Final Report
May 22, 2007

EPA Assistance Agreement No. LI-97106001(-2): Long Island Sound Ferry Monitoring

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1. Project Title and EPA Grant Number

Title: Ferry-based Observations for Science Targeting Estuarine Research in Long Island Sound (FOSTER-LIS)
EPA Grant number: Assistance Agreements Nos. LI-97106001 and LI-97106001-2

2. Grantee Organization and Contact Name:

Organization: Graduate School of Oceanography, University of Rhode Island, South Ferry Road, Narragansett, RI 02882
Contact Name: Dr. Daniel L. Codiga and Dr. Peter Cornillon

3. Public Summary

This project maintained ferry-based oceanographic sampling in eastern Long Island Sound (LIS). A ferry was equipped with an acoustic Doppler current profiler and a water property sampler. Vertical profiles of absolute water velocity, and near-surface water temperature, salinity, and chlorophyll fluorescence, were collected nominally 8 times daily along a transect between New London, CT and Orient Point, NY. This unique dataset is made possible by Cross Sound Ferry Services, who facilitate sampling from their vessel *MV John H* as an in-kind contribution; to achieve similar sampling with a research vessel would be incompatible with budgets of traditional research projects. The measurements are useful to address fundamental questions about the tidal and residual circulation, and water property characteristics, near the eastern mouth of the LIS estuary where it interacts most strongly with the coastal ocean. Basic data reduction and quality assurance was carried out on the measurements in order to produce gridded data products (GDPs) that are suitable for convenient use by modelers. The GDPs are available at the project website. The observations are useful for their key roles in calibrating, validating, and constraining hydrodynamic models, hence improving the water quality models they underlie, and thus helping improve water quality management decisions. Water quality models play a central role in total maximum daily load (TMDL) management methods now being applied to address the issue of hypoxia in LIS from a nutrient-load perspective. While hypoxia tends to occur in the western and central parts of LIS, the bulk of the exchange of water between LIS and the coastal ocean occurs at the eastern end, which makes ferry-based sampling in eastern LIS important to improve understanding of LIS-wide dynamics. Public outreach includes a display in the passenger area of the ferry with a real-time data presentation and an explanatory poster for laypeople, in addition to a project website that expands on the explanatory content of the poster and also provides visitors the ability to preview and download the GDPs.

4. Project Period: 10/1/2004 – 9/30/2005 (No. LI-97106001)
and 10/1/2005 – 11/30/2006 (No. LI-97106001-2)

5. Project description:
See public summary above.

6. Activities and Accomplishments:
The objectives listed in the 2004-05 and 2005-06 project narratives and work plans, submitted with their respective funding requests, have all been met:

1. Measurements of all planned parameters were collected from the ferry, during the planned intervals of time. Data coverage periods, and detailed explanations of the processing, calibration, quality assurance, and quality control of the data, are provided in a separate Technical Report (Codiga 2007; full citation below; PDF file included with this report).
2. GDPs have been created, by application of multiple processing stages developed for and applied to the raw data, so that these data are easy for modelers to obtain and use. Input from modelers at Hydroqual Inc was obtained, and used to determine the format and content of the GDPs.
3. The GDPs are available for preview and download at the project website (www.gso.uri.edu/foster). It was determined that the large volume of data files not included in the GDPs (such as raw and intermediate-stage values in the processing steps, as well as data that QA/QC steps determined were not of acceptable quality) made it impractical to distribute anything other than the GDPs at the project website. However, any and all files are available by request to d.codiga@gso.uri.edu.
4. The water velocity dataset has been used to isolate from the strong tidal currents, for the first time, the non-tidal residual circulation. The resulting analysis has fundamentally advanced our understanding of the pathways and rates of exchange between eastern LIS and the coastal ocean. These findings have been published in the peer-reviewed literature (Codiga and Aurin, 2007; full citation below; PDF file included with this report).
5. The characteristics of spatial and temporal variations in temperature, salinity, and chlorophyll in eastern LIS, as determined based on the near-surface water properties GDP, have been described and are presented below in section 8.
6. A public display in the passenger area presented data in real time and includes explanatory posters aimed at laypeople to raise awareness and appreciation for LIS and scientific issues underlying its water quality management. (PDF files of posters are included with this final report.)
7. The project website, www.gso.uri.edu/foster, has been established and incorporates expanded explanations of scientific issues relevant to the project, as well as the ability for visitors to preview and download the GDPs.

