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FERRYMON, FERRY-BASED MONITORING AND ASSESSMENT OF WATER QUALITY FOR NORTH CAROLINA'S PAMLICO SOUND

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EXECUTIVE SUMMARY

Several, interrelated factors impact water quality variables such as chlorophyll *a* in Pamlico Sound (PS), including watershed land use change, basin-wide nutrient management, episodic storms including hurricanes, and changes in sea level. Despite its importance as fisheries habitat and nursery, the PS has not been routinely monitored for water quality impacts. As a result, significant gaps in the data and knowledge base exist. To fill these gaps and support the sustainable use of the PS, we have developed anl automated, water quality monitoring tool aboard ferries that traverse the PS. This UNC-DENR-DOT partnered program, FerryMon (**www.ferrymon.org**), provides a unique and cost-effective monitoring system to evaluate both chronic and episodic trends in the PS water quality. NCWQWG funds were granted to calibrate *in situ* estimates of chlorophyll *a* with in vitro measurements to help establish it as an environmental indicator, identify and fill existing water quality data voids for the PS, and incorporate existing and future ferry-based data into a searchable geo-database and generate summary information for dissemination of results. FerryMon's 3 routes include Minnesott Beach to Cherry Branch, Cedar Island to Ocracoke Inlet, and Ocracoke Inlet to Swan Quarter. Each ferry has a flow-through system for sampling of near surface raw water, a plenum with an Endeco/YSI multi-probe meter, and a programmable, refrigerated ISCO water sampler. Surface water temperature, salinity, pH, chlorophyll *a*, and turbidity are sampled at 3 min intervals while the ferries are underway. Increased precision and accuracy in the determinations of chlorophyll *a* biomass along the ferry routes is essential in order to link surface water color measurements to aerial spectral surveys and use phytoplankton biomass as a response indicator for watershed or estuarine factors. To this end we have calibrated in situ chlorophyll *a* estimates relative to in vitro determinations using High Performance Liquid Chromatography (HPLC). Data summarization and analyses provide essential baselines and identification of knowledge gaps. We have generated descriptive statistics, time-space contour plots, time series and geostatistical results, and assessments of spatial and temporal variability in surface water quality data. The ferry-based data have been coupled with ancillary data from associated studies in the PS, meteorological information, and shoreline maps and aerial imagery to create a geo-database for use by scientists, managers, and stakeholders. FerryMon is ideally suited to accomplish these interrelated objectives because the data acquisition and analyses naturally lead to the identification of missing data and summary information for distribution. The distribution and abundance of phytoplankton and other surface color constituents is critical to future tracking of PS water quality and represent the most significant lack of scientific understanding needed for effective management.

Project Activities and Products

1. Daily near real-time water quality data collection, retrieval and interpretation from the 3 ferries currently instrumented. These include the Neuse River crossing, the Cedar Island-Ocrakoce crossing and the Swan Quarter-Ocracoke crossing. The current configuration and data collection intensity/frequency are shown below (Table 1). The following WQ parameters are routinely collected using the YSI Model 6800 multi-probe sonde sensor unit: Temperature,

Ferry Route	1	2	3
Origination	Cherry Branch	Cedar Island	Swan Quarter
Destination	Minnesott Beach	Ocracoke Island	OI/CI
Ferry Name	Floyd Lupton	Carteret	Gov. Hyde
Avg. Speed (knots)	8.0	10.7	10.4
# of crossings/day	40	4	2
# of data points/day	300	200	200-300

salinity/conductivity, pH, dissolved oxygen, turbidity and chlorophyll *a* (fluorescence). Sensor-based data are routinely downloaded at night and transmitted via cell phone to the laboratory of J. Ramus, Duke University Marine Lab. We are currently seeking funding for a Data Manager to help format, distribute and communicate data to various agencies and interested parties, including public educational institutions.

2. Biweekly to monthly collection of samples for nutrients (soluble nutrients, including nitrate, ammonium, phosphate, dissolved organic C, dissolved inorganic C, and particulate C,H,N), and diagnostic (of major algal functional groups) photopigments. Relevant photopigments include chlorophylls *a* and *b*, and the carotenoid pigments diagnostic for the major algal fundtional groups (dinoflagellates, diatoms, chlorophytes, cryptomonads and cyanobacteria). Samples are collected using an ISCO “carousel” water sample collector that is in line with the YSI sensing unit. Samples have been collected and are being processed according to schedule.

3. Simultaneous field sampling of 9 vertical profile locations in the W. Pamlico Sound in concert with FerryMon passages. The objective of this project component is to obtain information on the vertical physical-chemical structure of the water column at the same time that FerryMon is collecting near-surace water samples. This has enabled us to compare and calibrate FerryMon WQ data. These sampling trips have been conducted on approximately a bimonthly schedule. The UNC-IMS sampling stations in relation to FerryMon and other sampling efforts currently underway are shown in Figure 1.

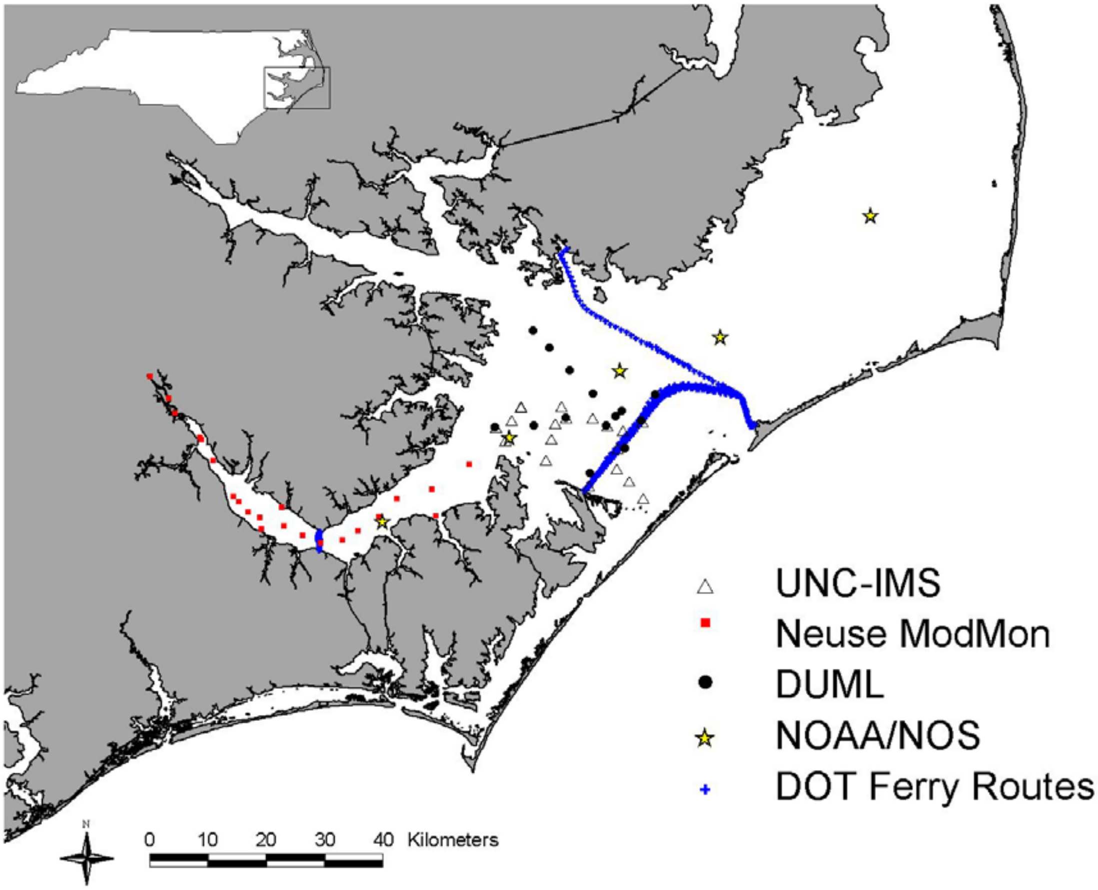


Figure 1: Location of FerryMon sampling tracks in relation to existing water quality monitoring programs in the Neuse R. Estuary and Pamlico Sound. These include the Neuse R. Estuary Modeling and Monitoring Program (ModMon), the Duke University Marine Lab sites that are periodically sampled by L. Crowder and J. Ramus, the NOAA-NOS (Beaufort Laboratory) sites that are sampled seasonally by P. Tester and colleagues, and the UNC-CH Institute of Marine Sciences bimonthly sampling program for the Western Pamlico Sound.

4. Use of FerryMon data to calibrate remote sensing flyovers of photopigments and turbidity of Pamlico Sound. Currently, these and parallel boat-based photopigment and turbidity data are being used to calibrate aircraft-mounted SeaWiFS flyovers being conducted by L. Harding and colleagues at the Horn Point Environmental Laboratory (CEES-Univ. of Maryland) as part of the collaborative Atlantic Coastal Ecological Indicator Consortium, ACE INC---www.aceinc.org. The frequency of these flyovers is 6 per year. An example of seasonal SeaWiFS flyover data that are currenly being calibrated by FerryMon and discrete monitoring (of chlorophyll *a* and turbidity) on Pamlico Sound is shown in figure 2.

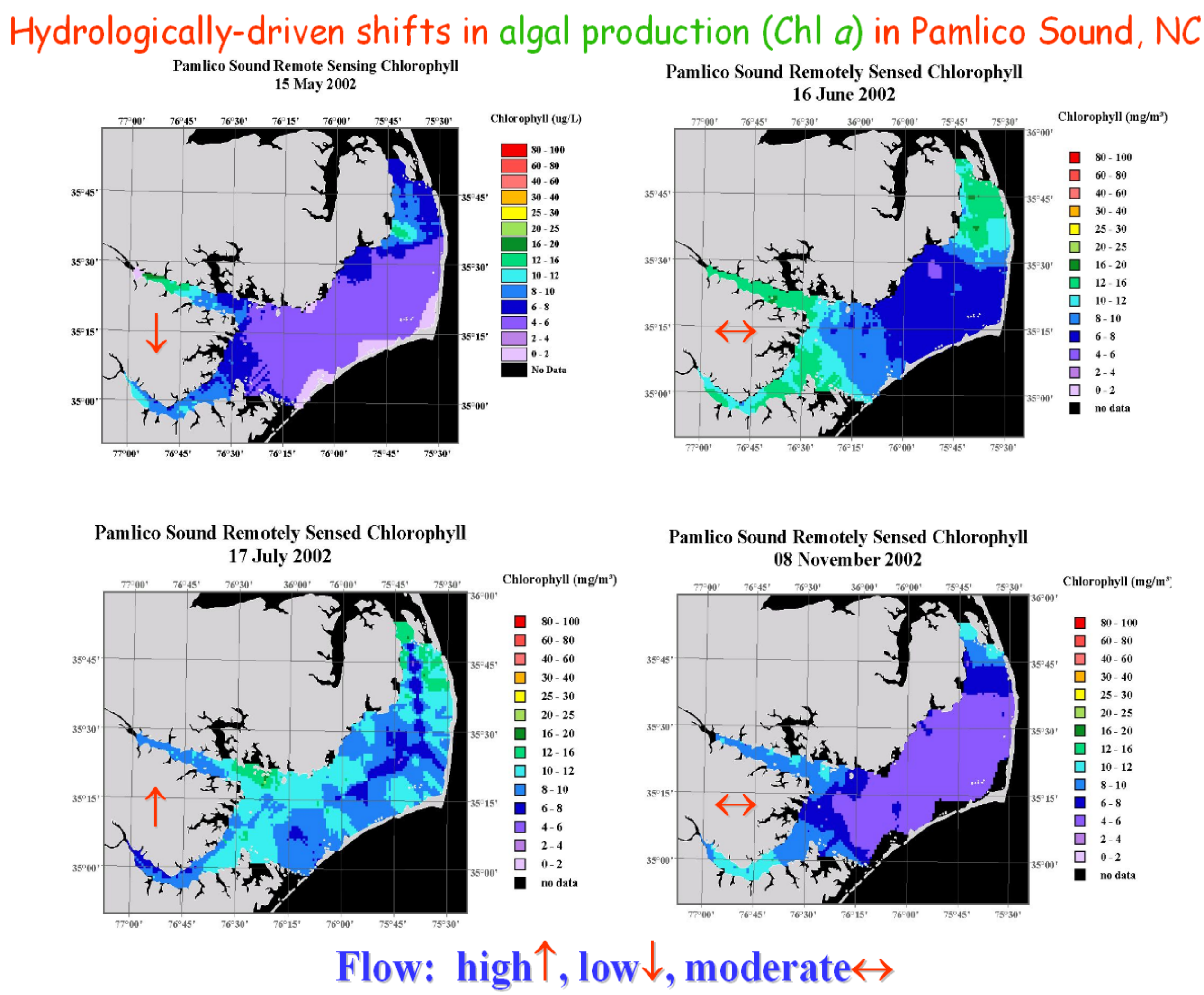


Figure 2. composite figure shows patterns of phytoplankton-based production in the greater Pamlico Sound based on SeaWiFS aircraft-based estimates of chlorophyll *a* concentrations (calibrated with FerryMon and discrete sampling data) during hydrologically-variable periods. Relative freshwater discharge (flow) conditions (upward for high flow, sideways for moderate flow and downwards for low flow) are indicated by the red arrow

5. Using FerryMon to assess water quality impacts of Hurricane Isabel on Pamlico Sound. We were able to deploy FerryMon and the parallel field assessment program prior to and after landfall of Hurricane Isabel, in September, 2003 to obtain water quality data for the Sound. FerryMon was the only program in place to assess Water quality impacts before and after the passage of this storm. Hurricane Isabel made landfall near Cedar Island and passed directly over Pamlico Sound on 18 September, 2003. Below is a short report on the initial hydrologic impacts of Hurricane Isabel on the Sound.

FerryMon as a Water Quality Monitoring Tool:

Assessing Hydrologic Impacts of a Transient Inlet to the Pamlico Sound Opened by Hurricane Isabel.

UNC-CH / DUKE / NC-DENR / NC-DOT

J. Ramus, Duke Marine Lab, Beaufort, NC

H.W. Paerl, UNC-Institute of Marine Sciences, Morehead City, NC

"I knew Hurricane Floyd --- and Isabel you ain't no Floyd."

Hurricane Isabel, a long-lived Cape Verde tropical cyclone, made landfall near Drum Inlet on the Outer Banks of North Carolina on September 18, 2003. Even as a Category 2 (90-100mph), Isabel is considered to be one of the most significant hurricanes to affect portions of northeastern North Carolina and east-central Virginia since Hurricanes Dennis and Floyd in 1999 (Paerl et al. 2001), Hazel in 1954 and the Chesapeake-Potomac Hurricane of 1933 (National Hurricane Center). Isabel is the latest of a recent spate of hurricanes that have struck the US East Coast, consistent with a projected increase in Atlantic hurricane frequency (Goldenberg et al. 2001). Isabel's most notable effects were storm surges on the Outer Banks and inland estuaries. Overwash breached Hatteras Island between Hatteras Village and Frisco, creating an inlet which measured about 1700 feet across with depths ranging to 20 feet. This was the site of a 1963 breach that had been repaired. Within a week the NC DoT and US Army Corps of Engineers began filling the breach with sand to restore NC 12 to the cut-off Hatteras Village. By November 18 the breach had been filled with dredged sand and NC 12 repaired.

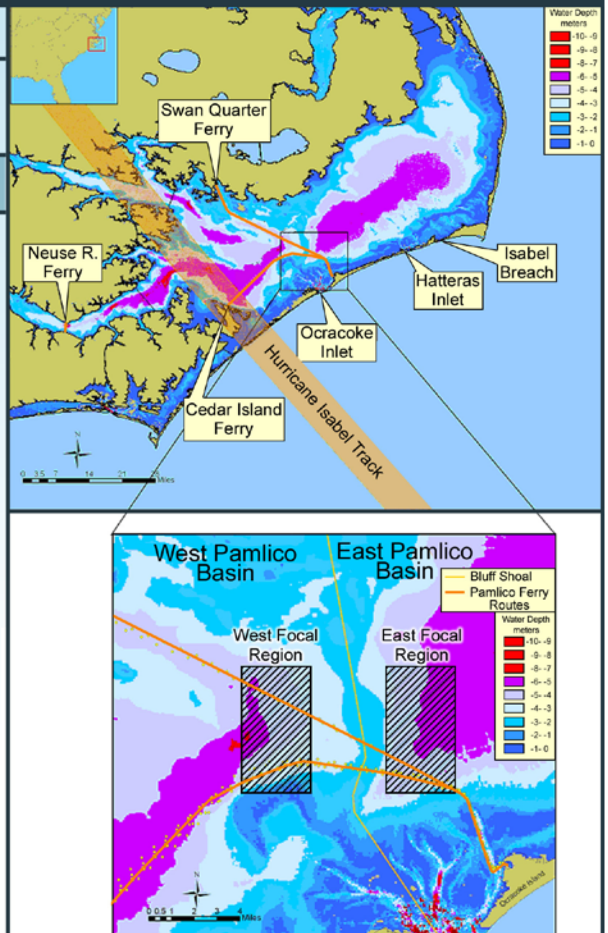


Figure 1

A large, albeit temporary inlet, should affect the hydrography of the Pamlico Sound, as do the three permanent inlets (Pietrafesa et al. 1996). The FerryMon automated water quality monitoring program (www.ferrymon.org) was fully operational before and after the passage of Hurricane Isabel. The ferries on the Cedar Island – Ocracoke and Swan Quarter – Ocracoke routes stopped regular service for only 36 hours around the passage of the hurricane. FerryMon data were used to detect the opening and closing of the new inlet, a two-month event. For this purpose, the most germane and relevant (to fisheries and water quality) property, salinity, was examined.

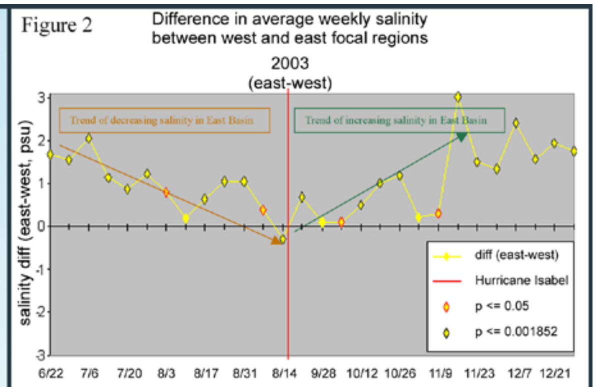
The Pamlico Sound is separated into two basins by Bluff Shoal which is positioned north-south at approximately -76.07 degrees West longitude. We hypothesized that the Bluff Shoal restricted exchanges of water between the two basins, and the basins exchange water with the coastal ocean somewhat independently of each other. The east basin receives fresh water mostly from the Chowan and Roanoke River watersheds via the Albemarle Sound, while the west basin receives fresh water mostly from the Tar-Pamlico and Neuse River watersheds.

We expect the new inlet to affect primarily the east basin because it connects that basin directly with the coastal ocean. On their Pamlico Sound routes, the ferries pass between the two basins by traversing the Bluff Shoal over roughly the same course (Buzzelli et al. 2003). We delineated 40 km2 areas, now called the east and west focal regions (East Focal Region &West Focal Region, Fig. 1), on either side of the Bluff Shoal, which the ferries transect. Salinity data were collected by each ferry every three minutes en route. Salinity data from the 4 months preceding and following Hurricane Isabel are included in the analysis.

The summary presentation of the data analysis is given in Fig. 2, which shows the salinity differences between the East Focal Region and West Focal Region (EFR & WFR). The differences are highly significant ($p <= 0.002$), and depict the sudden opening of the new inlet and its gradual closing.

For the months preceding Hurricane Isabel, the salinity differences between the EFR and WFR declined, i.e., the EFR became fresher relative to the WFR. This can be explained as follows. The area draining into the eastern Pamlico Sound (Chowan and Roanoke river watersheds), is 1.71 times that of the drainage basin emptying into the western Pamlico Sound (Tar-Pamlico and Neuse river watersheds) (Giese et al. 1979). For the months of 2001 preceding Hurricane Isabel precipitation in eastern North Carolina was above "normal", as was river discharge into the Pamlico Sound (http://nwis.waterdata.usgs.gov/nc/nwis/monthly). The discharge was greatest for the Chowan and Roanoke Rivers, for example the Roanoke River at Roanoke Rapids (USGS station 02080500) was 204% above the 73 year mean whereas streamflow statistics for the Neuse River at Kinston (USGS station 02089500) was 161% above the 73 year mean. Thus the east basin received a greater volume of fresh water than the west basin in the months of 2001 preceding Hurricane Isabel, hence a steady decline in east basin salinity (east minus west, Fig. 2) until Hurricane Isabel. The freshening trend in the east basin relative to the west basin reversed upon the opening of the new inlet (Fig. 2). The reversed trend continued until the inlet was closed, around November 18, and then the relative freshening in the east basin began again.

Figure 2



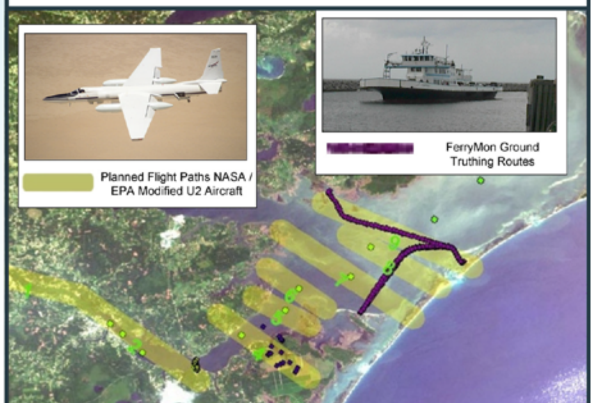


Figure 3
Planned Flight Paths of EPA / NASA Modified U2

Hurricane Isabel produced considerable human suffering, but the impact on the Pamlico Sound system was small. The new inlet formed 14 miles east of our east focal region and was flanked by two major inlets, namely Oregon and Hatteras Inlets. With the robust data stream produced by the FerryMon program we are able to demonstrate that the sudden inlet opening and slow closure could be detected as a signal in water quality. No other monitoring program was in place to detect that signal.

We offer this data only as an example of the utility of the FerryMon Program as a sensitive water quality monitoring tool. Using similar geostatistical methods, initially developed to track airborne pollutants, researchers at the University of North Carolina have used FerryMon data to model surface chlorophyll across the Pamlico Sound during summer blooms. Of greater signifigance to the ecosystem, is that FerryMon has proved to be an investment in monitoring infrastructure that has attracted researchers from the EPA Remote Sensing Branch and NASA to chose the Pamlico Sound as a target for remote sensing missions. The decisions to select the Pamlico Sound over other estuarine waters for the 2001 mission and flight plan for a possible summer 2004 mission have been due to in large part to the avialibility of the FerryMon Platform to calibrate and ground truth their instruments. (Fig 3)

The water quality baseline, and storm-related and human (i.e. nutrient) perturbations that FerryMon is documenting will prove invaluable in determining long-term trends in water quality and identifying potential needs for environmental management of the Nation's 2nd largest estuarine complex and its most important fisheries nursery.

For more information contact Dr. Hans Paerl at (252) 726-6841 ext. 133
or visit us online at : www.ferrymon.org

Publications supported by this project:

Paerl, H.W., J. Dyble, P.H. Moisander, R.T. Noble, M.F. Piehler, J.T. Pinckney, L. Twomey and L.M. Valdes. 2003. Microbial indicators of aquatic ecosystem change: Current applications to eutrophication studies. FEMS Microbial Ecology 1561:1-14.

Paerl, H.W., L.M. Valdes, J.L. Pinckney, M.F. Piehler, J. Dyble and P.H. Moisander. 2003. Phytoplankton photopigments as indicators of Estuarine and coastal eutrophication. BioScience 53(10).

Buzzelli, C.P., Ramus, J.R. and Paerl, H.W. 2003 Ferry-based monitoring of surface water quality in North Carolina estuaries. Estuaries 26:975-984.

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Paerl, H.W., L.M. Valdes, J. Adolf, B.L. Peierls, and L.W. Harding. 2004. Anthropogenic and climatic influences on the eutrophication of large estuarine ecosystems. Limnology and Oceanography (in review).

Presentations:

Paerl, H.W. 2003. Invited lecture. Developing and applying indicators of ecological change in estuaries: Human vs. climatic effects. Univ. of Calif., Davis, April, 2003.

