was used to determine how likely a station is to become hypoxic. This index combines chemical measurements into a single value that creates a univariate index from multivariate data. Seven metrics were used to calculate an HLI (Table 1): High values of bottom water salinity (BotSal), bottom water temperature (BotTemp), rate of occurrence for patterns of stratification, and percent of time hypoxic condition was previously found (%Hyp). The metrics were significantly correlated to decreases in bottom water dissolved oxygen with an experiment-wise error rate of 0.05, and hence are indicators of hypoxia. The stratified patterns represent profiles in which dissolved oxygen levels tend toward hypoxia near the bottom, and stations with high occurrences of these patterns will have a high likelihood of hypoxia. Low values of bottom water dissolved oxygen (BotDO), and low rate of occurrence for a well mixed water column were also used to indicate a high likelihood of hypoxia. Pattern one represents a well mixed water column with no salinity stratification or hypoxia, and high rates of occurrences of pattern one at stations indicates a low likelihood of hypoxia.

The station HLI rank was calculated by assigning a non-parametric score from each metric depending on its threshold value (Table 2). Metric values for stations were calculated for each metric. Thresholds were calculated by first rounding metric values to no decimal points, then dividing the range by five. The lowest value is the first threshold and thresholds thereafter are calculated by adding the divided range to the lowest value and so on. For example, BotSal had a range of 8 and a low value of 36, which meant that the threshold would begin at 36 and increase by 1.6 (range divided by 5) thereafter. The BotDO and well mixed profile metrics were sorted in descending ranks (4-0) and the BotSal, BotTemp, and stratified profile metrics were sorted in ascending ranks (0-4). Station HLI rank was calculated by averaging all metric ranks, hence stations with a high average rank (*i.e.*, 4) is designated as a station with a high likelihood for hypoxia to occur.

Hypoxia Disturbance Index

A hypoxia disturbance index (HDI) was created to analyze the frequency, extent and intensity of hypoxic events throughout the years sampled in UTMSI's spatial surveys (1994 - 2001). Like the HLI, this index combines chemical measurements into a single value that creates a univariate index from multivariate data. The intensity of hypoxia was determined by calculating the percent of time bottom water dissolved oxygen values were at or below 1, 2, and 3 mg l^{-1}. The extent or area of hypoxia was determined by calculating the percent of stations mean bottom water dissolved oxygen values were at or below 5, 4, and 3 mg l^{-1}. Frequency was determined by calculating the intensity and extent metrics for each year the spatial survey at was sampled by UTMSI. Six metrics were used to calculate an HDI, and a metric value was determined for each year sampled (Table 3 and 4). Percent of time for all samples were calculated from bottom water dissolved oxygen values. Percent of time for all stations was calculated from mean bottom dissolved oxygen data from table 5 .

Threshold values were established as approximately the 5th and 50th (median) percentile values. Metric values below the 5th percentile were scored as one; values between the 5th and 50th percentile were scored as three, and values above the 50th percentile were scored as five (Table 6). Yearly HDI ranks were calculated by averaging all intensity and extent metric ranks.

Effect of Climate Change

Data from the TNRCC, TPWD, and UTMSI were combined to determine annual variations in salinity, temperature, dissolved oxygen and nutrients. The climate change analysis included stations in the southern region of Corpus Christi Bay (~ 40 mi^2) and only included data from years in which all 12 months were sampled (Appendix A, Figure 3). To negate monthly bias, data was averaged by month and then by year. Analysis by year was calculated with a total of 1,964 data points with 245 from TNRCC, 178 from UTMSI, and 1,541 points from TPWD. The month of July was also analyzed with 173 data points from the above three data sources.

Statistical Analysis

Contours for bay wide dissolved oxygen maximum and minimum values were created with ArcView 3.1. Rates of occurrence for station profile patterns were determined by calculating the percent occurrence per station. The Pearson correlation coefficient was calculated for bottom water salinity and dissolved oxygen relationships, salinity stratification and wind speed relationships, climate change analysis, and historical relationships from station 10 and 2.

GIS Methods

ArcView 3.1 was used to create the GIS database. Shapefiles were created for each data theme: 1) fluvial and ground water system that empties water into Corpus Christi Bay, 2) agricultural land usage around the Laguna Madre and Corpus Christi Bay watershed, 3) Corpus Christi Bay and ocean water system, 4) surrounding landfills, and 5) hydrological and hypoxia data from sites within Corpus Christi Bay.

The shapefiles acted as layers that give representation to the model. These shapefiles included digital orthography (DOQ) and regular vector representations of the political boundaries of Nueces County. The lowest layer contained subterranean aquifers, as well as any landfills and hazardous landfill sites that surround and may leach into the bay. The third layer contained the hydrographic theme. The fourth and final layer will be a transparent outline of political boundaries.

The data for this GIS model came predominately from the TNRIS website. The data was transported using the File Transfer Protocol (FTP) area of the TNRIS website and was in an Arc Info (*.e00) format. The data was downloaded and converted to an ArcView shapefile using Import 71 conversion software. After the files were downloaded, they were unzipped, and opened ArcInfo coverages are converted to ArcView. Hydrographic data resides at UTMSI, and is already geo-referenced. Hydrographic data (pH, salinity, temperature, and dissolved oxygen) was collected from May 1994 through August 1999. A total of 854 observations have been taken, with long-term records at 12 of these stations in the critical area. Latitude and longitude at each station was taken with differential GPS (Garman 215/225 GPS). Hydrographic data, latitude and longitude, and each station name is entered into an Excel 97 spreadsheet, and then exported into ArcView software. The GIS model will comply with required data formats as outlined in the Texas GIS Implementation Plan of the Texas Geographic Information Council (TGIC), Department of Information Resources (DIR). The GIS data will conform to the Federal Geographic Data Committee (FGDC) document Content Standard for Digital Geospatial Metadata. ArcView is the PC version of ArcInfo, so electronic data is in an acceptable format.

Results

Appendices

Station location, depth profiles, historical data, the GIS model, and data tables are included in the appendices. Appendix A contains the station coordinates from the data used from UTMSI, TNRCC and TPWD. Appendix B contains depth profile figures of dissolved oxygen and salinity for the 2001 spatial survey. This appendix contains bimonthly profiles for stations 1, 2, 7, 8, 9, 10, 11, 12, 14, 18, 24, and 30 from June through August in the summer of 2001. Appendix C contains depth profile figures of dissolved oxygen and salinity for the 1997 spatial survey. This appendix contains profiles for stations 1, 2, 7, 8, 9, 10, 11, 12, 14, 18, and 30 from July in the summer of 1997. Appendix D contains depth profile figures of dissolved oxygen and salinity for the 1994 spatial survey. This appendix contains bimonthly profiles for stations 1, 2, 7, 8, 9, 10, 11, and 12 from May through August in the summer of 1994. Depth profiles from 1999 and 2000 for stations 1, 2, 7, 8, 9, 10, 11, 12, 14, 18, 24, and 30 can be found in Ritter and Montagna (2001). Appendix E contains the hydrographic values collected from the 2001 spatial survey. Appendix F contains the hydrographic values collected from the 2001 continuous recording at station 2 and 24. Appendix G, the layers that make up the GIS model, including the following layers: fluvial water systems, agricultural land usage, Corpus Christi Bay and ocean water system, and surrounding landfills. Appendix H contains historical mean surface and bottom water salinity and dissolved oxygen data from spatial surveys conducted by UTMSI for 1994, 1997, 1999 and 2000. Appendix I contains historical rates of occurrence for patterns from spatial surveys conducted by UTMSI for 1994, 1997, 1999 and 2000.

2001 Hydrographic Spatial Surveys

Station 14 had the highest mean surface salinity value and the lowest mean surface dissolved oxygen value (Figure 4). Station 30 had the highest surface dissolved oxygen and station 1 had the lowest surface salinity value. Station 8 had the highest mean bottom salinity value and station 10 had the lowest mean bottom dissolved oxygen value (Figure 5). Station 1 had the highest bottom dissolved oxygen value, as well as the lowest salinity value.

2001 Water Column Profiles

Three different patterns of dissolved oxygen and salinity profiles were found in the water column depth descriptions. In pattern one, the water column is well mixed with no salinity or dissolved oxygen stratification (Figure 6). In pattern two, the water column is well mixed with no salinity stratification, but with a decline in dissolved oxygen near the bottom. In pattern three, the water column is highly stratified with a halocline and a decline in dissolved oxygen towards hypoxia.

Station 1, followed by station 2 had the highest rate of occurrence for pattern one and station 24 had the lowest occurrence of pattern one in the northeastern region of the study area. (Figure 7). Station 12 and 18 had the highest rate of occurrence for pattern two and station 1 had the lowest. Station 8 and 24 had the highest rate of occurrence from pattern three.

Continuous Hydrographic Monitoring

Surface and bottom water parameters were within normal ranges for station 2 from July 9, 2001 through July 19, 2001 (Figure 8 and 9). On July 14, 2001 at station 24, surface water salinity increased (~ 4 ppt) and dissolved oxygen concentrations decreased (~ 4 mg l^{-1}) into hypoxic conditions (Figure 10). Hypoxic conditions were recorded daily and usually in the morning in bottom waters of station 24 from July 9 through July 19, 2001 (Figure 11). A drastic decline in dissolved oxygen concentration (~ 7 mg l^{-1}) was recorded on August 1, 2001 after a gradual increase in salinity (Figure 12). Short lived decreases in salinity (up to 10 ppt) were recorded from July 24, 2001 through August 7, 2001 in the bottom waters of station 2 (Figure 13). Hypoxic conditions were recorded in the bottom waters at station 2 from August 4, 2001 through August 7, 2001. High increases in salinity (~ 5 ppt) were recorded for bottom waters of station 24 (7/30/01 - 8/2/01) as well as continuously low dissolved oxygen concentrations from July 29, 2001 through August 9, 2001. (Figure 15).

Dissolved oxygen and temperature appear to cycle over the course of a day and may fluctuate with the tide (Figure 9-15). Dissolved oxygen appears to be directly related to bottom salinity over the ranges 34 - 41 ppt.

Dissolved oxygen and salinity were significantly correlated in the bottom waters of station 24 (Figure 16). July 9, 2001 through July 19, 2001 had an R value of 0.095, and a P value of 0.004. July 24, 2001 through August 7, 2001 had an R value of 0.429, and a P value of <0.0001.

During the summer of 2001, 49 separate instances of hypoxia were observed at station 24 (Tables 7 and 8). The duration of 30 instances were an hour or less, and hypoxia was recorded for a total of 85.75 hrs, 13.25 of which dissolved oxygen $\leq$ 1 mg l^{-1}.

Salinity Stratification Relationships

Increases in salinity stratification was significantly correlated to wind speed at station 2 from July 9, 2001 through July 21, 2001 ($P < 0.023$) (Figure 17). Increases in salinity stratification was significantly correlated to wind speed at station 2 and 24 from July 24, 2001 through August 8, 2001 ($P < 0.0001$, $P < 0.033$) (Figure 18). Freshets were recorded at station 2 from July 24, 2001 through August 8, 2001 as evidenced by highly unstratified salinity values.

Nutrient Relationships

Historical data from hypoxic station 10 indicated that salinity was significantly correlated to temperature, dissolved oxygen, dissolved organic nitrogen, and chlorophyll (Table 9). Dissolved oxygen was also significantly correlated to dissolved inorganic nitrogen, and temperature. Chlorophyll and phosphate were also significantly correlated at station 10. Historical data from normoxic station 2 indicated that salinity was significantly correlated to temperature, dissolved oxygen and chlorophyll. For both stations, increases in salinity corresponded to increases in temperature, dissolved oxygen and chlorophyll (Figure19 and 21). At station 10, dissolved inorganic nitrogen increased as salinity increased. Decreases in dissolved oxygen were correlated to increases in dissolved inorganic nitrogen and temperature at station 10 as well (Figure 20).

Hypoxia Likelihood Index

The index of hypoxia likelihood indicated that stations 7, 8, 10, and 24 had the highest likelihood of becoming hypoxic, followed by stations 11, 12, 18, 9, 14, and 30 (Figure 22). Stations 2 and 1 located near the ship channel were the least likely to become hypoxic. The distribution and grouping of I-HL ranks indicates that location is a factor in determining the likelihood of hypoxia.

Effect of Climate Change

The HDI indicated that disturbance caused by hypoxia is increasing over time; however, the increase is not significant ($P < 0.226$) (Figure 23). A high correlation value ($R= 0.662$) and an insignificant P value indicates that the number of years sampled is too low to yield a significant P value and continuing data in future years could prove that disturbance as expressed by frequency, extent and intensity is in fact increasing.

Based on monthly averages, temperature in Corpus Christi Bay reaches its peak in July and August (Figure 24). Salinity reaches its peak later in August and September. Dissolved oxygen reaches a minimum in July.

Since 1982, water temperature in the hypoxic area has significantly increased ($P < 0.009$) approximately 1.5ºC (Figure 25). No increases in salinity were found for yearly averages; however, dissolved oxygen decreased significantly since 1982 ($P < 0.036$).

At long term UTMSI stations 2 and 10, temperature has increased since 1987 and, in conjunction, dissolved inorganic nitrogen has decreased significantly since 1987 ($P < 0.017$).

Annual variations for the month of July indicate that temperature, as well as salinity have increased since 1982 (temperature was almost significant $P < 0.076$) (Figure 27). Dissolved oxygen has decreased significantly since 1982 ($P < 0.004$).

Discussion

Spatial Extent of Hypoxia

Archived dissolved oxygen data obtained for Corpus Christi Bay from UTMSI indicated that the southeastern portion of Corpus Christi Bay was subject to low oxygen conditions more often than any other region in the bay (Figure 5 and Appendix H). The spatial survey of Corpus Christi Bay was based on this information and was conducted to determine the spatial extent and patterns of hypoxia. Stations from the southeastern corner of the bay tended to have lower dissolved oxygen values and higher salinity values than those in the eastern corner (Figure 4 and 5). The southeastern region also has a higher likelihood of becoming hypoxic (Figure 22). Stations in the eastern region of the bay (1 and 2) had the lowest likelihood of becoming hypoxic. The eastern region of the bay is nearest the ship channel, which receives stronger water circulation because of tides than does the southeastern region. The circulation of water in the southeastern region of Corpus Christi Bay (the region prone to hypoxia) is minimal during the summer (Powell et al. 1997). Thus, slow or sluggish water circulation is believed to be a strong factor in causing hypoxia, because it allows salinity stratification to occur.

Three stratification patterns of salinity and dissolved oxygen were found in relation to the depth profiles taken at stations during the spatial survey. Pattern one represents a well mixed water column with no salinity or dissolved oxygen stratification. Pattern two represents a semi-mixed water column with no salinity stratification, but with a decline in dissolved oxygen tending towards hypoxia near the bottom. Pattern three represents a stagnant water column with salinity stratification and a decline in dissolved oxygen towards hypoxia near the bottom. Station 1 and 2 was dominated by pattern one (Figure 7). Both of these stations are located near the ship channel in the eastern region of the bay where water circulation and tides are strong. Station 12 and 18 had a high rate of occurrence for pattern two. Both these stations are located in the eastern to southeastern region of the bay where water circulation is not as strong as in the eastern region. Station 8 and 24 had a high rate of occurrence for pattern three. These stations are located in and near the southeastern and southern region of the bay where water circulation is minimal and hypoxia is likely to occur (Ritter and Montagna 2001). Trends in pattern locations indicate that there is a gradient in salinity stratification that is correlated to water circulation, where regions near the channel are well mixed and regions of the bay extending from the channel experience gradations in salinity stratification. Based on the pattern frequencies from the spatial survey, salinity stratification and hypoxic conditions increase as distance from the channel increases.

<u>Temporal Extent of Hypoxia</u>

Overnight or early morning hypoxia is thought to occur in Corpus Christi Bay, TX because photosynthesis during the day stops at night, but biological oxygen demand by aerobic respiration continues at night. Overnight hypoxia was not the norm during summers 1999, 2000, and 2001 (Ritter and Montagna 2001, Figure 8-15). Night onset (i.e., after 9 p.m.) of hypoxia was noted only 20 times out of 49 in 2001 (Table 7 and 8).

During the summers of 1999, 2000, and 2001 hypoxia was generally of very short duration (Ritter and Montagna 2001, Table 7 and 8). In 2001, 30 of 49 observed hypoxic events were for 1 hour or less. The longest duration observed in this study was for 10.25 hrs at station 24. The longest duration observed in 1999 was for 61.5 hrs at station 10, which was accompanied by hypoxia at station 11 that lasted for 39 hours (Ritter and Montagna 2001). The longest hypoxia event recorded in 2000 was for 13.25 hours. The duration of these events for 1999 through 2001 are much shorter than those described in Diaz and Rosenberg (1995). To avoid confusion, hypoxic events on the order of days are referred to as "brief" (after Diaz et al. 1992), and those on the order of hours will be referred to as "intermittent." It is possible that the short duration of most observed hypoxia events was not sufficient to create the physiological stress required to induce community response.

