Reanalysis of the Narragansett Bay Spatial Survey (Day Trippers) water column data for Temperature, Salinity, Density, and Dissolved Oxygen (2005 to 2013)

Warren L. Prell, David Murray, and Philip Howell
Department of Earth, Environmental, and Planetary Sciences
Brown University
Providence RI 02912

NBEP-15-128

Reference as:
Prell, W.L., Murray, D.W., Howell, P., 2015, Reanalysis of the Narragansett Bay Spatial Survey (Day Trippers) Water Column Data for Temperature, Salinity, Density, and Dissolved Oxygen (2005 to 2013), Narragansett Bay Estuary Program, NBEP-15-128

Reanalysis of the Narragansett Bay Spatial Survey (Day Trippers) water column data for Temperature, Salinity, Density, and Dissolved Oxygen (2005 to 2013)

INTRODUCTION AND BACKGROUND

Narragansett Bay is a medium-sized (370 km^2), relatively well-mixed temperate latitude estuary located in the northeastern states of Massachusetts and Rhode Island. The Bay has an average depth of 7.8 m, relatively low input of fresh water, and high tidal and wind mixing. Although Narragansett Bay was initially considered to be only moderately susceptible to adverse effects of nutrient loading and hypoxic conditions (Bricker et al. 1999), more recent studies have observed oxygen depleted waters and some fish kills, occurred in the mid and upper sections of Narragansett Bay (Deacutis, 1999). Unfortunately, only limited data were available to document dissolved oxygen (DO) levels in the Bay. In 1999, Dr. Christopher Deacutis of Narragansett Bay Estuary Program (NBEP) organized a survey team to measure the night-time dissolved oxygen throughout the upper Bay and Providence River. This volunteer team, later dubbed "The Insomniacs", was made up of eight to ten boat groups from various organizations in the Rhode Island and Massachusetts that sampled about 80 stations in upper Narragansett Bay, the Providence River, Greenwich Bay, and Mt. Hope Bay. Thirteen surveys were conducted during the summers from 1999 to 2003 (Prell, et al., 2004)

After a year hiatus in 2004, the spatial DO surveys were reorganized using new Sea-Bird SBE 19 Plus SEACAT profilers. These fast response sensors (4 measurements per second) enabled three boats to sample about 75 stations covering the Providence River, Greenwich Bay, and the East and West Passages of Narragansett Bay. Because DO exhibits little diurnal variability below the pycnocline, we conduct our surveys in the morning hours and call the new effort (2005-2013) the Day Trippers. The Seekonk and Providence River sections were sampled by Save The Bay (STB) and Brown University personnel (hereafter referred to as STB), the Upper Bay and East Passage were sampled by Brown University personnel (hereafter referred to as Brown), and Greenwich Bay and the West Passage were sampled by a combination of Narragansett Bay Estuary Program (NBEP), the University of Rhode Island (URI), and Rhode Island Department of Environmental Management (RIDEM) personnel (hereafter referred to as NBEP).

Stations were distributed throughout upper Narragansett Bay, the Providence River, Greenwich Bay, and the east and west passages, including Bristol harbor (Figure 1, Table 1). The sites are located both in navigational channels to provide maximum depth ranges, and in shoal areas away from the channels to provide spatial extent of DO. At each station, we measured depth profiles of temperature, salinity, and dissolved oxygen. The temperature and salinity measurements were used to calculate density values for each depth. Chlorophyll measurements were also made but are not included in this report as they need further corrections for sonde biases and lab measured chlorophyll samples.

From 2005 to 2013, we conducted 47 surveys (Table 2). The spatial surveys focus on the warm summer months during neap tides when the risk of hypoxia is believed to be greatest. During the summer months, warm waters support high productivity and respiration rates. In addition, the Bay is often stratified with a layer of relatively warm and low salinity surface water overlying colder and saltier deep water. This stratification can isolate the deep waters from sources of oxygen near the surface (the atmosphere or phytoplankton production of oxygen). Biochemical reactions and respiration in both the water column and the sediments remove oxygen from the waters. This oxygen demand coupled with warm waters and density stratification increases the risk of hypoxic conditions in the summer months, especially during neap tides when tidal mixing is low.

Below we briefly describe our sampling protocol (for more details see ***Dissolved Oxygen Profiles and Monitoring in Narragansett Bay Quality Assurance Project Plan (QAPP),*** Kiernan et al., 2014) and the various reanalysis efforts we conducted to produce an internally consistent and documented interpolated (0.5 meter (m)) data set of temperature, salinity, density, and dissolved oxygen. The data set spans nine years (2005-2013) and contains 47 surveys, at about 77 stations, 3296 individual profiles, and over half a million downcast measurements.

METHODS AND DATA:

INITIAL DATA COLLECTION AND PROCESSING

The sampling protocol is detailed in the Dissolved Oxygen QAPP, (Kiernan et. al, 2014) and is briefly summarized here. After activating, the CTD (Conductivity-Temperature-Depth sonde) was lowering into the water to await pump activation and oxygen equilibration. After equilibration (usually about one minute), the CTD was raised to near surface to obtain a sample at 1m (not always accomplished, see below). The CTD, which samples at 4 measurements per second) was then lowered at 1m per 4-5 seconds so that all sensors were measuring simultaneously. The CTD was lowered to the bottom and immediately lifted to avoid bottom disturbance, which can result in sediment and/or disturbed pore waters entering the pump and sensors.

Raw data files were downloaded and converted to SI units (International System of Units) using the SeaBird calibrations for each CTD. Only the downcast data were selected using time vs. depth and depth vs. salinity/density and DO profiles (details are given in the QAPP, 2014). Raw data files are archived at the Department of Earth, Environmental, and Planetary Sciences, Brown University, Providence RI 02912 and are available on request to Warren Prell or David Murray.

POTENTIAL SOURCES OF UNRELIABLE DOWNCAST DATA.

Although the sampling protocol is designed to minimize collection of unreliable data, circumstances arise, such as boat motion, instrument failure, and incorrect selection of cast depths, that may introduce data that is not representative of the water column structure. Here, we describe the potential sources of unreliable data and address the quality control measures to eliminate them from the final data set.

Surface (1m) data may be compromised if the CTD is not raised to above 1m so that no reliable measurements are made for that level (Figure 2A). If the CTD is lowered prior to the pump providing flow across the sensors, the measurements are anomalous until the pump is active.

Boat motion on windy days results in the CTD moving up and down during descent causing “loops or depth reversals” in the downcast data (Figure 2 B). These depth reversals do not reflect the structure of the water column and must be removed from the final data sets to provide a continuous profile.

The values of near bottom dissolved oxygen are of special interest as they directly impact the benthic community. Hence, we have focused on problematic bottom water measurements. When the CTD cage impacts the bottom, the pump inlet is only 0.15m above the bottom. If the CTD disturbs the bottom, sediments or pore water may be sampled if the CTD is allowed to sit on the bottom (note that the CTD is making 4 measurements per second) (Figure 2 C). In most cases this unreliable data can be eliminated by correctly selecting the bottom of the downcast so that data are not included after contact with the bottom. However, bottom contact of only a few seconds may not be recognized in some cases. We have systematically reexamined all casts to eliminate false bottom measurements.

REANALYSIS RESULTS

REANALYSIS OF 1M DATA

Failure to follow sampling protocol is the primary reason for the lack of a reliable data at the surface (1m) level. Rough weather conditions, excessive boat motion and equipment malfunction are also factors. In 175 cases (out of 3296 casts) where the first reliable measurement was >1m but <1.25m, data recorded at the measured depth was assigned to the 1m sample. In 111 of these 175 instances, the first measured depth was shallower than 1.1m. In 29 cases, where the first reliable measurement was >1.25m but <1.5m, the initial interpolated value for those sites is assigned to 1.5m instead of 1m. In 4 additional cases, where the first reliable measurement was >1.5m but <1.75m, data recorded at the measured depth was assigned to 1.5m as the starting sample. In the worst case, 1 site had a starting measurement at 1.91m. The first interpolated value for this site is 2.0m.

BOAT MOTION CORRECTIONS

An optimal downcast should have continuously decreasing depth values. However, excessive boat motion during a high sea state or error on the part of the operator lowering the CTD occasionally led to brief reversals in the depth profile, especially across strong water column gradients. This motion, “depth reversal or loop”, was corrected with a data processing step in which a software algorithm retained each sample as long as depth increased from the previous sample. If a shallower depth was encountered, then that sample and subsequent ones were eliminated until the depth value prior to the reversal was exceeded. This process resulted in continuously decreasing depth values for all downcasts.