Paerl, H.W. 2003. Invited lecture: Estuarine Eutrophication, Hypoxia and Anoxia Dynamics: Causes, Consequences and Controls. 7th International Symposium on Fish Physiology, Toxicology, and Water Quality, Tallinn, Estonia, May 12-15, 2003.

Paerl, H.W. 2003. Historic and technical support for a nitrogen reduction strategy for the Neuse River Estuary. Invited presentation, 4th National Workshop on Constructed Wetlands/BMPs for Nutrient Reduction and Coastal Water Quality Protection, Wilmington, NC, June, 2003.

Paerl, H.W. 2003. Assessing and managing nutrient-enhanced eutrophication in estuarine and coastal waters influenced by human and climatic perturbations. Invited lecture, Coastal

Restoration and Enhancement through science and Technology (CREST) Conference, Thibodaux, LA, July, 2003.

Paerl, H.W. 2003. Developing indicators to identify human and climatic alterations of water quality in estuaries. Invited presentation, US EPA Office of Rsearch and devlopment, Washington, DC. August, 2003.

Paerl, H.W. 2003. The Atlantic Coastal Environmental Indicator Consortium (ACE INC). Invited presentation, EPA Region IV Conference, "Using ORD Research in regional decision Making", EPA Region IV Headquarters, Atlanta, GA, August, 2003.

Paerl, H.W. et al. 2003. ACE INC: Developing indicators to assess human and climatically-induced ecological change in the coastal zone. Invited talk, Ecological Society of America Meetings, Savannah, GA, Oct. 2003.

Paerl, H.W. 2003. Linking atmospheric nitrogen deposition to ecological effects along the estuarine-coastal gradient. Invited presentation. NADP Long-Term Monitoring Symposium: Supporting Science and Informing Policy". Washington, DC. Oct., 2003.

Paerl, H.W. 2003. The Atlantic Coastal Environmental Indicator Consortium (ACE INC): An overview of current and future activities. Presentation, 3rd Annual Estuarine and Great Lakes Ecological Indicator Consortium meeting, Bodega Bay, CA. Dec. 2003.

Paerl, H.W. 2004. Developing indicators to assess human and climatic impacts on estuarine and coastal water quality and ecological condition. Invited lecture, Smithsonian Environmental Research Center, Edgewater MD, February, 2004.

Paerl, H.W. 2004. Anthropogenic and climatic influences on the eutrophication of large estuarine ecosystems. Invited lecture, Dept. of Marine Science, Univ. of Georgia, Athens, GA. March, 2004.

Paerl, H.W. 2004. Developing and applying indicators of human and climatically-induced changes in estuarine and coastal water quality. Invited lecture, Coastal Indicator Symposium, Rutgers Univ. Institute of Coastal Research and N.J. Cousteau Coastal Sanctuary, New Brunswick, NJ, April, 2004.

Paerl, H.W., L.M Valdes, J. Dyble, P. H. Moisander, B. Peierls and J.L. Pinckney. 2004. Microalgal indicators of human and climatically-induced ecological change in estuaries. Invited Lecture, American Society of Limnology and Oceanography, Summer 2004 Meetings, Savannah, GA, June, 2004.

Paerl, H.W., J. Dyble, J.L. Pinckney, P.H. Moisander, and M.F. Piehler 2004. The structure and function of aquatic microbial communities: Is what you see what you get? Plenary Lecture, International Society of Limnology meetings, Lahti, Finland, August, 2004

Project Website: www.ferrymon.org

This website is maintained by Alan Joyner (**arjoyner@email.unc.edu**). The website has been designed to be interactive and materials conveyed in it are available for instructional purposes upon request. The website is currently being used by the Carteret Co. School District, the NC Museum of Natural History and Science (Raleigh) and the Maritime Museum (Beaufort).

FINAL REPORT

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ACKNOWLEDGEMENTS

The FerryMon Project is a cooperative effort between the North Carolina Department of Environment and Natural Resources (DENR), the North Carolina Department of Transportation (DOT), Duke University Marine Laboratory (DUML), the University of North Carolina at Chapel Hill Institute of Marine Sciences (IMS), and the AllTel Corporation. We acknowledge the considerable efforts of Jerry Gaskill and Dan Noe (DOT), Tim Boynton (DUML), Tom Walbert (DOT), Tom Gallo (IMS), Patrick Sanderson (IMS), Christina Tallent (IMS), Lexia Valdes (IMS), Ben Peierls (IMS), and Jeffrey Priddy (DUML).

ABSTRACT

The Albemarle-Pamlico Estuarine System (APES) is North America's second largest estuary and provides critical habitat for the southeastern U.S. fishery. Despite its importance as essential fish habitat, the APES has not been monitored systematically as other estuaries for habitat impacts associated with altered water quality. Monitoring water quality in complex estuarine systems requires many years of data using innovative applications of resources and technology. We equipped three North Carolina ferries with a flow-through system that includes a computerized multi-probe sensor and a refrigerated, automated water sampler to accumulate surface water data as they traverse the NC estuaries. This program, FerryMon, is feasibility study to monitor water quality status and trends in the APES using existing resources and remote sampling. Intensive temporal and spatial data obtained from the ferry routes provide an environmental baseline and are used to assess the patterns and variability in surface water hydrography, dissolved constituents, and particulate matter. The instruments communicate with a dedicated shipboard computer to sample at regular intervals depending upon the vessel speed and time of day. Presently, surface water temperature, salinity, dissolved oxygen, pH, turbidity, and chlorophyll are sampled at 3 min intervals. The system is differentially geo-positioned, the digital data are downloaded nightly, and approximately 600 data points are generated per day among the three ferry routes. The objectives of data analyses during the first two years of FerryMon were to develop data management procedures, to assess spatial and temporal variability in surface water properties, and to investigate spatial and temporal patterns. We tracked surface water temperature, salinity, pH, turbidity, and chlorophyll *a* along the three ferry routes by aggregating the data temporally from hours to months and spatially into 10 km segments. The monthly level of aggregation provided the best compromise among the variance and shape of the resulting distributions. While temperature, salinity, and pH measurements were quite stable, in situ estimates of turbidity and chlorophyll *a* estimates were extremely variable. In fact, these were so variable that we had to establish maximum values of 500 NTU and 100 μg L^{-1} for turbidity and chlorophyll *a* during data processing. Each of the ferry flow-through systems was fitted with a de-bubbling mechanism after establishing that entrained bubbles interfered with the optical sensors. The 200,000 lines of surface water data over the first two years of this study reinforce the assertion that passenger ferries make reliable oceanographic vessels. However, there are theoretical, technical, and logistic challenges in using ferries as sampling platforms. FerryMon is not hypothesis based but rather represents an opportunistic way to acquire surface water hydrographic and concentration data across large portions of the estuaries. All of the instrumentation and software programs were created specifically for FerryMon and had not been thoroughly tested prior to ferry deployment. Many comparisons and cross-calibrations among in situ estimates, in vitro concentrations from ferry sampled water, and in vitro concentrations from shipboard studies are required to reduce the observed variability in the optical measurements. Despite some challenges, the use of the automated, ferry-based data acquisition system to provide surface water truth data to calibrate aerial imagery is promising. Satellite platforms offer wide scale sampling over coastal waters not possible with traditional shipboard methods. The spectral signals obtained by remote sensors must be calibrated and referenced relative to surface water concentrations of chlorophyll *a* biomass, total suspended solids, and CDOM. Using the ferry-based systems to help characterize surface water spectral properties and calibrate coastal ocean color sensors is one of the most potentially valuable functions of FerryMon. These applications will make the monitoring of habitat quality over a wide range of spatial and temporal scales possible in the NC estuaries.

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(1) Introduction

Estuarine hydrography and biogeochemistry are highly variable and require several years of monitoring data to understand (Stanley 1993; Sin et al. 1999; Buzzelli et al. in press). Although there are long-term monitoring programs in the Neuse and Pamlico River Estuaries (Stanley, 1993; Luettich et al. 2000), similar programs have been more difficult in the Pamlico Sound (PS) due to its comparatively large size. Therefore, the ecological status of the PS remains uncertain due to the overall lack of water quality monitoring information. Not only was the status of the PS unknown prior to large environmental perturbations such as the hurricanes of 1999, fluctuations in the biogeochemical balance of the PS following such high discharge events remain poorly understood due to the scarcity of baseline hydrographic and biogeochemical data. The large and shallow NC estuaries provide essential fish habitat to a variety of ecologically and commercially important species (Steele, 1991; Dame et al. 2000) and the lack of a monitoring program is potentially crippling for research and management efforts.

The watersheds of the Albemarle-Pamlico Estuarine System (APES) experienced relatively slow development until the late 20th century when land use changes and associated watershed impacts accelerated (Riggs, 2001). Intensive row crop agriculture, industrial scale animal husbandry, and urbanization resulted in altered hydrology and increased nitrogen loading to the rivers in the piedmont area, particularly the Neuse River (Stow et al. 2001). Although there have been indications of eutrophication in the upstream reaches of the Neuse River including nuisance algal blooms and loss of submersed vegetation (Paerl, 1983; Copeland and Gray, 1991), there has been no discernable increase in nutrient loading to the coastal estuary (Stow et al. 2001). This is most likely due to the high nutrient removal potential of the upstream floodplain wetlands which normally buffer the coastal water bodies from inputs, but can become a source of organic material sources during times of river flooding. The resulting estuarine water quality patterns are highly variable and require many years of intensive monitoring data to track and explain (Stanley 1993; Luettich et al. 2000; Stow et al. 2001).

In response to concerns over changes in watershed nutrient loading, the North Carolina legislature mandated remediation measures including basin-wide nutrient management plans. Although these plans are desirable, it is difficult to detect responses to the remediation measures because there are no established programs to monitor water quality and ecological signatures in the PS. As demonstrated by the hurricanes of 1996 and 1999, meteorologically driven, short-term, high volume discharge events complicate detection of potential impacts of altered watershed land use, which fluctuate on multi-annual time scales (Jordan et al. 1991; Gallegos et al. 1992; Paerl et al. 2001). The dearth of background water quality data for the Sounds makes assessment of estuarine status under combined conditions of altered land use, mitigation efforts, and variable meteorology an important challenge for North Carolina.

Faced with these challenges we recognized the potential of the North Carolina ferries as monitoring platforms to help establish a water quality record. Following the widespread effects of the 1999 hurricanes on the coastal watersheds and estuaries (Paerl et al. 2001), the state of North Carolina helped to expedite a water quality monitoring program using the Department of Transportation Ferry Division. Although underutilized in aquatic studies in the United States, ferries have served as oceanographic platforms in Scandinavia and Japan where researchers used high frequency surface water data from ferry routes to monitor water quality (Althuis et al. 1994;

Harashima et al. 1997; Rantajarvi et al. 1998). There are examples of smaller, vessel-mounted, real-time sampling systems used to characterize estuarine water bodies (Madden and Day 1992). The Ferry Monitoring (FerryMon) program was designed to track surface water quality status and trends by recording data across temporal scales ranging from diel to inter-annual.

Here we summarize the FerryMon program since it began in the fall of 2000. This summary includes a description of the ferry routes, instrumentation, data acquisition and management, data-base development, data methods and analyses, some interpretation of surface water quality characteristics, and an overall summary of the project history and status. Our short-term goals were to develop a ferry-based, flow-through system and to quantify the variability inherent in surface water properties. A better appreciation of the systematic and random errors will increase the confidence of the remote measurements into the future. Our long-term goal is to create a web-accessible, interactive geo-database for researchers, managers, educators, and interested citizens (http://www.ferrymon.org).

(2) Site Description and Ferry Routes

Neuse River Estuary (NRE) and Pamlico Sound (PS)

The NRE and PS are part of the APES located in North Carolina (Fig. 1). The major geologic feature of the APES is the string of barrier islands known as the Outer Banks that isolate the estuaries from the coastal ocean (Fig. 1). Due to the Outer Banks, circulation in the APES is less sensitive to oceanic forces and responds rapidly to variations in freshwater discharge and wind mixing (Stanley and Nixon 1992; Luettich et al. 2000). The NRE is a lateral sub-estuary of PS and spans approximately 75 km between Streets Ferry Bridge (SFB) and PS (Fig. 1; Table 1; Buzzelli et al in press). The estuary widens to almost 6.5 km downstream of New Bern, NC while a sharp bend at Minnesott Beach (MB) splits the NRE into upper and lower segments. The surface area is 455 km^2 and the freshwater flushing time is estimated to range 25-200 days (Table 1). Although not tidally dominated, the NRE usually exhibits typical estuarine circulation with downstream flow at the surface and the upstream movement of saline water near the bottom (Luettich et al. 2000). Reduced freshwater discharge in the summer is usually accompanied by salinity stratification over a large portion of the NRE (Buzzelli et al. 2002). At over 4000 km^2 the PS is a wider, larger basin than the NRE that is fed by a number of lateral sounds and sub-estuaries (Fig. 1; Table 1; Xie and Pietrafesa 1999). The PS receives inputs from several different watersheds including the Chowan, Roanoke, Tar-Pamlico, and Neuse (Ramus et al. in press). Oceanic exchange is limited to Oregon, Hatteras, and Ocracoke Inlets (Fig. 1). The PS is comparatively shallow (average depth = 4.5 m) and freshwater flushing times could be up to 11 months based upon input and volume characteristics (Paerl et al. 2001). Circulation in PS is primarily wind-driven (Xie and Pietrafesa 1999). Widespread stratification and reduced bottom water oxygen occurred in the open waters of the PS following a huge amount of freshwater from a sequence of extra-tropical storms (Paerl et al. 2001). Historically, there have been few studies of hydrography and biogeochemistry in the PS (Roelofs and Bumpus 1953; Schwartz and Chestnut 1973; Ramus et al. in press).

There have been a number of water quality studies in the NRE and the PS over the past several years (Fig. 1). These studies are compatible in that they monitored some combination of water column transparency, dissolved nutrients, and particulate materials using traditional shipboard sampling methods. However, they have been conducted at different times and locations depending upon the specific goals of the particular projects. The scales of the studies ranged from fine scale vertical migration of planktonic assemblages to using surface water spectral data to calibrate satellite imagery (Fig. 2). Studies at different scales of resolution are necessary to monitor the response of the estuary to an environmental perturbation, such as the increase in chlorophyll *a* concentrations following the hurricanes in 1999 (Fig. 2; Paerl et al. 2001). Ferry-based monitoring complements these various studies ideally as an independent source of intensive surface water data, as boundary data for modeling exercises, and a way to link the different scales of variability (Fig. 2).

Ferry Routes

The North Carolina Department of Transportation's Ferry Division operates a fleet of ferries that cross the APES at six locations (http://www.ncferry.org). These vessels carry passengers and vehicles and provide a critical transportation link across the APES. The routes span riverine inputs to the PS (the lower Neuse and Pamlico River routes), the open water (the Pamlico and Currituck Sound routes), and exchanges with the coastal ocean (the Hatteras and Ocracoke Inlet routes). We chose 3 routes over which to develop the FerryMon system that included Minnesott Beach to Cherry Branch (route 1, shipboard the M/V Floyd Lupton), Cedar Island to Ocracoke Inlet (route 2, shipboard the M/V Carteret), and Ocracoke to Swan Quarter (route 3, shipboard the M/V Governor Hyde; Fig. 3; Table 2). Route 1 traverses the lower NRE, while routes 2 and 3 connect the Outer Banks with the mainland by crossing the southern basin of the PS (Fig. 3). The vessels range in length from 150' to 220' and in cruising speeds from 8 to 10 kts (Table 2). The ferries operate on a daily schedule with route 1 running from 0500-1100 h and routes 2 and 3 from approximately 0700 to 1900 h. Ferry service ceases only in dense fog or when winds exceed 40 knots. The M/V Floyd Lupton crosses the NRE 40 times daily (20 round trips), the M/V Carteret crosses the southern basin of PS 4 times daily (2 round trips), and the M/V Hyde travels from Swan Quarter to Ocracoke Inlet twice daily (1 round trip).

(3) Materials and Methods

(A) Flow-through System and Instrumentation

Each ferry houses a flow-through system for sampling of near surface water (0.0-1.5 m; Fig. 4). The automated monitoring system takes raw water at rates of >15 L min^{-1} through a sea chest near the front of the ship using an impeller pump. The water passes through a coarse strainer, into a vortex debubbler (MSRC VDB-1, Ocean Instrument Lab, SUNY at Stony Brook), and then into a 20.32 by 40.64 cm cylindrical PVC plenum (13 L). The de-bubbling mechanism was not part of the original design but was added to each of the three ferry flow-through systems in late 2001. Initial results indicated that bubbles interfered with the optical sensors, particularly along routes 1 and 2. We discuss some of the ramifications of instrument modifications later in the report.

A YSI-MA 6600 (Endeco/YSI, Marion, MA) unit equipped with conductivity (salinity or S), temperature (T), pH, DO, turbidity (NTU), and chlorophyll fluorescence (CHL) probes is plugged through an O-ring sealed port into the PVC plenum (Fig. 4; Table 2). The YSI 6600 units are switched with newly calibrated units approximately monthly in the winter, bi-weekly in the spring and fall, and weekly in the summer. The YSI 6600 is interfaced with a shipboard computer that is dedicated to data storage and retrieval using a data logger and modem (Fig. 4). Navigation is provided by a Furuno 1850 DGPS ($\pm$ 10 m precision) interfaced with the computer to log sample locations by date, time, latitude, and longitude. The surface water YSI data are sampled at 3 min intervals while the ferries are underway, although route 1 was sampled at a 1 min interval from November 2000 to March 2001. The 3 min interval was better suited to the longer routes (2 and 3; Fig. 3) and still provided an abundance of daily data. Logged data are downloaded nightly to a computer located at the Duke University Marine Laboratory, Beaufort, N.C., through a modem and cellular phone located on the ferry.

We can obtain aqueous grab samples for laboratory analyses of particulate and dissolved matter using an ISCO 6700FR refrigerated sampler (Fig. 4). The ISCO unit holds 24 1-L bottles and can be programmed to sample at regular intervals while the ferry is underway. Both the YSI data loggers and ISCO sampler are activated when the ship's speed exceeds 6 knots to avoid sampling water in the ferry turning basin. We started using the ISCO samplers in conjunction with bi-weekly (NRE) and monthly (PS) research cruises conducted by personnel at the UNC-IMS. Our goal was to accumulate point data near the ferry routes to provide an independent source of cross-calibration information. All 24 bottles were filled over approximately 8 crossings (ca. 3 bottles crossing^{-1}) on each day of ISCO use on the NRE. The concentrations were determined using a suite of techniques at the UNC-IMS laboratory (Buzzelli et al. in press). There are ongoing comparisons between the ferry-based and IMS shipboard data that will increase our confidence in using the ferry as an oceanographic vessel. Here we report concentrations of nitrate + nitrite (NO_x^-), ammonium (NH_4^+), silicate (SiO_4^-), ortho-phosphate (PO_4^{-3}), total dissolved nitrogen (TDN), in vitro chlorophyll *a* (CHL), particulate carbon and nitrogen (PC and PN), and the molar C:N (CN) determined from NRE water sampled using the ISCO shipboard the M/V Lupton for 13 dates between18 June 2001 and 18 June 2002. We are still accumulating surface water concentration data from route 2 because of technical difficulties with the ISCO shipboard the M/V Carteret throughout most of 2001 and into 2002.

(B) Data Processing and Data-base Development

The FerryMon Information Manager (IM), Dr. Christopher Buzzelli, developed a protocol to organize and transform the raw surface water data into formats that are useful for analyses and interpretation. Jeffrey Priddy of DUML is in the process of writing computer scripts to automate the data processing and management steps. It starts with daily QA/QC of the data by visually inspecting the data from the previous day. Each week, the customized YSI 6600 software creates two newly named files for each of the three ferry routes. One file (G) contains the speed, direction, and location (latitude and longitude) of the ferry at each of the sampling locations while the other sonde (S) file contains the YSI 6600 data at each location. Surface water data acquisition occurs during ferry operating hours and concludes with nightly downloads of the data to these weekly files (Fig. 5). Following transfers of previous weeks' data to a server, the archived S data are combined with the latitude and longitude data from the DGPS, transformed by filtering by ferry speed over ground (SOG) to remove potential near-basin sampling locations, and re-sorted by time and date to accommodate further processing (Fig. 5). The IM further checks and edits the data values during each step of the processing procedures, especially regarding the YSI 6600 turbidity and CHL data. We used shipboard data from the UNC-IMS cruise stations near the ferry routes as a reference to establish maximum values of 500 NTU and 100 $\mu g\ L^{-1}$ for turbidity and CHL, respectively. These values provided the upper thresholds for data reduction and the final data files used for analyses and interpretation were heavily edited and reviewed for content by the IM.

(C) Data Analyses and QA/QC

The objectives of data analyses during the first two years of FerryMon were to help develop data management procedures, assess spatial and temporal variability, and investigate spatial and temporal patterns (McCormack and Ord 1979). The objectives were accomplished through a series of data manipulation, graphical presentations, and quantitative techniques to visualize the ferry-based surface water data. It is important to remember that these data can be in 4 dimensions including latitude (x), longitude (y), time, and some property such as salinity. Therefore, the techniques to visualize them must be both innovative and integrative.

Every few months the processed data from each ferry route were appended to existing large files. We performed a final check of the value ranges and imported the large files into ArcView, a geographic and spatial analysis application. We generated sampling location maps and calculated the distance between the shoreline and each of the sampling locations using a customized ArcView application (http://www.jennessent.com/arcview/arcview_extensions.htm). The calculated distances were used in time-space plots and to designate a segment location along the ferry route. In particular, the data from routes 2 (CI to OI) and 3 (SQ to OI) were split into 10 km segments to create time series of data at aggregated locations. In most cases we generated an interpolated time-space map with time (d) as the x axis and distance from the shoreline (m) as the y-axis. These plots incorporate all of the instantaneous values from the edited files and were used to locate interesting surface water features in time and space. Additionally, the various surface water properties were plotted vs. distance offshore in scatter-plots to investigate spatial dependence (Rossi et al. 1992; Haining 1997). We generated descriptive statistics including the mean, standard deviation, standard error, coefficient of variation, minimum, maximum, mode, median, skewness, kurtosis over an entire ferry route for the entire time or for a particular segment or time period.

The ISCO data from the NRE were combined with the corresponding hydrographic data from the YSI 6600 to create a sub-data set used in correlation analysis to investigate potential relationships among the full suite of variables. Because there are different files and formats among the GPS and ISCO data, matching ISCO sampling times with ferry locations was done manually by the IM. The ISCO sampler was set-up in the morning and usually collected data from 1000 to 1300 h. However, sometimes the ISCO failed to sample due to unknown mechanical failure, other times the YSI 6600 unit was off-line, and on several dates the program that controls the ISCO did not work and the samples were collected in the basin during ferry layover. These factors limited the amount of coupled YSI/ISCO data that remained for analyses. Further, at times some variables approached or were below detection limits (BDL) of the UNC-IMS laboratory and required special consideration (Table 3).

The goal of using the ferry ISCO water sampler on the same day as the UNC-IMS research cruises was to assess the variability and differences between the two monitoring platforms. Increased confidence in the ferry-based measurements will reduce the need for regular point sampling in the field. There are many ways to pursue inter-calibrations among the ferry and traditional shipboard methods. All of the ferry ISCO sampling locations from the NRE between June 2001 and June 2002 were mapped resulting in a cluster of ferry sampling locations $\leq$ 0.35 km from Marker 9, which is where UNC-IMS does hydrographic profiles and collects water. We calculated average daily temperature, salinity, pH, CHL (YSI and ISCO + lab), NO_x^-, NH_4^+, SiO_4^-, PO_4^{-3}, TDN, PC, PN, and CN for the selected ferry locations. The data from Marker 9 were filtered using the list of ferry-based sampling dates to generate a sample size of 13-16 for the statistical comparisons. The composite data set had two columns for each of the variables listed above representing the FerryMon (FM) and Marker 9 (M9) data, respectively. We calculated descriptive statistics before performing paired sample t-tests and correlation analyses to distinguish among the two platforms. Estimates of chlorophyll *a* received more detailed treatment than the other variables because it is an indicator of estuarine status and is perhaps the most important water quality constituent recorded by FerryMon. Additionally, we have four separate measures of chlorophyll *a* among the ferry-based ISCO with fluorometric laboratory analyses at UNC-IMS (FMISCO), the ferry-based in situ estimate from the YSI 6600 (FMYSI), the UNC-IMS surface water sample from Marker 9 with fluorometric laboratory analyses (M9LAB), and the UNC-IMS surface water reading from its YSI 6600 (M9YSI). We used box plots to assess the overall distributions of these data and performed paired t-tests and correlation analyses to investigate the differences in the resulting concentrations.