In this study (2001), the intensity of hypoxia was categorized as dissolved oxygen $\leq$ 2 mg l^{-1} or $\leq$ 1 mg l^{-1} (Table 1 and 2). Of the time station 24 was hypoxic (i.e., $\leq$ 2 mg l^{-1}), 15.5 % of the time, dissolved oxygen was $\leq$ 1 mg l^{-1} indicating intermittent hypoxia may only rarely be intense. The low intensity of dissolved oxygen stress may not have breeched the tolerance levels of many species, especially given the intermittent nature of typical observed events during 1999, 2000 and 2001.

Short lived salinity decreases, or freshets, were observed in bottom waters of station 2 from July 24, 2001 through August 7, 2001 (Figure 13 and 18). These low values of salinity are believed to be seepage of freshwater from a groundwater source. Similar drops in salinity in bottom water was observed at station 24 in 2000 (Ritter and Montagna 2001). Freshets do not appear to affect the occurrence or persistence of hypoxia and are not correlated to decreases in dissolved oxygen.

Hypoxia Causes

A variety of factors are thought to contribute to the onset of benthic hypoxia in Corpus Christi Bay, TX. Hypoxia results when the balance between dissolved oxygen sources and sinks yields a concentration of less than 2 mg l^{-1}. Several factors are thought to affect these sources and sinks at the study site. Photosynthesis is the primary source of dissolved oxygen, but diffusion across the air-water surface also occurs.

Photosynthesis by phytoplankton or benthic diatoms is the primary source of dissolved oxygen. The process of photosynthesis is measured by the amount of chlorophyll in the water column. Photosynthesis is especially important in regions prone to hypoxia. Photosynthesis was also found to be regulated by salinity and the amount of phosphate in the water column (Table 9). In Corpus Christi Bay, increases in salinity increase chlorophyll concentration. Phytoplankton show an affinity for higher salinities. This affinity likely corresponds to the annual summer bloom that occurs in temperate regions (Thurman and Burton 2001). The correlation to phytoplankton and phosphate indicates that potassium is a limiting resource for phytoplankton growth. Photosynthesis is controlled by physical factors and it is a key factor in dissolved oxygen concentrations in regions prone to hypoxia.

Another source of dissolved oxygen that effects the occurrence of hypoxia is diffusion across the air-water surface. Diffusion and mixing processes bringing surface dissolved oxygen to the bay bottom. It has been postulated that water column stratification impeded mixing processes and was a key factor in the onset of hypoxia in Corpus Christi Bay (Ritter and Montagna 1999). This study and others also support this theory (Ritter and Montagna 2001). Water column stratification is associated with high temperatures and salinity levels, both with occur in summer months. In fact, low oxygen conditions in Corpus Christi Bay occur in the summer months of July and August (Figure 24).

Salinity stratification is the strongest cause of hypoxia. Historical data from both a normoxic and a hypoxic station indicated that high salinity levels were significantly correlated to low dissolved oxygen levels (Figure 19 and 21). High levels of salinity in bottom waters at station 24 were significantly correlated with low dissolved oxygen levels (Figure 16). High levels of salinity in bottom water is indicative of a stratified and stagnant water column.

Salinity stratification is likely caused by three primary factors. Water circulation in Corpus Christi Bay is associated with salinity stratification. The occurrence of hypoxic patterns indicated that stratification increased as distance from the channel and water circulation increased. The second primary factor in facilitating salinity stratification is wind. High wind speeds tend to mix the shallow depths in Corpus Christi Bay, while low wind speeds attribute to a stratified water column. In the present study, low wind speeds were significantly correlated to stratification (Figure 17 and 18). The third factor of stratification is the occurrence of hypersaline water. During the summer, evaporation is highest (average evaporation rate for south Texas is 151 cm yr^{-1}) and may cause hypersaline water to be created in situ; however, there is no evidence that stratification is caused by the influx of a hypersaline water body, such as Laguna Madre water.

Other factors besides salinity stratification may also contribute to the onset of hypoxia. Increased biological oxygen demand (BOD), nutrient enrichment and sluggish water movement may contribute to the deposition of organic material (TOC) in an already organically rich area. The increase in TOC can then fuel microbial respiration increasing the rate of dissolved oxygen depletion. Nutrient enrichment does not seem to be a primary factor in the occurrence of hypoxia. Significant correlations were found between dissolved inorganic nitrogen and dissolved oxygen at station 10; however, nitrogen levels have significantly decreased in the bay since 1987 (Figure 26). There is also no indication that there is more TOC in sediments of the hypoxic area than other areas of Corpus Christi Bay (Ritter and Montagna 2001).

Overall, hypoxia appears to be caused primarily by physical and biological factors. The role of anthropogenic effects are indirect. The area has sluggish circulation because almost all tidal energy is constrained to the deepened Corpus Christi Ship Channel. On the other hand, there is scant evidence of nutrient or organic enrichment in the area.

Effect of Climate Change

Change in the climate, such as temperature, appears to be indirectly affecting dissolved oxygen levels in Corpus Christi Bay. Since 1987, temperature has increased significantly in conjunction with significant decreases in dissolved oxygen concentrations (Figure 25). Increases in temperature are directly linked to increases in salinity, which is most likely due to evaporation (Figure 19 and 21).

Significant increases were not shown in yearly averages because salinity is primarily dominated by drought and flooding events; however, salinity did significantly increase since 1982 during July (Figure 27).

Other studies have shown that dissolved oxygen is decreasing due to anthropogenic inputs of nitrogen and phosphate (Pokryfki and Randall 1987, Rabalais et al. 1991). In Corpus Christi Bay, dissolve inorganic nitrogen and phosphate have significantly decreased and are not likely the cause of the decreasing dissolved oxygen concentrations (Figure 26). Decreases in dissolved oxygen are most likely due to increases in salinity and salinity stratification which has increases over the years due to higher water temperatures and climate change.

Summary

In summary, hypoxia occurs in summer, predominantly in the southeastern region of Corpus Christi Bay. Hypoxic events appear to be predominantly intermittent and are associated with salinity stratification of the water column particularly during times of low wind speeds. Salinity stratification appears to be a product of evaporation and a consequence of denser water near the bottom.

References

Dauer, D. M., A. J. Rodi Jr., and J. A. Ranasinghe. 1992. Effects of low dissolved oxygen events on the macrobenthos of the lower Chesapeake Bay. Estuaries 15:384-391.

Diaz, R. J., R. J. Neubauer, L. C. Schaffner, L. Pihl, and S. P. Baden. 1992. Continuous monitoring of dissolved oxygen in an estuary experiencing periodic hypoxia and the effect of hypoxia on macrobenthos and fish. Science of the Total Environment (Suppl. 1992):1055-1068.

Diaz, R. J. and R. Rosenberg. 1995. Marine benthic hypoxia: a review of its ecological effects and the behavioural responses of benthic macrofauna. Oceanography and Marine Biology Annual Review 33:245-303.

Harper D. Personal communication.

Gunter, G. 1942. Offatts Bayou, a locality with recurrent summer mortality of marine organisms. The American Midland Naturalist 28(3):631-633.

Martin, C. M. and P. A. Montagna. 1995. Environmental assessment of LaQuinta Channel, Corpus Christi Bay, Texas. Texas Journal of Science 47:203-222.

McKinney, L. D. and D. E. Harper. 1980. The effects of hypoxia on the structure of benthic marine communities in the western Gulf of Mexico. American Zoologist 20:742 (abstract).

Montagna, P. A. and R. D. Kalke. 1992. The effect of freshwater inflow on meiofaunal and macrofaunal populations in the Guadalupe and Nueces Estuaries, Texas. Estuaries 15:307-326.

Montagna, P. A. and R. D. Kalke. 1995. Ecology of infaunal mollusca in south Texas estuaries. American Malacological Bulletin 11(2):163-175.

Orlando, S. P. Jr., L. P. Rozas, G.H. Ward, and C. J. Klein. 1991. Analysis of salinity structure and stability for Texas estuaries. Strategic Assessment Branch, National Oceanic and Atmospheric Association, National Ocean Service, Rockville, Maryland.

Phil, L., S. P. Baden, R. J. Diaz, and L. C. Schaffner. 1992. Hypoxia-induced structural changes in the diet of bottom-feeding fish and Crustacea. Marine Biology 112:349-361.

Pokryfki L., and R.E. Randall. 1987. Nearshore hypoxia in the bottom water of the northwestern Gulf of Mexico from 1981 to 1984. *Mar. Environ. Res.* 22:75-90.

Port of Corpus Christi Authority. 1993. Phase II. Safeharbor Environmental Impact Statement. Port of Corpus Christi Authority, Corpus Christi, Texas.

Powell, G., J. Matsumoto, and W. L. Longley. 1997 Effects of structures and practices on the circulation and salinity patterns of the Corpus Christi Bay National Estuary Program Study Area. CCBNEP-19. Texas Natural Resources Conservation Commission, Austin, Texas.

Rabalais N. N., R. E. Turner, Wiseman W.J., and D.F. Boesch, 1991. A brief summary of hypoxia on the northern Gulf of Mexico continental shelf: 1985-1988, p.35-47. *In* R. V. Tyson and T.H. Pearson (eds.), Modern and Ancient Continental Shelf Anoxia. Geological Society Special Publication No. 58. Geological Society Publishing House, Bath, United Kingdom.

Rabalais N. N. and R. E. Turner (eds.). 2001. Coastal Hypoxia: Consequences for Living Resources and Ecosystems. Coastal and Estuarine Studies 58, American Geophysical Union, Washington, D.C.

Rabalais, N. N., R. E. Turner and W. J. Wiseman, Jr. 2001. Hypoxia in the Gulf of Mexico. Journal of Environmental Quality 30(2): 320-329.

Ritter, C. and P. A. Montagna. 2001. Cause and effect of hypoxia (low oxygen) in Corpus Christi Bay, Texas. Coastal Management Program Report. Grant no. 00-051-R. University of Texas Marine Science Institute, Technical Report number 2001-001.

Ritter, C. and P. A. Montagna. 1999. Seasonal hypoxia and models of benthic response in a Texas bay. Estuaries 22:7-20.

SAS Institute Inc. 2001. Procedures Guide for Personal Computers, Version 8.1. SAS Institute Inc., Cary, North Carolina.

Texas Water Development Board. 2001. Ambient water quality data website. http://hyper20.twdb.state.tx.us/data/bays_estuaries/sondpage.html

Thurman H. V. and E. A. Burton. 2001. *Introductory Oceanography*. 9th Edition. Prentice Hall, New Jersey.

Tyson, R. V. and T. H. Pearson. 1991. Modern and ancient continental shelf anoxia: an overview, p.1-24. In R. V. Tyson and T. H. Pearson (eds.), Modern and Ancient Continental Shelf Anoxia. Geological Society Special Publication No. 58.

Weisberg, S. B., Ranasinghe J. A., Dauer, D. M., Schaffner L. C., Diaz R. J., and Frithsen, J. B. 1997. An estuarine benthic index of biotic integrity (B-IBI) for Chesapeake Bay. Estuaries 20:149-158.

Table 1. Metric definitions for HLI.

Metric	Definition
BotDO	Mean bottom water dissolved oxygen value
BotSal	Mean bottom water salinity value
BotTemp	Mean bottom water temperature
Pattern 1	Rate of occurrence (%) for pattern one
Pattern 2	Rate of occurrence (%) for pattern two
Pattern 3	Rate of occurrence (%) for pattern three
%Hyp	Percent of Time Hypoxic ($\leq$ 2 mg l^{-1})

Table 2. Threshold values for metrics in HLI.

	Scoring Criteria				
	0	1	2	3	4
BotDO	$\geq$4.8	4.7-3.9	3.8-3	2.9-2.1	$\leq$2
BotSal	$\leq$36	36.1-37.7	37.8-39.4	39.5-41.1	>41.2
BotTemp	$\leq$29	29.1-29.3	29.4-29.6	29.7-29.9	$\geq$30
Pat1	$\geq$63.6	63.5-45.1	45-26.6	26.5-8.1	$\leq$8
Pat2	0	0.7-8.5	8.6-17	17.1-25.5	$\geq$25.6
Pat3	0	0.1-13.5	13.6-27	27.1-40.5	$\geq$40.6
%Hyp	0	0.1-13.5	13.6-27	27.1-40.5	$\geq$40.6

Table 3. Metric definitions for HDI.

Metric	Definition
%≤3	Percent of time bottom water samples were equal to or less than 3 mg l^{-1}.
%≤2	Percent of time bottom water samples were equal to or less than 2 mg l^{-1}.
%≤1	Percent of time bottom water samples were equal to or less than 1 mg l^{-1}.
%≤Sta5	Percent of stations with average bottom water dissolved oxygen value equal to or less than 5.
%≤Sta4	Percent of stations with average bottom water dissolved oxygen value equal to or less than 4.
%≤Sta3	Percent of stations with average bottom water dissolved oxygen value equal to or less than 3.

Table 4. HDI metric values for all years sampled.

	All Samples			All Stations		
	%≤3	%≤2	%≤1	%Sta≤5	%Sta≤4	%Sta≤3
1994	4.2	0.0	0.0	12.5	12.5	0.0
1997	27.3	0.0	0.0	81.8	54.5	27.3
1999	8.3	8.3	2.8	75.0	41.7	25.0
2000	5.6	0.7	0.0	83.3	0.0	0.0
2001	16.7	11.1	3.5	83.3	75.0	8.3

Table 5. Average bottom water dissolved oxygen values for stations.

Sta	1994	1997	1999	2000	2001
1	6.42	6.60	5.65	5.99	6.0
2	5.95	4.55	5.48	5.15	5.1
7	6.00	3.89	2.87	4.45	3.3
8	5.47	4.67	2.93	4.37	3.3
9	5.50	4.88	3.59	4.05	4.0
10	3.94	3.20	4.21	4.27	2.5
11	4.94	2.45	4.2	4.66	3.5
12	5.35	5.14	4.55	4.91	3.7
14	.	3.29	5.37	4.5	3.7
18	.	2.77	3.7	4.55	4.0
24	.	.	4.06	4.25	3.0
30	.	2.58	2.96	4.14	4.3

Table 6. Metric scores and averages for HDI.

	1994	1997	1999	2000	2001
%≤3	1	3	3	3	3
%≤2	1	1	3	1	3
%≤1	1	1	1	1	1
%Sta≤5	3	5	5	5	5
%Sta≤4	1	5	3	1	5
%Sta≤3	1	3	3	1	3
Avg Rank	1.3	3.0	3.0	2.0	3.3

Table 7. Observed hypoxia events at station 24 during first deployment (7/9/01 - 7/19/01).

Begin		End		Duration of Hypoxia (hrs)	
Date	Time	Date	Time	≤ 2 mg l^{-1}	≤ 1 mg l^{-1}
A) 9 July - 19 July					
10-Jul	6:16	10-Jul	9:46	3.50	0.00
11-Jul	8:31	11-Jul	11:31	3.00	0.00
13-Jul	6:01	13-Jul	8:16	2.25	0.00
13-Jul	9:31	13-Jul	9:46	0.25	0.00
14-Jul	6:01	14-Jul	6:16	0.25	0.00
14-Jul	6:46	14-Jul	8:46	2.00	0.00
14-Jul	10:46	14-Jul	12:16	2.00	0.00
14-Jul	13:01	14-Jul	13:31	0.50	0.00
15-Jul	4:01	15-Jul	13:16	9.50	1.50
15-Jul	20:16	15-Jul	20:31	0.25	0.00
15-Jul	20:46	15-Jul	1:31	3.25	0.50
16-Jul	1:46	16-Jul	2:31	0.75	0.25
16-Jul	3:01	16-Jul	3:16	0.25	0.00
16-Jul	5:01	16-Jul	6:01	1.00	0.50
16-Jul	6:16	16-Jul	6:46	0.50	0.00
16-Jul	7:01	16-Jul	9:46	2.75	0.25
16-Jul	10:16	16-Jul	10:31	0.25	0.00
16-Jul	11:01	16-Jul	14:01	3.00	0.00
17-Jul	0:01	17-Jul	0:31	0.50	0.00
17-Jul	1:46	17-Jul	8:46	7.00	4.25
17-Jul	11:01	17-Jul	11:16	0.25	0.00
17-Jul	11:31	17-Jul	11:46	0.25	0.00
19-Jul	7:16	19-Jul	10:46	4.00	0.00
Subtotal A				47.25	7.25

Table 8. Observed hypoxia events at station 24 during second deployment (7/24/01 - 8/7/01).