BOTTOM (DEEPEST) MEASUREMENT CORRECTIONS

To identify possible bottom measurement anomalies, we calculated the difference between the deepest 0.5m interpolated value and the deepest value in the raw downcast data. This comparison revealed a number of negative density anomalies, which should not occur in a stable stratified water column. Examination of 42 profiles (out of 3296) revealed that the bottom anomalies were caused by interaction of the CTD with the bottom sediments and/or released pore waters. The density anomalies were compared to the entire profile and the lower interpolated value was confirmed or corrected. In the vast majority of cases, the lower 0.5 m interpolated value was representative of the near bottom values. No values were eliminated based on only the dissolved oxygen values. In general, anomalies were small we did not eliminate any data. In the highly stratified Seekonk River, the Providence River, and parts of Greenwich Bay, large changes in density and dissolved oxygen were common in the lowermost meter to half meter and positive density anomalies were common but considered representative of the water column.

CTD COMPARISONS: ANALYSIS OF DIP-IN DATA

To document any systematic biases between the Seabird CTDs, we conducted direct comparisons by measuring joint profiles between the respective CTDs (Brown-NBEP and Brown-STB). For the Brown-NBEP dip-ins, the CTDs were cabled together (unless weather conditions prevented mooring boats together) and tests were generally conducted in the lower part of the upper bay (UPB02), which is weakly stratified. For the Brown-STB dip-ins, CTDs were not cabled together and lowered side-by-side (within a few boat lengths) and tests were conducted in the upper part of the upper bay (BBT3-UPB11), which is more stratified than the Brown-NBEP site. Differences between joint profiles were calculated to identify any anomalies that might be due to instrumental biases, lack of common top samples, or bottom samples impacted by disturbed sediment and pore waters. In the Brown-STB data, 45 near surface measurements were eliminated due to lack of reliable data at the uppermost comparison.

Data analysis of the Brown-STB paired measurements (37 profiles and 696 interpolated values) and the Brown-NBEP comparisons (44 profiles and 628 interpolated values) revealed no systematic biases between the CTDs temperature, salinity, and density (mean and median differences were 0.00 to 0.01) and that the variability was higher in the Brown-STB data, as indicated by the higher standard deviations of the comparisons (Table 3). The mean and median differences in dissolved oxygen ranged from -0.06 to 0.05 mg/l, with the higher variability in the upper bay.

The probability distribution plots of the difference between CTDs (Figure 3) shows that most of the variance is in the upper and lower one percent of the population and that the Brown-STB upper bay comparisons are the most variable. We conclude that no systematic offset exists between the three CTDs, especially below the pycnocline where the water column is more uniform, and that the majority of the variability we observe is due to slight depth differences in sampling the more stratified upper bay profiles.

The only significant bias corrections based on the dip-in comparisons were to the dissolved oxygen values in 2009 and 2010 (see Appendix A, data correction notes). Following the 2010 season the oxygen sensors were returned to SeaBird, Inc. for calibration.

INTERPOLATION OF FINAL DATA SET

Given the large size of the data set, the uneven depth sampling, and discussions with RIDEM, NBEP and other stakeholders, we determined that linear interpolation of the water column data at 0.5m intervals, starting at 1m, was adequate for addressing most water quality issues and facilitating use of the data in water quality management programs. Following all the corrections made to the downcast measurements (discussed above), each profile was linearly interpolated at a 0.5 m interval. The final interpolated data set is initially reported as a single file that contains 47 surveys, 3296 profiles, and 50134 interpolated values of temperature, salinity, density, and dissolved oxygen. The file is structured by a sequence number, date, time, boat group, station identification, latitude, longitude, and water depth (m). Data are reported as salinity (‰), temperature (^{0}C), density (sigma t, kg/m^3), dissolved oxygen concentration (mg/l), and dissolved oxygen saturation (%). (see Table 4 for an example of the file structure). The final interpolated data set is a tab delimited text file that is available from the Publications menu on the NBEP website (http://www.nbep.org) or the Insomniac/Day Trippers website (http://www.geo.brown.edu/georesearch/insomniacs/)

Interactive maps of the distribution of DO for each survey are available at: http://www.geo.brown.edu/georesearch/insomniacs/ Note that the maps are based on the processed raw data and may vary slightly from the interpolated data set. Under the menu **Data ’05-“13**, the following maps and plots are available for each survey: Surface (~1m) Saturation (%), Bottom DO (mg/l), and Minimum DO in the water column (mg/l). Also available are selected depth-

distance transects of temperature, salinity, and DO superposed on density contours. To provide a temporal context for the spatial surveys, time series of bottom DO, and potential DO forcing factors (tidal range, wind speed, and river flow) and boundary conditions (bottom and surface water temperature and salinity and air temperature) are also presented. All time series data are from the Bullocks Reach fixed monitoring buoy, which is maintained by the Narragansett Bay Commission and are available at:
(http://snapshot.narrabay.com/app/WaterQualityInitiatives/FixedSite)

The high resolution (4 samples per second) data files have been corrected for biases, boat motion, and anomalous values and are available on request.

STATISTICAL SUMMARY OF SPATIAL SURVEY DATA

The interpolated data set is a nine year (2005-2013) summary of the spatial distribution of water column structure and is a rich resource to document the spatial variability of dissolved oxygen in Narragansett Bay. Subsequent studies will further explore the different time and space scales of DO variability and its relation to the physical structure of the water column. Additionally, the goal will be to relate the spatial patterns to the fixed-site temporal data to provide a comprehensive framework of DO variability in Narragansett Bay. Here, we focus on the bottom water characteristics and provide some summary statistics to explore the overall structure of the bottom dissolved oxygen data.

Initially, we compiled the bottom temperature and salinity of all stations to provide a physical context for evaluating the bottom dissolved oxygen. We then calculated the mean and standard deviation for the bottom DO at all stations. We also calculated the median value of bottom DO and the minimum value observed for each station. The statistics are summarized in Table 5 and illustrated in Figures 4 to 8.

The distribution of temperature and salinity in the bottom waters are shown in Figure 4. The mean bottom temperature is 20.6 ^{0}C with a standard deviation of 2.9 ^{0}C. We note that about 20% of the bottom temperatures are less than 18 ^{0}C and that hypoxia seldom occurs below this value. Most of the temperatures <18 ^{0}C occur in June or September. The mean bottom salinity is 29.28 ‰ with a standard deviation of 2.00 ‰. A few salinity outliers are below 18 ‰ and are not included in Figure 4. Overall, the benthic environment is relatively uniform with most of the variability found in the shallower stations in the Seekonk-Providence Rivers and Greenwich Bay.

The mean bottom DO ranges from 1.22 mg/l at Providence River station PRC07 to 6.37 mg/l at the shallow West Passage site WPS08. Mean bottom DO increases irregularly from north (Seekonk and Providence Rivers) to south (lower East and West Passages). The variety of depths and location of coves and embayments (especially Greenwich Bay) make the change with latitude clear but irregular (Figure 5, lower panel).

To simplify the relative changes, the data was sorted by the mean bottom DO, which groups sites with similar DO values (Figure 5, upper panel). The standard deviations of the mean and the minimum observed DO are also included on these plots. Of the 77 sites, 2 sites (3%) have mean bottom DO <2.0 mg/l, 12 sites (16%) have mean bottom water DO < 3.0 mg/l, and 39 sites (51%) have mean bottom DO < 4.0 mg/l.

Variability of the single minimum observed DO at each of the 77 sites, documents that 38 sites (49%) have a minimum observed of < 1.0 mg/l and 64 sites (83%) have a minimum observed DO of < 2.0 mg/l. These trends and variability are illustrated in the probability distribution plots for mean and median bottom DO (Figure 6) and for the minimum observed DO at each station (Figure 7).

The variability of mean bottom DO, as captured by the standard deviation, is highly related to the water depth of the station (Figure 8, upper panel). Of the 13 sites that have standard deviations > 2.0 mg/l, 11 sites have mean water depths < 4.0 m (Figure 8). Almost all the high variability sites are in Greenwich Bay or the upper Providence River.

Future work will further explore the structure of bottom DO, minimum DO, and maximum DO at each and generate a set of maps and figures to document the trends and levels of variability. Subsequent studies will also relate the spatial DO patterns to the fixed site buoy temporal data. The goal of this work will be to fully explore and document the different time and space scales of DO variability and its relation to the physical structure of the water column.