7. Modeling:
This project did not involve computational simulation or modeling. A major impetus for the project was, however, to collect observations that are of key importance for purposes

of calibrating and validating models to improve their fidelity. The measurements collected in this project fill an identified gap (see Long Island Sound Study Science and Technical Advisory Committee, Systemwide Eutrophication Model Workshop, October 23-24, 2003, Stony Brook University) in observations needed to improve hydrodynamic modeling and therefore improve the water quality modeling it underlies. In this project, raw data have been collected and processed, and gridded data products have been created that are easy for modelers to obtain and use.

8. Summary of Findings:

8a. Rates and pathways of water circulation relevant to water quality

Fundamental advances in our understanding of aspects of the residual circulation and exchange between eastern LIS and the coastal ocean have already been made based on the water velocities GDP generated by this project. The abstract of Codiga and Aurin (2007), the first resulting peer-review article (published in Continental Shelf Research) is included here:

Residual currents in eastern Long Island Sound (LIS) are investigated using direct velocity measurements from an acoustic Doppler current profiler mounted on a ferry. Circulation at the site has major influence on exchange of water and water-borne materials between LIS and the coastal ocean. Ferry sampling enables sufficient averaging to isolate the residual motion from stronger tidal currents, and captures its spatial structure. Mean along-estuary currents based on about 2 years of sampling reveal a vigorous estuarine exchange circulation (peak 25–30 cm s^{-1} at depth), with flow eastward out of the estuary in the upper water column of the southern half and inward westward movement strengthening with depth over the central and north section. Application of volume conservation implies there is a strong eastward current out of the estuary in the shallowest 7 m where no measurements were made, as expected for estuarine exchange flow. Water from the Connecticut River, entering LIS on the north shore nearby to the west, does not appear to exit the estuary directly eastward along the north shore unless this occurs wholly in the shallow layer not sampled. Transverse currents have complex structure with generally northward (southward) flow where shallow outward (deep inward) motion occurs. An idealized semi-analytic solution for transverse-vertical structure of along- and across-estuary flow has limited success accounting for observed currents, despite inclusion of bathymetric, frictional, and rotational influences; this suggests the importance in LIS of dynamics it omits, in particular stratification, or does not represent with sufficient realism, such as complex bathymetry. Estimated annual-mean exchange volume transport, based on the better-sampled deep inward component, is 22,700±5000 m^3 s^{-1}. This is comparable to previous estimates from some salt budget and hydrographic analyses, and implies advection contributes substantially to the total salt transport, contrary to results of a recent box-model analysis of hydrographic measurements. At seasonal timescales, changes to the transverse-vertical velocity structure are modest, but amplitude variations cause exchange volume transport increases (decreases) to 30,000 m^3 s^{-1} (18,000 m^3 s^{-1}) in the summer (winter) months; a power-law dependence of exchange on river flow, as seen in *other estuaries, is not supported. Strengthened summer transport is associated with enhanced stratification, suggesting that mixing effects modulate the exchange. To the extent that advection by residual flow contributes to total exchange between LIS and coastal waters, the flushing of materials from LIS should occur substantially faster in summer than in winter.*

8b. Spatial and temporal characteristics of near-surface water properties

The near-surface water properties GDP generated by the project facilitates description of spatial and temporal characteristics of temperature, salinity, and chlorophyll distributions in eastern LIS (Figures 1, 2, and 3 respectively below). The first near-surface water property samples in the GDP are from June 15, 2005 and the last are from September 5, 2006. There are a total of 2,255 ferry transits with acceptable quality during this interval.