For many presentations the data were aggregated over different temporal scales ranging from hourly (NRE route 1) to annual and presented in box-and-whisker plots helped us examine the variability in surface water hydrographic properties. Salinity is a conservative variable that provides an overall indication of the balance between fresh and salt water inputs so we used auto-correlative statistical techniques to examine salinity patterns and patch sizes across the PS (Rossi et al. 1992). We also generated a time series of salinity from near Ocracoke Inlet to examine the time scale of salt fluctuations through the inlet.   Finally, a 3-way ANOVA was used to assess changes in average salinity and CHL concentrations as a function of time of day, distance from the shoreline, and calendar season for the SQ route 3 data.

The results are presented in the following order: ferry route 1 (Minnesott Beach to Cherry Branch), ferry route 3 (Swan Quarter to Ocracoke Inlet), and ferry route 2 (Cedar Island to Ocracoke Inlet). It is important to remember that a single individual, the Information Manager, was responsible for all QA/QC, data processing, data-base development, and data analyses. Additionally, it was rare when all three ferry-based systems functioned properly simultaneously. The result is that the data from among the three routes are in different stages of processing at all times depending upon the status of the data acquisition and the demands on the IM. Due to equipment difficulties, data gaps, and restraints on the IM we were unable to include all the data from all three routes in this report. However, most of the reliable data between fall 2000 and fall 2002 was included. Route 1 is the shortest route but has been in service for the longest period and has the greatest number of data points from November 2000 to September 2002. Data analyses started with November because September to October was a start-up and testing phase. Route 3 provided the most complete data set with the fewest problems and interruptions from May 2001 to May 2002. We used this full year of data to investigate spatial and temporal patterns at different scales. Finally, the data collection from route 3 has been more problematic throughout its inception so we included the results from the latter part of 2002 when we had more confidence in the flow-through system.

(4) Results

(A) Ferry Route 1 Minnesott Beach to Cherry Branch

From 1 November 2000 to 14 September 2002 we accumulated 120,434 surface water recordings of T, S, pH, NTU, and CHL along the approximately 3 km stretch between Minnesott Beach (MB) and Cherry Branch (CB; Fig. 5). Temperature ranged from 2.1-34.9 °C and followed regular seasonal patterns (Table 4). There were few outstanding spatial differences in T between MB and CB (Fig. 6A). The range between minimum and maximum daily temperature was greatest in the spring and fall while median hourly temperature hovered near 27.5 °C in the summer with few obvious diel patterns (Fig. 7). Surface water salinity was much more variable than temperature over time and space (Fig. 6B). Salinity ranged from approximately 2.0 to 24.0 psu. Salinity was greatest late in 2001 and during the summer of 2002 during times of reduced rainfall and river discharge. The widest range in daily salinity occurred in the spring and summer (Fig. 8). Median salinity was approximately 9.0, 14.0, 8.0, and 10.0 in the spring, summer, fall, and winter, respectively, but with no noticeable diel changes in salinity in any of the seasons (Fig. 8). pH ranged from 3.9-9.4 but required fine scales to resolve the spatial and temporal patterns (Table 4 and Fig. 6C). Overall, pH was lowest in the summer, greatest in the winter, and there was a slight increase in surface water pH throughout the day in the spring and summer but not in the fall and winter (Fig. 9). In situ values for turbidity and CHL demonstrated the most variability (Table 4 and Figs. 10 and 11). Recall that we established maximum values of 500 NTU and 100 μg L^{-1} for turbidity and CHL during data processing. Despite these efforts, the resulting data distributions for these two variables were highly positively skewed (Figs. 10 and 11). Turbidity was patchy and reached its maximum values at over 100 NTU in the summer and fall 2001 (Fig. 6D). June 2002 also had high NTU values, although they were reduced in spatial and temporal extent. It was difficult to differentiate hourly NTU due to the overall high levels of variability (Fig. 10). In situ estimates of CHL ranged from 0-40 μg L^{-1} and were very patchy in time and space (Fig. 6E). The greatest values occurred in late March 2001, June 2001, September 2001, April 2002, and July 2002. As with NTU it was difficult to assess diel variability, although CHL concentrations did increase to 20 μg L^{-1} in the late afternoon in the summer and decreased to approximately 15 μg L^{-1} at midday in the winter (Fig. 11).

The ISCO sampler shipboard the M/V Lupton provided 342 data points over 16 sampling dates after the raw surface water data were processed and linked to the YSI 6600 locations (Fig. 12). NO_x^- concentrations ranged from below detection limits (1.06) to 13.6 μg L^{-1} and averaged 1.2 $\pm$ 2.0 (sd) μg L^{-1} (Table 4). The greatest average NO_x^- concentration of nearly 3.0 μg L^{-1} occurred in July 2001 although the concentrations appeared to vary slightly along the ferry route (Fig. 13A). NO_x^- concentrations were less than 2 μg L^{-1} much of the time and rarely exceeded 5 μg L^{-1} (Fig. 14 A). Ammonium (NH_4^+) concentrations ranged from 2.4 to 101.9 and averaged 12.9 $\pm$ 11.2 (sd) μg L^{-1} (Table 4). Measured NH_4^+ concentrations were almost as variable as the NO_x^- concentrations, but did not approach detection limits as frequently. The greatest NH_4^+ levels were recorded in June-July 2001 and 2002 (Figs. 13B and 14B). Dissolved silicate (SiO_4^-) concentrations were less variable, ranged from 13.4-84.0 μM and averaged 49.1 $\pm$ 19.0 μM (Table 4). Concentrations of SiO_4^- were greatest (ca. 60 μM) throughout most of the summer of 2001 (Figs. 13C and 14C). Dissolved ortho-phosphate (PO_4^{-3}) ranged from below detection limits (0.35) to 131.0 μg L^{-1} and averaged 31.4 $\pm$ 40.4 μg L^{-1} (Table 4). PO_4^{-3} concentrations were considerably greater in August-October 2001 than at other times including most of 2002 when the variances were almost as high as the reduced mean values (Figs. 13D and 14D). In vitro or laboratory determined chlorophyll concentrations ranged from 4.3-57.9 μg L^{-1} and averaged 16.0 $\pm$ 7.8 μg L^{-1} (Table 4). The greatest concentrations and levels of variability were observed in September 2001 and April-June 2002 with the lowest values in late 2001 (Figs. 15A and 16A). Total dissolved nitrogen (TDN) ranged from 157.6-518.7 μg L^{-1} and averaged 315.1 $\pm$ 44.1 μg L^{-1} (Table 4). Concentrations of PC ranged from 697.7-6904.8 μg L^{-1} and averaged 1835.8 $\pm$ 705.8 μg L^{-1} while PN ranged from 133.9-957.8 μg L^{-1} and averaged 296.0 $\pm$ 84.2 μg L^{-1} (Table 4). Overall, the greatest values of TDN, PC, and PN occurred in the spring and early summer 2002 (Figs. 15B-D, 16B-D). Molar C:N calculated from PC and PN averaged 7.2 + 1.2 and was greatest in February 2002 (Table 4 and Figs. 15E and 16E). TDN, PC, PN, and CN had the lowest overall variability with coefficients of variation ranging 0.14-0.38 (Table 4).

(B) Ferry Route 3 Swan Quarter to Ocracoke Inlet (PS)

The edited data set contained 36,053 surface water recordings from 23 May 2001 to 26 May 2002 along ferry route 3 (Fig. 17 and Table 5). The means and standard deviations were 18.5 $\pm$ 6.5, 21.9 $\pm$ 2.8, 8.2 $\pm$ 0.2, 12.9 $\pm$ 32.1 and 6.4 $\pm$ 10.0 for T, S, pH, NTU, and CHL, respectively. Mean and median values were similar in the cases of temperature, salinity, and pH but the distribution of values for turbidity and CHL were positively skewed and leptokurtic (Table 5). Temperature exhibited temporal but no obvious spatial variability while salinity fluctuated from 15 to approximately 30 psu with time and location (Fig. 18A and 19). Turbidity values and CHL concentrations were generally low from May to September and December 2001, but increased in magnitude and patchiness in October 2001 and the spring of 2002 (Fig. 18D and 18D). Salinity was fairly constant in time at different locations along the transect length with the greatest variations observed near Ocracoke Inlet (Fig. 19). Salinity at Ocracoke Inlet demonstrated an essentially random pattern with no obvious correlation between successive values lagged in time (Fig. 20).

Aggregating the data into a series of discreet time intervals influenced the variances and shapes of the data distributions (Fig. 21). The number of values beyond the 10^{th} and 90^{th} percentiles (outside error bars) decreased for all 5 variables as the temporal interval progressed from minute to month. The variance and skewness in the turbidity and CHL measurements resulted from the large number of values beyond the 90^{th} percentile, which inflated the means well above the median values (Fig. 21D and 21E). Overall, temperature, salinity, and pH maintained narrower distributions and overall less variance than turbidity and CHL at the minute and daily levels of aggregation (Fig. 21). The monthly level of aggregation provided the best compromise among the variance and shape of the resulting distributions so we used it to examine patterns from the first year of sampling using all of the data from ferry route 3 (Fig. 22). First, temperature exhibited a distinct annual cycle while salinity varied little between May 2001 and May 2002 (Fig. 22A and 22B). Second, average CHL estimates were highly variable in September 2001, October 2001, and February to April 2002 (Fig. 22E). These values may have contributed to the observed variability in the turbidity measurements in October 2001 and March 2002 (Fig. 22D).

All of the monthly semi-variograms of salinity had a similar logarithmic shape so we selected four (June 2001, September 2001, December 2001, April 2002) to illustrate seasonal patterns (Fig. 23). The logarithmic shape of the semi-variograms indicated a non-stationary relationship with no discernable upper threshold (or sill) for the semi-variance (Haining 1997). A lower threshold was evident as the semi-variance did not change dramatically with spatial lags of up to 5000 m. However, the semi-variance increased at a higher rate with spatial lags of 7000-22,000 m so that salinity values from sampling locations greater than 5 km apart were negatively correlated. The salinity differences, and therefore the range in semi-variances, across Pamlico Sound were most pronounced in the spring (Fig. 18B; Fig. 23A and 22D).

Mean salinity values varied significantly with time of day (morning, mid-day, afternoon), season, and distance from Swan Quarter (Fig. 24A). Although the temporal and spatial variations in mean salinity were slight in some cases, all tests were significant due to the large sample size. The overall spatial gradient in salinity between Swan Quarter and Ocracoke Inlet provided one of the most compelling statistical results ($p \leq 0.0001$; Fig. 24A inset). Despite widely variable values estimates of CHL concentrations, it varied significantly with time of day, season, and distance (Fig. 24B). However, the results were not as obvious as those for salinity as different combinations of the independent variables influenced the distribution of the CHL mean concentrations differently. Seasonal differences in observed CHL provided another interesting result ($p \leq 0.0001$; Fig. 24B inset). As in the Neuse River and other Atlantic temperate estuaries, the phytoplankton biomass maximum and minimum occurred in the spring and winter, respectively. Mean CHL concentrations were < 8 $\mu g\ L^{-1}$ for all seasons.

(C) Ferry Route 2 Cedar Island to Ocracoke Inlet (PS)

We accumulated 26,272 surface water readings along ferry route 2 from 11 June 2002 to 9 November 2002 (Table 6 and Fig. 25). Temperature ranged from 13.7-31.8 and averaged 25.2 °C. As with the other two routes, there were few obvious spatial patterns in temperature (Fig. 26A and 27A) while the widest variations in temperature occurred in October 2002 (Fig. 28A). Salinity ranged from approximately 8.5 to 36.2 psu and was greatest in the summer of 2002 and least in October 2002 (Table 6 and Fig. 26B). There were spatial differences in salinity with greater values and variability at Ocracoke Inlet (Figs. 26B and 27B). Median salinity values did not vary substantially by month when all data were included (Fig. 28B). pH ranged from 6.2-9.0 and averaged 8.0 (Table 4). Overall, pH followed a comparatively narrow range with a CV = 0.07 and did not exhibit much spatial or temporal variability (Figs. 26C, 27C, and 28C). As the case in ferry routes 1 and 3, turbidity and CHL values were the most variable in time and space (Fig. 26D and 25E). The CV for turbidity was nearly 1.0 and the distribution was heavily positively skewed (Table 6). There were no spatial patterns in turbidity (Fig. 27D) although a greater range of values was observed in September and October 2002 (Fig. 28D). CHL estimates were less variable than turbidity but were equally skewed (Table 6). CHL approached 20 $\mu g\ L^{-1}$ in July and September 2002 (Fig. 26E). Spatial trends were difficult to decipher although there were a greater number of high values recorded nearer to Cedar Island (Fig. 27E). Median monthly CHL ranged from 5-10 $\mu g\ L^{-1}$ throughout the latter part of 2002 with September having the largest range in values (Fig. 28E). The average daily salinity time series near Ocracoke Inlet was highly variable (Fig. 29).

(D) Calibration Comparisons and QA/QC

After data processing and sorting the sample size varied from 13-16 for the data comparisons between the FerryMon sampled water (FMISCO, FMYSI) and the Marker 9 data (M9LAB, M9YSI). We recorded similar means and standard deviations for temperature, pH, NH_4^+, SiO_4^-, PO_4^{-3}, PN, and CN among the FerryMon and Marker 7 data (Table 7). The results of the paired t-tests indicated that the mean values for all of the variables did not differ among the FerryMon and Marker 7 data (Table 8). Values for pH, NH_4^+, and PN were the most similar. Correlation tests revealed that recorded values for temperature, salinity, SiO_4^-, and PO_4^{-3} were highly correlated among the FerryMon and Marker 9 data while TDN and CN were only weakly correlated over the sampling interval (Table 9). The fact that NO_x^- concentrations did not agree among the two data sets was due to the often undetectable levels and the overall high variability of this water quality constituent in the Neuse River Estuary. Median CHL concentrations ranged from 17.0-18.6 $\mu g\ L^{-1}$ among the FMISCO, FMYSI, and M9LAB data while the M9YSI median value was 9.7 $\mu g\ L^{-1}$ (Figure 30). The FMYSI data exhibited a wider distribution that was somewhat negatively skewed. The t-statistic indicated no difference between FMISCO and FMYSI, FMISCO and M9LAB, FMYSI and M9LAB, and FMYSI and M9YSI (Table 10). Of these comparisons, FMYSI vs. M9LAB was the most compelling ($p = 0.88$). The correlation results were slightly different as FMISCO and M9YSI were highly correlated and M9LAB and M9YSI were weakly correlated (Table 10). More coordinated, paired and grouped sampling from the four sampling methods are required to reduce overall variability, develop calibration curves, and increase the confidence in the in situ, surface chlorophyll *a* readings of the ferry-based YSI 6600.

(E) History and Status of FerryMon

The use of ferries as sampling platforms to help monitor surface water quality in North Carolina is an elegant concept. The certified and dedicated ferry personnel function in compliance with U.S. Coast Guard regulations for vessels carrying passengers for hire. The ferries cross the estuaries all day, every day, and only cease operation in strong winds (> 40 knots) or dense fog. In this regard we can provide almost continuous data streams from along the ferry routes that can be analyzed and aggregated over a range of spatial and temporal scales. However, there are theoretical, technical, and logistic challenges in the maintenance of these data streams. FerryMon is not hypothesis based but rather represents an opportunistic way to acquire surface water hydrographic and material data across large portions of the estuaries. Hence, there are problems in the interpretation of the information gathered in FerryMon because of this lack of theoretical base. It is very difficult to adequately generate and test hypotheses about data that has already been collected. No ISCO water sampler was included as part of the flow-through system shipboard the M/V Gov. Hyde due because of limited space inside the ferry engine room and logistical troubles in the retrieval of filled bottles. All of the instrumentation and software programs were created specifically for FerryMon and therefore had not been thoroughly tested prior to ferry deployment. There have been some problems associated with the software that controls the ISCO water samplers shipboard both the M/V Lupton and the M/V Carteret. Specifically, the program that marks the sampling time of each bottle and sends the result to an output file has not worked. We were unable to match water samples with times, and therefore locations, from the first few deployments of the ISCO shipboard both ferries and therefore possess some unreferenced data. Fewer problems occurred with the YSI software although there have been software modifications made from necessity.   Here are the individual histories of the three ferry systems.

The system shipboard the M/V Lupton was to start in September 2000 but experienced a hardware problem in the data logger control box. A service technician from YSI/Endeco visited and fixed the problem. Sampling began 4 October 2000 and the first YSI unit collected at 1 min intervals until November 2000 as a test period to establish procedures such as the nightly flushing of the system with freshwater. There were problems with the cellular communications because of spotty coverage in the area around Cherry Point (Fig. 1). The Instrument Manager (Tim Boynton) created naming conventions and formats for the ferry-based data during this start-up time. The M/V Lupton was taken out of service for one week in late October 2000. The YSI system began to function properly from November 2000 until February 2001 when we interrupted service to test the ISCO sampler. Since the programs that mark the ISCO sampling times have not worked, the technician who retrieves the filled bottles must manually record the sampling times from the ISCO before the unit is reset. The system worked well with monthly YSI instrument changes from February through July 2001 when 2 YSI sondes were sent back to YSI/Endeco to repair the turbidity and chlorophyll sensors. The units were switched with newly calibrated units approximately every 2 weeks in 2001 until the Lupton went on a reduced schedule in November 2001. In March 2002 there were some problems with the wiper that cleans the sensor heads. We noticed during the first full year that we regularly obtained sporadic, unusually high estimates of turbidity and chlorophyll. The IM isolated these values and discovered that they were very unusual and probably resulted from bubble interference with the sensors. We consulted YSI/Endeco technicians who agreed that bubbles generated in the flow-through system were affecting the results. Therefore we ordered de-bubbling mechanisms for all 3 ferries with the de-bubbler added to the Lupton in the early 2002. The de-bubbler served to stabilize the values and provided increased confidence in the data stream. However, in June 2002 we noticed some strange values and discovered that pressure had been greatly reduced in the flow-through system. It seems that the combination of the de-bubbler and the use of the ferry air-conditioning had de-pressurized the system. These problems were solved by Tim Boynton and ferry personnel and data were collected until 12 August 2002 when the M/V Lupton was taken out of service for repairs. The flow-through system was moved to the M/V Neuse on 12 August 2002 and functioned shipboard that ferry until 26 September 2002 when the Lupton returned. The flow-through system, YSI instrument, and ISCO unit functioned properly throughout the remainder of 2002.

The system shipboard the M/V Carteret was complete on 15 February 2001 with data collected at 3 min intervals. Over the first few months we experienced many problems with the ISCO sampler and the GPS linkages. The YSI instruments were replaced with newly calibrated units on 1 May 2001, 21 May 2001, and 14 June 2001. In July 2001 the system sprung a leak because someone tried to switch the YSI unit without removing the screws. On 20 July 2001 technicians discovered a blockage in the outflow line that created unusually high pressure in the plenum and forced the YSI unit out of the top portal, scoring the sides of the instrument. This problem occurred again on 1 August 2001 but was fixed by ferry personnel. The system functioned properly throughout the remainder of 2001 with the exception of the ISCO bottle counter, which never worked correctly. Tim Boynton worked with the ISCO bottle counter program modules throughout the fall of 2001 to no avail. We decided to manually record the bottle sampling times immediately after each deployment. On 20 February 2002 we learned that the system was leaking severely and that the ferry personnel were trying to reduce the increased pressure. The M/V Carteret was taken out of service in late February 2002 and did not return until 17 May 2002. During this time a de-bubbling mechanism was added and the pressure situation was corrected by the addition of a release valve to the flow-through system. There were additional problems with the GPS files during this second start-up in late May 2002 and there were plumbing changes on the ferry that affected the system in June 2002. Tim Boynton worked with the ISCO bottle programs throughout the summer 2002 and on 24 September 2002 reported that the ISCO sampler would finally operate when the desired ferry speed was reached, but that the bottle counting program still did not work. The system functioned properly throughout the remainder of 2002.

The system shipboard the M/V Gov. Hyde was complete on 21 May 2001 with data collected at 3 min intervals. This system is slightly different because it does not include an ISCO water sampler and had no manual ON/OFF switch in the beginning. As with the M/V Carteret, there were initial problems with the software that records the GPS and ferry speed information. We experienced some trouble with data storage and retrieval in June and July 2001 so Tim installed an uninterrupted power source (UPS) to run the ferry data computer. The system functioned well until September and October 2001 when it suffered more trouble with the data logger. Everything was reset on 17 October and an ON/OFF switch was installed. The Hyde was repaired for several days and the system was back on 26 October 2001. This happened again early in November 2001. The system functioned smoothly until April 2002 when the de-bubbling mechanism was installed. We thought that the addition of the de-bubbler was the right option although we had not observed any bubble problems associated with the Hyde. Data collection went on until late October 2002 when the data looked uncertain and it was discovered that oil had leaked into the raw water plenum. On 26 November ferry personnel cleaned the plenum and changed the YSI instrument. The system functioned properly throughout the remainder of 2002.

(5) Discussion

FerryMon represents a collaborative effort among several state and academic institutions to opportunistically collect surface water data from the North Carolina estuaries using the NC Department of Transportation ferries as monitoring platforms. This program will help establish a water quality baseline for Pamlico Sound and allow us to track status and trends by recording data across temporal scales ranging from diel to inter-annual. The first two years of this study reinforce the assertion that passenger ferries make reliable oceanographic vessels (Althuis et al. 1994; Harashima et al. 1997; Rantajarvi et al. 1998). We were able to accumulate intensive records of temperature, salinity, pH, turbidity, and chlorophyll *a* from the three ferry routes. Additionally, the concentrations of dissolved and particulate material in the surface water were determined through automated sampling and laboratory analyses. It is our hope that the ferry deployment could replace regular shipboard oceanographic studies and greatly expedite field data collection. However, there remain many calibrations and quality checks that must be performed for this to occur and despite relative success during the first two years, there are technical and interpretative problems with the continuous flow-through measurements.

The sampled water comes from a turbulent, 1-2 m thick layer of surface water that is pumped through a filter and de-bubbler prior to reaching the YSI 6600 sensors. It is possible that the breakage and maceration of phytoplankton cells and other particulate material causes problems in the determination of values and concentrations. We hope that this is not the case, but we did observe considerable variability in the in situ estimate of chlorophyll biomass that could be related to cell breakage. As mentioned previously, we experienced many problems among the different variables due to the production of bubbles. The severity of the bubble issues varied among the three ferries with the greatest bubble interference resulting from the push-pull propulsion system of the M/V Lupton. Dissolved oxygen (DO) concentrations were omitted from all analyses because bubble production and interference makes the dissolved oxygen measurements spurious at best. Additionally, surface water DO concentrations vary little in most of the NC estuaries (Buzzelli et al. in press). We noticed few troubles with the temperature, salinity, and pH sensors that were bubble related and these properties demonstrated very low levels of variability overall. However, the optical measurements of turbidity and fluorescence were very sensitive to bubbles in the raw water plenum and extremely variable. Presently, the development of seasonal curves to calibrate the in situ estimates of turbidity and chlorophyll *a* is of utmost importance.

Use of the automated, ferry-based data acquisition system to provide surface water truth data to calibrate aerial imagery offers one of the most promising applications of FerryMon. The ability of satellite and aircraft remote sensing to detect and track changes in estuarine spectral signatures is advancing rapidly. Satellite platforms offer wide scale sampling over coastal waters not possible with traditional shipboard methods (Khorram and Cheshire, 1985; Joint and Groom, 2000). However, the water-emerging signals obtained by remote sensors must be calibrated and referenced relative to material concentrations in the water column (Sathyendranath et al. 2000). Materials such as phytoplankton pigments, suspended solids, and colored dissolved organic matter (CDOM) establish the optical properties of water bodies, particularly in optically complex waters (Case II) such as the APES (Woodruff et al. 1999; Sathyendranath et al. 2000). These three groups of substances should provide the primary thrust of future data collection using the ferries as chlorophyll *a* biomass, total suspended solids, and CDOM can be determined from water sampled using the ferry-based ISCO units. Despite the advantage of having an oceanographic vessel taking data on any given day, the empirical curves to calibrate spectral imagery require a large quantity of accumulated data to reduce overall variability. Calibration data sets are usually grouped seasonally and contain many years of water column data (Harding et al. 1995). The YSI turbidity and chlorophyll *a* data is ample for these purposes. However, the huge variability of the in situ turbidity and chlorophyll *a* values requires calibration relative to in vitro standards. Comparisons and cross-calibrations among in situ estimates, in vitro concentrations from ISCO sampled water, and in vitro concentrations from shipboard point studies are fully necessary to help reduce the observed variability in the optical measurements. Increased confidence in the ferry-based measurements will reduce the need for the coordination of shipboard studies with aerial flyovers and allow the ferries to function as surface truth data collection vessels any time that there is an aerial survey or satellite pass. The potential of the ferry-based data to help calibrate coastal ocean color sensors is one of the most potentially valuable functions of FerryMon that will make monitoring habitat quality over a wide range of spatial and temporal scales possible in the NC estuaries.