Begin		End		Duration of Hypoxia (hrs)	
Date	Time	Date	Time	≤ 2 mg l^{-1}	≤ 1 mg l^{-1}
B) 24 July - 7 August					
25-Jul	4:01	25-Jul	4:16	0.25	0.00
25-Jul	4:16	25-Jul	4:31	0.25	0.00
25-Jul	5:01	25-Jul	7:01	2.00	0.00
25-Jul	7:16	25-Jul	8:01	0.75	0.00
25-Jul	9:16	25-Jul	9:31	0.25	0.00
25-Jul	9:46	25-Jul	10:01	0.25	0.00
26-Jul	2:01	26-Jul	3:16	1.25	0.00
26-Jul	6:01	26-Jul	6:16	0.25	0.00
26-Jul	6:31	26-Jul	14:01	7.50	0.00
26-Jul	14:31	26-Jul	15:01	0.50	0.00
30-Jul	10:16	30-Jul	12:01	0.75	0.00
30-Jul	12:16	30-Jul	13:01	0.75	0.00
30-Jul	17:31	30-Jul	20:16	2.75	0.00
1-Aug	7:31	1-Aug	11:16	3.75	0.75
1-Aug	11:31	1-Aug	12:16	0.75	0.00
2-Aug	21:16	2-Aug	21:31	0.25	0.00
5-Aug	1:31	5-Aug	2:16	0.75	0.00
6-Aug	3:46	6-Aug	14:01	10.25	5.25
6-Aug	5:01	6-Aug	6:46	1.75	0.00
6-Aug	6:31	6-Aug	7:01	0.50	0.00
6-Aug	1:46	6-Aug	2:01	0.25	0.00
6-Aug	2:31	6-Aug	2:46	0.25	0.00
6-Aug	3:46	6-Aug	4:01	0.25	0.00
6-Aug	9:46	6-Aug	10:01	0.25	0.00
6-Aug	10:31	6-Aug	11:46	1.25	0.00
7-Aug	10:31	7-Aug	11:16	0.75	0.00
Subtotal B				38.5	6
Total A+B				85.75	13.25

Table 9. Correlation values for hydrographic parameters for hypoxic station 10 and normoxic station 2. Top triangle in table is correlation values for station 10 and bottom triangle is values for station 2. Top number in cell is Pearson correlation coefficient, and bottom number in cell is P value.

		Station 10					
		Salinity (ppt)	Temp (ºC)	D.O. (mg l^{-1})	PO_4 (µM)	DIN (µM)	Chl (µg l^{-1})
Station 2	Salinity (ppt)		0.4363 0.0014	-0.4894 0.0003	0.0545 0.7318	0.3286 0.0336	0.7499 0.0050
	Temp (ºC)	0.3257 0.0331		-0.8124 <0.0001	0.2139 0.1737	0.1446 0.3608	0.2622 0.4104
	D.O. (mg l^{-1})	-0.3756 0.0131	-0.8492 0.6302		-0.2427 0.1215	-0.4537 0.0025	-0.3345 0.2880
	PO_4 (µM)	0.0454 0.7924	0.3177 0.0590	-0.3175 0.0592		0.1466 0.3308	0.5538 0.0399
	DIN (µM)	0.0219 0.8989	0.0533 0.7575	0.1113 0.5181	0.0245 0.8825		-0.1982 0.4970
	Chl (µg l^{-1})	0.8526 0.0009	0.5274 0.0955	-0.5622 0.0719	0.3410 0.2411	-0.3349 0.2633	

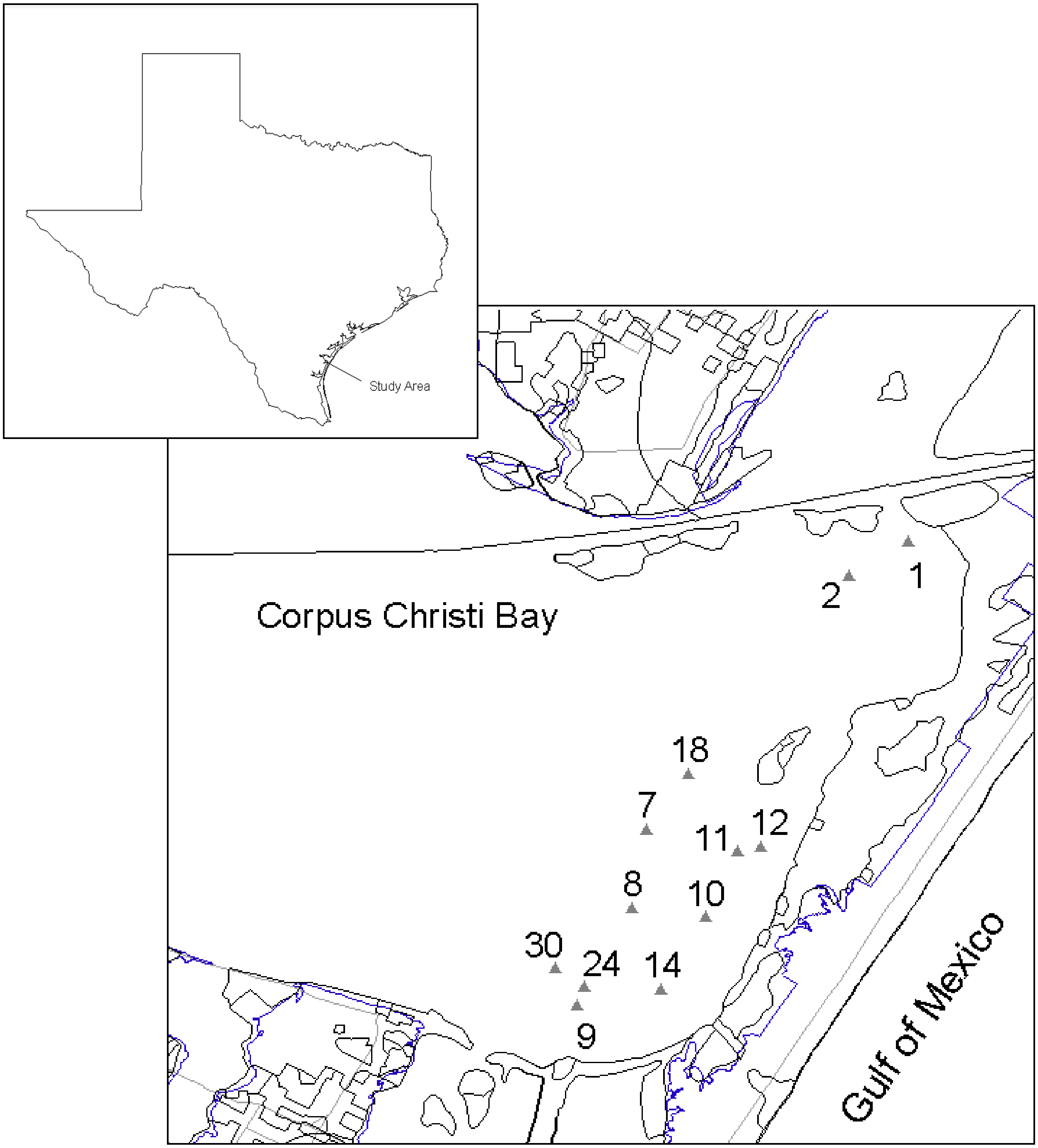


Figure 1. Map of study area.

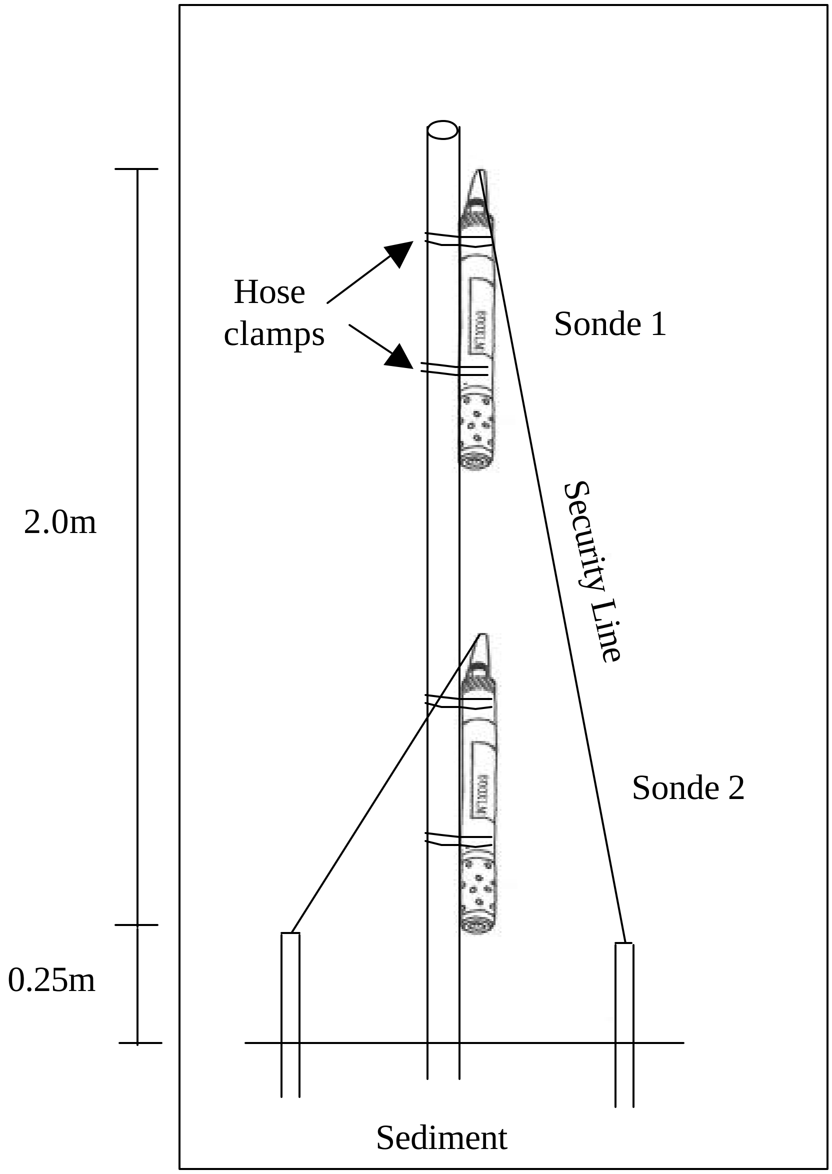


Figure 2. YSI mooring system.

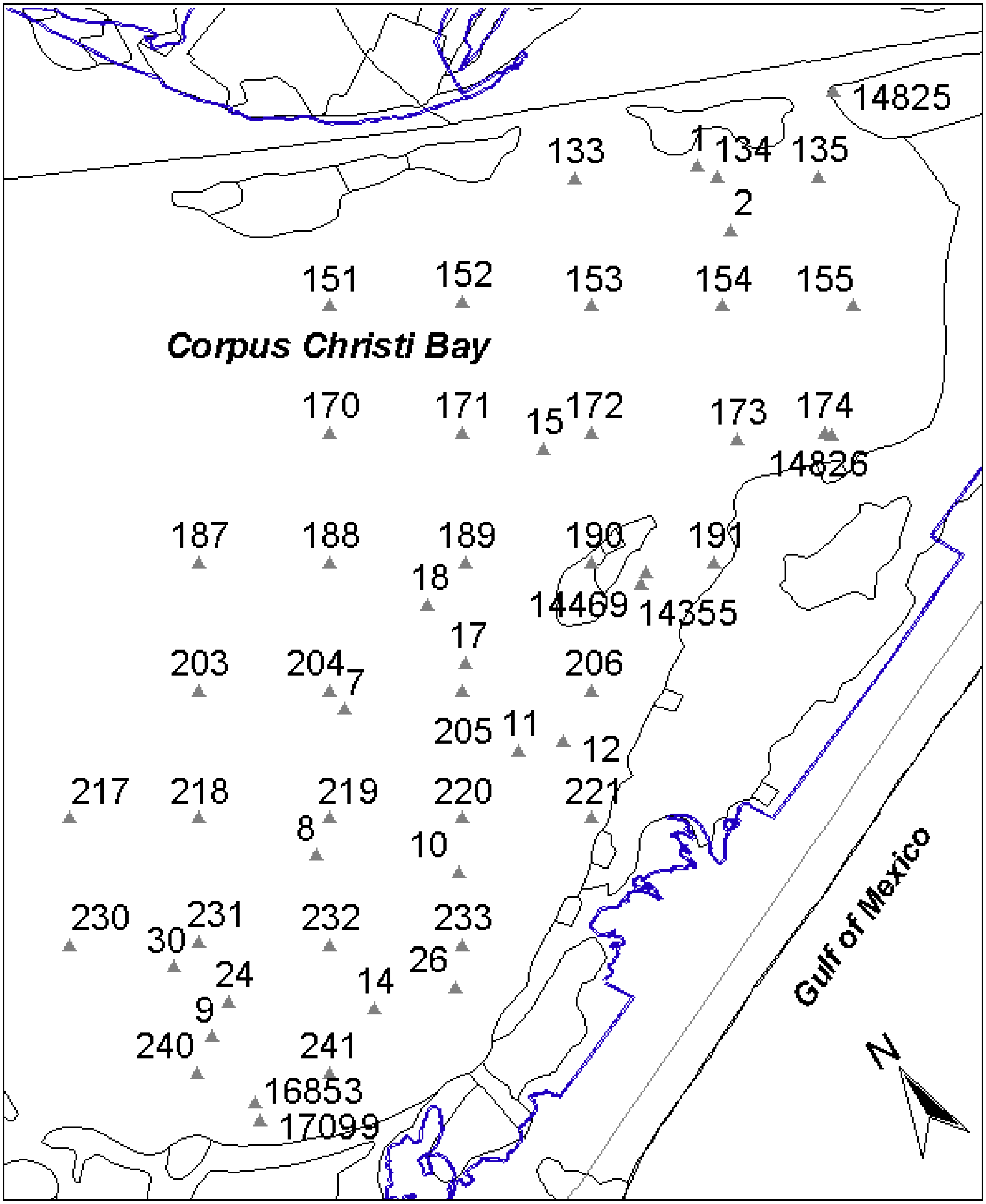
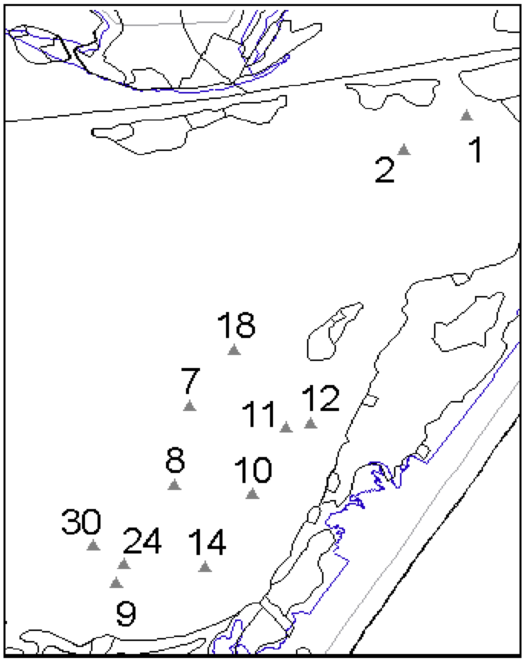
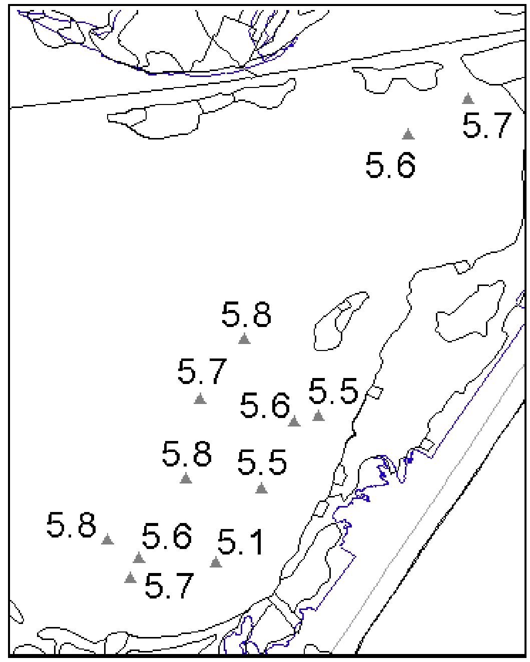


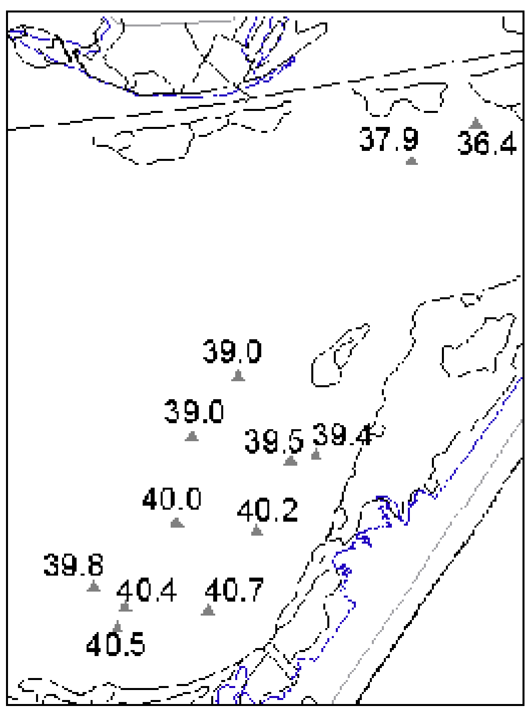
Figure 3. Map of stations used in climate change analysis.