Data coverage periods are explained in detail in the technical report. Sampling from dates between February 1 and June 15, 2005 was also carried out and these data are available on request (they have not been included in the GDP because during this interval the water velocity sampling was not operating and latitude/longitude positions were not recorded). These data are of good quality and could be of used for analyses that do not require accurate assignment of lat-lon positions, for example situations where mean values across the entire ferry transit would suffice. Sampling from dates prior to February 1, 2005 was also carried out and is available on request. It has not been included in the GDP because just prior to February 1, 2005 a different pump was installed, as a result of erratic behavior of the previous pump, which had been serving well for some time but then became unable to hold its prime as a result of changed vessel protocols for testing the ship cooling system pumps. The gap in coverage in Figures 1-3 between January 6 and February 18, 2006 was because the ferry was not operating. Shorter gaps between February 18 and March 8, 2006; between June 19 and July 1, 2006; and between August 20 and September 4, 2006 were due to instrument malfunction and associated delays for troubleshooting and problem resolution.

The temperature record (Figure 1) shows the expected seasonal signal with peak temperatures in the range of about 20-25 deg C during August and September. Data coverage did not capture minimum values well but it can be surmised that they are in the range of about 3-5 deg C and occur in February and March. The lateral structure across the sound from North to South indicates a gradient that is strongest in summer, with the southern waters about 3-5 degrees warmer than the northern. The gradient weakens and reverses direction in winter, with values about 1-2 degrees cooler to the south. These characteristics are as expected for the pattern of flow determined by the water velocities GDP described above, in which the shallow eastward outflow from the estuary is concentrated in the south. More rapidly moving waters in the southern portion of the ferry transit would thus be expected to have characteristics (colder in winter, warmer in summer) most like the waters originating farther up-estuary to the west.

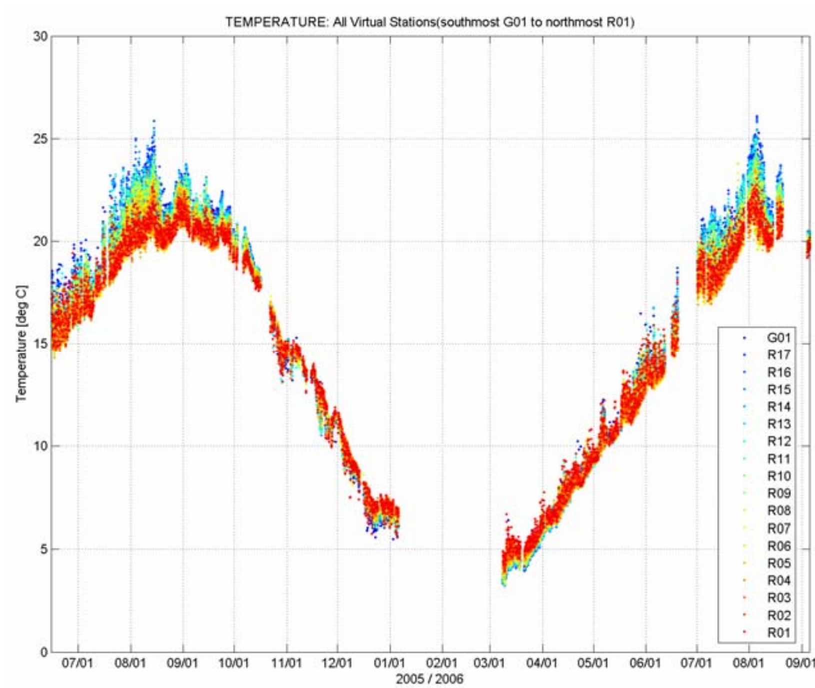

Figure 1. Summary of temperature measurements in near-surface water properties GDP.