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Table 1. General characteristics of the Neuse River Estuary (NRE) and Pamlico Sound (PS). The average value is shown in parentheses.

	NRE	PS
Length (km)	**75**	**100-140**
Width (km)	**6.5**	**35-50**
Depth (m)	**2.0-7.0 (4.5)**	**0.5-8.0 (4.5)**
Surface Area (km2)	**455**	**4350**
Volume (m3)	**1.6 x 109**	**26 x 109**
Flushing Time	**25-200 days (55)**	**3-11 months**
Estuarine Type	**Partially stratified, wind driven, no tides**	**Partially stratified to well-mixed, wind driven, tides at inlet**

Table 2. Specifications for FerryMon sampling. The surface water variables that are digitally monitored include temperature (T), salinity (S), pH, dissolved oxygen (DO), turbidity (NTU), and total chlorophyll (chl). Ferries 1 and 2 include a refrigerated, programmable ISCO device to collect discreet water samples for laboratory analyses of dissolved inorganic nutrients, particulate matter, total chlorophyll, and photopigments.

Ferry Route	1	2	3
Date Started	Nov 2000	Feb 2001	May 2001
Ferry Name	Floyd Lupton	Carteret	Governor Hyde
Origination	Cherry Branch	Cedar Island	Swan Quarter
Destination	Minnesott Beach	Ocracoke Island	OI, CI
Avg. Speed (knts)	8.0	10.7	10.4
# of crossings d^{-1}	40	4	2
# of data points d^{-1}	300	200	200-300
Instruments			
YSI 6600	T, S, pH, DO, NTU, chl (all 3 ferries)		
ISCO 6700FR	water/lab	water/lab	none
YSI Interval	3 min (4/01 to present)		
# of data points/day	N = 700-800		

Table 3. Detection limits for several of the variables provided by the laboratory at the University of North Carolina Institute of Marine Sciences (UNC-IMS) to help in analyses and interpretation of the concentrations determined from water samples collected with the ISCO units. We created the working concentrations by assuming that all values below detection limits (BDL) were equal to BDL * 0.5. This is an important consideration because a sample that is BDL is not necessarily zero and still provides a viable data point in analyses.

Variable	Detection Limit	Working Concentration
NO_x^- (μg L^{-1})	1.06	0.53
NH_4^+ (μg L^{-1})	4.69	2.35
SiO_4^- (μM)	0.18	0.09
PO_4^{-3} (μg L^{-1})	0.35	0.18

Table 4. Descriptive statistics for 14 surface water variables sampled along ferry route 1 between Cherry Branch and Minnesott Beach. The statistics include mean, standard deviation (sd), standard error (se), minimum and maximum values (min and max), the coefficient of variation (CV), and indices of skewness and kurtosis. The top half of the table contains the descriptive statistics for temperature (T), salinity (S), pH, turbidity, and chlorophyll *a* (CHL_{ysi}). These variables were determined using the YSI 6600 for a total sample size of 120,433 from 1 November 2002 to 14 September 2002. In situ values beyond the upper limits for turbidity (500 NTU) and chlorophyll *a* (100 $\mu g\ L^{-1}$) were omitted (see . The bottom half of the table contains the descriptive statistics for the laboratory concentrations of nitrate + nitrite (NO_x^-), ammonium (NH_4^+), silicate (SiO_4^-), ortho-phosphate (PO_4^{-3}), total dissolved nitrogen (TDN), in vitro chlorophyll *a* (CHL), particulate carbon and nitrogen (PC and PN), and molar C:N (CN) determined from water samples taken using the ferry ISCO sampler. The total sample size for ISCO water samples was 342 between18 June 2001 to 18 June 2002.

	T (°C)	S (psu)	pH	turbidity (NTU)	CHL_{ysi} ($\mu g\ L^{-1}$)
Mean	15.18	11.1	8.0	18.2	18.6
Sd	7.4	3.7	0.4	39.9	12.8
Se	0.02	0.01	0.001	0.12	0.04
Min	2.1	1.9	3.9	0.0	0.0
Max	34.9	23.7	9.4	499.8	100.0
CV	0.49	0.34	0.04	2.19	0.69
Skewness	0.62	0.61	-0.48	7.06	2.74
Kurtosis	-0.78	-0.22	2.5	59.1	10.3

	NO_x^- ($\mu g\ L^{-1}$)	NH_4^+ ($\mu g\ L^{-1}$)	SiO_4^- (μM)	PO_4^{-3} ($\mu g\ L^{-1}$)	TDN ($\mu g\ L^{-1}$)	CHL ($\mu g\ L^{-1}$)	PC ($\mu g\ L^{-1}$)	PN ($\mu g\ L^{-1}$)	CN
Mean	1.2	12.9	49.1	31.4	315.1	16.0	1835.8	296.0	7.2
Sd	2.0	11.2	19.0	40.4	44.1	7.8	705.8	84.2	1.2
Se	0.11	0.61	1.03	2.18	2.39	0.42	38.17	4.55	0.07
Min	0.2	2.4	13.4	0.2	157.6	4.3	697.7	133.9	4.8
Max	13.6	101.9	84.0	131.0	518.7	57.9	6904.8	957.8	11.8
CV	1.7	0.87	0.39	1.29	0.14	0.49	0.38	0.28	0.17
Skewness	3.85	3.99	0.63	1.18	0.66	1.30	2.14	1.58	1.07
Kurtosis	15.45	24.22	-1.45	-0.28	2.68	3.14	9.89	10.19	1.39

Table 5. Descriptive statistics for 5 surface water variables sampled during the first year of data collection along ferry route 3 between Swan Quarter and Ocracoke Inlet. The statistics include mean, standard deviation (sd), standard error (se), minimum and maximum values (min and max), the coefficient of variation (CV), skewness and kurtosis, and the median and modal values. Data collected at 3 min intervals while the ferry was underway resulted in a total sample size of 36,053 for these variables from 23 May 2001 to 26 May 2002.

	T (°C)	S (psu)	pH	turbidity (NTU)	CHL ($\mu g\ L^{-1}$)
mean	18.5	21.9	8.2	12.9	6.4
sd	6.5	2.8	0.2	32.1	10.0
se	0.034	0.015	0.001	0.169	0.053
min	3.0	9.3	7.6	0.4	0.0
max	31.4	36.4	8.6	497.7	100.0
CV	0.35	0.13	0.02	2.49	1.56
skewness	-0.24	0.36	-1.02	8.37	5.68
kurtosis	-0.93	2.2	0.14	86.9	37.3
median	18.2	22.0	8.2	5.5	4.1
mode	15.2	20.3	8.3	3.1	2.9

Table 6. Descriptive statistics for 5 surface water variables sampled along ferry route 2 between Cedar Island and Ocracoke Inlet. The statistics include mean, standard deviation (sd), standard error (se), minimum and maximum values (min and max), the coefficient of variation (CV), skewness and kurtosis, and the median and modal values. Data collected at 3 min intervals while the ferry was underway resulted in a total sample size of 26,272 for these variables from 11 June 2002 to 9 November 2002.

	T (°C)	S (psu)	pH	turbidity (NTU)	CHL ($\mu g\ L^{-1}$)
mean	25.2	26.8	8.0	11.7	9.6
sd	4.2	1.8	0.1	11.5	4.0
se	0.026	0.011	0.001	0.071	0.025
min	13.7	8.5	6.2	0.0	0.4
max	31.8	36.2	9.0	152.9	77.2
CV	0.17	0.07	0.01	0.98	0.42
skewness	-1.18	-0.30	-1.64	1.80	0.94
kurtosis	0.44	17.92	11.53	5.10	5.45
median	26.5	26.6	8.0	6.9	9.4
mode	27.0		8.0	32.9	10.7

Table 7. Descriptive statistics for Neuse River Estuary surface water variables determined using both shipboard point (Marker 9) and FerryMon ISCO (FMISCO) sampler from 18 June 2001 to 18 June 2002. The sample size ranged from 13-16. The average (avg), standard deviation (sd), and standard error (se) are provided for temperature (T), salinity (S), pH, nitrate + nitrite (NO_x^-), ammonium (NH_4^+), silicate (SiO_4^-), ortho-phosphate (PO_4^{-3}), total dissolved nitrogen (TDN), particulate carbon (PC), particulate nitrogen (PN), and molar C:N (CN).

	Marker 9			FMISCO		
	avg	sd	se	avg	sd	se
T	21.3	5.78	1.60	22.2	5.40	1.35
S	12.1	4.06	1.13	13.2	3.54	0.89
pH	8.0	0.40	0.11	8.0	0.34	0.09
NO_x^-	0.85	1.15	0.32	1.25	1.00	0.25
NH_4^+	11.1	4.92	1.37	11.7	6.03	1.51
SiO_4^-	58.5	25.1	7.00	50.1	19.4	4.85
PO_4^{-3}	29.4	37.62	10.43	31.1	40.43	10.11
TDN	278.0	87.12	24.16	314.2	31.32	7.83
PC	1718.0	338.1	93.79	1892.5	527.9	132.0
PN	301.3	70.63	19.59	296.0	55.46	13.87
CN	6.85	1.29	0.36	7.35	1.17	0.29

Table 8. Paired t-test results for Neuse River Estuary surface water variables determined using both shipboard point (Marker 9) and FerryMon ISCO (FMISCO) sampler from 18 June 2001 to 18 June 2002. The sample size ranged from 13-16 among the comparisons. The variables included temperature (T), salinity (S), pH, nitrate + nitrite (NO_x^-), ammonium (NH_4^+), silicate (SiO_4^-), ortho-phosphate (PO_4^{-3}), total dissolved nitrogen (TDN), particulate carbon (PC), particulate nitrogen (PN), and molar C:N (CN). The null hypothesis was Marker 9 = FMISCO. We were unable to reject this hypothesis for any of the paired tests.

Marker 9 vs FMISCO	t-value	p-value
T	1.441	0.175
S	1.017	0.329
pH	-0.090	0.929
NO_x^-	0.825	0.426
NH_4^+	0.035	0.973
SiO_4^-	-1.003	0.336
PO_4^{-3}	1.398	0.187
TDN	1.750	0.106
PC	1.094	0.296
PN	-0.262	0.798
CN	1.537	0.150

Table 9. Correlation results for Neuse River Estuary surface water variables determined using both shipboard point (Marker 9) and FerryMon ISCO (FMISCO) sampler from 18 June 2001 to 18 June 2002. The sample size ranged from 13-16 among the comparisons. The variables included temperature (T), salinity (S), pH, nitrate + nitrite (NO_x^-), ammonium (NH_4^+), silicate (SiO_4^-), ortho-phosphate (PO_4^{-3}), total dissolved nitrogen (TDN), particulate carbon (PC), particulate nitrogen (PN), and molar C:N (CN). The correlation coefficient (r) and probability values (p-values) between the Marker 9 and FMISCO are provided.

Marker 9 vs FM ISCO	r	p-value
T	0.93	<0.0001
S	0.88	<0.0001
pH	0.46	0.202
NTU	-0.17	0.988
NO_x^-	-0.19	0.501
NH_4^+	0.34	0.091
SiO_4^-	0.63	0.0006
PO_4^{-3}	0.90	<0.0001
TDN	0.51	0.018
PC	0.17	0.168
PN	0.43	0.139
CN	0.76	0.008

Table 10. Comparisons among chlorophyll a concentration estimates from the Neuse River Estuary ferry crossing using t-tests and correlation analyses. The values were determined using the ferry-based ISCO water sampler with subsequent lab analysis (FMISCO), the in-situ ferry-based YSI 6600 (FMYSI), the discreet bi-weekly surface water sample from marker 9 using both lab analysis (M9LAB) and the in situ YSI 6600 (M9YSI). The sample size ranged from 13-16 among the comparisons. The table lists the particular comparison, the t-statistic and p-values from paired t-tests, and the r and p-values from the correlation analyses. The null hypothesis for the t-tests was equality among the paired comparisons. We were unable to reject this hypothesis for any of the paired tests.

	t-statistic	p-value	r	p-value
FMISCO vs FMYSI	-1.03	0.32	0.18	0.59
FMISCO vs M9LAB	-1.52	0.15	0.63	0.03
FMISCO vs M9YSI	2.12	0.05	0.81	0.001
FMYSI vs M9LAB	0.16	0.88	0.05	0.89
FMYSI vs M9YSI	1.69	0.11	0.02	0.96
M9LAB vs M9YSI	2.28	0.04	0.65	0.02

Figure 1. Location map for the lower APES including the Pamlico River Estuary, the Neuse River Estuary, Pamlico Sound, and the Outer Banks.

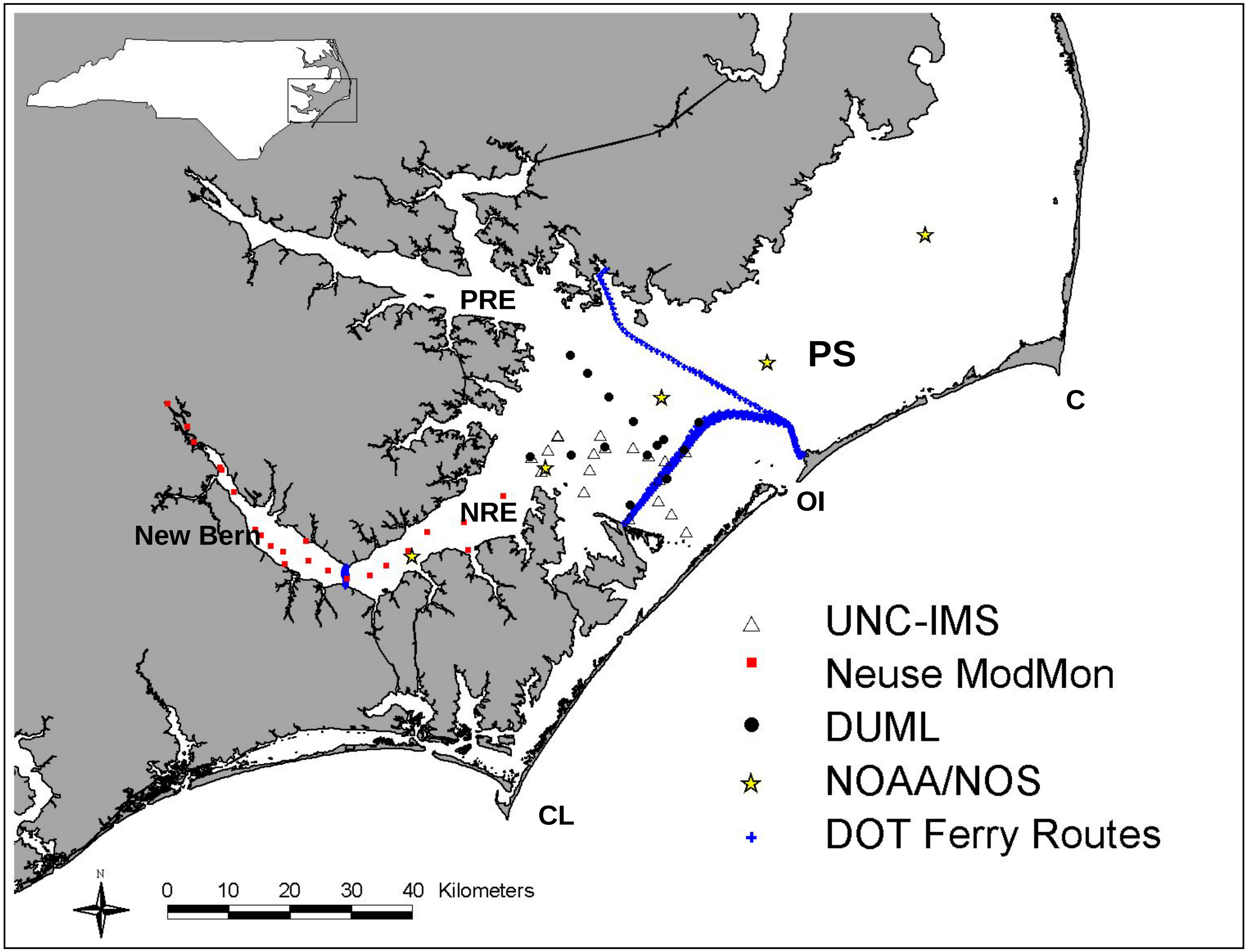

Figure 2. Conceptualized time-space plot demonstrating different scales of monitoring given a hypothetical estuarine response such as a large phytoplankton bloom.

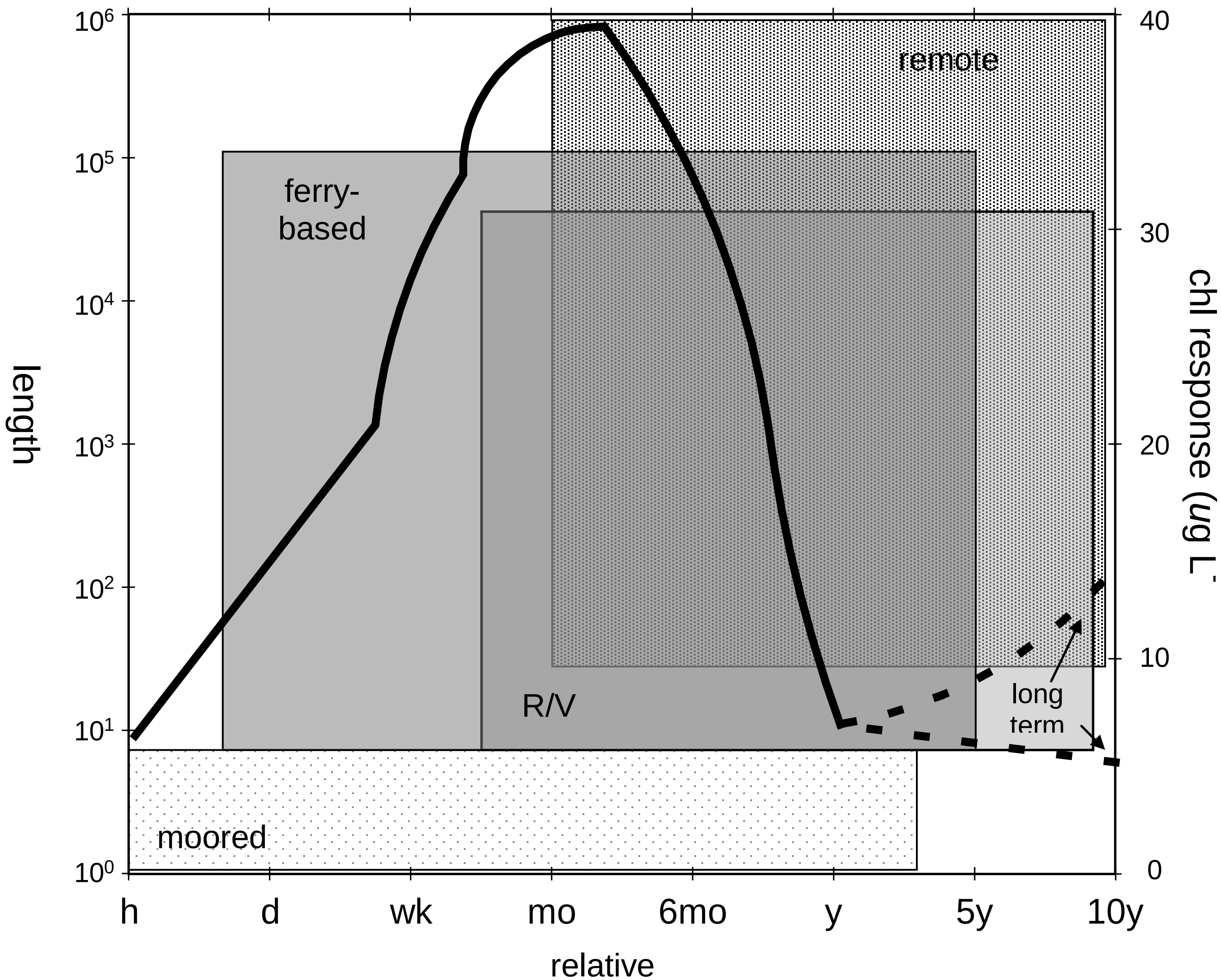

Figure 3. Map zoom series depicting the State of North Carolina, the southern APES, ferry route 1 in the Neuse River Estuary, and ferry routes 2 and 3 that cross the Pamlico Sound.

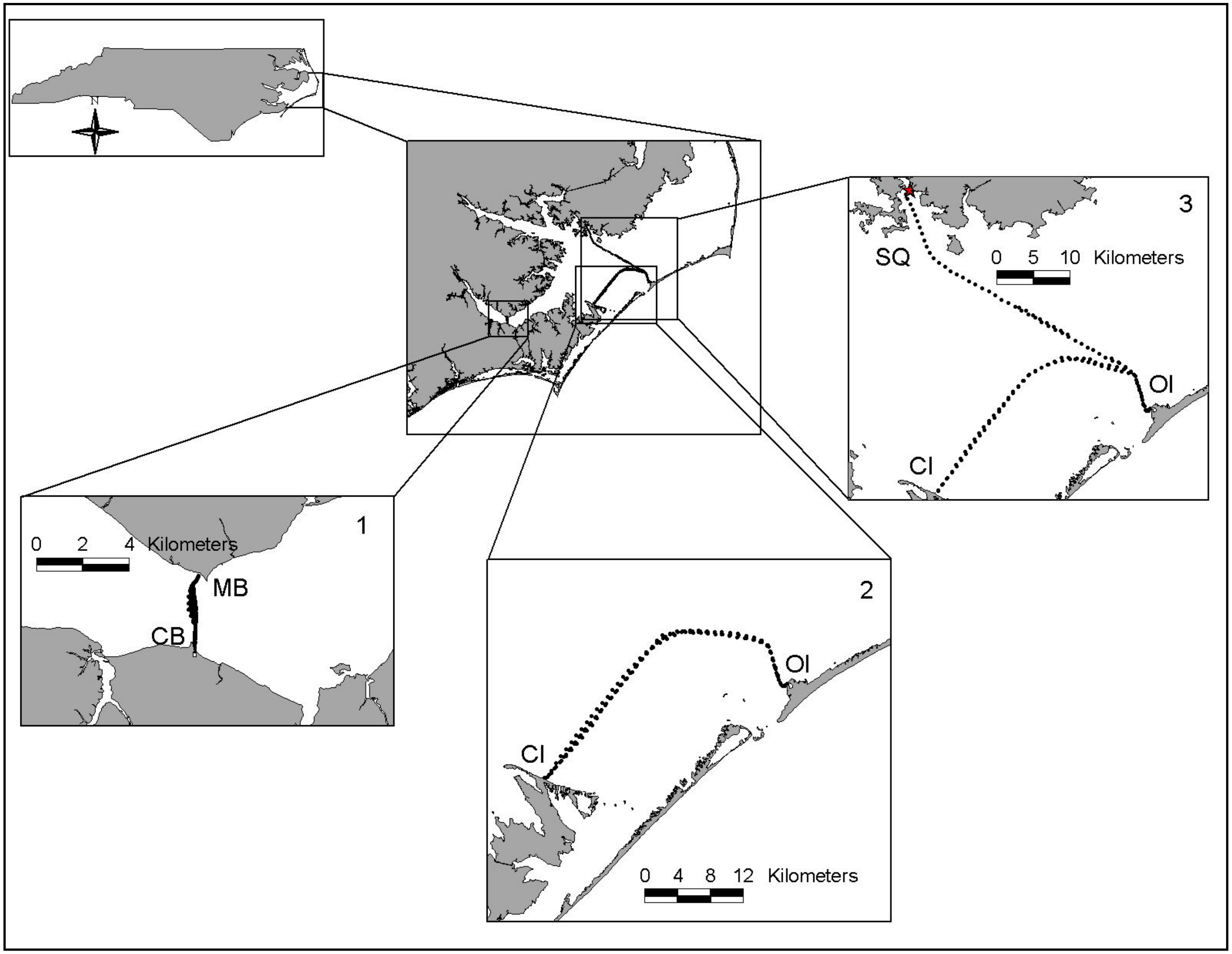

Figure 4. Schematic of the ferry-based water and data flow systems.