A

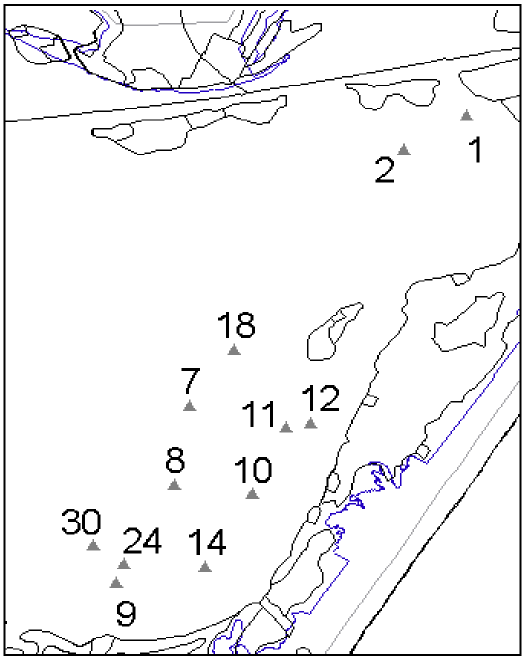


B.

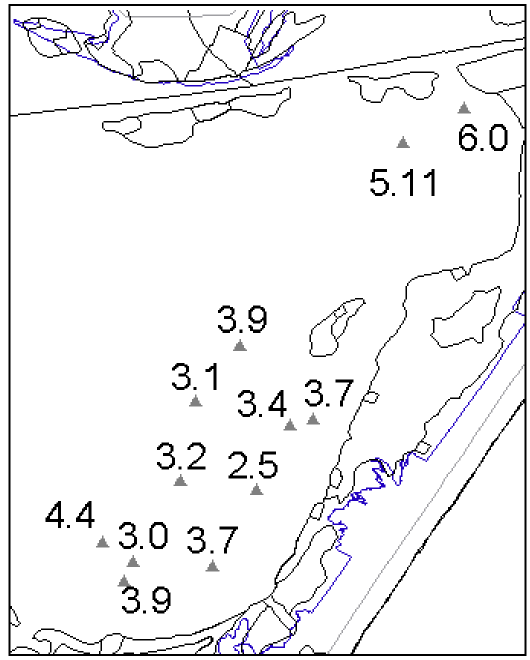


C.

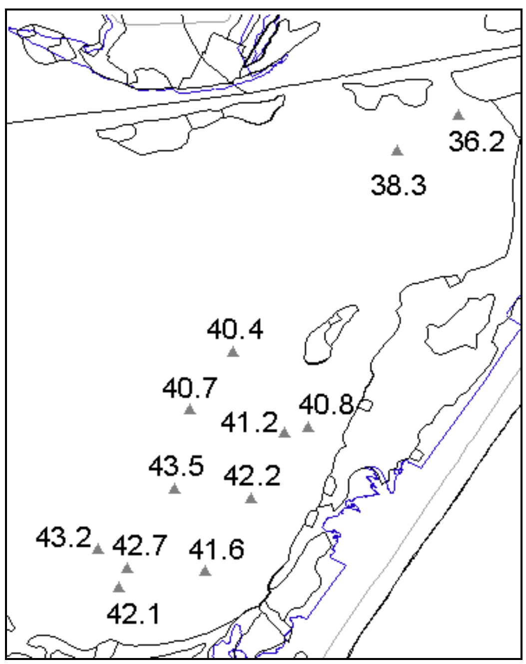
Figure 4. Mean surface water values for salinity and dissolved oxygen, 2001. A. Map of stations. B. Mean surface dissolved oxygen. C. Mean surface salinity.



A.



B.



C.

Figure 5. Mean bottom water values for salinity and dissolved oxygen, 2001. A. Map of stations. B. Mean bottom dissolved oxygen. C. Mean bottom salinity.

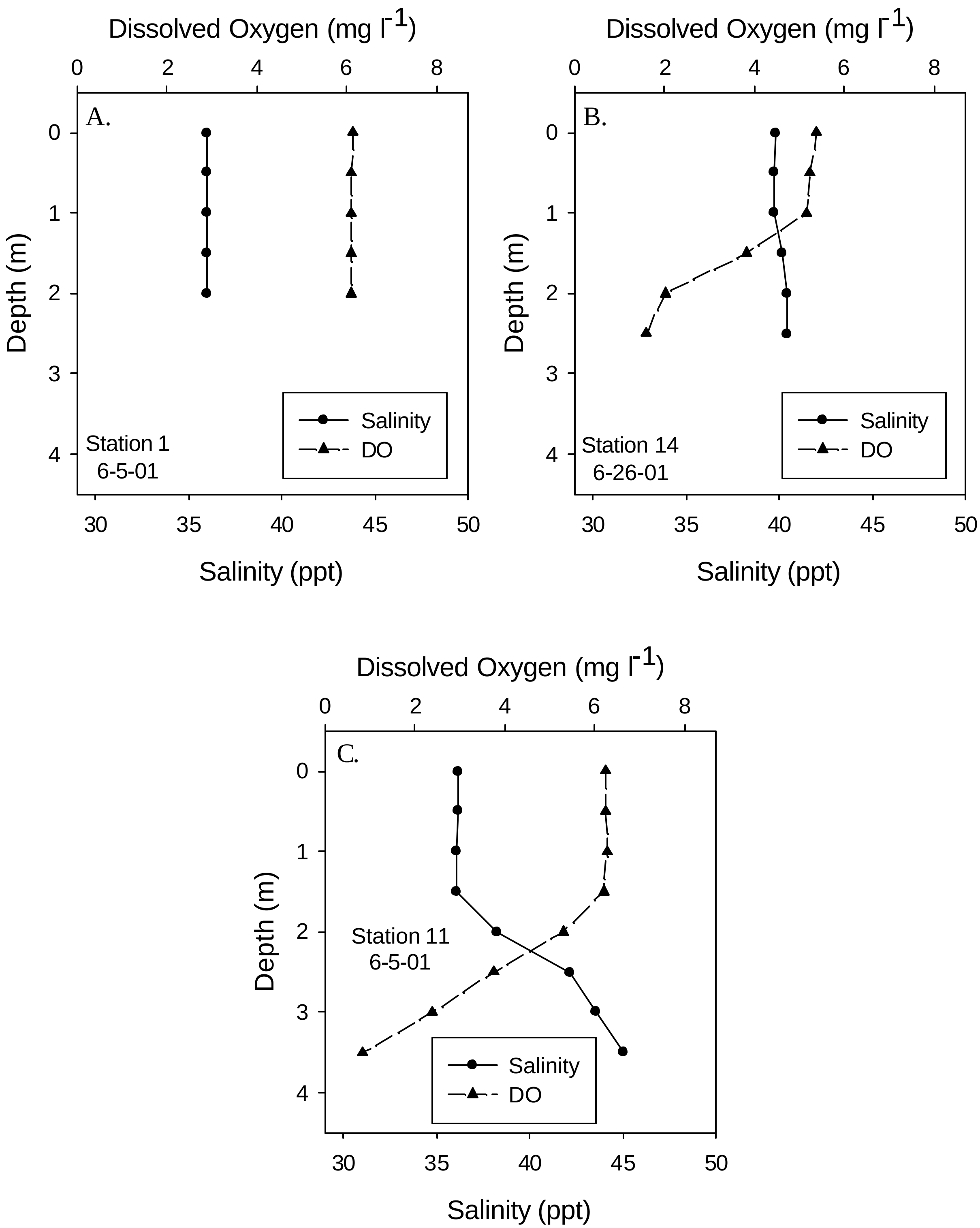


Figure 6. Depth profile patterns. A. Pattern one. B. Pattern two. C. Pattern three.

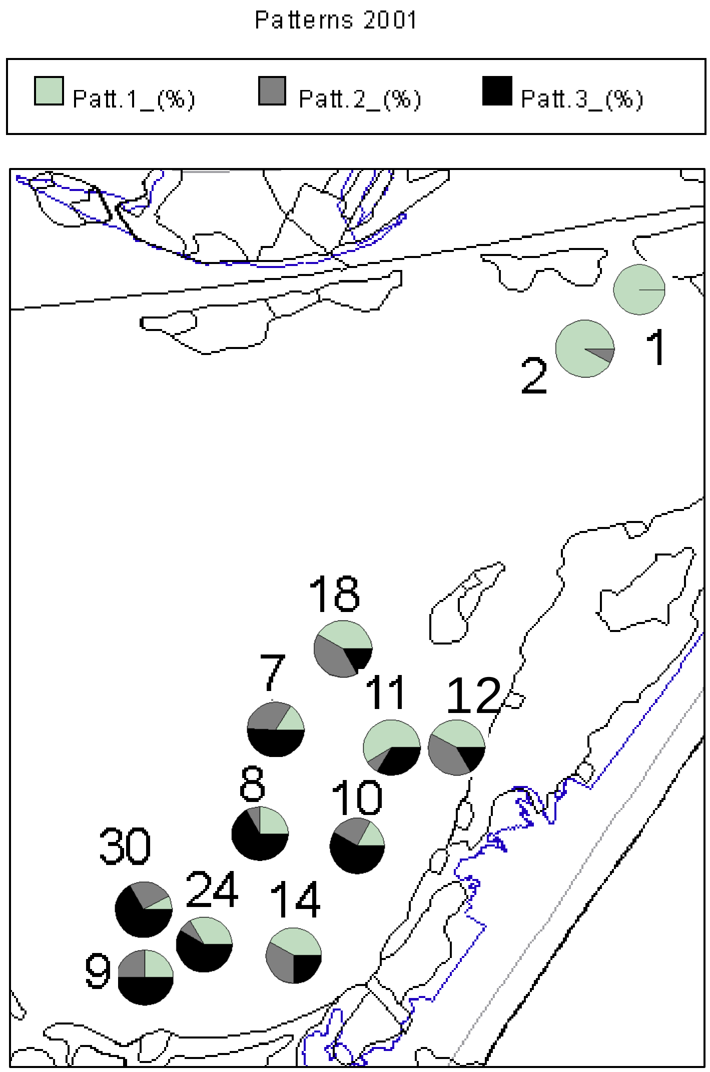


Figure 7. Rate of occurrence in percent for pattern 1, 2, and 3 during 2001.

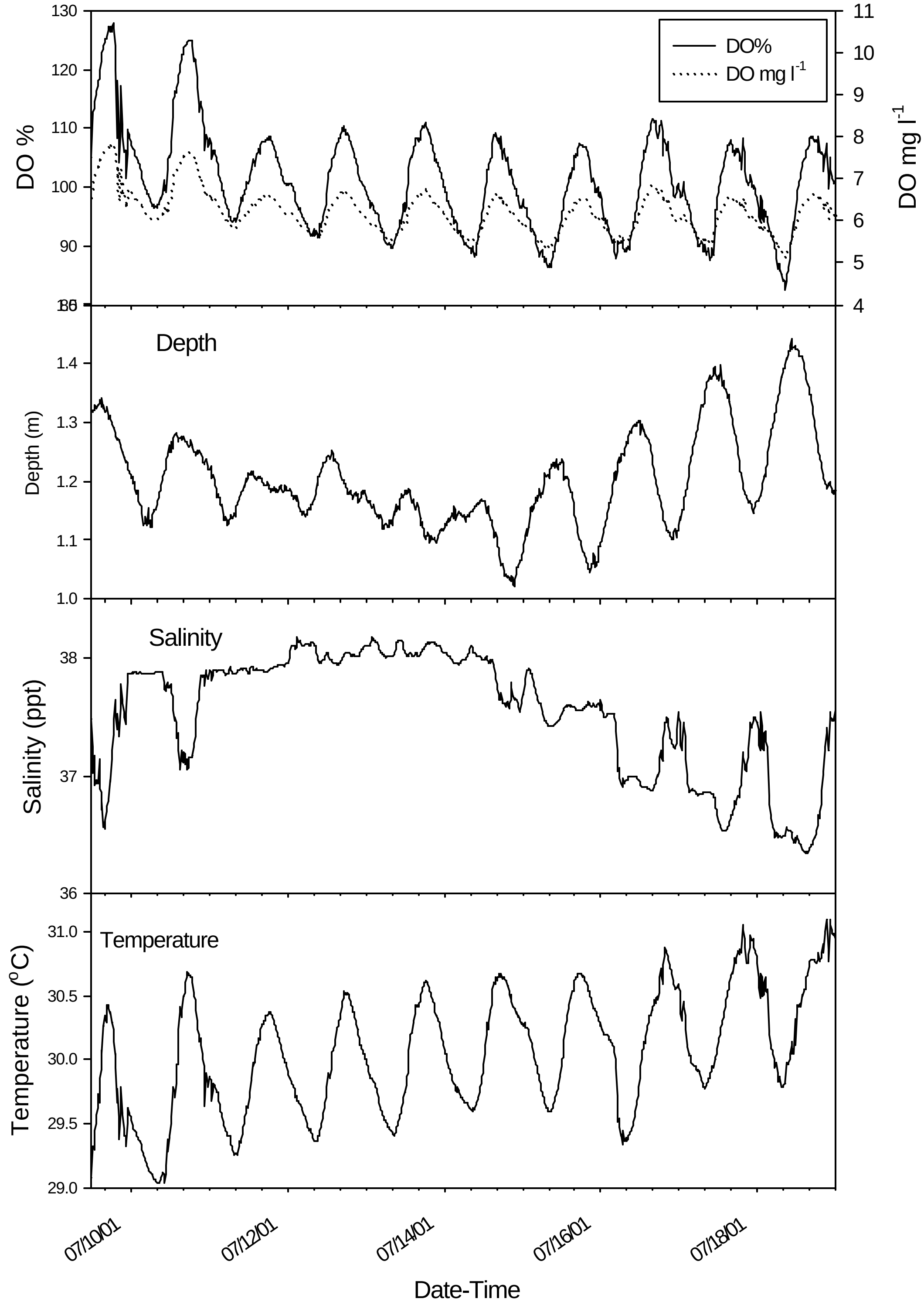


Figure 8. Continuous monitoring surface water parameters for station 2 during 7/9/01 - 7/19/01 deployment.

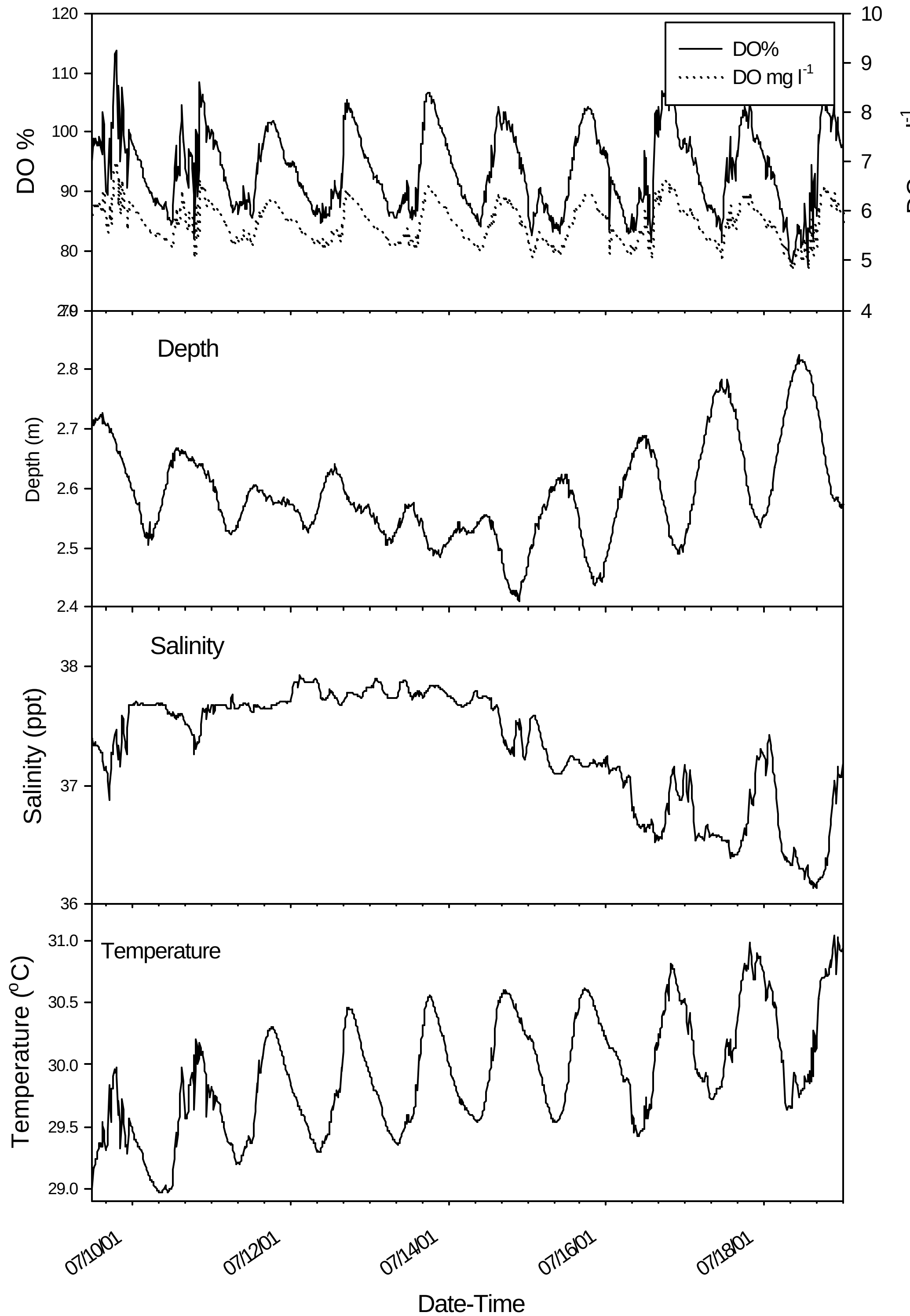


Figure 9. Continuous monitoring bottom water parameters for station 2 during 7/9/01 - 7/19/01 deployment.