Acknowledgements

Support for this reanalysis report was provided by funding from the United States Environmental Protection Agency to the Narragansett Bay Estuary Program in conjunction with the Rhode Island Natural History Survey and awarded pursuant to Section 320 of the Clean Water Act.

Support for the collection, processing, and the initial analysis of the survey data was supported by the NOAA Center for Sponsored Coastal Ocean Research, Coastal Hypoxia Research Program (CHRP) Awards to W. Prell (NA05NOS4781201 and NA11NOS4780043), and the NOAA Bay Window Project, (NOAA Award NA05NMF4721253). Support for operations and Brown student participation was provided by Brown University, the Doherty Oceanography Chair, and the Brown Undergraduate Teaching and Research Awards (UTRA).

Survey data collection was assisted by a diverse group of over fifty individuals including: Brown University students, staff, and faculty, NBEP staff,

URI staff and students, RIDEM staff, Save the Bay staff, the Nature Conservancy staff, and Roger Williams University students, among others.

Data processing was performed by Brown University students under the supervision of David, Murray and Warren Prell. Student data processors included: Alicia Barlow, Alex Chuman, Jesse Farmer, Monika Mostowy, Adalyn Naka, Kevin Rogers, Tim Rovinelli, Marie Siwicki, Monica Skeldon, Emily Washington, Andrea Weber, and Lena Weiss.

Software programming and web site design by Phil Howell (Brown).

References

Bricker, S.B., C.G. Clement, D.E. Pirhalla, S.P. Orlando, and D.R.G. Farrow, 1999, *National Estuarine Eutrophication Assessment: Effects of Nutrient Enrichment in the Nation's Estuaries*, NOAA, National Ocean Service, Special Projects Office and the National Centers for Coastal Ocean Science. Silver Spring, MD.

Deacutis, C., 1999, Nutrient Impacts and Signs of Problems in Narragansett Bay (pp7-23), In: Kerr, M. (Ed.). 1999. *Nutrients and Narragansett Bay: Proceedings of a Workshop on Nutrient Removal from Wastewater Treatment facilities*, RI Sea Grant. Narragansett RI, 64 pp.

Kiernan S., Murray, D., Prell, W., and Deacutis, C., 2014, *Dissolved Oxygen Profiles and Monitoring in Narragansett Bay Quality Assurance Project Plan*, Water Resources Division, Rhode Island Department of Environmental Management, 235 Promenade Street, Providence, Rhode Island 02908

Narragansett Bay Commission, (http://snapshot.narrabay.com/app/WaterQualityInitiatives/FixedSite)

Prell, W., Saarman, E., Murray, D., Deacutis, C., 2004. Summer-Season, Nighttime Surveys of Dissolved Oxygen in Upper Narragansett Bay (1999-2003). Data available at http://www.geo.brown.edu/georesearch/insomniacs.

Station ID	Field Sampling Crew	Latitude (°N)	Longitude (°W)	Average Bottom Depth (m)	# Profiles
BBT1	STB	41.7132	-71.3212	5.08	38
BBT2	STB	41.7124	-71.3341	6.47	33
BBT3	STB/Brown	41.7126	-71.3442	8.91	56
BH05	Brown	41.6760	-71.2841	4.78	27
BH07	Brown	41.6714	-71.2808	5.06	27
BH10	Brown	41.6668	-71.2878	4.96	27
BRT1	STB	41.7355	-71.3601	4.94	33
BRT2	STB	41.7338	-71.3660	12.58	33
BRT3	STB	41.7330	-71.3683	8.17	33
BRT4	STB	41.7328	-71.3708	6.23	32
BRT6	STB	41.7268	-71.3750	2.55	33
EPN02	Brown	41.6311	-71.2980	19.82	39
EPN03	Brown	41.6395	-71.3055	14.42	39
EPN04	Brown	41.6500	-71.2932	7.90	39
EPN05	Brown	41.6537	-71.3112	13.67	46
EPN06	Brown	41.6714	-71.3121	14.09	46
EPN08b	Brown	41.6513	-71.3241	6.86	46
EPS01	NBEP	41.5764	-71.3131	21.27	35
GRB_A	NBEP	41.6814	-71.4194	3.82	44
GRB_B	NBEP	41.6898	-71.3930	2.69	45
GRB_C	NBEP	41.6956	-71.3897	2.55	46
GRB_D	NBEP	41.6824	-71.4380	3.56	45
GRB01	NBEP	41.6868	-71.4454	2.87	45
GRB02	NBEP	41.6914	-71.4451	2.77	46
GRB03	NBEP	41.6766	-71.4342	3.46	46
GRB04	NBEP	41.6684	-71.4382	4.66	46
GRB05	NBEP	41.6585	-71.4437	3.09	46
GRB06	NBEP	41.6768	-71.4211	4.37	45
GRB07	NBEP	41.6725	-71.4043	8.52	47
GRB09	NBEP	41.6675	-71.3881	11.13	49
GRB10	NBEP	41.6770	-71.3918	2.96	46
GRB12	NBEP	41.6765	-71.4042	3.19	42
PRC02	STB	41.7618	-71.3767	12.97	47
PRC05b	STB	41.7794	-71.3718	13.81	47
PRC07	STB	41.7808	-71.3854	6.26	48
PRC08b	STB	41.7675	-71.3824	3.41	47
PRN01	STB	41.7937	-71.3811	12.82	47
PRN03b	STB	41.8039	-71.3919	12.91	46
PRN07	STB	41.8164	-71.3969	7.88	47
PRN08	STB	41.8168	-71.3876	7.62	39
PRS03	STB	41.7278	-71.3623	12.66	47
PRS04	STB	41.7373	-71.3555	3.03	47
PRS07	STB	41.7464	-71.3707	14.00	47
PRT01	STB	41.7766	-71.3707	2.77	33
PRT02	STB	41.7799	-71.3750	2.53	32
PRT03	STB	41.7799	-71.3777	2.23	33
PRT04	STB	41.7797	-71.3803	2.21	33
RWU03	Brown	41.6459	-71.2728	6.91	38

RWU03b	Brown	41.6618	-71.2778	6.96	39
RWU05	Brown	41.6300	-71.2698	20.46	39
SR01	STB	41.8433	-71.3722	3.63	39
SR02	STB	41.8347	-71.3778	5.21	39
SR03	STB	41.8222	-71.3869	6.51	39
UPB01	NBEP	41.6634	-71.3747	18.00	47
UPB02	Brown/ NBEP	41.6749	-71.3696	6.92	80
UPB03	Brown	41.6769	-71.3504	12.46	48
UPB04b	Brown	41.6711	-71.3291	6.26	46
UPB05	Brown	41.6886	-71.3134	15.12	45
UPB06	Brown	41.6975	-71.2975	5.38	47
UPB07b	Brown	41.7136	-71.2923	8.57	48
UPB08	Brown	41.6988	-71.3236	13.73	48
UPB09b	STB	41.7137	-71.3131	5.18	45
UPB10	STB	41.7183	-71.3434	14.30	48
UPB11	STB	41.7115	-71.3363	13.44	54
UPB12	STB	41.7068	-71.3537	3.04	45
UPB13	Brown	41.6906	-71.3459	6.66	47
WPS01	NBEP	41.5880	-71.3420	12.70	42
WPS02	NBEP	41.5770	-71.3654	11.64	42
WPS04	NBEP	41.5865	-71.4025	10.34	44
WPS05	NBEP	41.5978	-71.3958	10.43	37
WPS07	NBEP	41.6088	-71.3962	9.65	44
WPS08	NBEP	41.6196	-71.4012	2.62	42
WPS09	NBEP	41.6197	-71.3700	6.66	44
WPS10	NBEP	41.6312	-71.3861	8.71	45
WPS11	NBEP	41.6489	-71.3916	6.63	45
WPS13	NBEP	41.6440	-71.3604	6.23	44
WPS14	NBEP	41.6199	-71.3471	7.15	44

Table 1. Station identification, boat group, location, water depth and number of occupations for each station. BBT=Barrington Beach Transect, BH=Bristol Harbor, BRT=Bullock's Reach Transect, EPN=East Passage North, EPS=East Passage South, GRB Greenwich Bay, PRC=Providence River Central, PRN=Providence River North, PRS=Providence River South, PRT=Providence River Transect, RWU=Roger Williams University, SR=Seekonk River, UPB=Upper Bay, WPS=West Passage South

Survey Date	Stations		Survey Date	Stations
7/14/05	49		6/8/10	76
8/2/05	52		7/8/10	80
8/29/05	48		7/22/10	79
			8/6/10	80
6/6/06	51		8/19/10	79
7/6/06	51		9/2/10	70
8/3/06	50			
8/11/06	34		6/28/11	79
8/31/06	49		7/27/11	79
			8/11/11	36
6/7/07	65		8/25/11	60
6/26/07	65			
7/24/07	65		6/19/12	79
8/14/07	64		7/17/12	79
8/24/07	64		8/14/12	79
			8/27/12	80
6/16/08	71		9/11/12	79
7/16/08	76			
7/25/08	75		6/18/13	79
7/31/08	76		7/3/13	79
8/14/08	76		7/16/13	80
8/26/08	76		8/1/13	80
9/11/08	75		8/15/13	80
			8/29/13	80
6/18/09	79			
7/15/09	78			
7/23/09	79			
8/4/09	79			
8/13/09	78			
9/1/09	79			

Table 2. Dates of the spatial surveys and the number of stations occupied. A total of 47 surveys were completed with a resulting 3296 water column profiles.