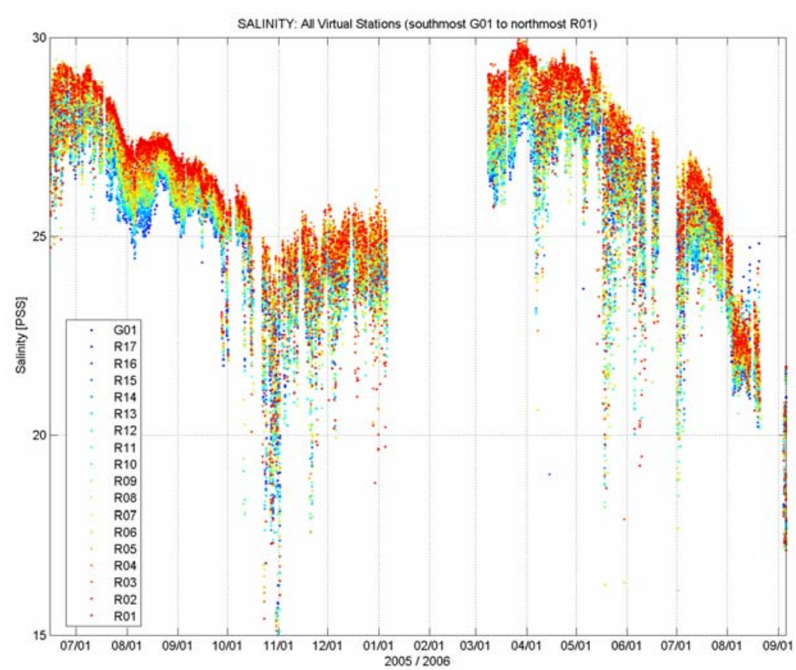

Figure 2. Summary of salinity measurements in near-surface water properties GDP.

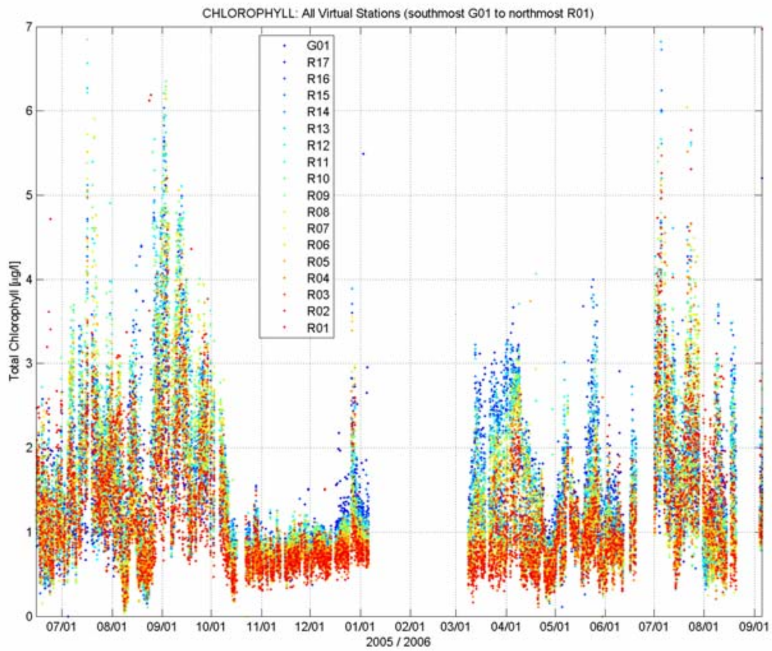

Figure 3. Summary of chlorophyll measurements in near-surface water properties GDP.