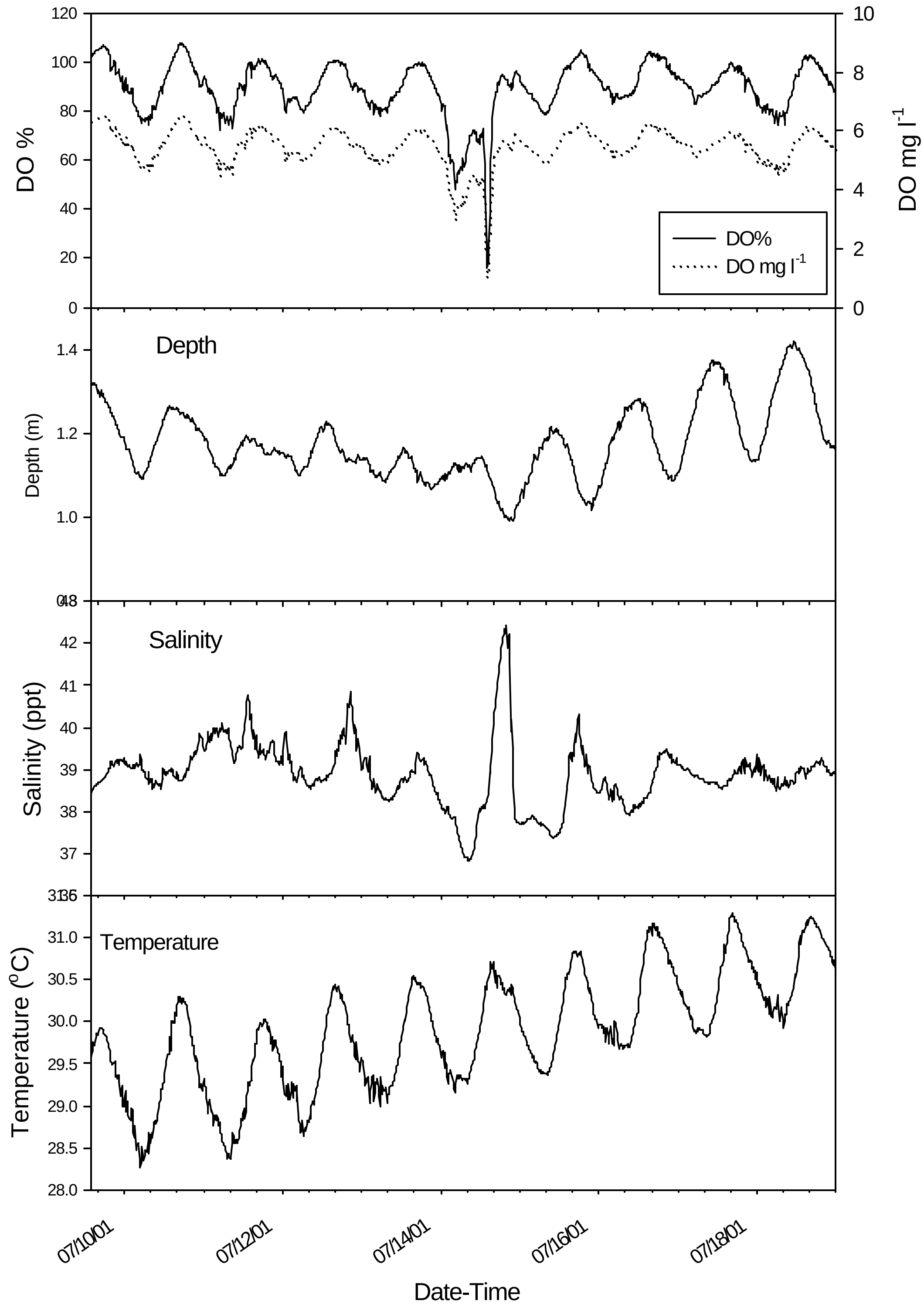


Figure 10. Continuous monitoring surface water parameters for station 24 during 7/9/01 - 7/19/01 deployment.

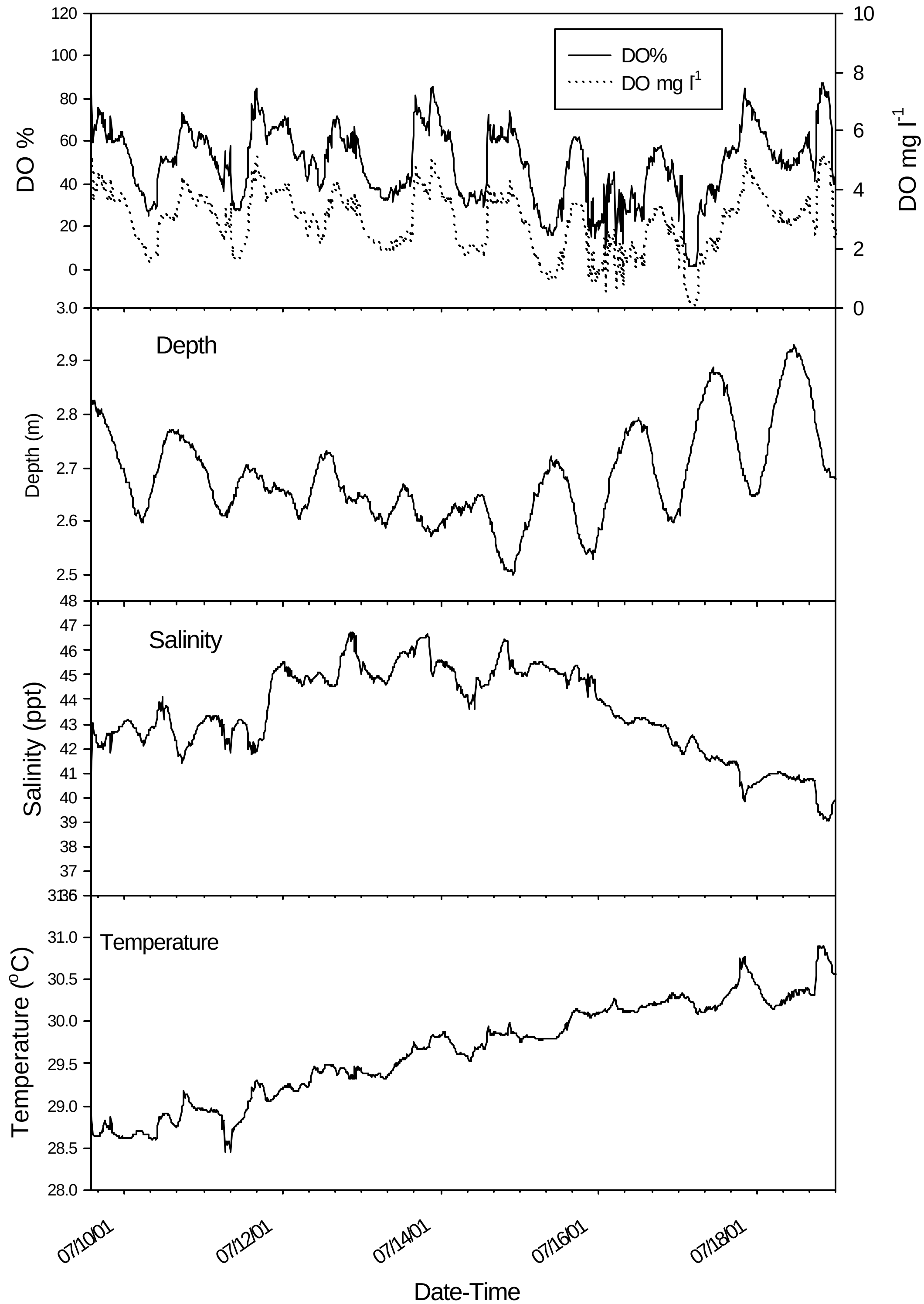


Figure 11. Continuous monitoring bottom water parameters for station 24 during 7/9/01 - 7/19/01 deployment.

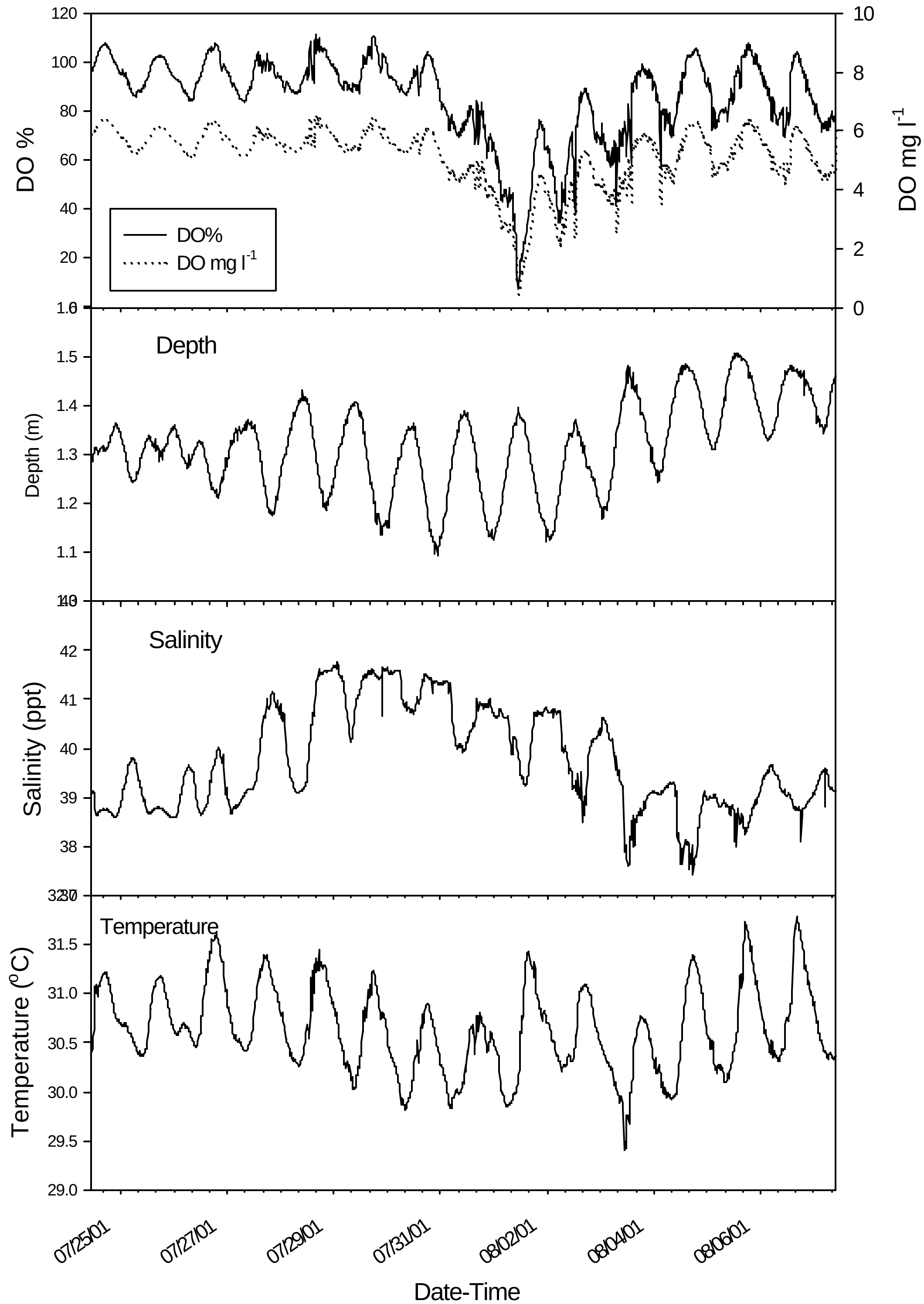


Figure 12. Continuous monitoring surface water parameters for station 2 during 7/24/01 - 8/7/01 deployment.

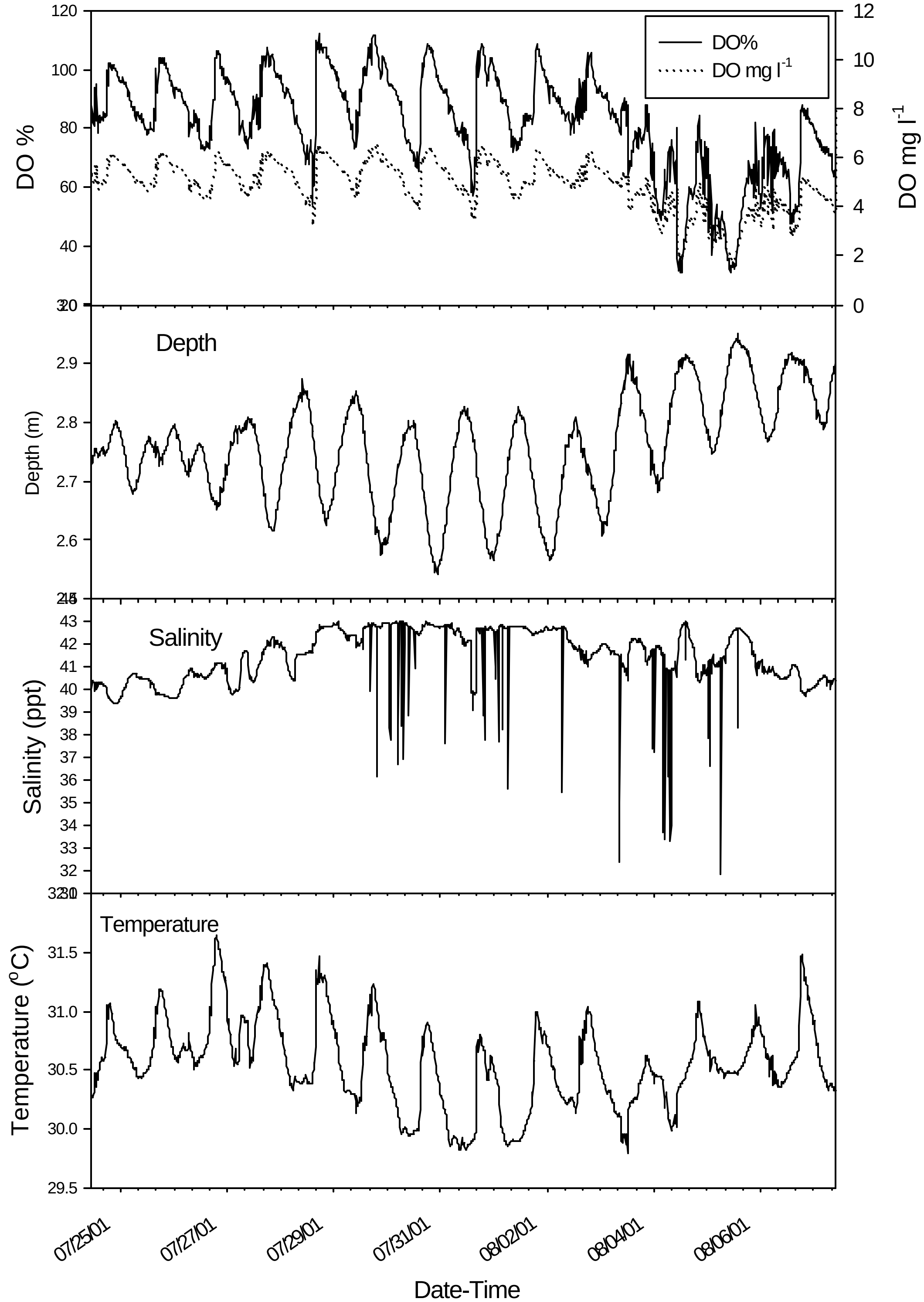


Figure 13. Continuous monitoring bottom water parameters for station 2 during 7/24/01 - 8/7/01 deployment.