	Salinity	Temperature	Density	DO	n =
B-NBEP Average	0.01	-0.01	0.01	-0.06	628
B-NBEP Median	0.00	0.00	0.00	-0.04	628
B-NBEP St Dev	0.07	0.06	0.06	0.17	628
B-STB Average	0.01	0.00	0.01	0.00	696
B-STB Median	0.01	0.00	0.01	0.05	696
B-STB St Dev	0.09	0.11	0.09	0.27	696

Table 3. The average, median, and standard deviation of CTD dip-in differences for salinity (ppt), temperature (^{0}C), Density (σt), and dissolved oxygen (mg/l) between the Brown and NBEP CTDs and the Brown and STB CTDs. Statistics are based on 44 and 37 profiles, respectively.

Seq #	Date	Group	Station	Lat	Lon	Time	Depth (m)	Salinity (ppt)	Temp (deg C)	Density (sigma T)	DO (mg/l)	DO (% sat)
1	7/14/05	Brown	UPB07b	41.7136	-71.2923	6:45	1	27.11	22.8	18.01	6.64	90.3
2	7/14/05	Brown	UPB07b	41.7136	-71.2923	6:45	1.5	27.13	22.8	18.03	6.63	90.2
3	7/14/05	Brown	UPB07b	41.7136	-71.2923	6:45	2	27.14	22.8	18.05	6.62	90.2
4	7/14/05	Brown	UPB07b	41.7136	-71.2923	6:45	2.5	27.14	22.7	18.06	6.62	90.1
5	7/14/05	Brown	UPB07b	41.7136	-71.2923	6:45	3	27.15	22.7	18.07	6.6	89.8
6	7/14/05	Brown	UPB07b	41.7136	-71.2923	6:45	3.5	27.16	22.7	18.07	6.61	89.8
7	7/14/05	Brown	UPB07b	41.7136	-71.2923	6:45	4	27.16	22.7	18.08	6.62	89.9
8	7/14/05	Brown	UPB07b	41.7136	-71.2923	6:45	4.5	27.17	22.7	18.09	6.62	90.1
9	7/14/05	Brown	UPB07b	41.7136	-71.2923	6:45	5	27.18	22.7	18.09	6.62	90.1
10	7/14/05	Brown	UPB07b	41.7136	-71.2923	6:45	5.5	27.18	22.7	18.1	6.6	89.8
11	7/14/05	Brown	UPB07b	41.7136	-71.2923	6:45	6	27.19	22.7	18.11	6.61	89.7
12	7/14/05	Brown	UPB07b	41.7136	-71.2923	6:45	6.5	27.2	22.7	18.12	6.63	89.9
13	7/14/05	Brown	UPB07b	41.7136	-71.2923	6:45	7	27.21	22.7	18.13	6.61	90
14	7/14/05	Brown	UPB07b	41.7136	-71.2923	6:45	7.5	27.21	22.7	18.13	6.62	89.8
15	7/14/05	Brown	UPB07b	41.7136	-71.2923	6:45	8	27.22	22.7	18.14	6.62	90
16	7/14/05	Brown	UPB07b	41.7136	-71.2923	6:45	8.5	27.23	22.7	18.15	6.61	89.9
17												
18	7/14/05	Brown	PRN07	41.8164	-71.3969	7:28	1	10.12	22.2	5.37	6.91	86.7
19	7/14/05	Brown	PRN07	41.8164	-71.3969	7:28	1.5	15.83	21.7	9.8	6.16	85.9
20	7/14/05	Brown	PRN07	41.8164	-71.3969	7:28	2	20.12	20.8	13.26	5.34	72.6
21	7/14/05	Brown	PRN07	41.8164	-71.3969	7:28	2.5	22.14	20.6	14.85	5.25	65.2
22	7/14/05	Brown	PRN07	41.8164	-71.3969	7:28	3	23.14	20.6	15.59	5.64	66.9
23	7/14/05	Brown	PRN07	41.8164	-71.3969	7:28	3.5	23.52	20.7	15.86	5.76	70.1
24	7/14/05	Brown	PRN07	41.8164	-71.3969	7:28	4	24.29	20.6	16.47	5.57	73.5
25	7/14/05	Brown	PRN07	41.8164	-71.3969	7:28	4.5	25.42	20.2	17.43	5.08	73.6
26	7/14/05	Brown	PRN07	41.8164	-71.3969	7:28	5	26.68	19.5	18.55	4.66	67.9
27	7/14/05	Brown	PRN07	41.8164	-71.3969	7:28	5.5	27.28	19.1	19.11	4.49	62.3
28	7/14/05	Brown	PRN07	41.8164	-71.3969	7:28	6	27.83	18.7	19.62	4.43	58
29	7/14/05	Brown	PRN07	41.8164	-71.3969	7:28	6.5	28.07	18.6	19.84	4.4	56.4
30	7/14/05	Brown	PRN07	41.8164	-71.3969	7:28	7	28.31	18.4	20.06	4.37	55.7
31	7/14/05	Brown	PRN07	41.8164	-71.3969	7:28	7.5	28.56	18.2	20.29	4.34	55.3
32	7/14/05	Brown	PRN07	41.8164	-71.3969	7:28	8	28.7	18.1	20.43	4.3	54.9

Table 4. Example of the interpolated data set. Structured by sequence number, date, boat group, station identification, location, interpolated sample depth and water quality metrics (salinity, temperature, density, dissolved oxygen (mg/l), and dissolved oxygen % saturation. The final interpolated data set is a tab delimited text file that is available from the Publications menu on the NBEP website (http://www.nbep.org) or the Insomniac/Day Trippers website (http://www.geo.brown.edu/georesearch/insomniacs/)

Station	Mean Bottom DO	Minimum Bottom DO	Median Bottom DO	St Dev of Mean Bottom DO
BBT1	3.22	0.50	3.33	1.80
BBT2	3.77	0.76	3.56	1.31
BBT3	3.70	1.22	3.66	0.83
BH05	3.77	0.77	3.42	1.93
BH07	4.11	1.56	4.28	1.48
BH10	3.70	1.18	3.52	1.43
BRT1	3.86	1.27	3.76	1.59
BRT2	3.38	1.30	3.42	0.86
BRT3	3.03	1.26	2.87	0.88
BRT4	3.00	0.90	2.76	1.22
BRT6	5.72	1.87	5.69	2.04
EPN02	5.20	3.06	5.22	0.71
EPN03	4.86	2.81	4.81	0.78
EPN04	4.88	3.31	4.93	0.70
EPN05	4.79	2.63	4.86	0.82
EPN06	4.53	2.43	4.63	0.89
EPN08b	4.51	2.00	4.63	1.22
EPS01	5.84	4.53	5.67	0.67
GRB-A	3.89	0.29	4.07	2.09
GRB-B	4.37	1.77	4.50	1.21
GRB-C	3.77	0.36	4.18	1.76
GRB-D	3.97	0.21	4.02	2.11
GRB01	3.81	0.42	3.26	2.02
GRB02	3.52	0.23	3.34	1.84
GRB03	3.86	0.36	4.35	2.04
GRB04	2.73	0.19	1.75	2.08
GRB05	2.92	0.16	2.51	2.18
GRB06	3.55	0.24	3.75	1.77
GRB07	3.43	0.14	3.51	1.51
GRB09	3.76	0.94	3.81	1.17
GRB10	4.84	1.56	4.73	1.58
GRB12	5.50	0.50	5.72	1.64
PRC02	3.05	0.69	3.02	1.16
PRC05b	2.79	0.61	2.74	1.15
PRC07	1.22	0.14	0.94	1.12
PRC08b	3.81	1.15	3.28	2.19
PRN01	2.42	0.14	2.45	1.32
PRN03b	2.02	0.09	2.04	1.42
PRN07	1.88	0.11	1.56	1.27
PRN08	2.48	0.18	2.53	1.50
PRS03	3.59	1.29	3.49	1.07
PRS04	5.08	1.38	5.08	1.80
PRS07	3.31	0.57	3.30	1.10