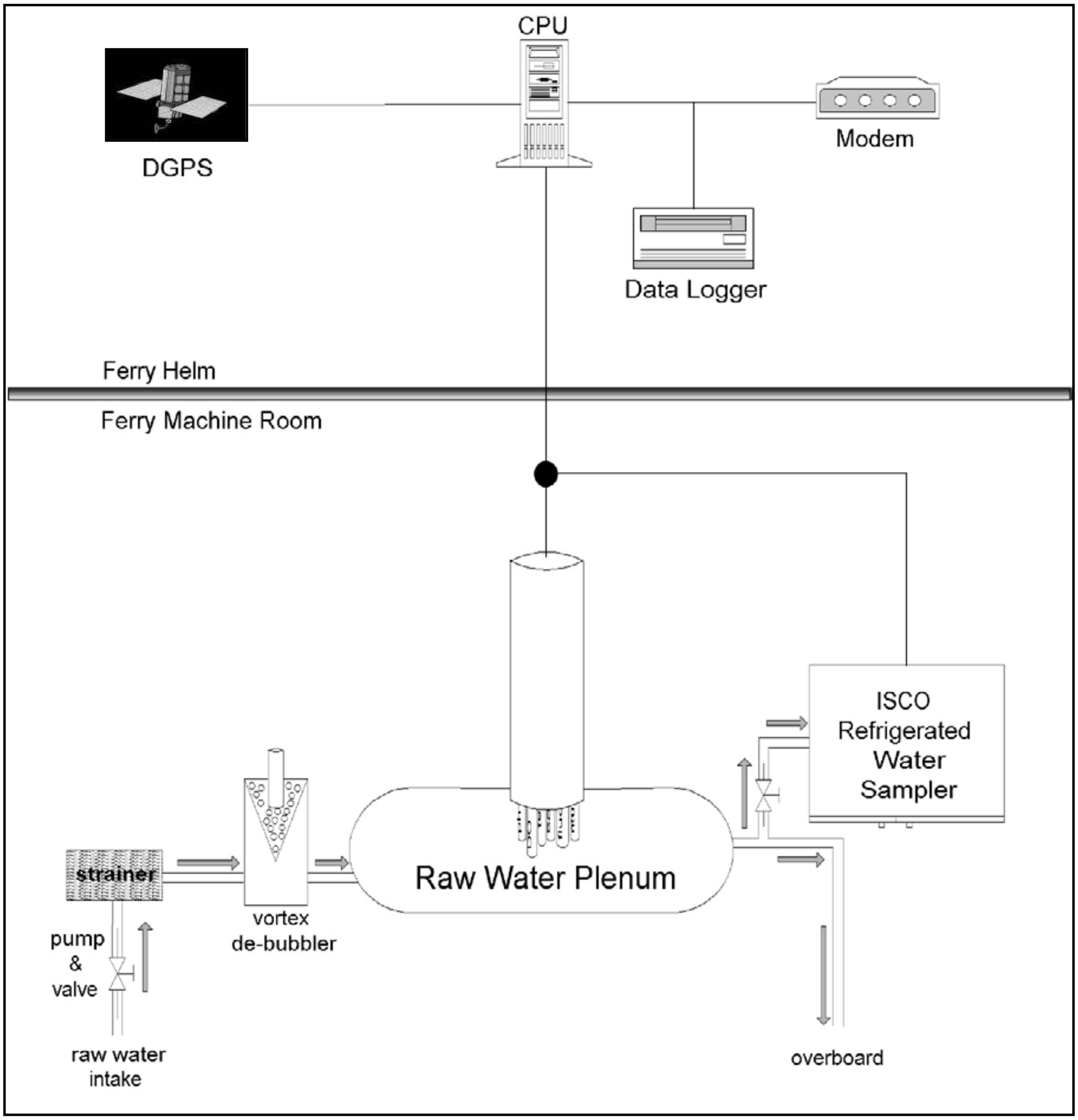

Figure 5. Information flow diagram for processing, analyses, and application of the ferry-based data.

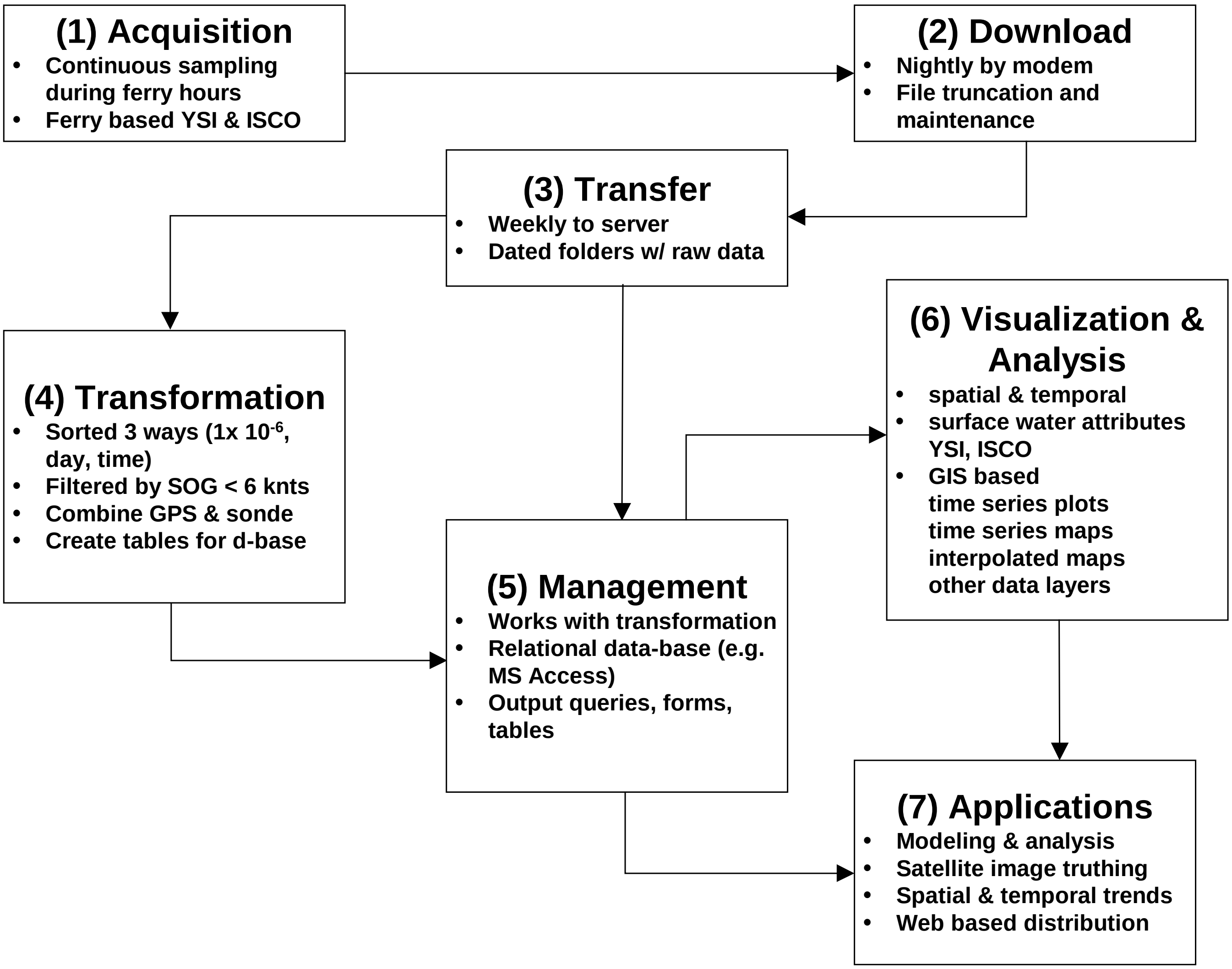

Figure 6. Interpolated time-space contour plots created from data collected across the Neuse River Estuary shipboard the M/V Floyd Lupton from November 2000 to September 2002. Individual plots include temperature, salinity, pH, turbidity, and chlorophyll *a*.

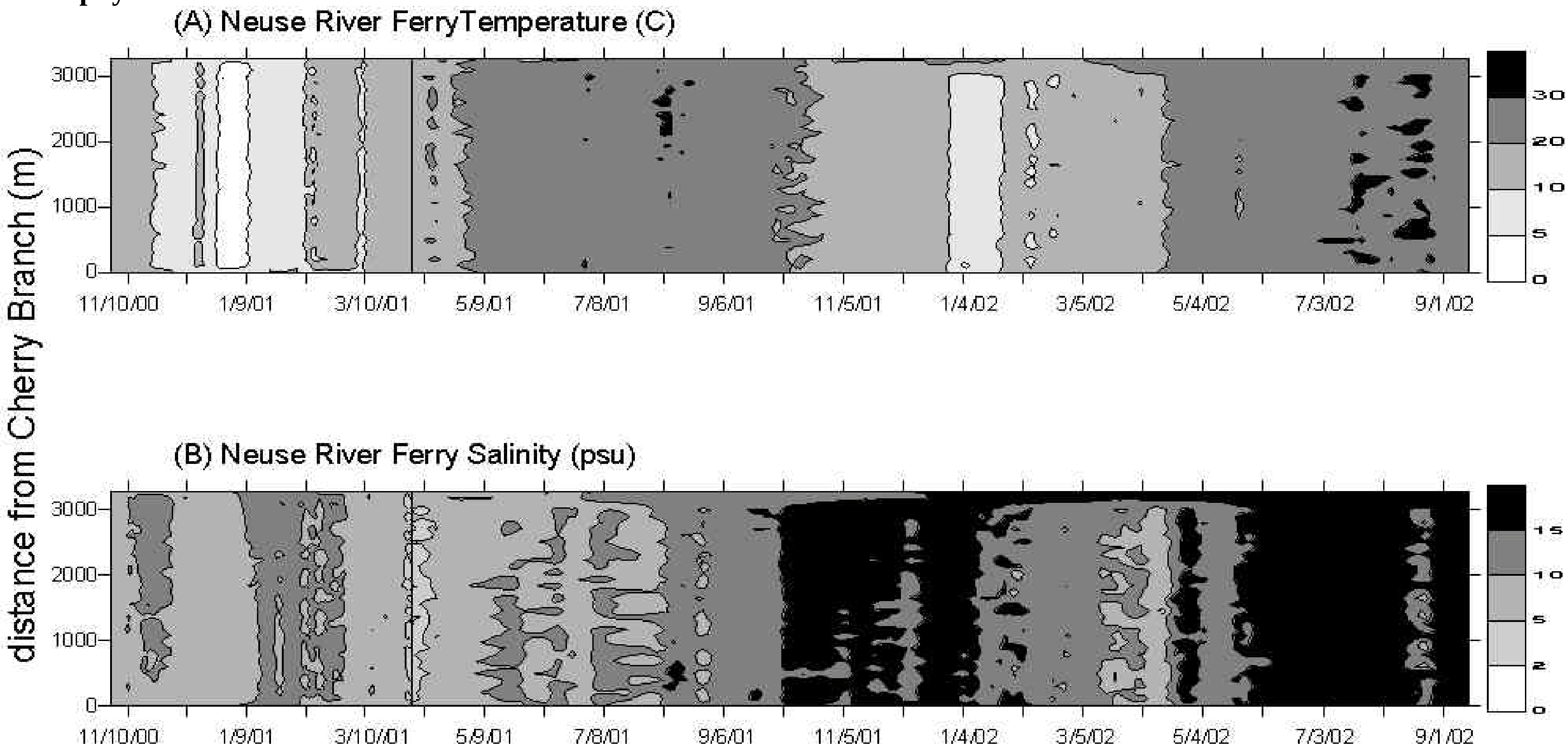

Figure 6 continued

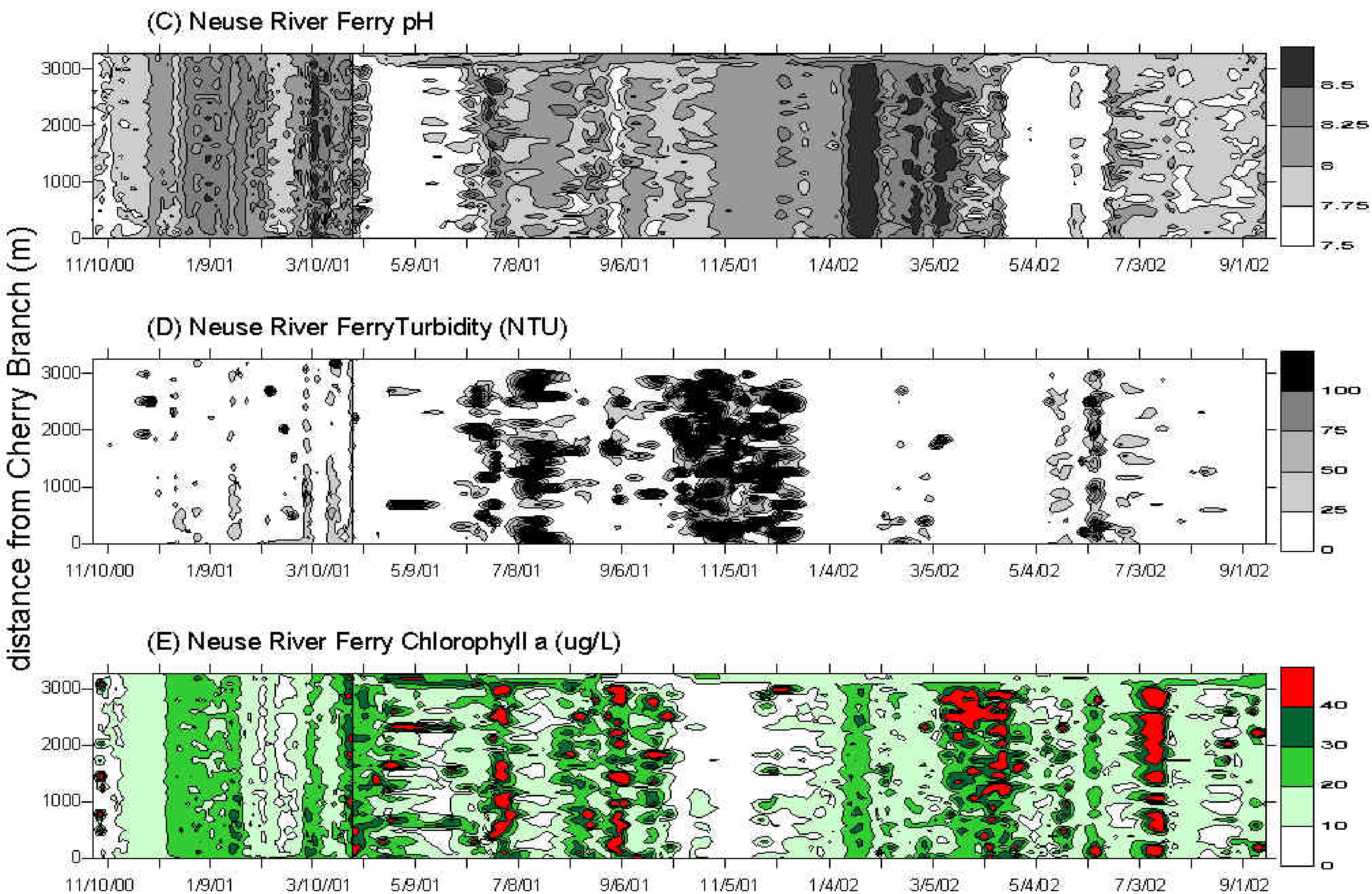

Figure 7. Hourly temperature values from data collected across the Neuse River Estuary shipboard the M/V Floyd Lupton from November 2000 to September 2002. The ferry runs from approximately 0500 h to 0100 daily and the data were split into calendar seasons.

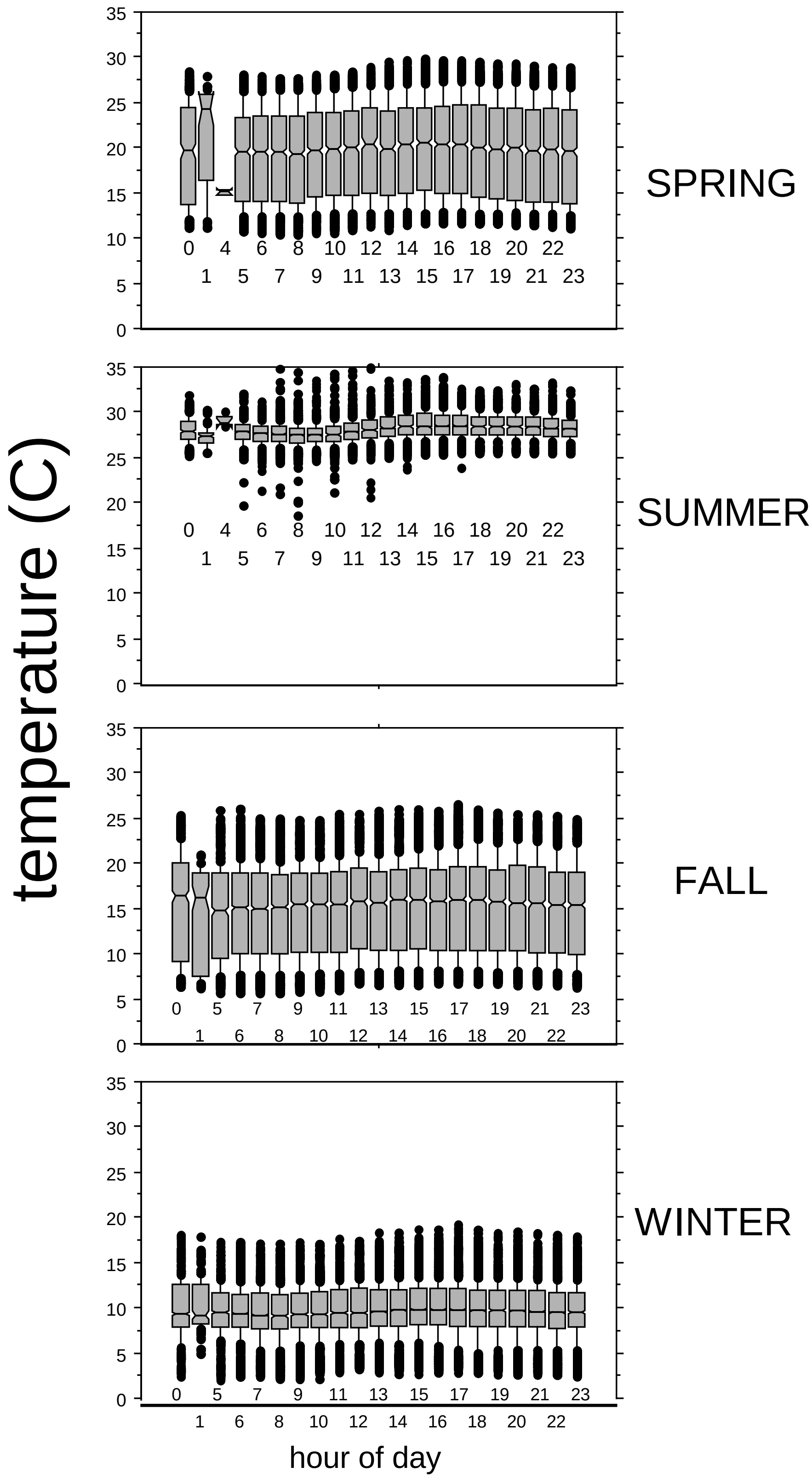

Figure 8. Hourly salinity values from data collected across the Neuse River Estuary shipboard the M/V Floyd Lupton from November 2000 to September 2002. The ferry runs from approximately 0500 h to 0100 daily and the data were split into calendar seasons.

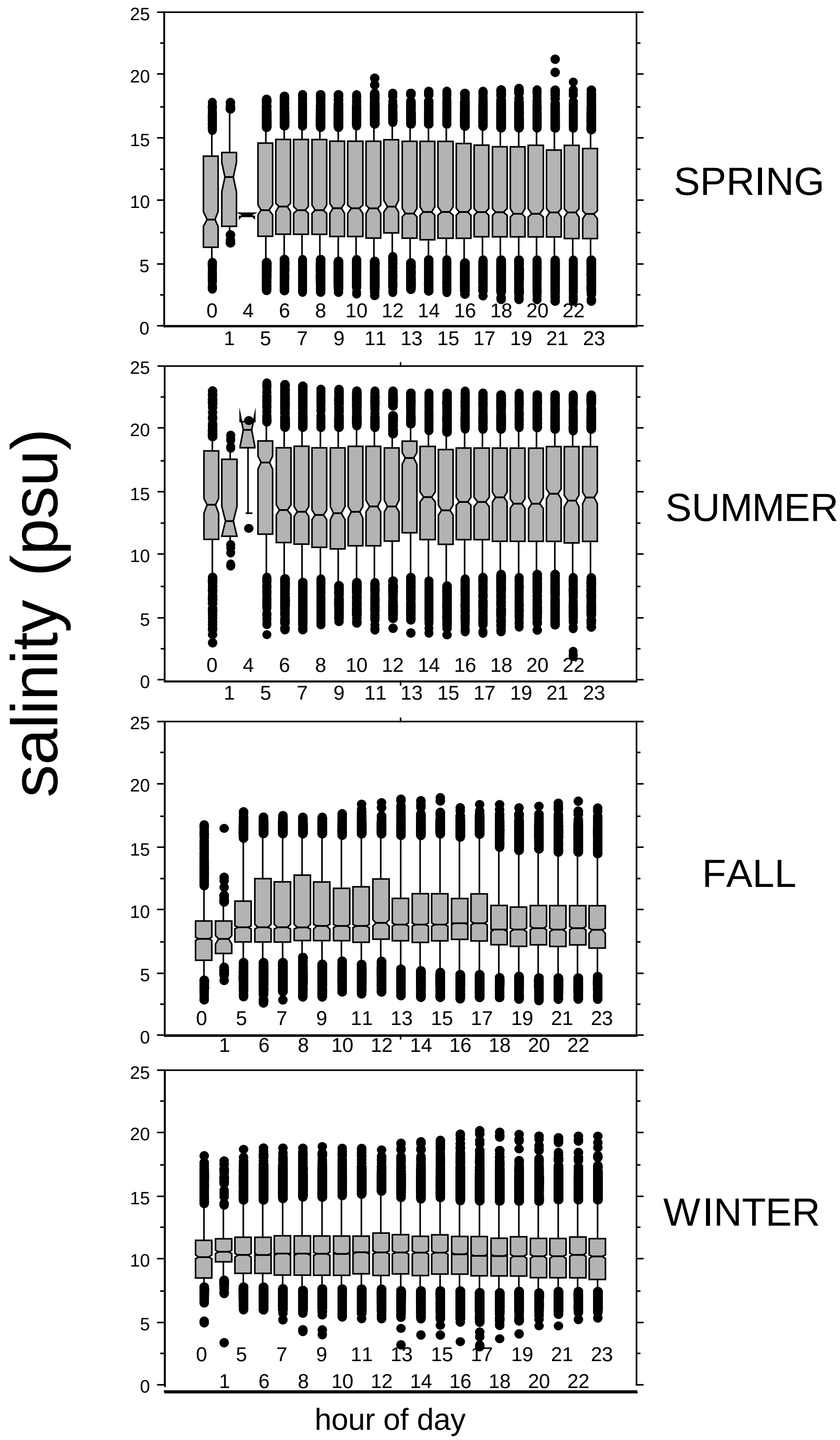

Figure 9. Hourly pH values from data collected across the Neuse River Estuary shipboard the M/V Floyd Lupton from November 2000 to September 2002. The ferry runs from approximately 0500 h to 0100 daily and the data were split into calendar seasons.