Seasonality in the salinity record (Figure 2) appears less regular than the temperatures. Highest values of 27-30 PSS are reached in both August 2005 and March-April of 2006, and minima in the range between 17 and 22-25 PSS (with extreme events lower than 15 PSS) are seen in October-November 2005 and in September 2006. Events of day-week timescales are more prominent than in the temperature record. These characteristics are consistent with other historic salinity observations; it should be noted that Fall 2005 had extremely anomalous record-high rainfall. Through the year, the salinity toward the southern end of the ferry transits generally remains lower than in the north. As with the north-south temperature gradients, this is consistent with the eastward flow out of the estuary being most pronounced to the south and carrying water originating from the west where salinities are known to be lower. The influence of fresh water from the Thames River to the north side of the ferry transit is apparently felt only intermittently at the northernmost virtual station (R01) in the ferry transit. As was also deduced in the analysis of the velocities, the implication is that the influence of the fresh water from the Connecticut River is not felt strongly along the northern portion of the estuary to the east of the river mouth, which suggests that its effects are predominantly to the west of where it enters the sound.

The chlorophyll measurements (Figure 3) show roughly similar peak values, ranging from 4-6 µg/l, through most of the year, in contrast to a wintertime period starting in mid-October with lower values in the range of about 0.25 to 1.25 µg/l. The overall ranges of values, variability, and weak seasonality is in good agreement with those for eastern LIS presented in a comprehensive multi-year analysis of the chlorophyll samples in the CT DEP hydrographic survey dataset (Li et al., 2002, Temporal and spatial variability of Chlorophyll in Long island Sound, Long Island Sound Research Conference Proceedings, Groton, CT). The onset of the wintertime low values in mid-October 2005 may be related to the prolonged period of record-high rainfall that commenced in September that year. There is a clear north-south gradient, with the higher values toward the southern portion of the ferry transit, throughout the year. As described above, this also is consistent with the interpretation that the water to the south is originating farther up-estuary toward the west, where chlorophyll concentrations are known to be higher.

8c. Relevance to LIS water quality monitoring program

The observations have revealed and quantified a north-south gradient in circulation and water properties in the vicinity of The Race in eastern LIS. This information is relevant to the sampling design of the water quality monitoring program carried out by CT DEP. If the goal of the monitoring program is to resolve this gradient, at least two sampling stations are needed in this area, for example one to the north of the central along-estuary axis, and one to the south. On the other hand, if only one station can be maintained, for example because of budgetary constraints, then the goal of monitoring the water quality of either the northern or the southern portion of the gradient could be achieved, as long as the station is located to the north or south of the central axis of the estuary. Historically, a single station has been sampled and it is located near the central axis. The new observations are therefore important (a) to understand and interpret the historical data with respect to the north-south gradient, as well as (b) potentially to adjust the position of the station in the future, in order to achieve the aims of the monitoring program.

8d. Quality assurance and operational lessons learned

Requirements of the Quality Assurance Project Plan were substantially met. See the technical report for detailed descriptions of data processing and implementation of quality control. For completeness, these comments relating to quality assurance for the water properties GDP are included:

a. In the QAPP, it is stated that rough sea states degrade the data quality. This was true prior to February 2005, at which point a new pump was installed. The GDP values are all from later than this date, when data quality was not found to vary with sea state.

b. In the QAPP, a 2-second sampling interval was anticipated. A 30-second interval was found to be sufficient, and was used instead. This did not impact the objectives of the study, yet made data collection and handling more practical.

c. In the QAPP, anticipated limits for removal of outliers were stated. It was found these were not necessary so they were not implemented. Details regarding outlier removal and all aspects of data handling are explained in the technical report.

d. Laboratory calibrations of the chlorophyll sensor were performed in June 2005, January 2006, and May 2006. This was less frequent than planned in the QAPP, but the calibration results were stable. It should also be noted that in previous project progress reports, the preliminary plots of chlorophyll showed uncalibrated μg/l units; the calibrated values are roughly half as high (for details see the technical report).

Operational lessons learned include (a) that the task of maintaining the sampling system, once initial installation and testing is complete, is generally substantially more labor-intensive for surface water property sensors than for water velocity sampling; and (b) that creation of gridded data products and establishment of a functional website to make them available is more labor intensive than had been anticipated.