PRT01	4.51	1.19	3.56	2.79
PRT02	4.47	0.81	3.74	2.48
PRT03	5.21	1.01	4.57	3.08
PRT04	4.89	1.34	4.28	2.63
RWU03	4.80	1.88	4.84	1.15
RWU03b	4.22	2.15	4.25	1.01
RWU05	5.38	3.69	5.38	0.62
SR01	2.39	0.20	1.82	1.70
SR02	2.32	0.21	1.95	1.61
SR03	2.45	0.28	2.34	1.50
UPB01	4.03	1.07	4.16	1.25
UPB02	4.42	0.85	4.39	1.36
UPB03	3.34	0.73	3.42	1.45
UPB04b	4.00	1.29	3.84	1.38
UPB05	4.38	1.78	4.53	0.93
UPB06	4.04	0.70	4.06	1.90
UPB07b	4.50	0.50	4.63	1.68
UPB08	4.26	0.93	4.35	0.99
UPB09b	3.74	0.51	3.45	2.09
UPB10	4.04	1.29	3.94	0.91
UPB11	4.09	0.98	4.20	0.98
UPB12	5.70	1.15	5.41	1.97
UPB13	3.38	0.81	3.32	1.25
WPS01	5.34	4.09	5.21	0.80
WPS02	5.43	3.34	5.34	0.87
WPS04	4.36	1.97	4.37	0.92
WPS05	4.04	1.63	4.08	0.83
WPS07	3.98	1.10	3.99	1.10
WPS08	6.37	3.45	6.24	1.52
WPS09	4.62	1.57	4.71	1.15
WPS10	3.71	0.78	4.18	1.34
WPS11	4.39	0.39	4.61	1.46
WPS13	4.58	1.89	4.67	1.27
WPS14	4.89	2.68	4.66	1.03

Table 5. Summary of mean bottom DO, the standard deviation of the mean bottom DO, the median DO, and the minimum DO observed at each station. All units are mg/l. Time interval is 2005 to 2013.

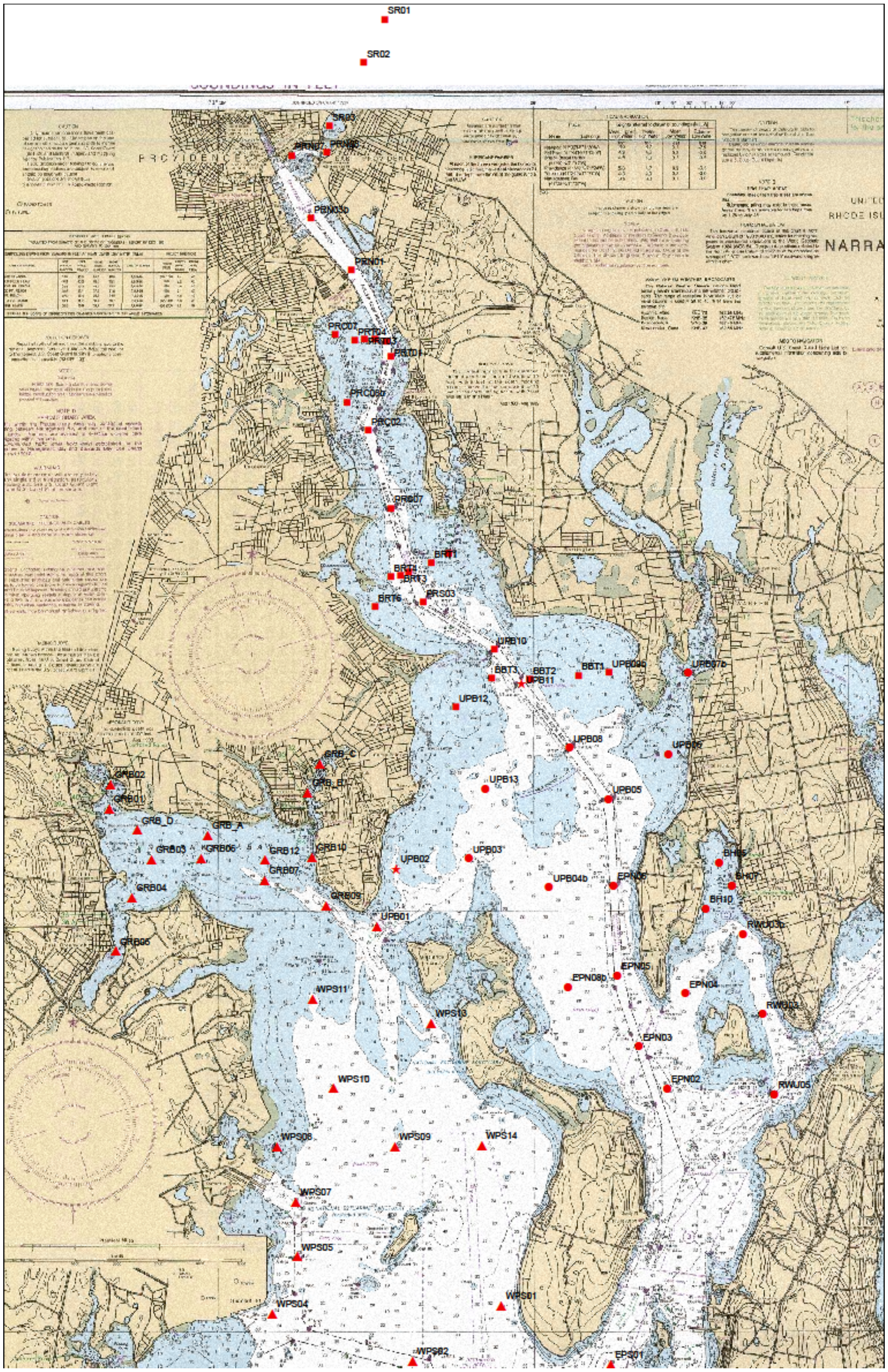

Figure 1. Location of spatial survey stations. See Table 1 for coordinates, water depths, number of measurements, and key to station names. (from the Dissolved Oxygen QAPP, Kiernan, et al, 2014). See Table 2 for the dates of all surveys and the number of stations occupied.

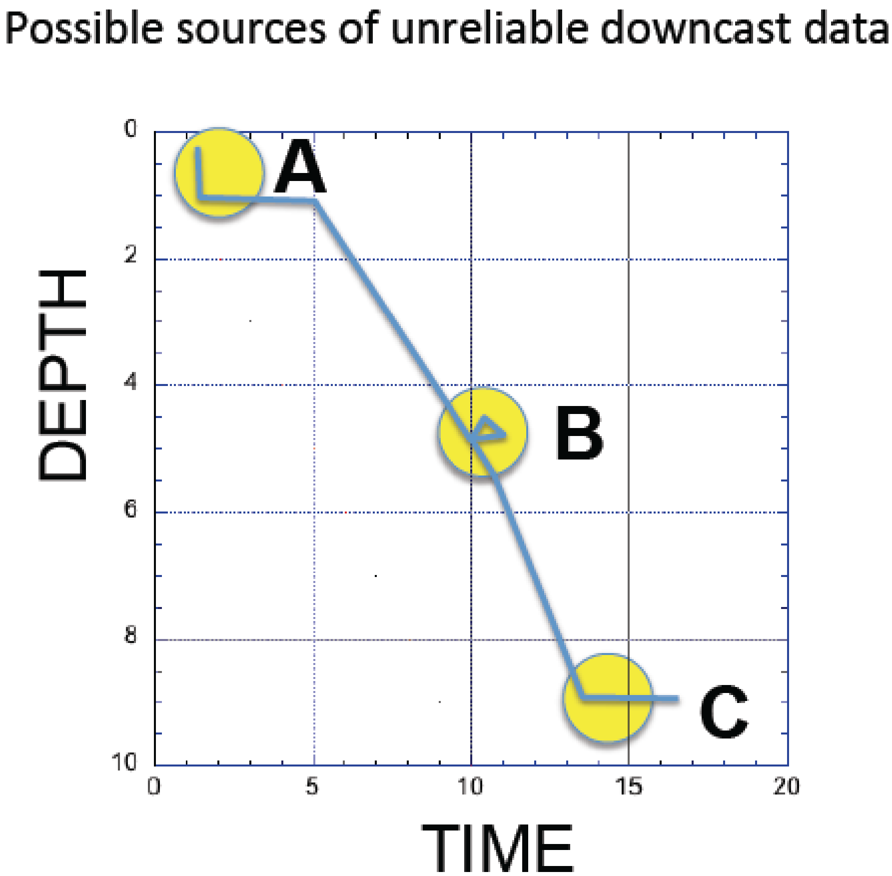

Figure 2. Downcast of CTD depth vs. time to illustrate the generic sources of unreliable data. (A) Possible errors in initial depth or pump failure; (B) Depth reversals due to boat motion; (C) Effects of bottom contact, including sediment or pore waters entrained by pump.