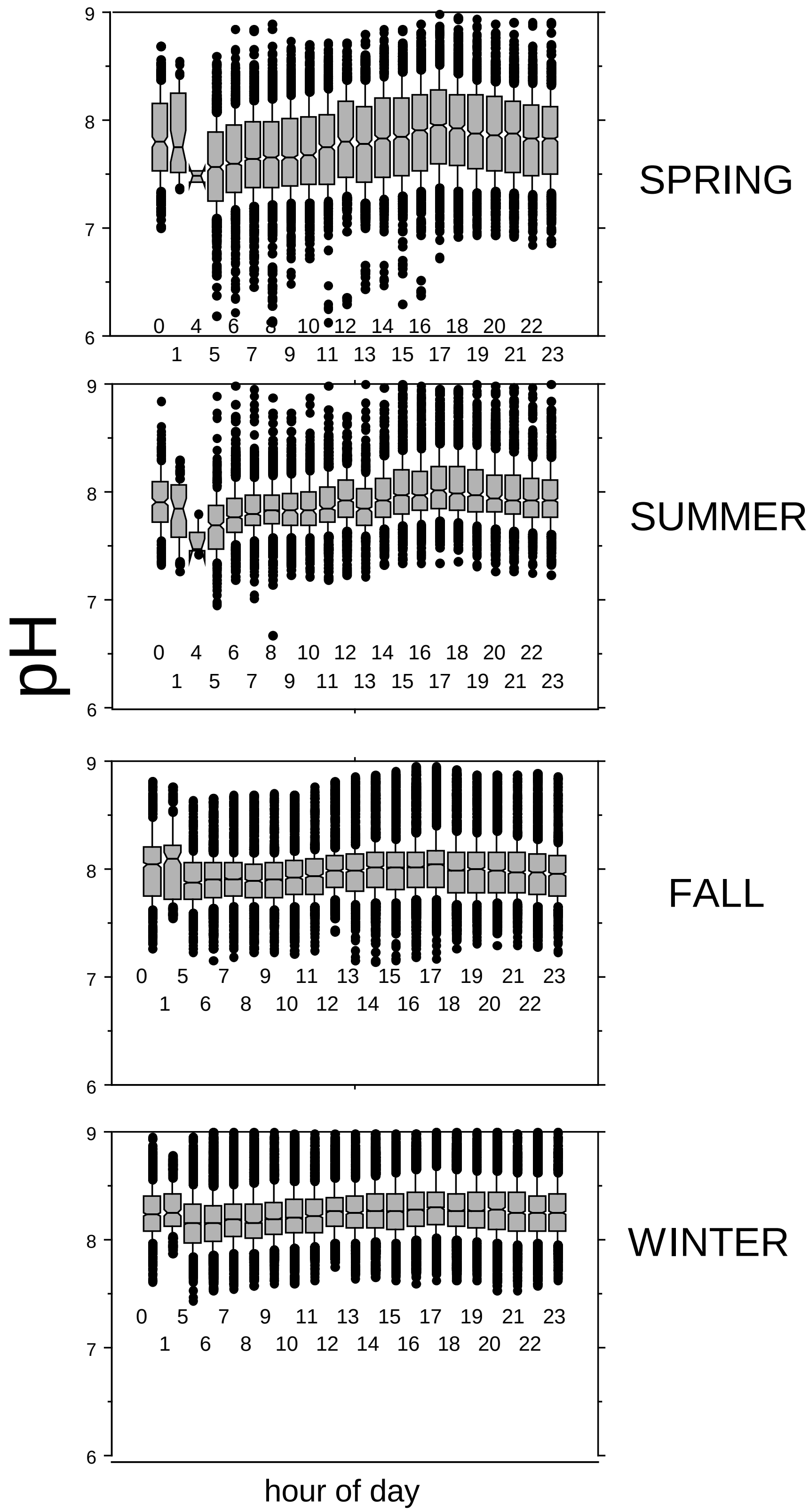

Figure 10. Hourly turbidity values from data collected across the Neuse River Estuary shipboard the M/V Floyd Lupton from November 2000 to September 2002. The ferry runs from approximately 0500 h to 0100 daily and the data were split into calendar seasons.

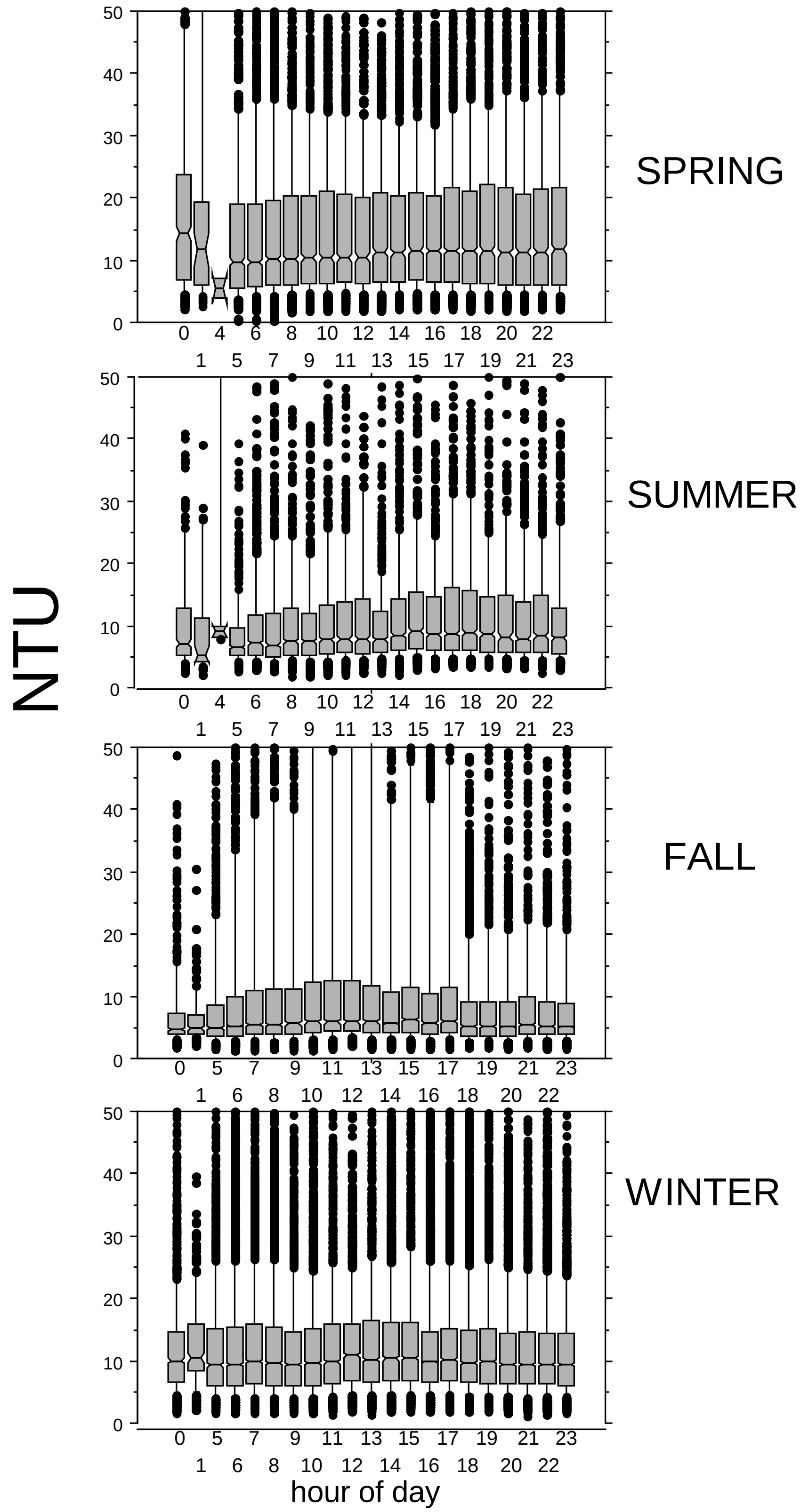

Figure 11. Hourly chlorophyll *a* values from data collected across the Neuse River Estuary shipboard the M/V Floyd Lupton from November 2000 to September 2002. The ferry runs from approximately 0500 h to 0100 daily and the data were split into calendar seasons.

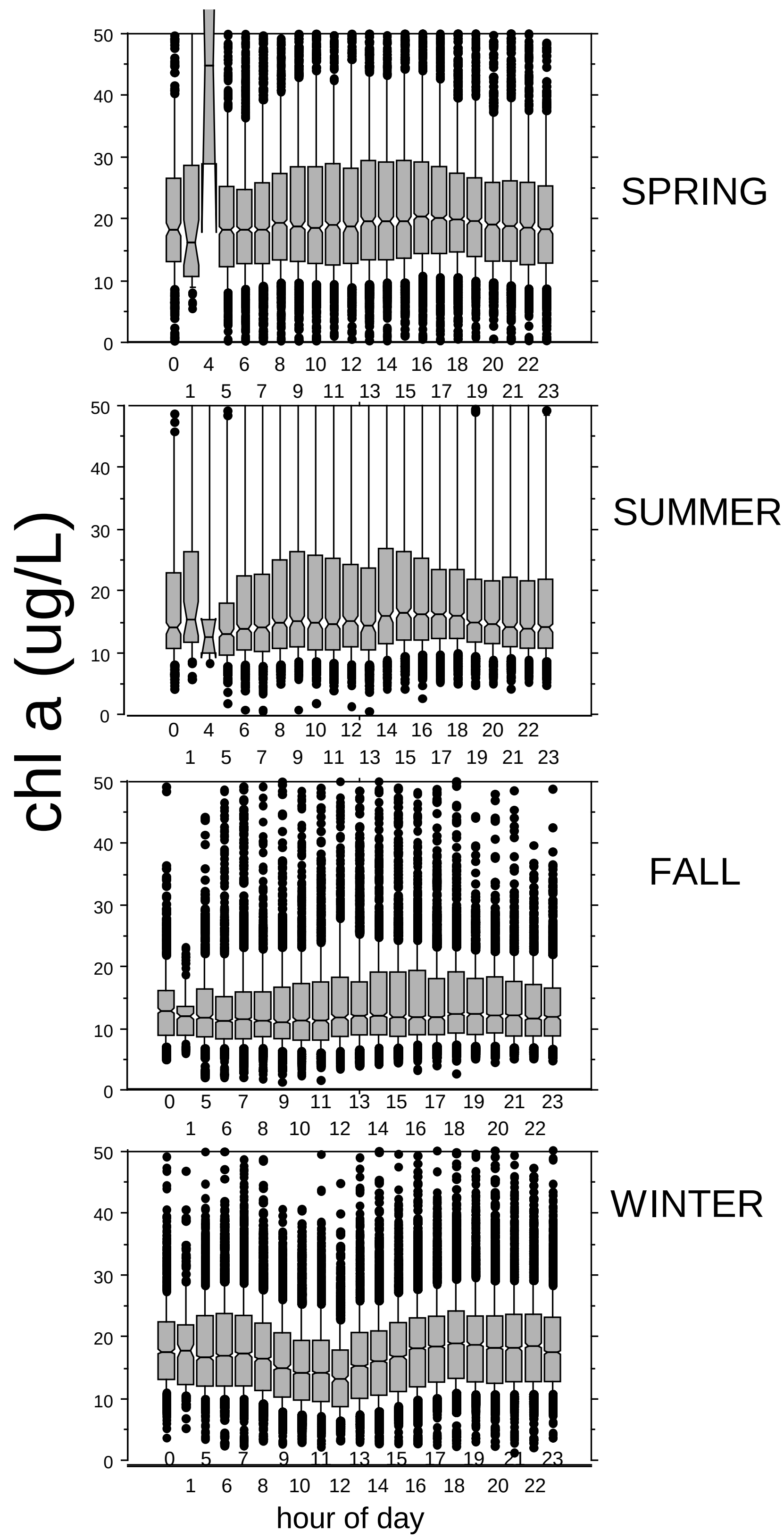

Figure 12. Map of ISCO sampling locations across the Neuse River Estuary from 18 June 2001 to 18 June 2002.

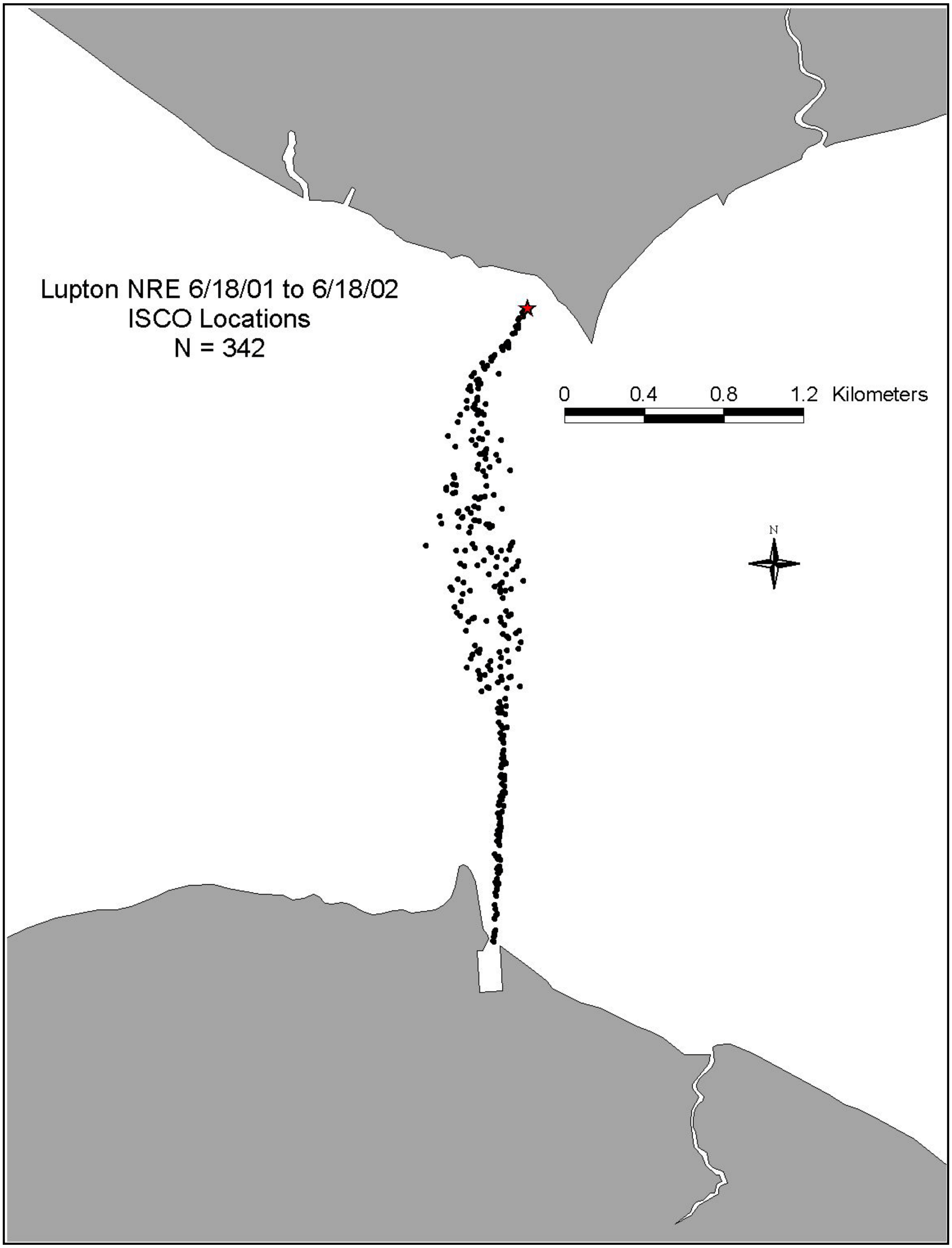

Figure 13. Average daily values and standard deviations of dissolved concentrations determined from water sampled using the ISCO sampler shipboard the M/V Floyd Lupton from 18 June 2001 to 18 June 2002. Values are included for nitrate + nitrite (NO_x^-), ammonium (NH_4^+), silicate (SiO_4^-), and ortho-phosphate (PO_4^{-3}) from 18 June 2001 to 18 June 2002.

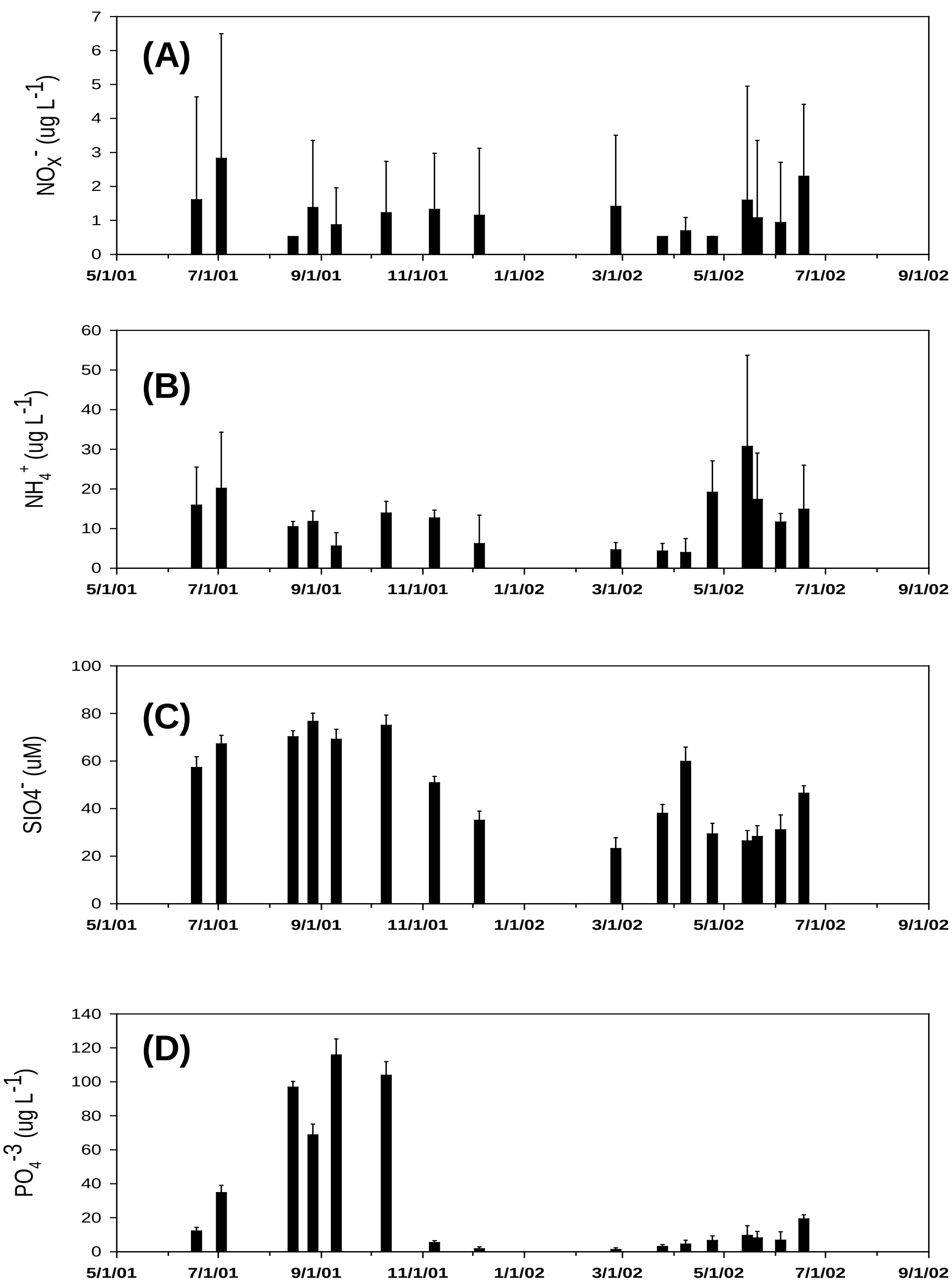

Figure 14. Interpolated time-space contour plots created from data collected across the Neuse River Estuary shipboard the M/V Floyd Lupton from 18 June 2001 to 18 June 2002. Individual plots include nitrate + nitrite (NO_x^-), ammonium (NH_4^+), silicate (SiO_4^-), and ortho-phosphate (PO_4^{-3}).

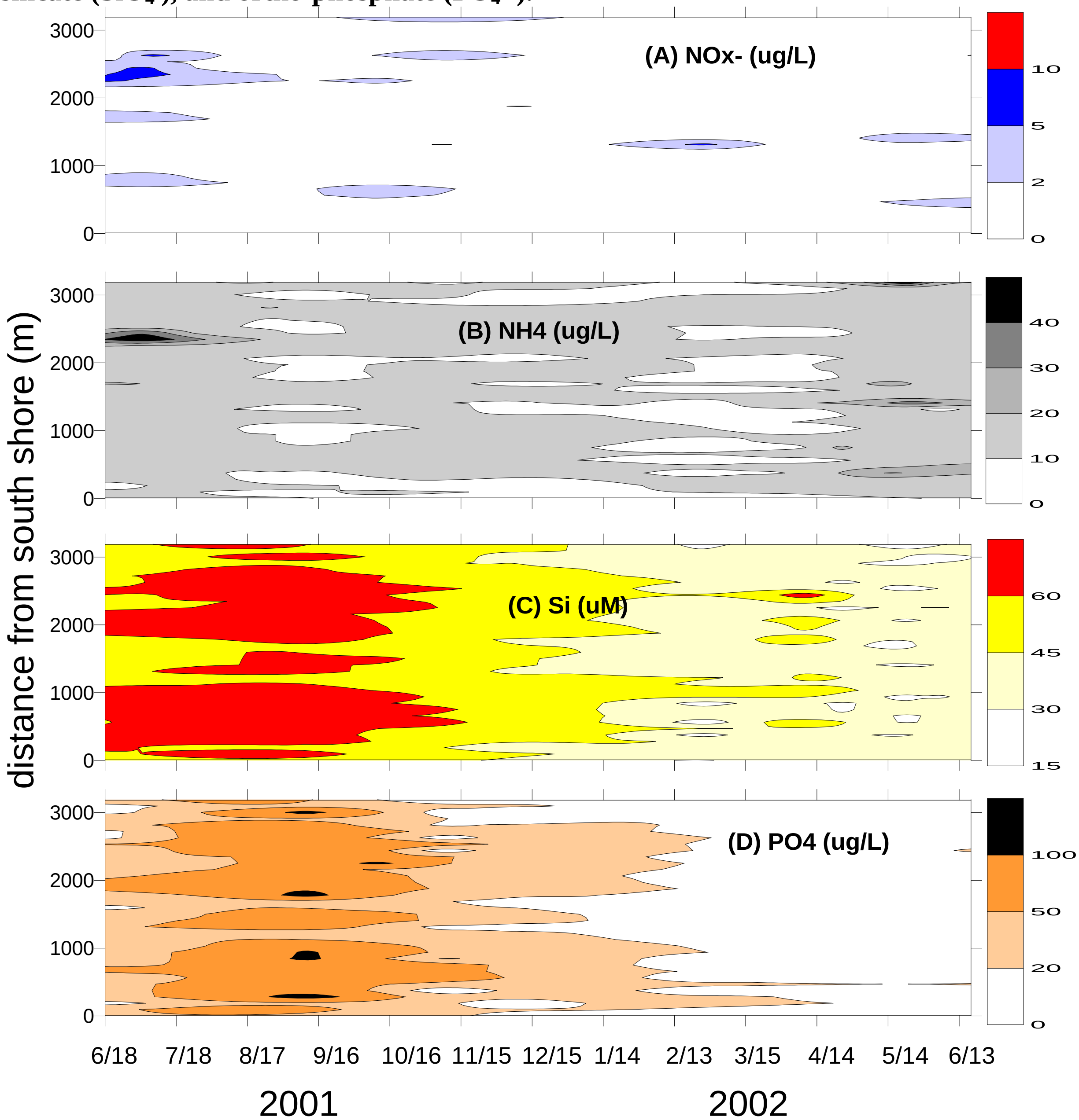

Figure 15. Average daily values and standard deviations of particulate concentrations determined from water sampled using the ISCO sampler shipboard the M/V Floyd Lupton from 18 June 2001 to 18 June 2002. Values are included for total dissolved nitrogen (TDN), in vitro chlorophyll *a* (CHL), particulate carbon and nitrogen (PC and PN), and the molar C:N (CN).