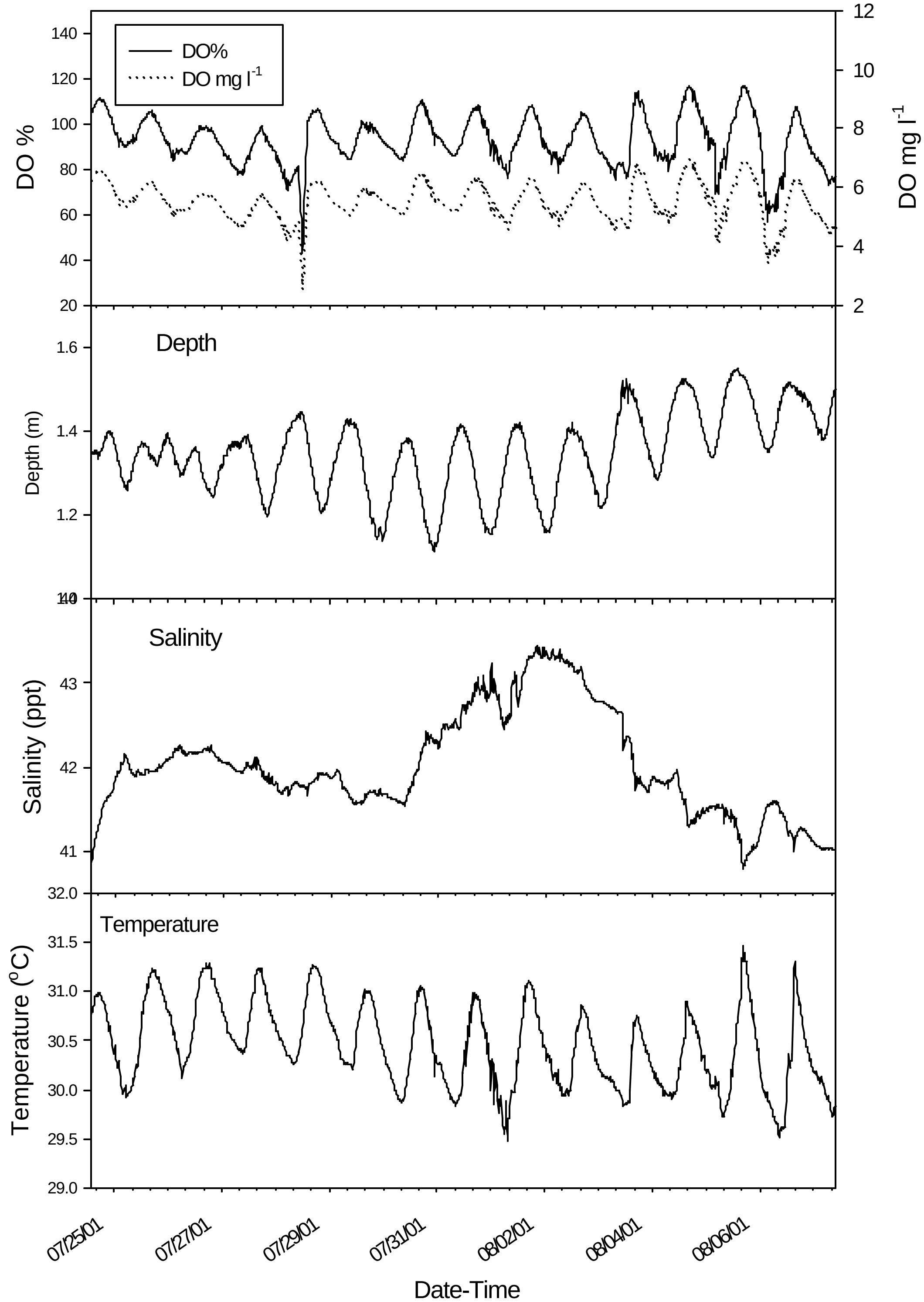


Figure 14. Continuous monitoring surface water parameters for station 24 during 7/24/01 - 8/7/01 deployment.

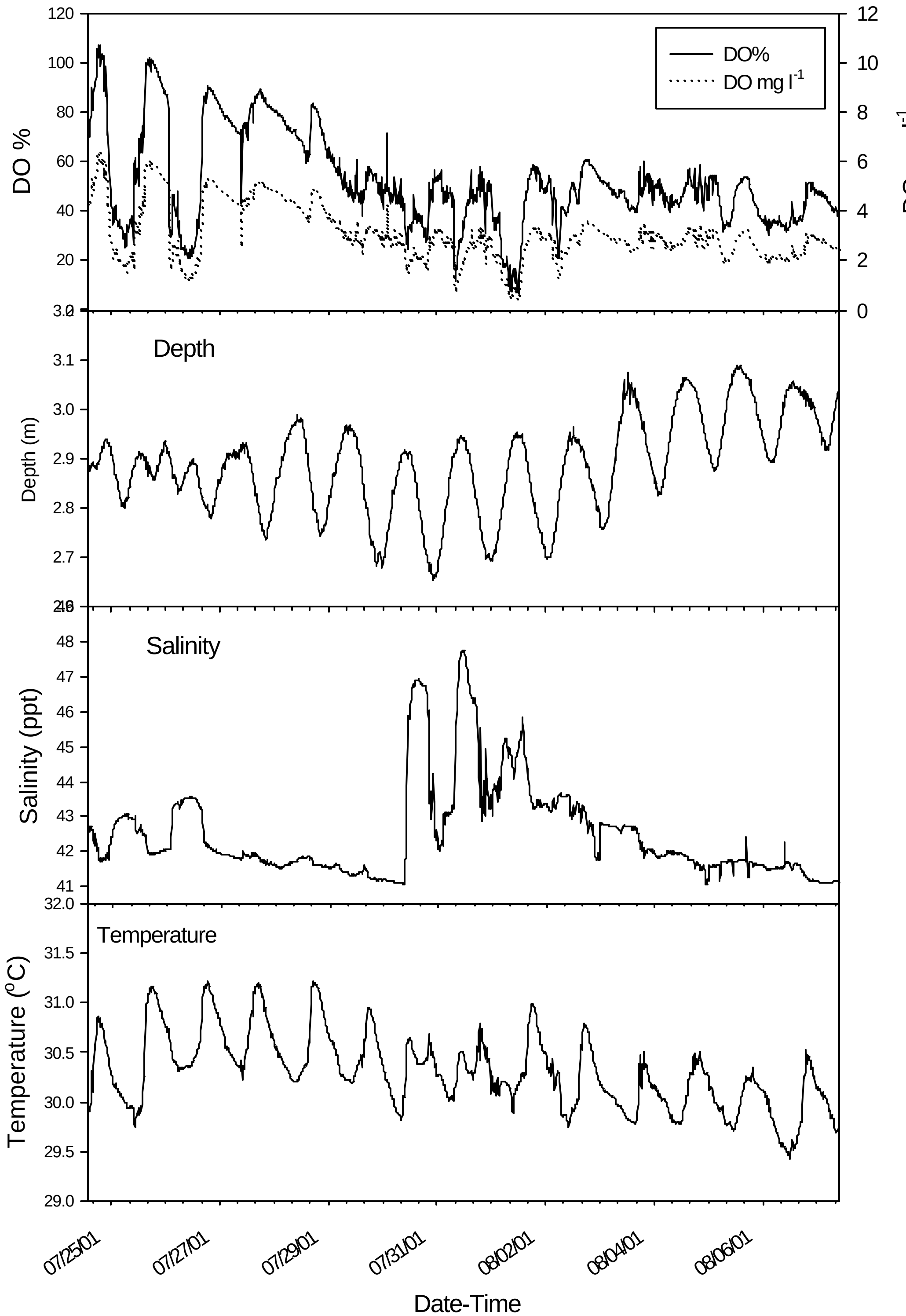


Figure 15. Continuous monitoring bottom water parameters for station 24 during 7/24/01 - 8/7/01 deployment.

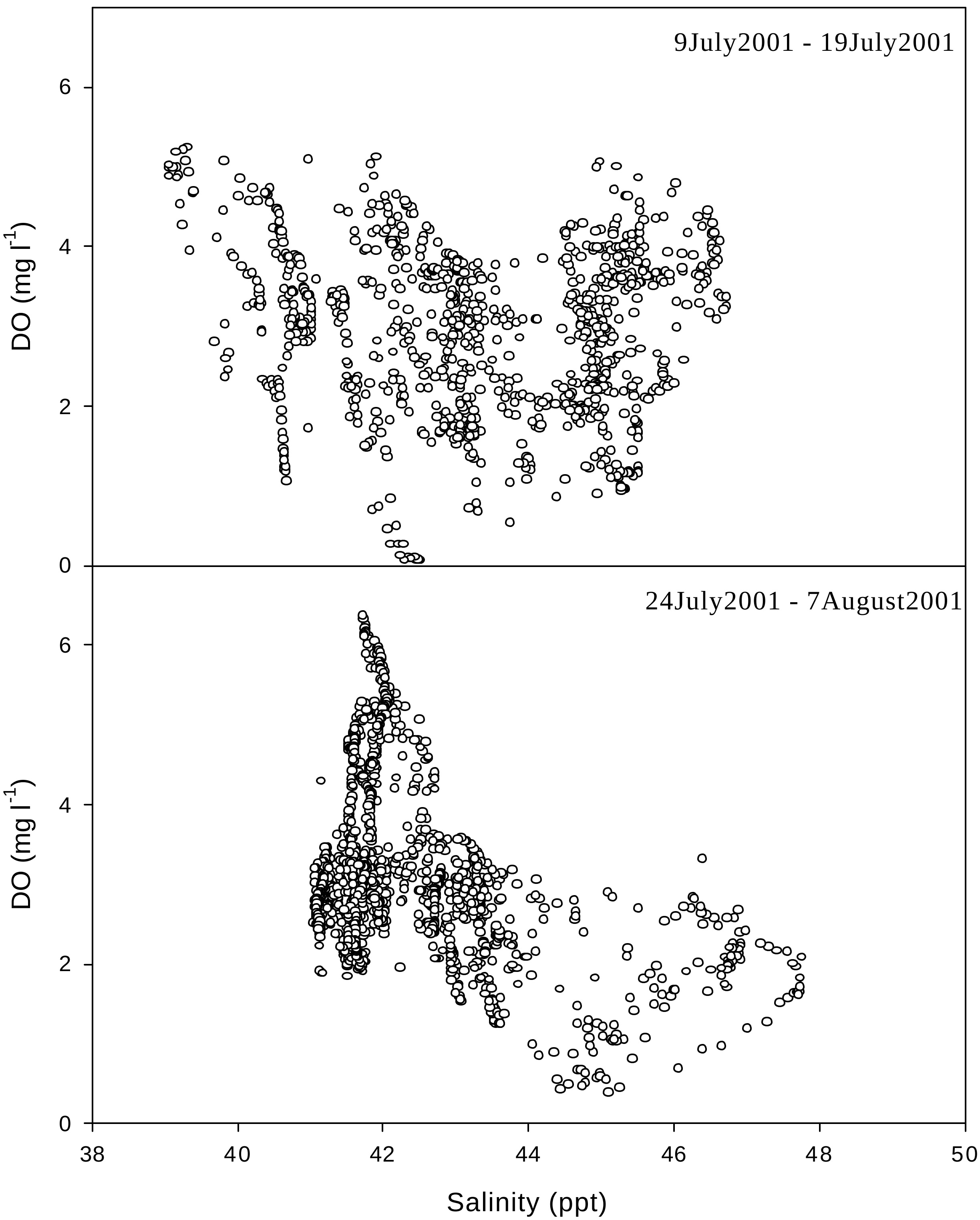


Figure 16. Bottom water salinity and dissolved oxygen relationship at hypoxic station 24.

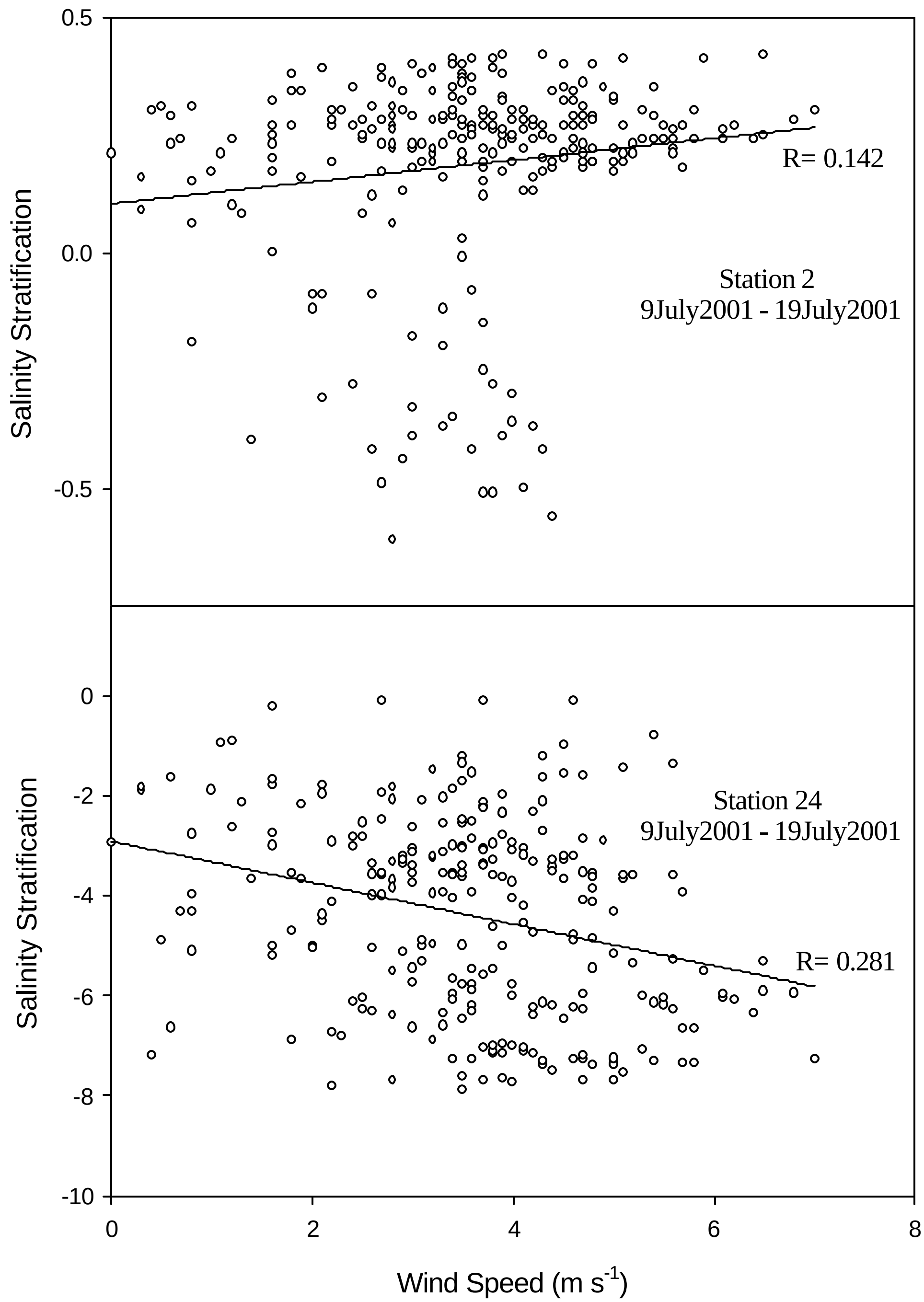


Figure 17. Salinity stratification and wind speed relationship at station 2 and 24 during 7/9/01 - 7/19/01 deployment.

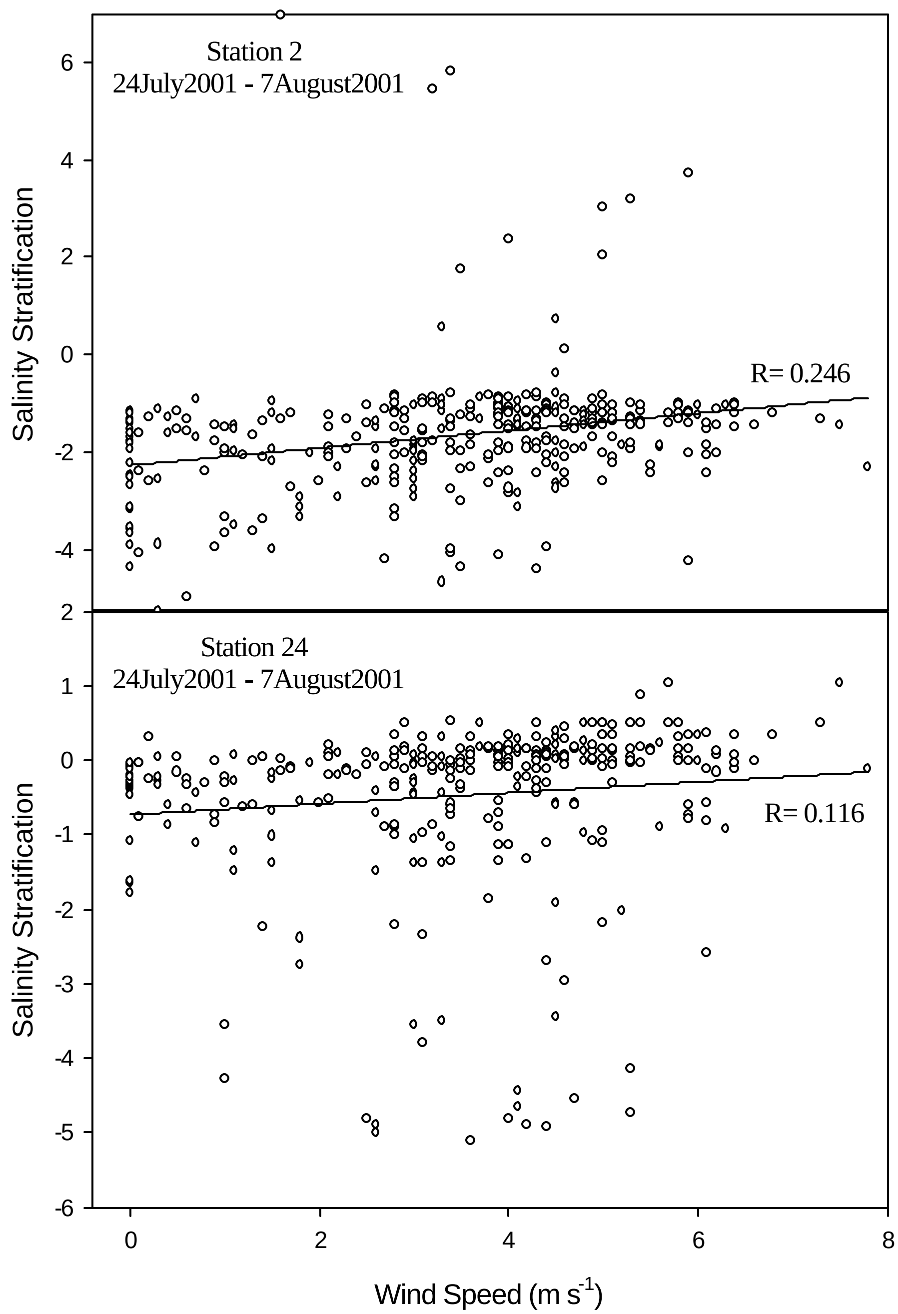


Figure 18. Salinity stratification and wind speed relationship at station 2 and 24 during 7/24/01 - 8/7/01 deployment.