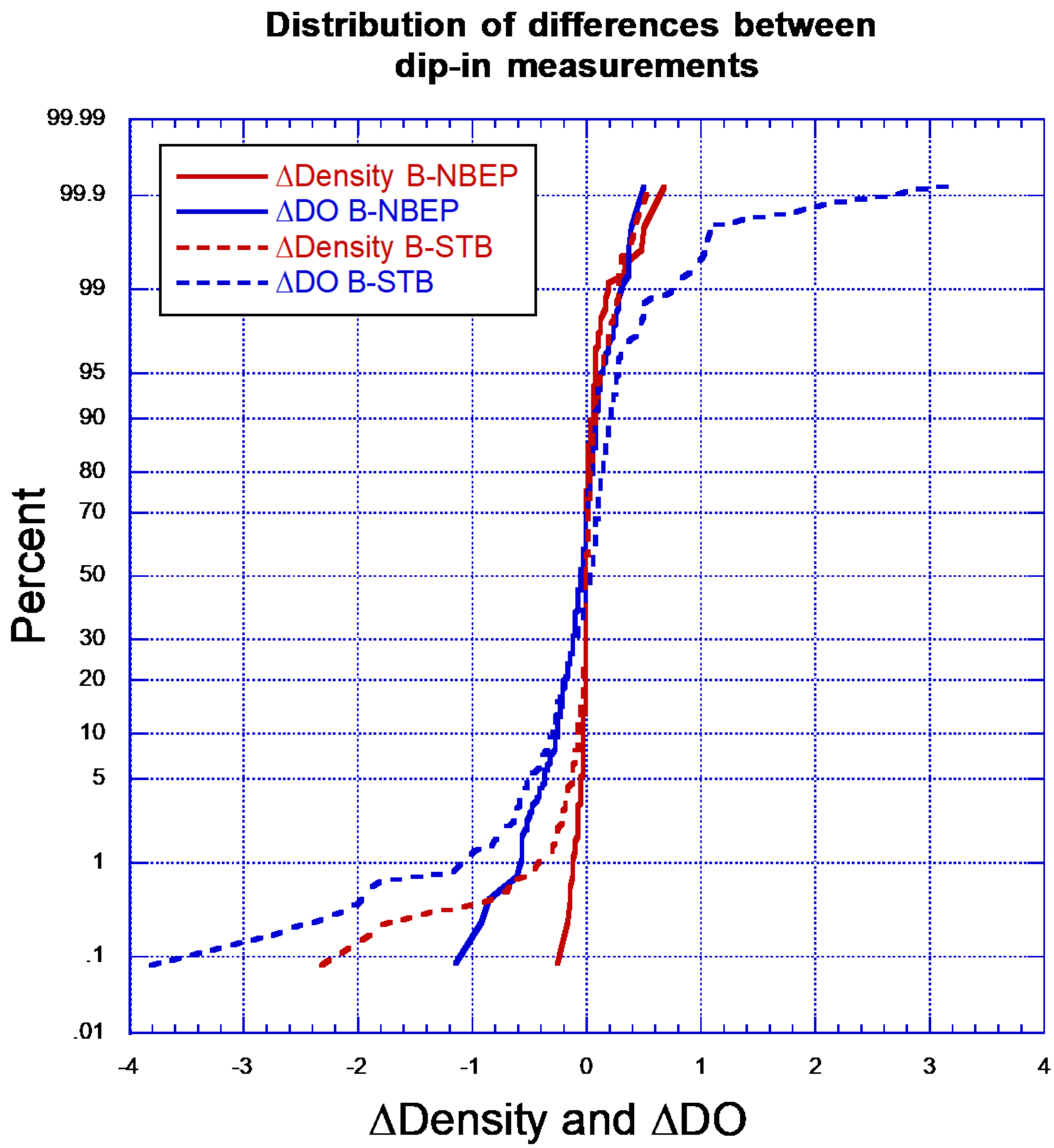

Figure 3. Probability distribution of the difference in density (ΔDensity) and dissolved oxygen (ΔDO) from the dip-in comparisons with the Brown-NBEP and Brown-STB CTDs. Data are interpolated values for 44 and 37 profiles, respectively.

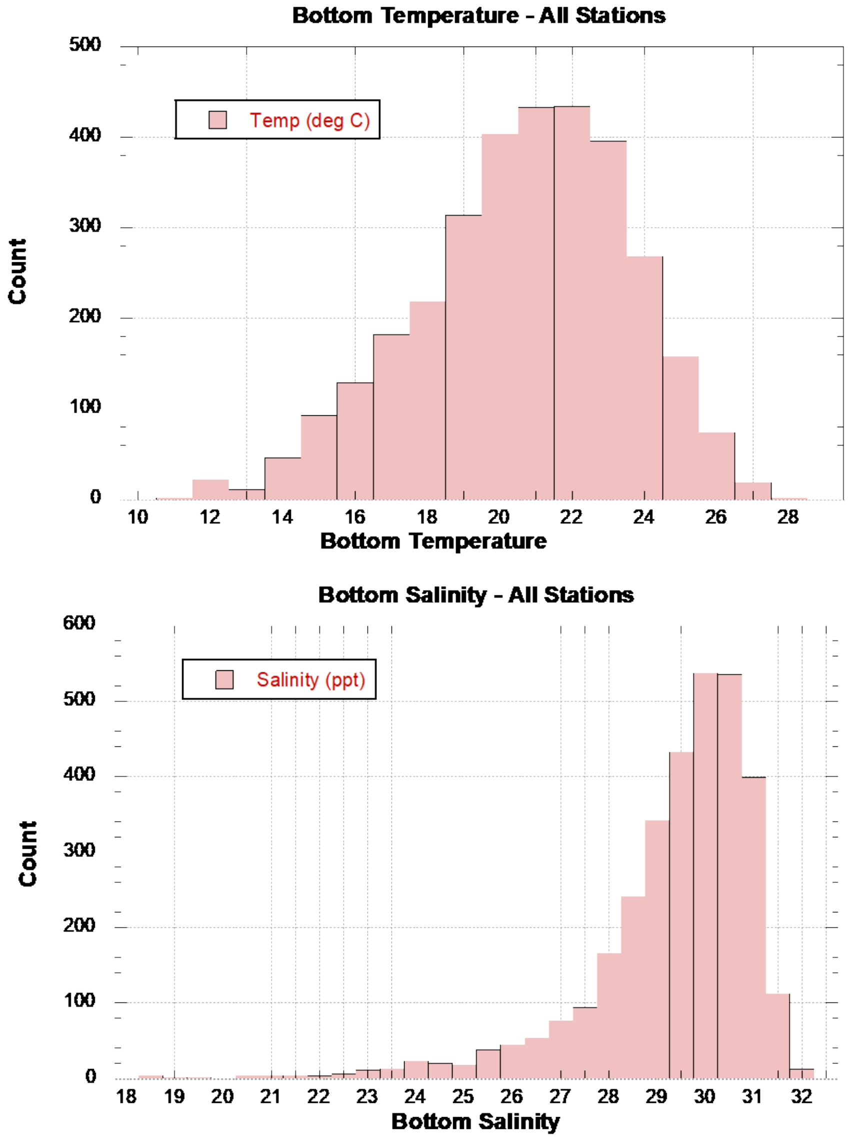

Figure 4. Distribution of bottom temperature (upper panel) and bottom salinity (lower panel) for all stations (2005-2013). N = 3296.