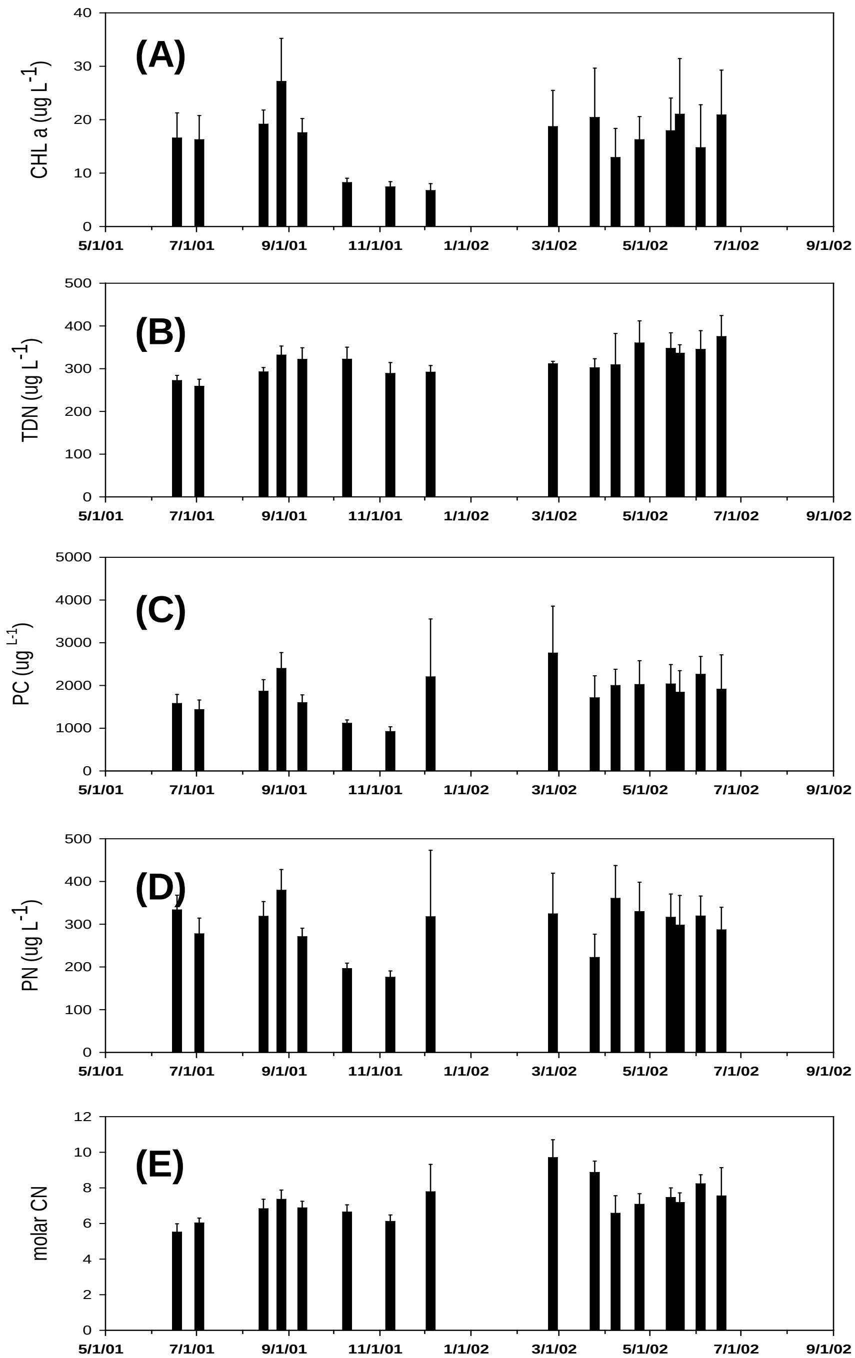

Figure 16. Interpolated time-space contour plots created from data collected across the Neuse River Estuary shipboard the M/V Floyd Lupton from 18 June 2001 to 18 June 2002. Individual plots include total dissolved nitrogen (TDN), in vitro chlorophyll *a* (CHL), particulate carbon and nitrogen (PC and PN), and the molar C:N (CN).

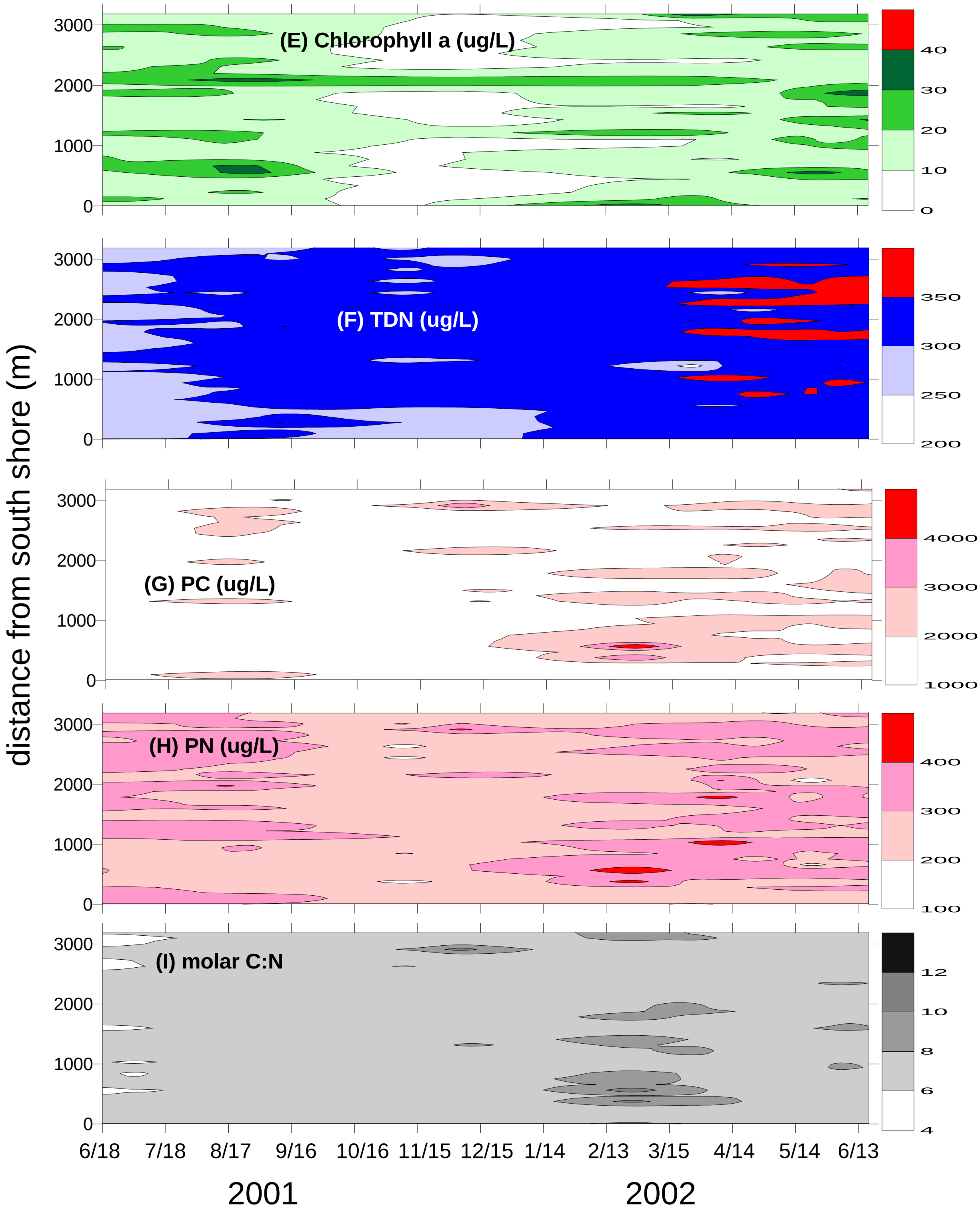

Figure 17. Map of sampling locations along ferry route 3 between Swan Quarter and Ocracoke Inlet. This route was split into 10 km segments for some of the data analysis.

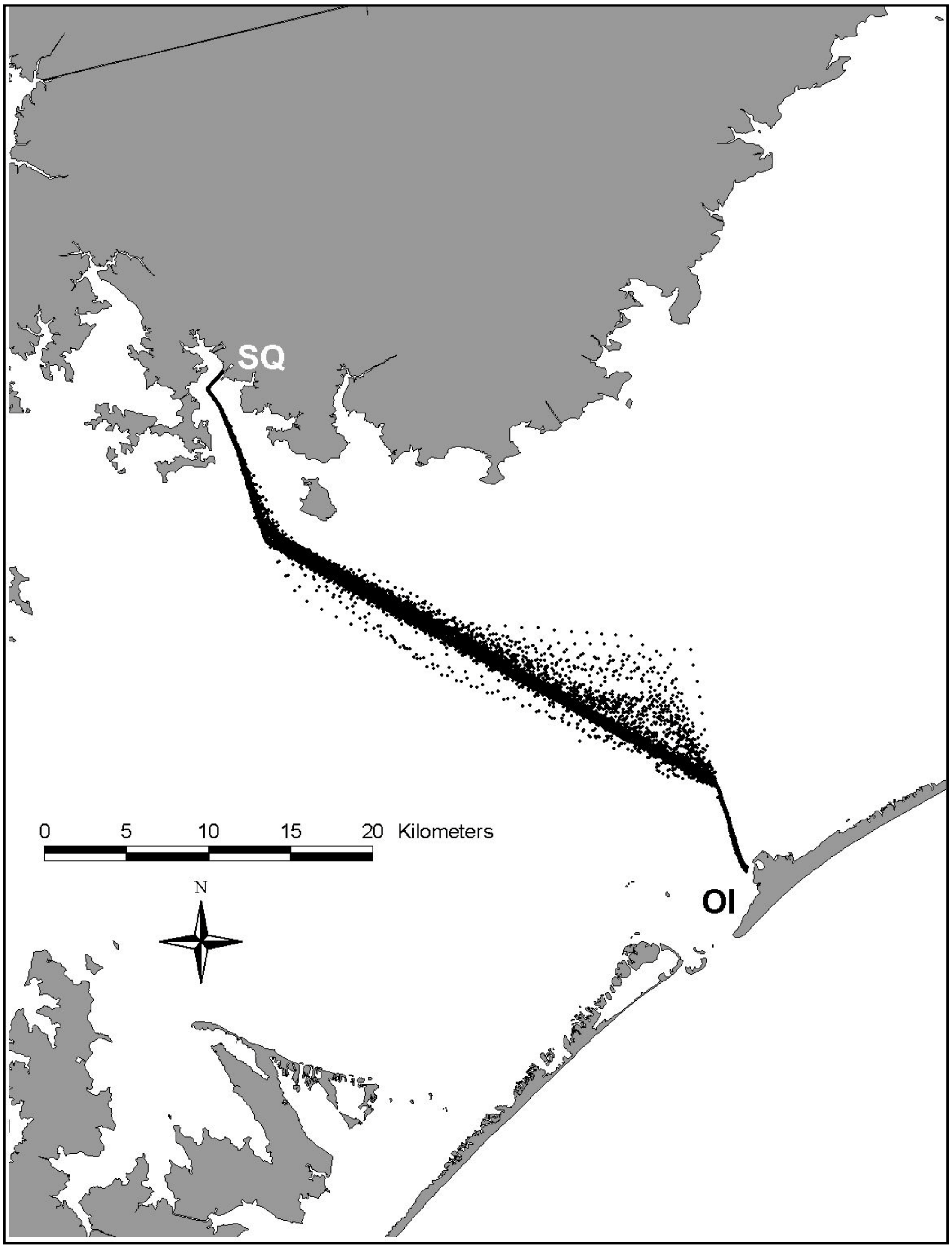

Figure 18. Interpolated time-space plot of temperature, salinity, pH, turbidity, chlorophyll *a* from ferry route 3 between Swan Quarter and Ocracoke Inlet and 24 May 2001 to 24 May 2002.

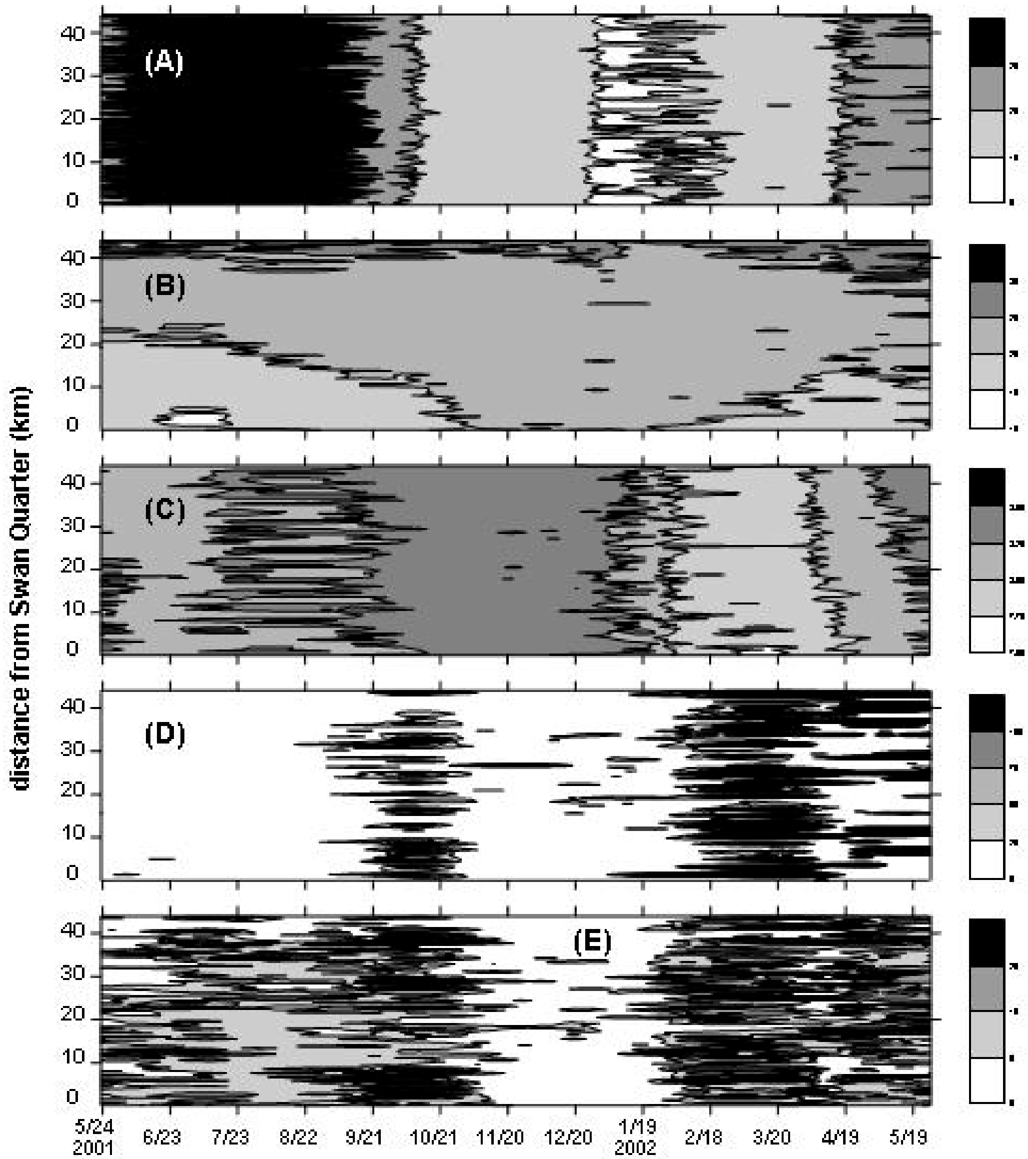

Figure 19. Time series of salinity values from 24 May 2001 to 24 May 2002 for different segments of the route between Swan Quarter and Ocracoke Inlet.

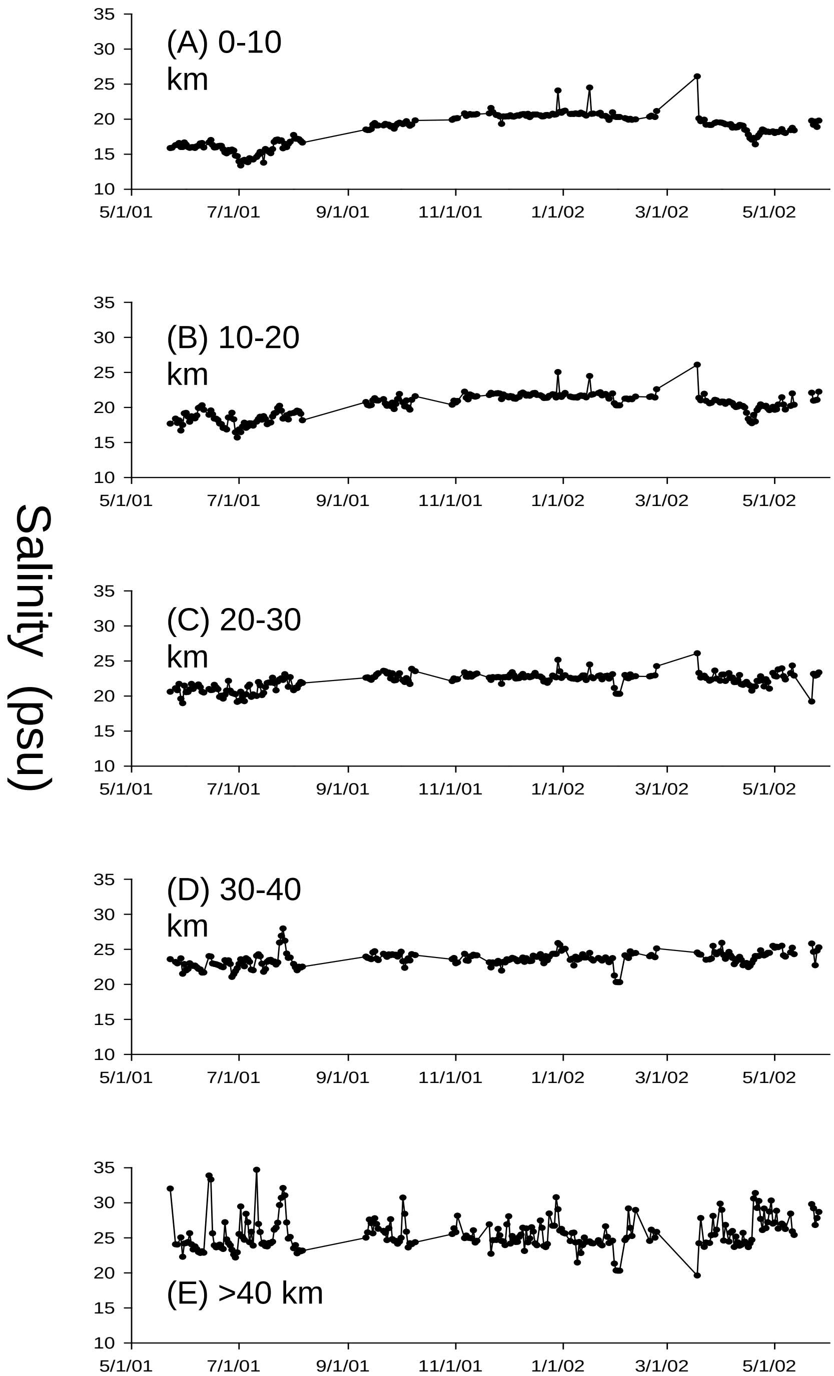

Figure 20. Semi-variogram analysis of salinity values using semi-variogram using over 200 days of average daily salinity values from near Ocracoke Inlet with a base 1 d lag interval. The y-axis is the semi-variance or the sum of the squared difference between successive data values lagged at multiples of the base interval.

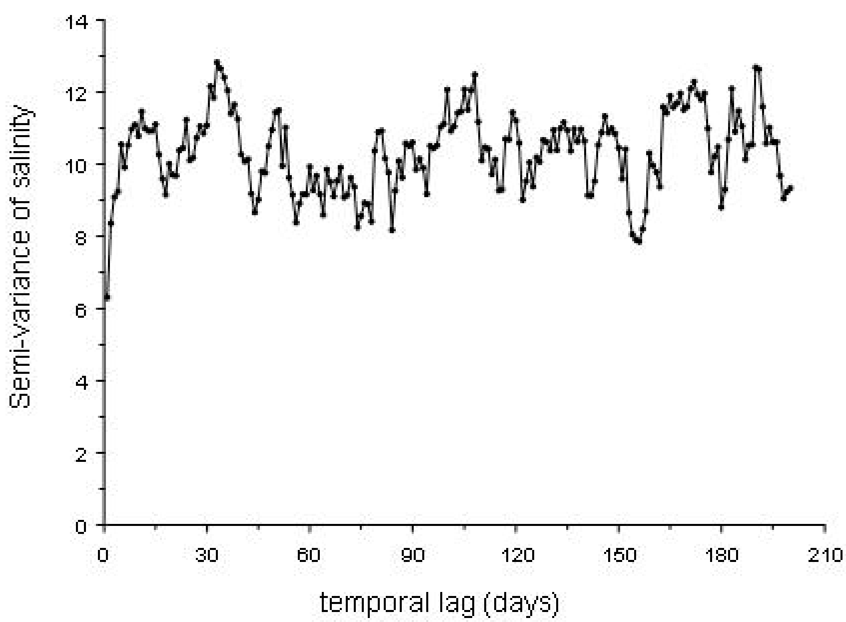

Figure 21. Box and whisker plots of temperature, salinity, pH, turbidity, and chlorophyll *a* from the Swan Quarter data aggregated at different temporal intervals (minute, day, month, season, year).

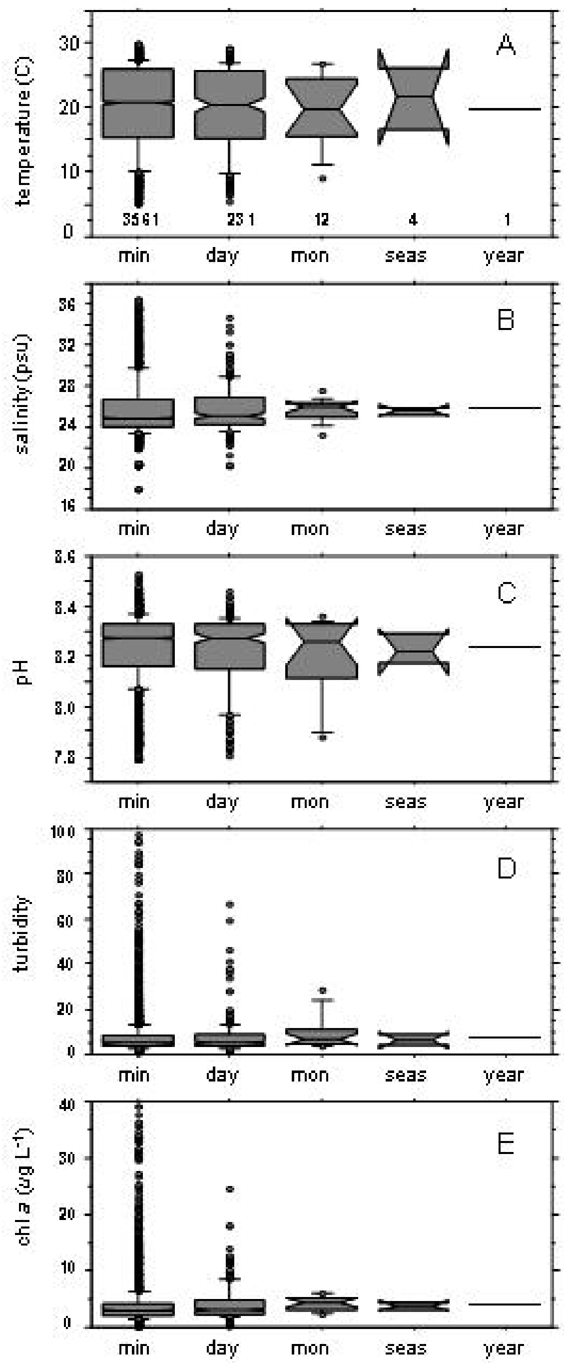

Figure 22. Monthly averages and standard deviations for temperature, salinity, pH, turbidity, chlorophyll *a* from ferry route 3 over all data points from 23 May 01 to 26 May 02.