9. Conclusions:

Through the support of these grants, routine sampling of water velocity profiles and near-surface water properties from a ferry in eastern LIS has continued for 2 additional years. These data are of recognized importance to support modeling, and therefore water quality management decisions that rely on model results. Gridded data products have been created and made available to modelers, in formats they helped devise, by straightforward download from the project website. Independent of modeling activities, initial analysis and interpretation of the data products is advancing scientific understanding of LIS circulation relevant to water quality, and ongoing studies will continue to do so. For example, a clearer understanding of the pathways and rates of water exchange between eastern LIS and the coastal ocean has been generated. In addition, horizontal gradients in near-surface temperature, salinity, and chlorophyll concentrations, that are relevant to the sampling design of the LIS water quality monitoring program, have been identified and quantified. Sampling from this commercial ferry has proven highly cost-effective, making possible the generation of useful datasets at a tiny fraction of the cost that would be incurred were they to be made using traditional research vessels. Outreach has been accomplished by a project website as well as a real-time data presentation with explanatory posters, aimed at laypeople, in the passenger area of the ferry. The value of the full length of the dataset in addressing inter-annual variability such as climatic and ecological changes increases with each additional year that sampling can be supported, so it is hoped that the coastal ocean observing systems presently under active development will soon incorporate funds to further sustain this measurement program.

10. Presentations/Publications/Outreach

a. A project website has been established (www.gso.uri.edu/foster) and includes descriptions of the project targeted at laypeople, as well as the capability for visitors to preview and download the data products.

b. On board the ferry, in the passenger area, a flat-panel PC screen presented the observations in real time as they were collected. A poster explains how to read the real-time display. A second larger poster presents a description of the overall project, including the scientific issues and how they connect to managing water quality in LIS.

c. The following oral presentations have been made:

“Observed residual circulation in eastern Long Island Sound: Transverse-vertical structure and exchange transport”, Long Island Sound Research Conference, Stony Brook, NY, November 2004. Codiga, D.L and D.A. Aurin.

“Timeseries measurements in eastern Long Island Sound: Ferry-based sampling of currents and water properties”, Planning workshop for Mid-Atlantic Coastal Ocean Observatory Regional Association (MACOORA), Groton, CT, January 2005.

“Ferry-based sampling in Eastern Long Island Sound: An existing Coastal-IOOS asset for MACOORA”, MACOORA meeting, Baltimore, MD. October, 2006. Given by Larry Swanson.

“Seasonal Variation of Estuarine Exchange Circulation in Eastern LIS”, Long Island Sound Research Conference, New London, CT, October 2006. Codiga, D.L and D.A. Aurin.

“Ferry-Based Observations of Estuarine Exchange Flow in Eastern Long Island Sound”, Physical Oceanography Seminar, Graduate School of Oceanography, URI, December 2006.

d. This is a list of scientists who have expressed an interest in using the data products generated from this project:

John St John, Hydroqual, Inc
Bob Wilson, Stonybrook University
Kamazima Lwiza, Stonybrook University
Penny Vlahos, University of Connecticut
Heidi Dierssen, University of Connecticut
Mike Whitney, University of Connecticut
Rhead Enion, Yale School of Forestry & Environmental Sciences

11. Other information:

PDFs of the following documents are submitted with this final report:

Codiga, 2007. FOSTER-LIS gridded data products: Observed current profiles and near-surface water properties from ferry-based oceanographic sampling in eastern Long Island Sound. Technical Report 2007-01. Graduate School of Oceanography, University of Rhode Island, Narragansett, RI. 14pp.

Codiga, D.L. and D.A. Aurin, 2007. Observed residual circulation in eastern Long Island Sound: transverse-vertical structure, and exchange transport. *Cont. Shelf Res.* 27, 103-116.

Project description poster (installed in ferry passenger area).

Explanation poster for real-time display (installed in ferry passenger area).