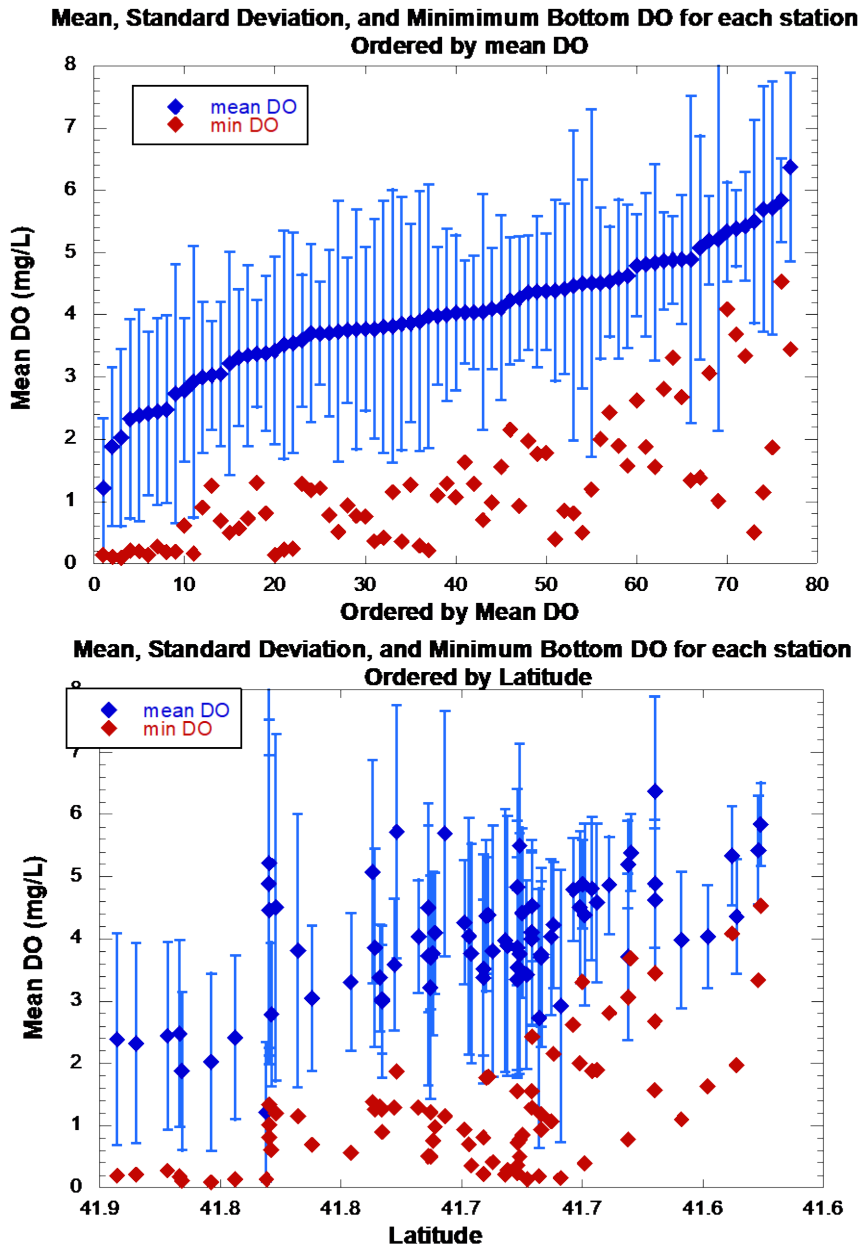

Figure 5. The distribution of mean, standard deviation, and minimum bottom water dissolved oxygen (DO) for each station. Upper panel is ordered by increasing mean DO in the 77 stations. Lower panel is ordered by latitude.

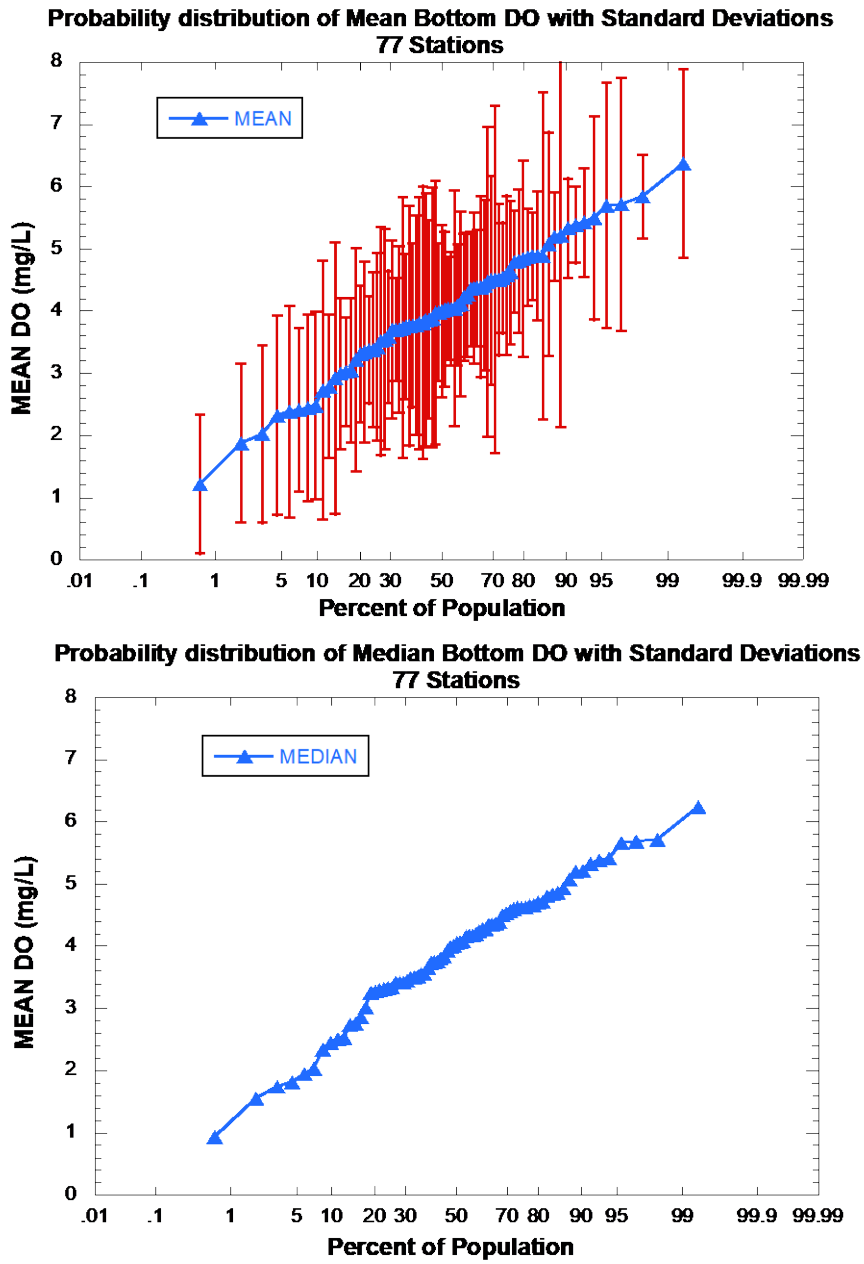

Figure 6. The probability distribution of mean (upper panel) and median (lower panel) bottom dissolved oxygen (DO) for each station (n=77). Standard deviations are shown around the mean values.

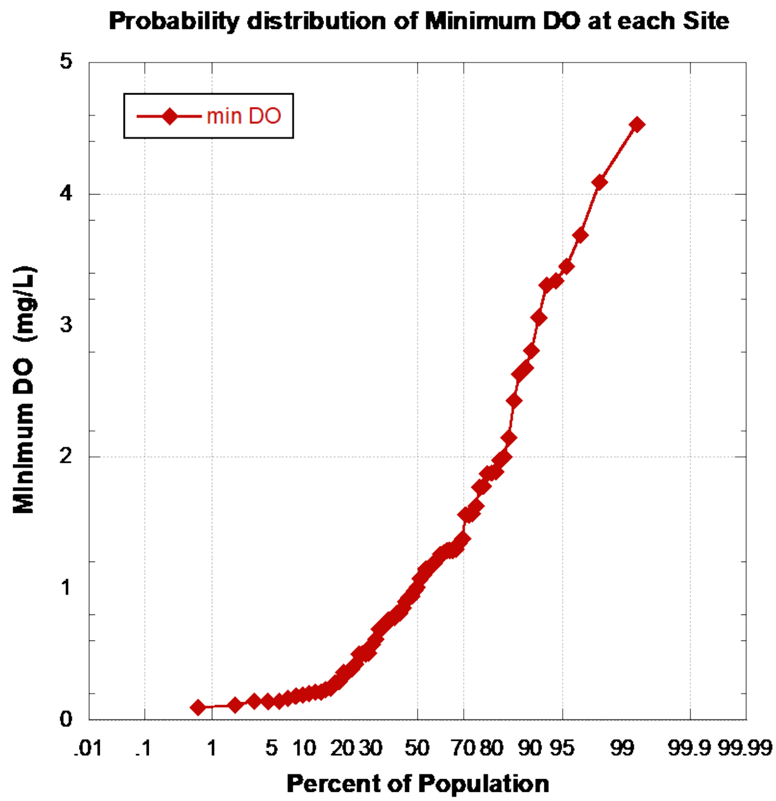

Figure 7. Probability distribution of the minimum dissolved oxygen (DO) observed at each site during all the surveys.