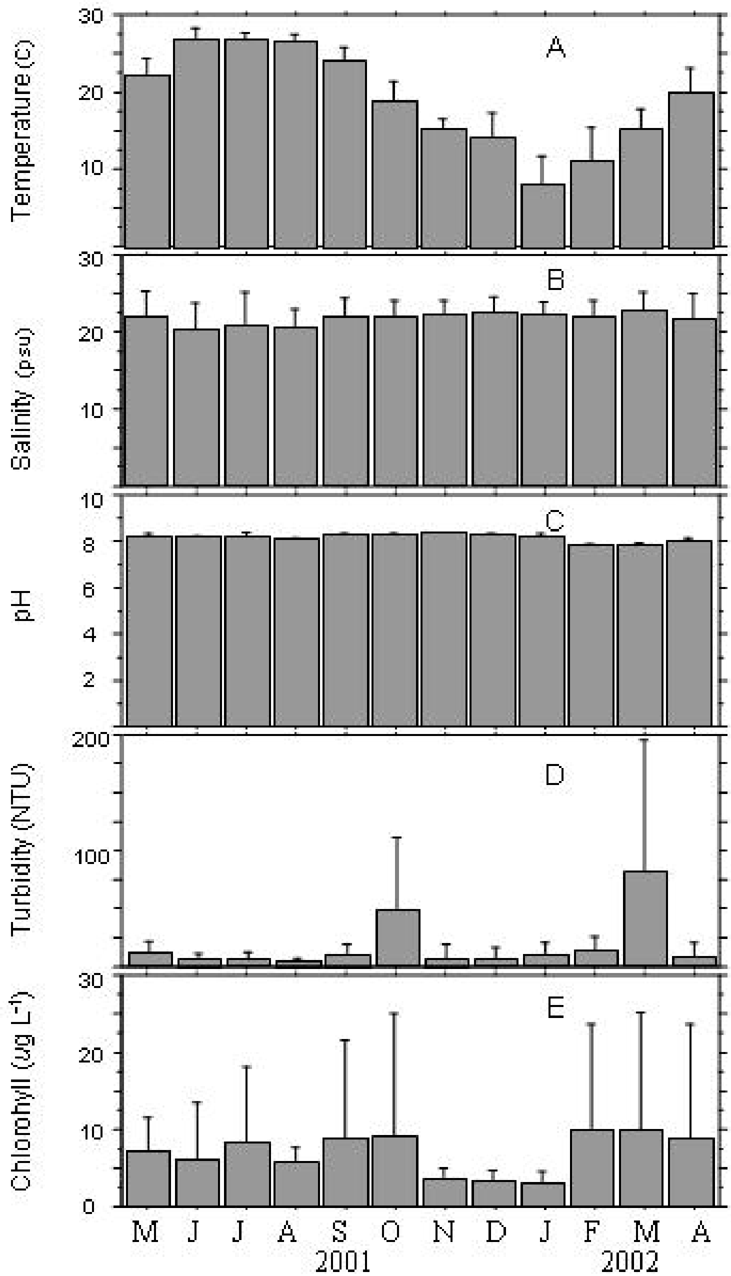

Figure 23. Spatial analysis of salinity values across Pamlico Sound using a series of semi-variograms for different months.

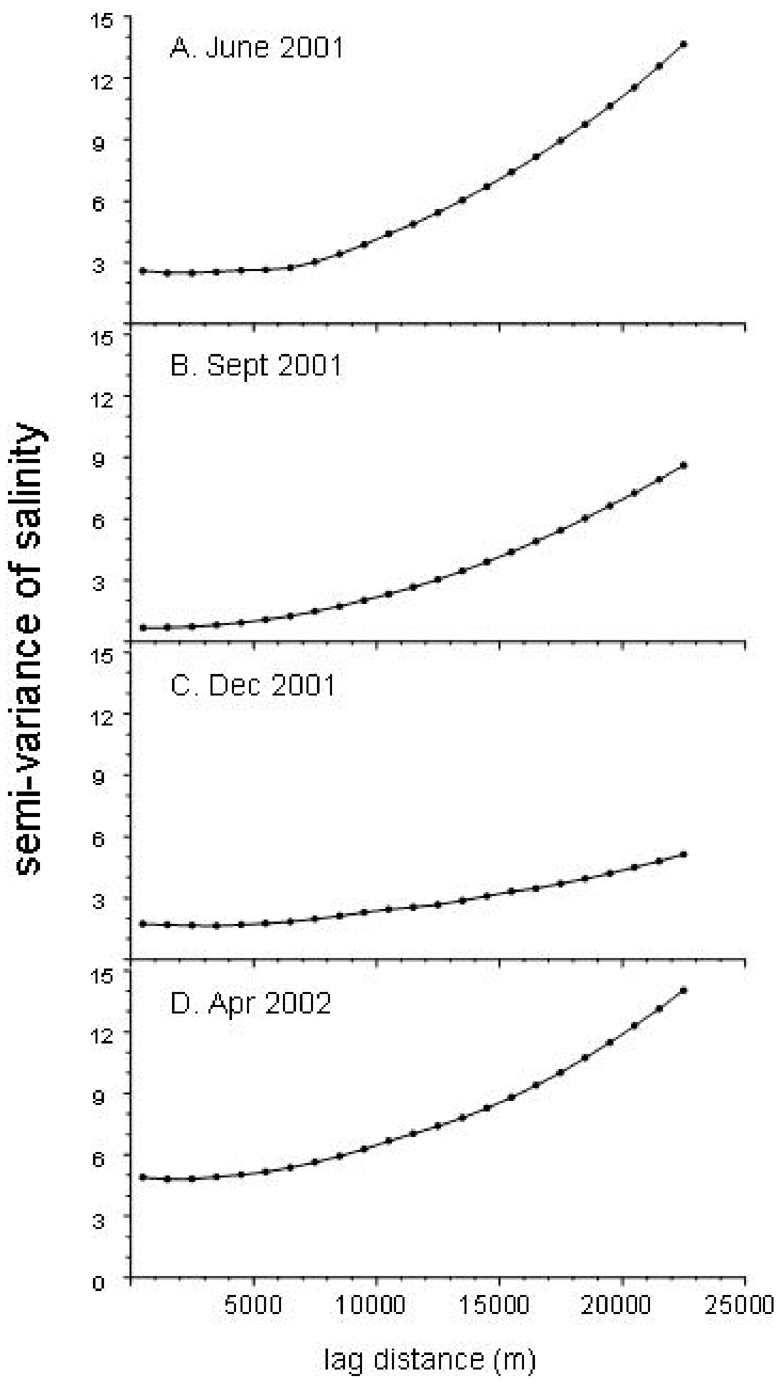

Figure 24. Interactive bar plots (mean $\pm$ standard error) resulting from 3-Way ANOVA of salinity and chlorophyll *a* data from ferry route 3. The independent variables were season (spring, summer, fall, winter), time of day (am, mid, pm), and location along the route (legend). The inset plots demonstrate the effects of individual independent variables.

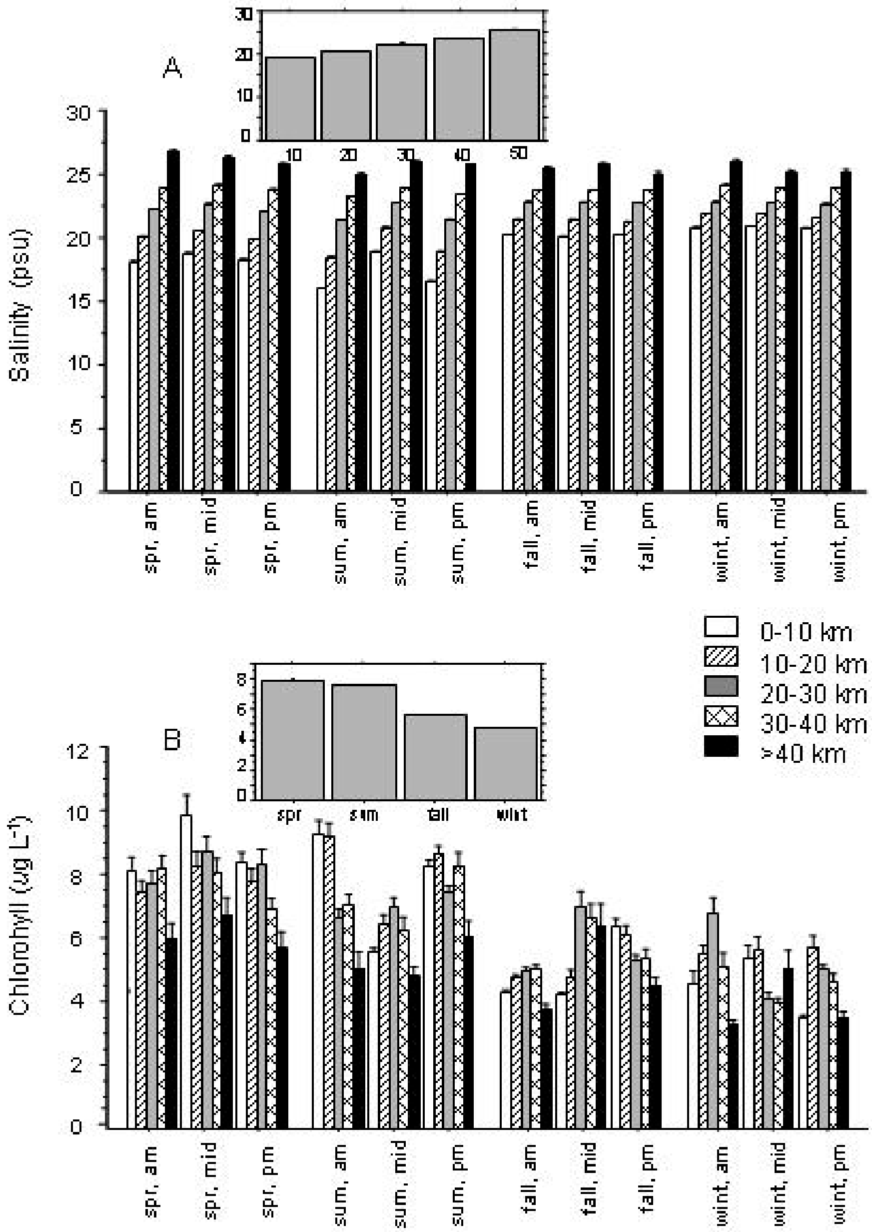
A
Salinity (psu)
B
Chlorohyll (ug L-1)
0-10 km
10-20 km
20-30 km
30-40 km
>40 km
spr, am
spr, mid
spr, pm
sum, am
sum, mid
sum, pm
fall, am
fall, mid
fall, pm
wint, am
wint, mid
wint, pm
spr
sum
fall
wint

Figure 25. Map of sampling locations along ferry route 2 between Cedar Island and Ocracoke Inlet from 13 June-12 November 2002. This route was split into 10 km segments for some of the data analysis.

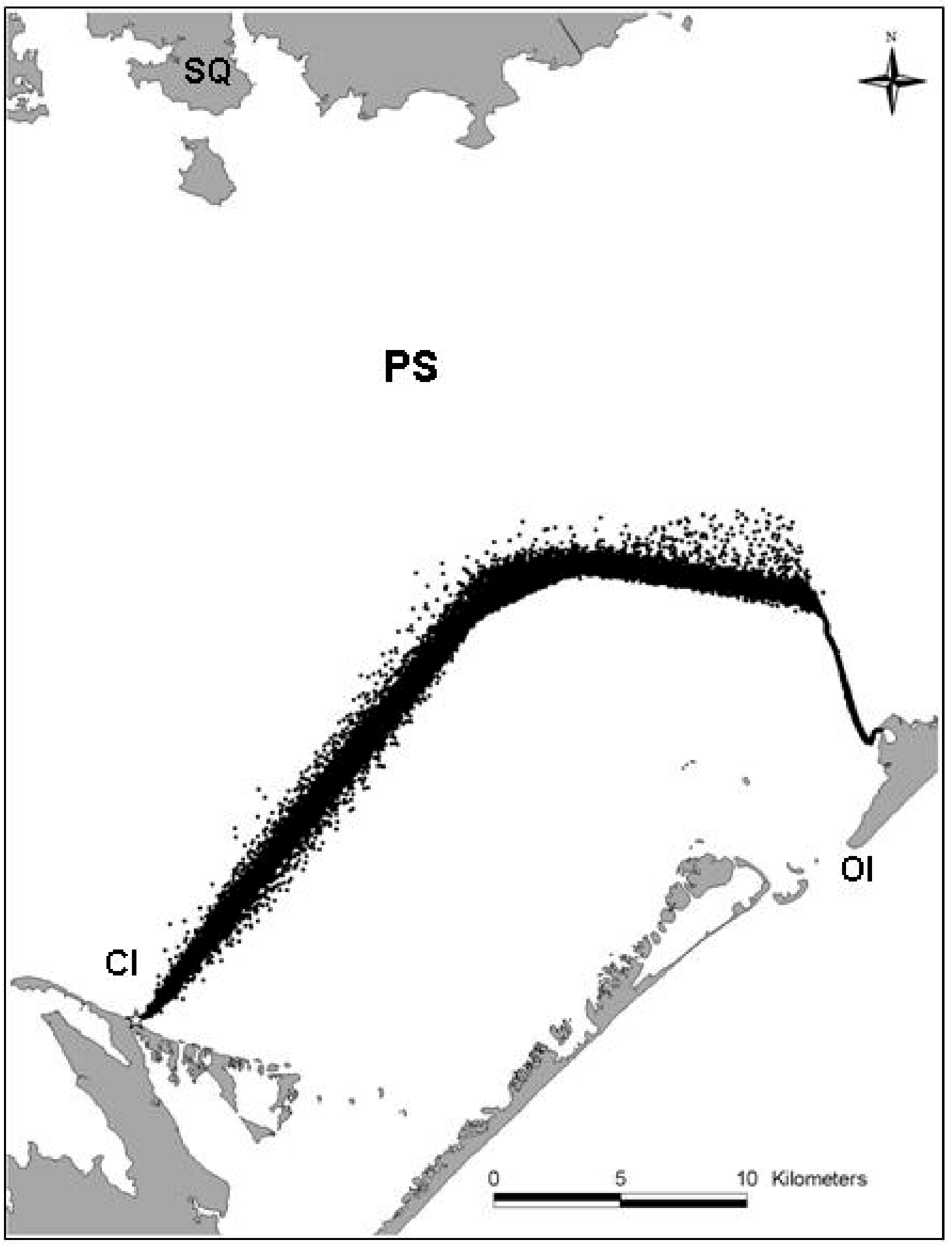

Figure 26. Interpolated time-space plot of temperature, salinity, pH, turbidity, and chlorophyll *a* from ferry route 2 between Cedar Island and Ocracoke Inlet and 13 June-12 November 2002.

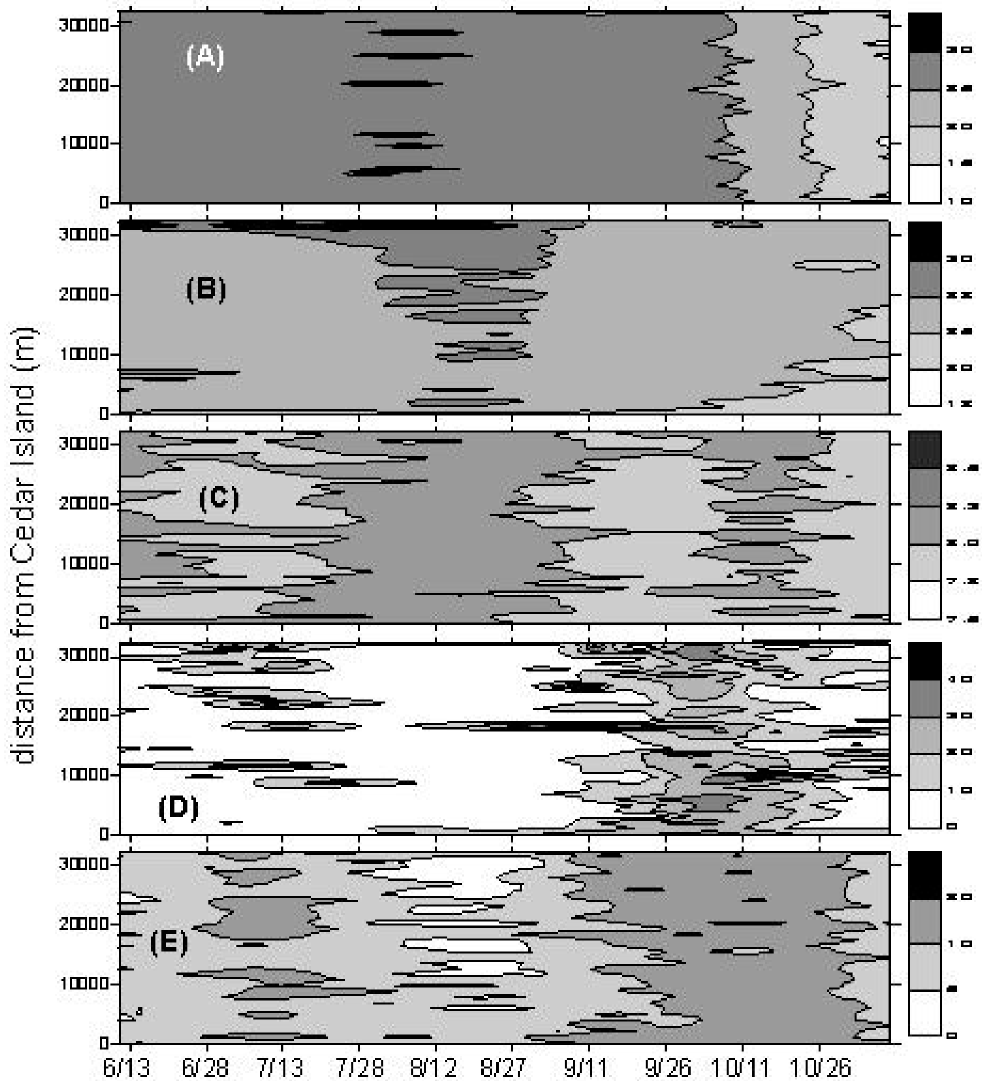

Figure 27. Property vs. distance plots for all YSI data collected along ferry route 2 (Cedar Island to Ocracoke Inlet) from 13 June-12 November 2002. Plots include temperature, salinity, pH, turbidity, and chlorophyll *a*.

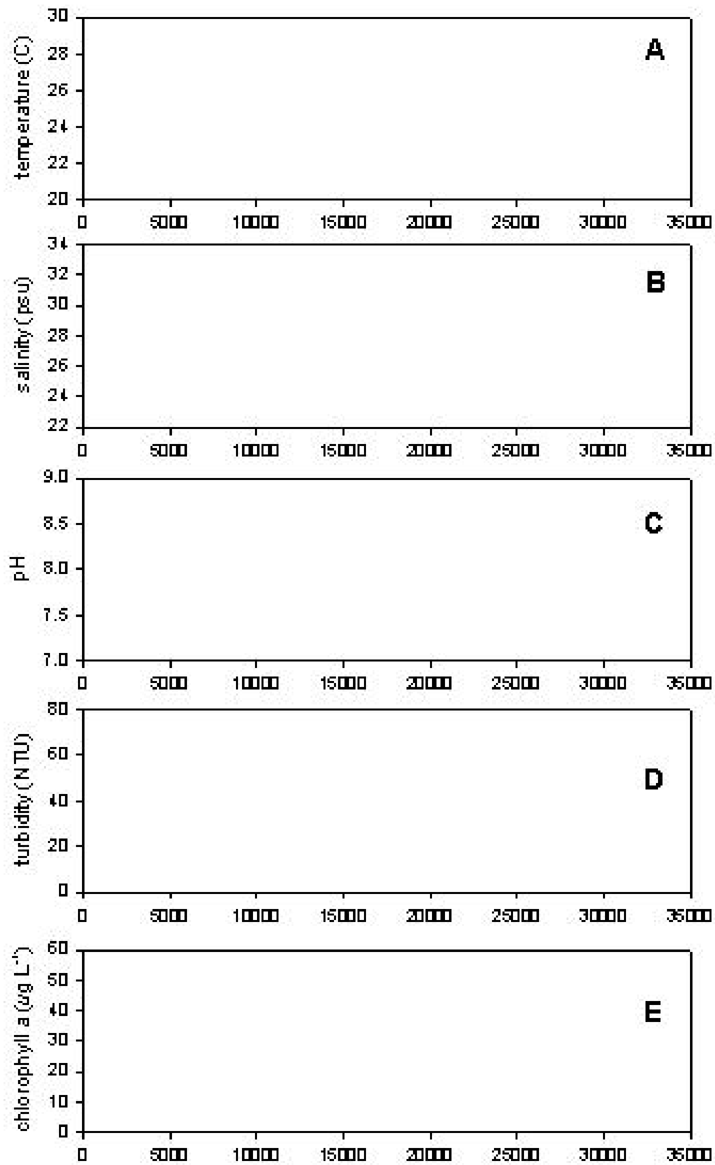

Figure 28. Monthly box and whisker plots of temperature, salinity, pH, turbidity, and chlorophyll *a* from ferry route 3 (Cedar Island and Ocracoke Inlet).

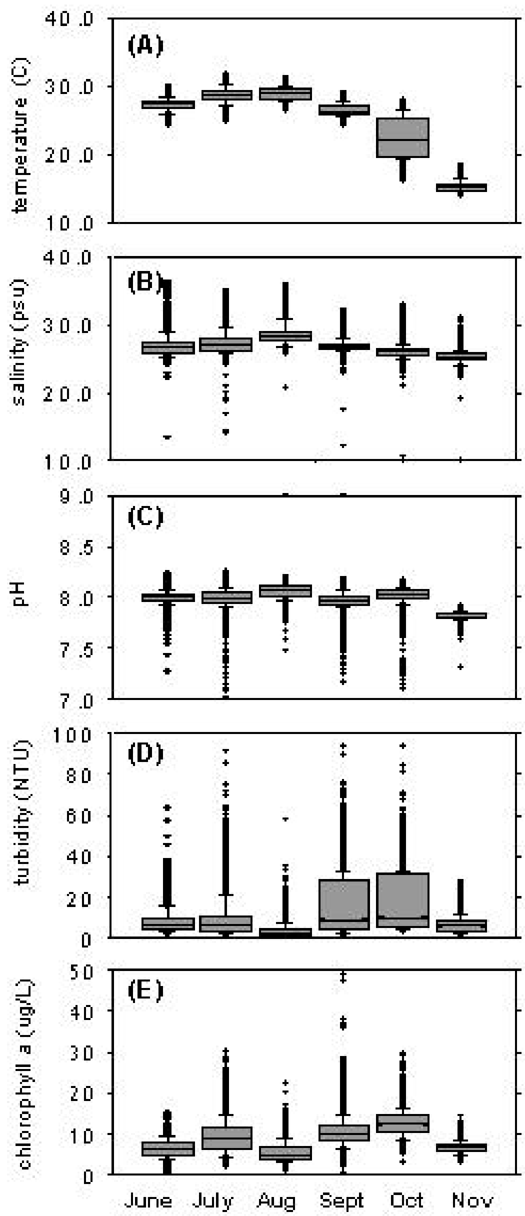

Figure 29. Time series of average daily salinity (± standard deviation) from the ferry-based data collected near Ocracoke Inlet.

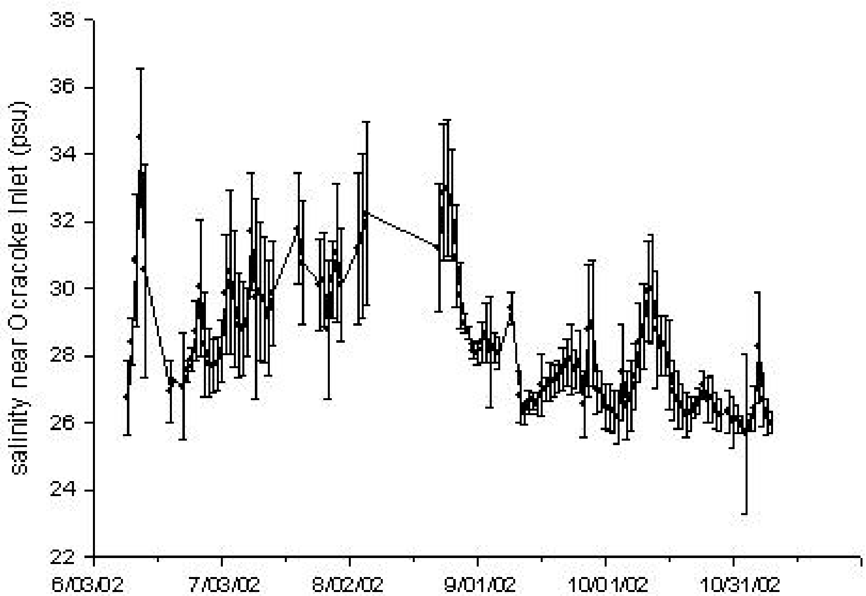

Figure 30. Box plots of chlorophyll a concentrations sampled and determined four different ways.