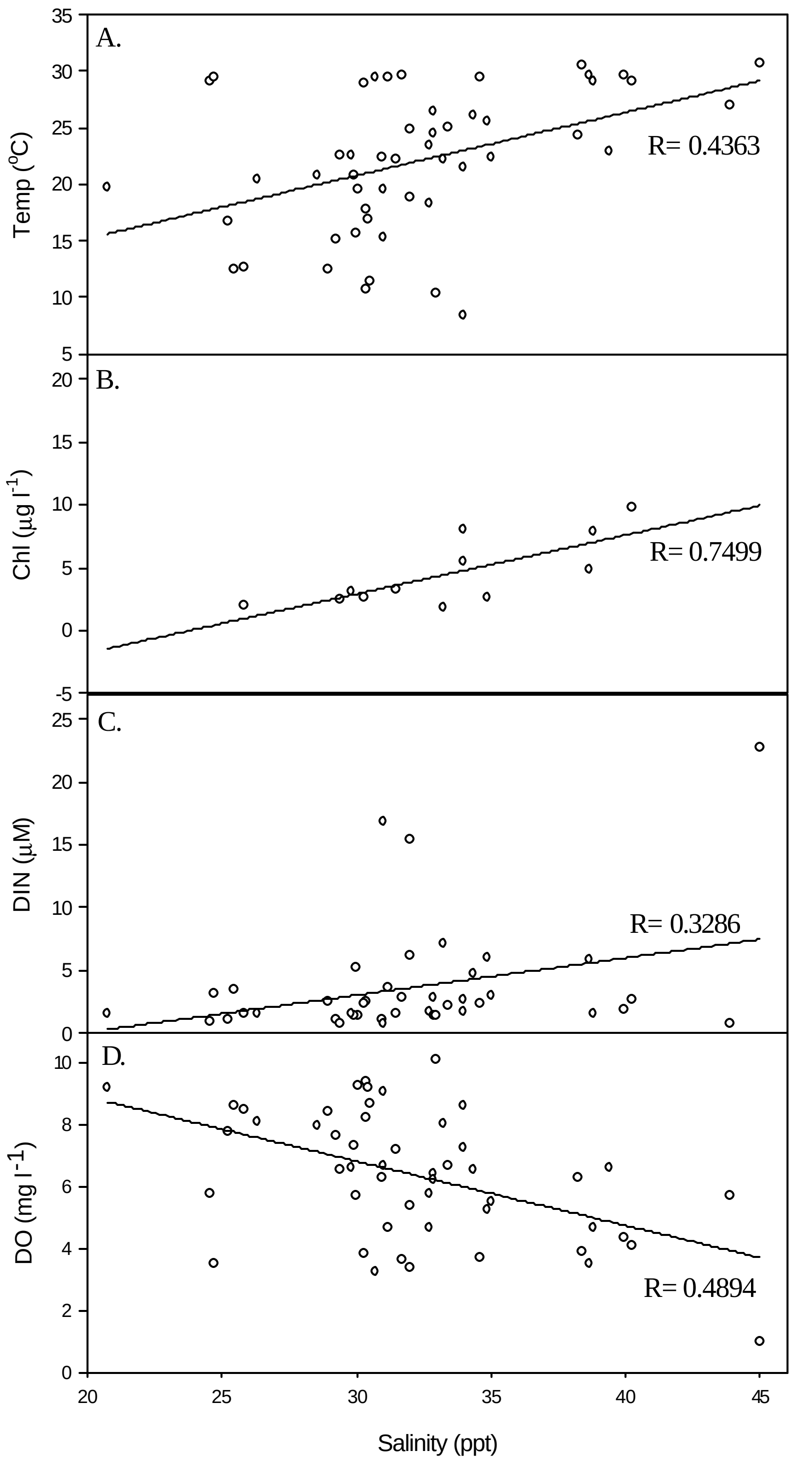


Figure 19. Hydrographic relationships with salinity at hypoxic station 10. Values are averages or surface and bottom water parameters. A. Salinity versus temperature. B. Salinity verses chlorophyll. C. Salinity versus dissolved inorganic nitrogen. D. Salinity verses dissolved oxygen.

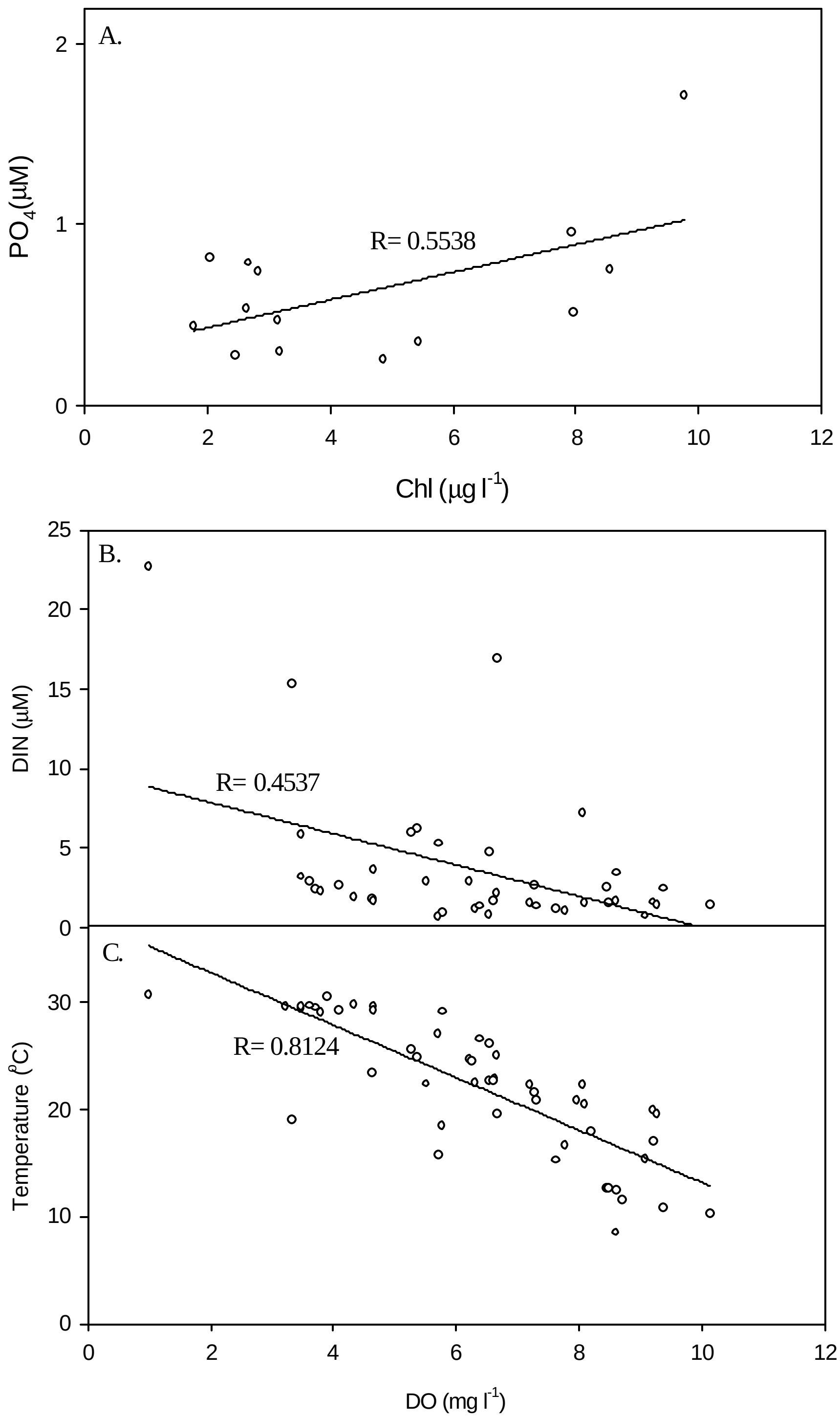


Figure 20. Hydrographic relationships with chlorophyll at hypoxic station 10. Values are averages or surface and bottom water parameters. A. Dissolved oxygen verses dissolved inorganic nitrogen. B. Dissolved oxygen verses temperature.

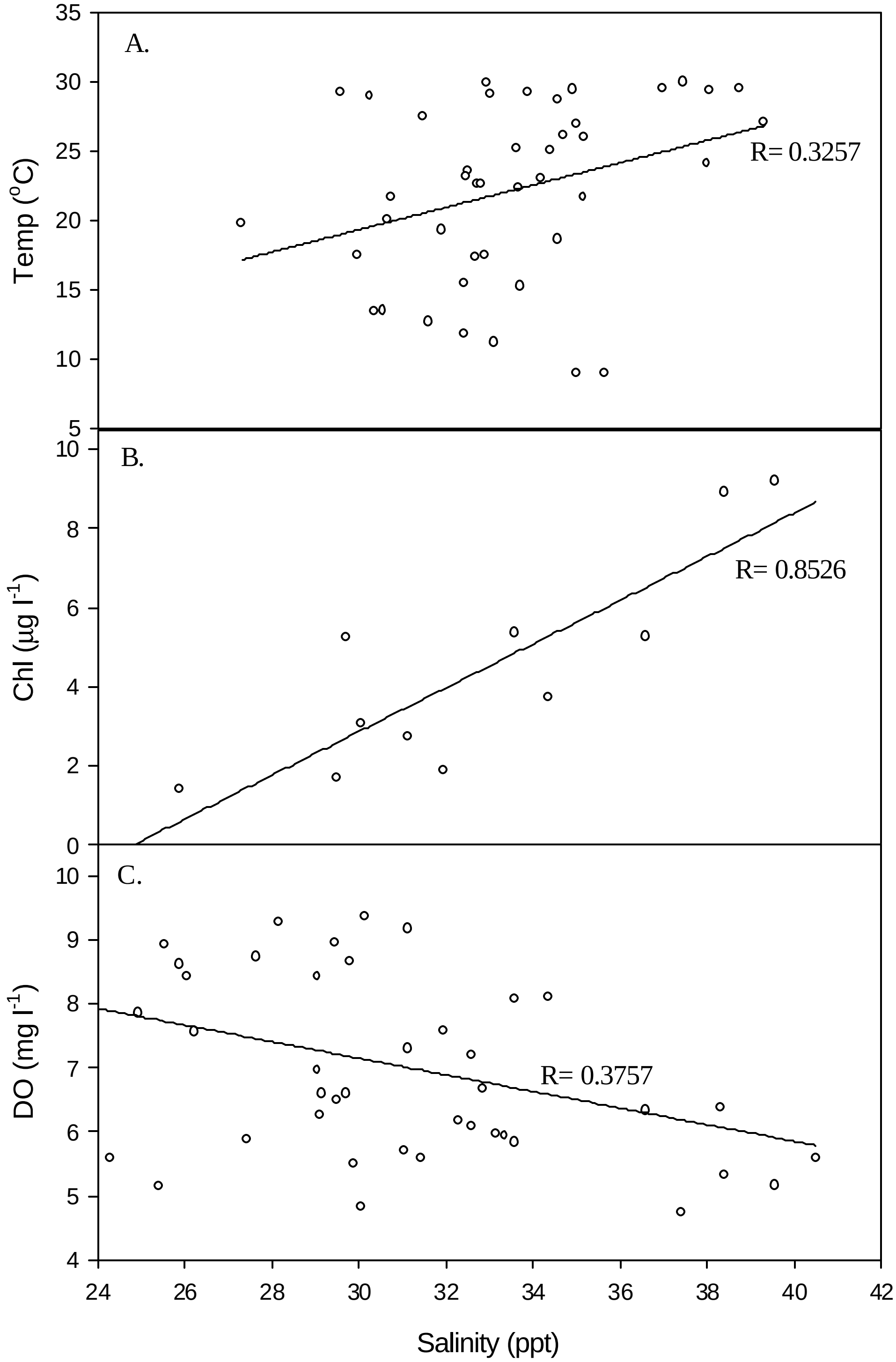


Figure 21. Hydrographic relationships with salinity at normoxic station 2. Values are averages or surface and bottom water parameters. A. Salinity versus temperature. B. Salinity verses chlorophyll. C. Salinity verses dissolved oxygen.

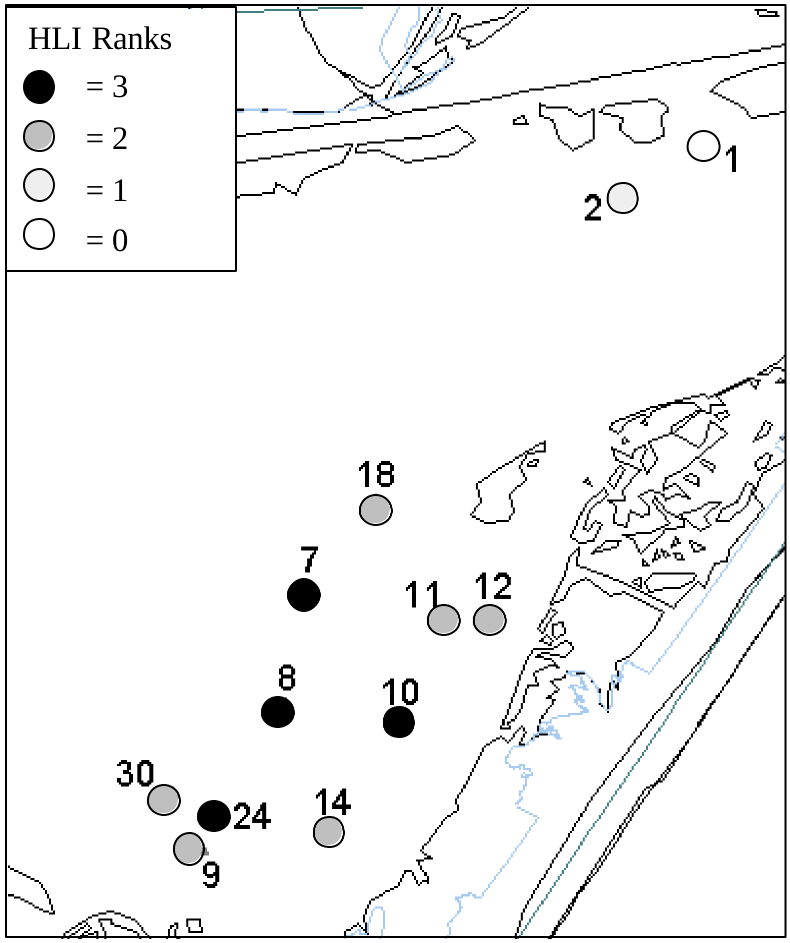


Figure 22. Hypoxia likelihood index for 2001. Stations with high ranks (i.e., 3) have a high likelihood of becoming hypoxic.