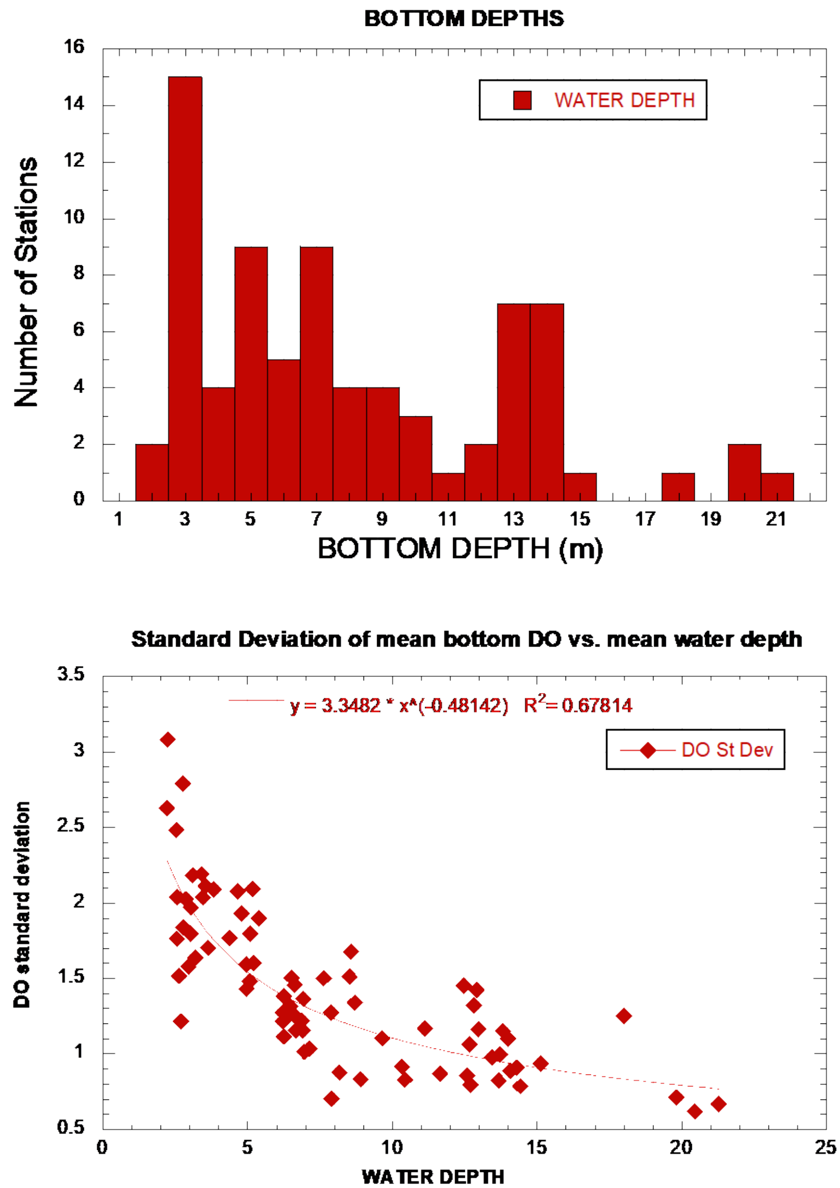

Figure 8. The distribution of water depths at the 77 sites (upper panel) and the distribution of variability (standard deviation) of mean bottom DO as a function of water depth (lower panel).

Appendix A. Notes on calibration factors used to correct biases and offsets in the original data files and corrections to final interpolated files.

2009-07-15- Correction of 1.1056 applied (multiplied) to measured Brown O2 (mg/l) and (% sat) due to offset of Brown (SB4731) sonde compared to STB (SB4944) and NBEP (SB4729)
2009-07-23- Correction of 1.1056 applied (multiplied) to measured Brown O2 (mg/l) and (% sat) due to offset of Brown (SB4731) sonde compared to STB (SB4944) and NBEP (SB4729)
2009-08-04- Correction of 1.1056 applied (multiplied) to measured Brown O2 (mg/l) and (% sat) due to offset of Brown (SB4731) sonde compared to STB (SB4944) and NBEP (SB4729)
2009-08-13- Correction of 1.1056 applied (multiplied) to measured Brown O2 (mg/l) and (% sat) due to offset of Brown (SB4731) sonde compared to STB (SB4944) and NBEP (SB4729)
2009-09-01- Correction of 1.1056 applied (multiplied) to measured Brown O2 (mg/l) and (% sat) due to offset of Brown (SB4731) sonde compared to STB (SB4944) and NBEP (SB4729)
2010-06-08- Correction of 1.1017 applied (multiplied) to measured STB O2 (mg/l) and (% sat) due to offset of STB (SB4944) sonde compared to Brown (SB4731). correction of 0.9353 applied (multiplied) to measured NBEP O2 (mg/l) and (% sat) due to offset of NBEP (SB4729) sonde compared to Brown (SB4731).
2010-07-08- Correction of 1.1017 applied (multiplied) to measured STB O2 (mg/l) and (% sat) due to offset of STB (SB4944) sonde compared to Brown (SB4731). correction of 0.9353 applied (multiplied) to measured NBEP O2 (mg/l) and (% sat) due to offset of NBEP (SB4729) sonde compared to Brown (SB4731).
2010-07-22- Note: correction of 1.1017 applied (multiplied) to measured STB O2 (mg/l) and (% sat) due to offset of STB (SB4944) sonde compared to Brown (SB4731). correction of 0.9353 applied (multiplied) to measured NBEP O2 (mg/l) and (% sat) due to offset of NBEP (SB4729) sonde compared to Brown (SB4731).
2010-08-06- Correction of 1.1017 applied (multiplied) to measured STB O2 (mg/l) and (% sat) due to offset of STB (SB4944) sonde compared to Brown (SB4731). correction of 0.9353 applied (multiplied) to measured NBEP O2 (mg/l) and (% sat) due to offset of NBEP (SB4729) sonde compared to Brown (SB4731).
2010-08-19- Correction of 1.1017 applied (multiplied) to measured STB O2 (mg/l) and (% sat) due to offset of STB (SB4944) sonde compared to Brown (SB4731). correction of 0.9353 applied (multiplied) to measured NBEP O2 (mg/l) and (% sat) due to offset of NBEP (SB4729) sonde compared to Brown (SB4731).
2010-09-02- Correction of 1.1017 applied (multiplied) to measured STB O2 (mg/l) and (% sat) due to offset of STB (SB4944) sonde compared to Brown (SB4731). correction of 0.9353 applied (multiplied) to measured NBEP O2 (mg/l) and (% sat) due to offset of NBEP (SB4729) sonde compared to Brown (SB4731).
2012-08-27- UPB11 (STB) - pump not on for scans 12524 - 12533 only.
2012-08-27 -UPB12 (STB) - pump not on for scans 13081 - 13106 only.

Corrections to Interp File 4/21/14

6/18/09	UBP11	BROWN	ELIM 1-3.0m	PUMP FAILURE
7/23/09	UPB11	Brown	ELIM 1-6.5m	PUMP FAILURE
8/06/10	BRT3	STB	ELIM 1-5.0m	PUMP FAILURE
8/06/10	WPS05	NBEP	ELIM 1-3.5m	PUMP FAILURE
8/06/10	UPB13	Brown	ELIM 1-2.5m	PUMP FAILURE
8/27/12	UPB12	STB	ELIM 1-1.5m	PUMP FAILURE