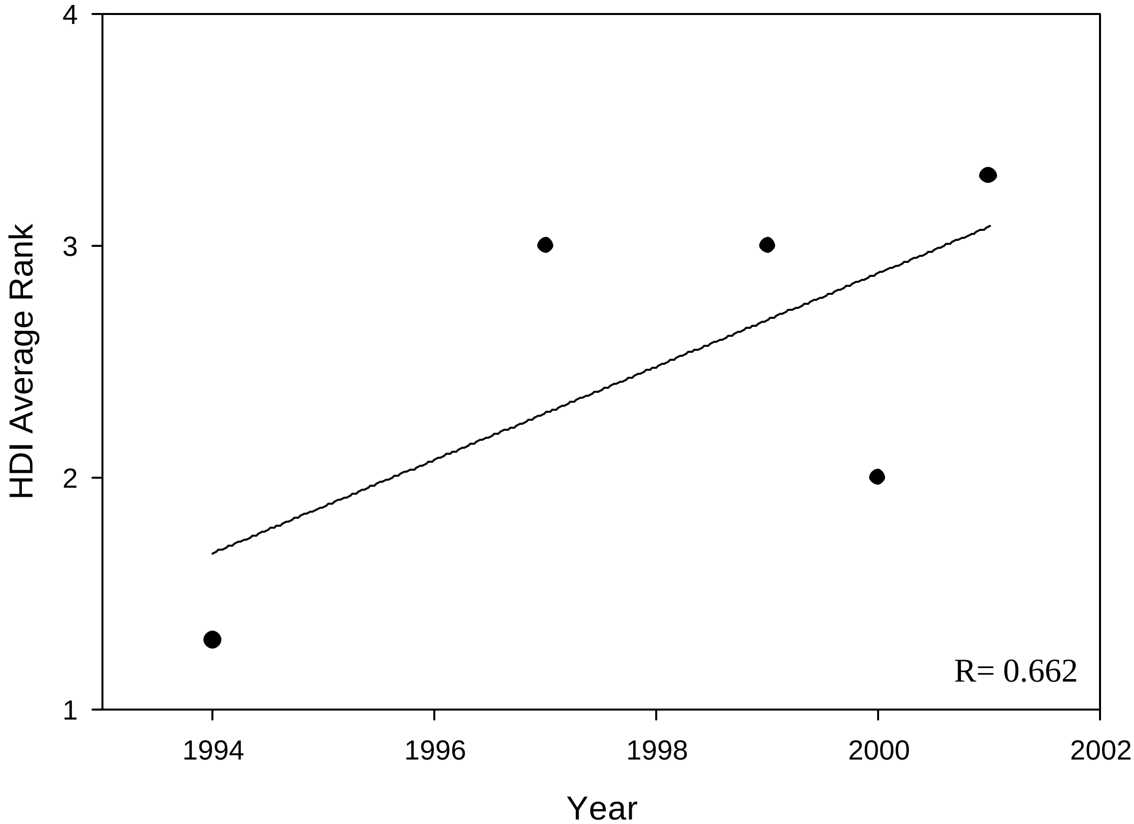


Figure 23. HDI average ranks for 1994, 1997, 1999, 2000 and 2001.

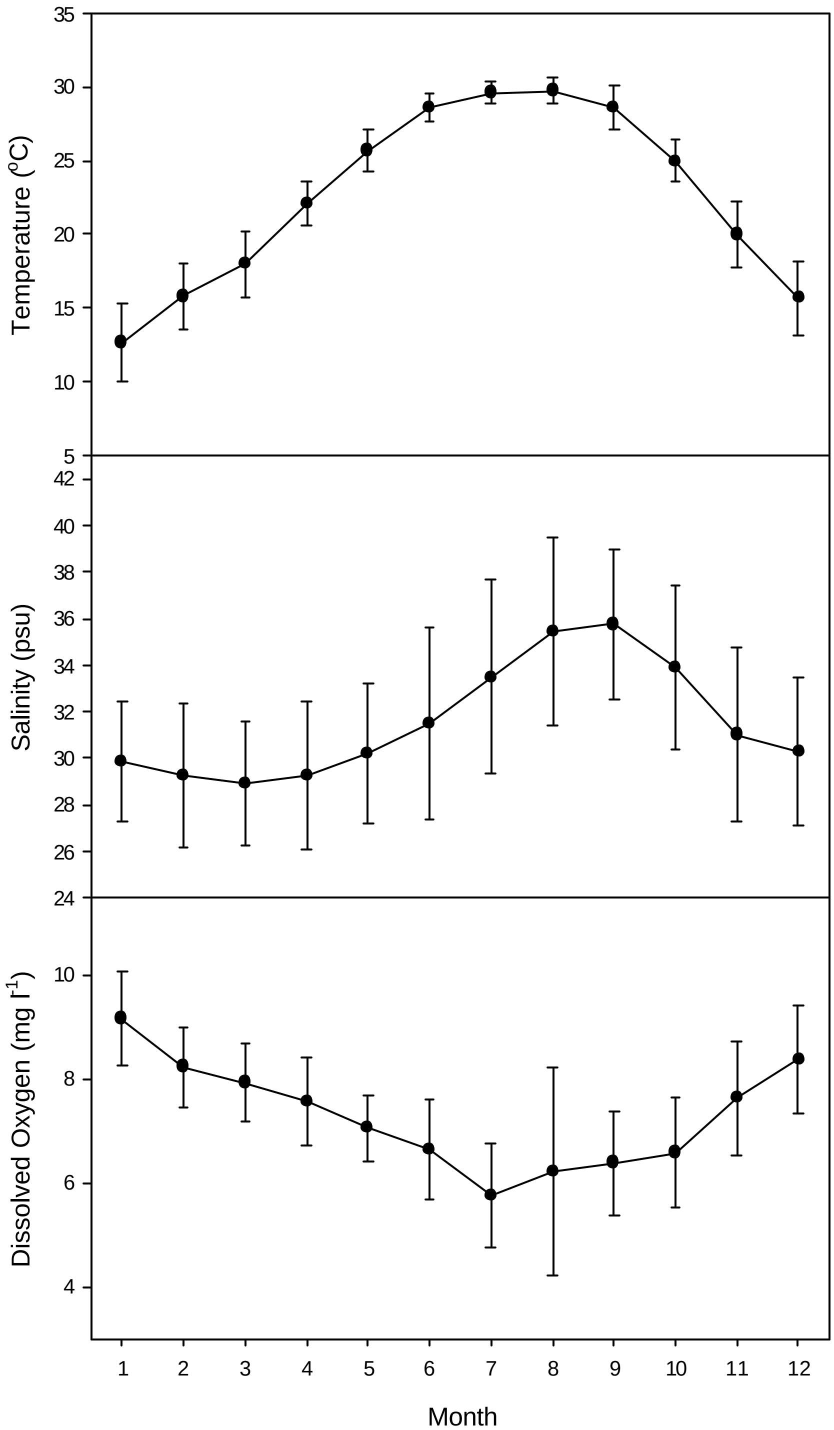


Figure 24. Monthly values for temperature, salinity and dissolved oxygen from combined UTMSI, TNRCC, and TPWD data.

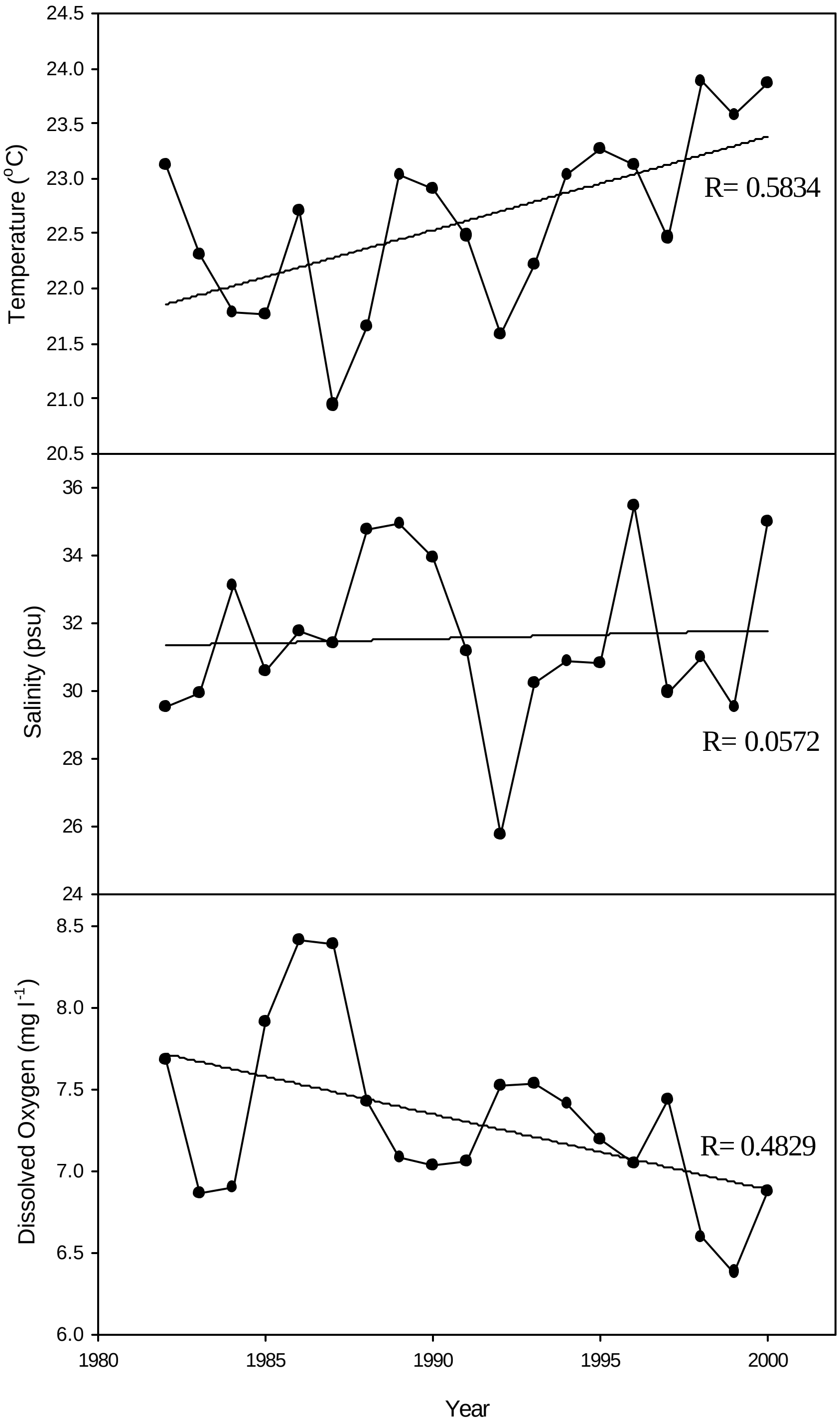


Figure 25. Annual variations in temperature, salinity and dissolved oxygen from combined UTMSI, TNRCC, and TPWD data.

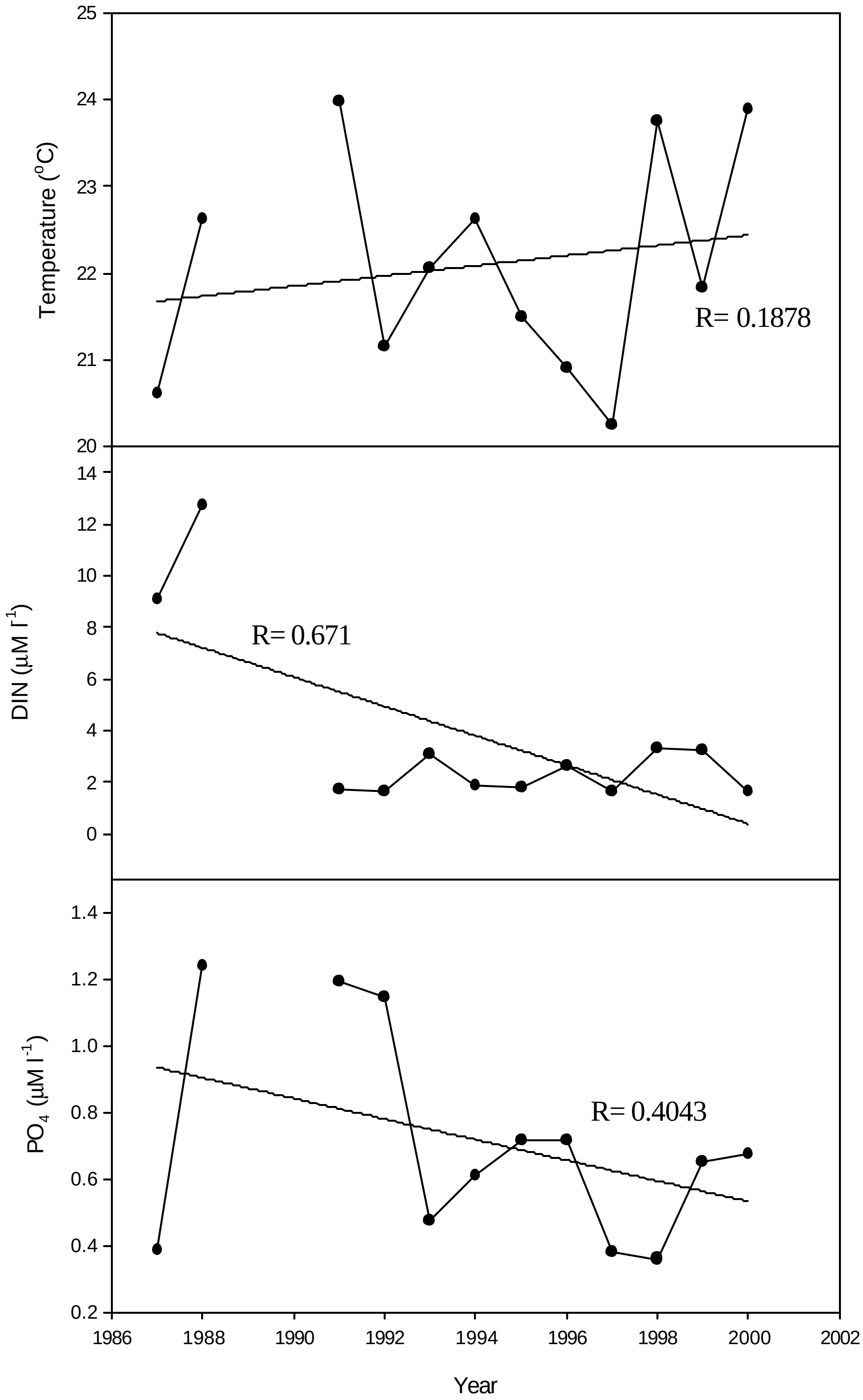


Figure 26. Annual variations in temperature, dissolved inorganic nitrogen, and phosphate from long term UTMSI stations 2 and 10.

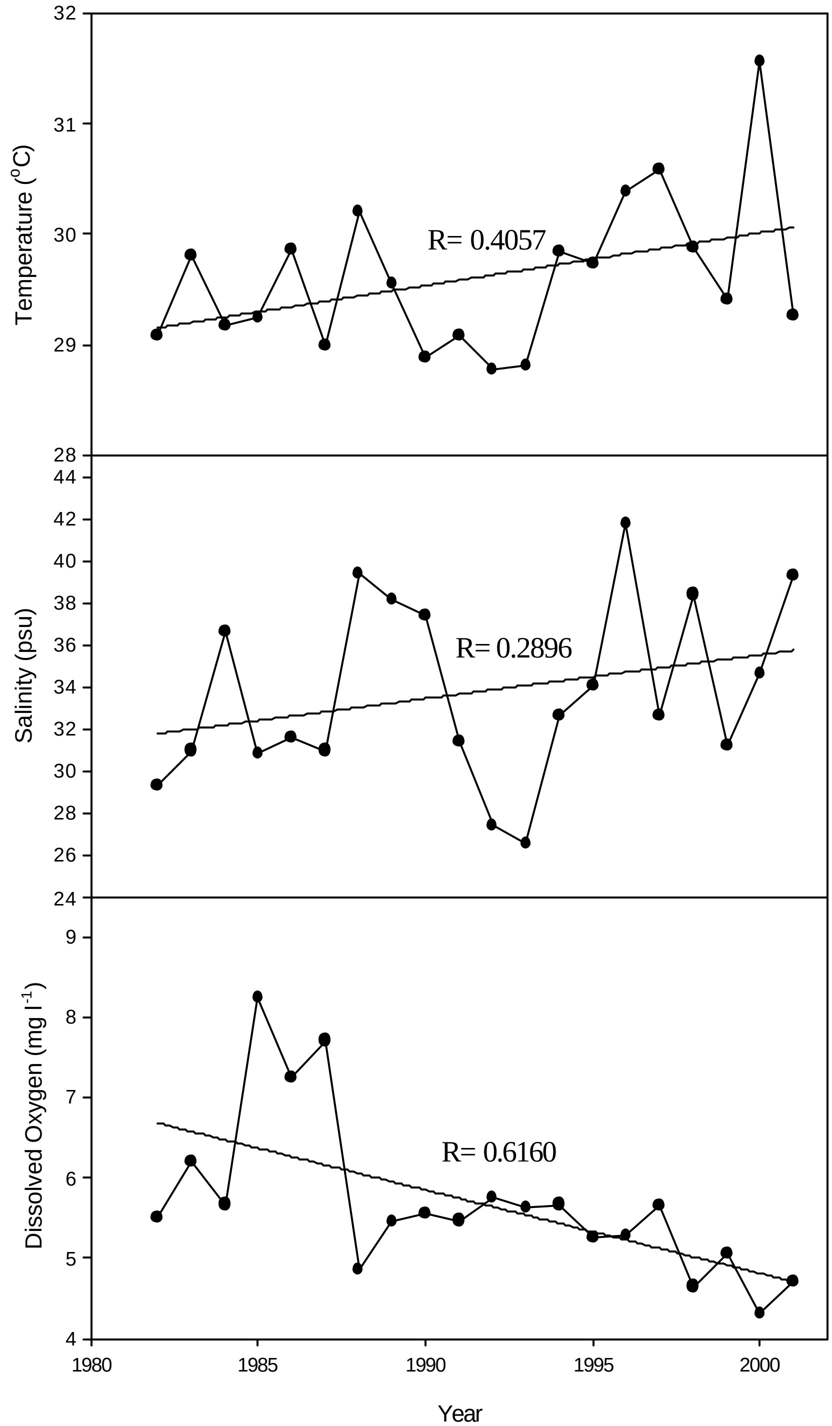


Figure 27. Annual variations in temperature, salinity and dissolved oxygen for the month of July from combined UTMSI, TNRCC, and TPWD data.