ABSTRACT

Title of thesis: SAMPLING ERRORS ARISING FROM ENTRAINMENT AND INSUFFICIENT FLUSHING OF OCEANOGRAPHIC SAMPLING BOTTLES

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Collection of representative water samples is important for accurately determining biological and chemical constituents. Modern carousel packages can permit bottle "soak times" to approach zero while increasing the impacts of entrainment due to their large size. In addition, some modern sampling bottles have relatively small openings relative to their volumes, a factor that inhibits flushing. Examination of qualitative evidence from various expeditions suggested that insufficient "soak times" can produce unrepresentative water samples. In this study, historical data are presented, but the emphasis is on field experiment data that better quantifies the errors that can arise from insufficient bottle flushing. The experiments suggest that under some conditions, soak times of more than 2 minutes may be required to collect representative water samples. The experiments also suggest the occurrence of stratification within bottles. The impact of insufficient soak times on some chemical gradients is discussed and improved sampling protocols are suggested.

SAMPLING ERRORS ARISING FROM ENTRAINMENT AND INSUFFICIENT FLUSHING OF OCEANOGRAPHIC SAMPLING BOTTLES

By

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INTRODUCTION

Obtaining representative samples is a problem that pervades the scientific enterprise. Early in the history of oceanography, investigators such as Nansen gave considerable thought to the design of sampling bottles (Fig. 1a) and thermometers (Sverdrup et al, 1942). The process of obtaining representative water samples may need renewed attention, given the potential efficiency designed into modern water sampling packages, the increasing cost of ship and wire time, and the desire to maximize sampling frequency.

Only a few decades ago oceanographic in-situ water sampling required attaching an array of relatively small individual bottles to a hydrowire (Fig. 1b). These bottles were often equipped with reversing mercury thermometers that required several minutes of “soak” time for equilibration, and the bottles were tripped by messengers that mechanically closed the bottles by descending the wire at ~ 150-200 m/min from the ship platform (U.S. Naval Oceanographic Office Pub. 607, 1968; Sverdrup et al., 1942). This process could add appreciably to the “soak” times required for thermal equilibration. This technology has been largely replaced by Conductivity-Temperature-Depth (CTD) rosette systems (carousels; Fig. 2) with bottles that can be electronically triggered to close (trip) at the moment a bottle reaches a sampling depth (if so desired). In addition, the need for obtaining “clean” samples and/or large samples for various biological and trace metals programs has sometimes resulted in the employment of sampling bottles that can have small opening areas relative to bottle volume, a factor that inhibits flushing (Weiss, 1971). Although a recent ongoing program, GO-SHIP, suggests waiting at least 20 seconds at depth before tripping bottles, and in some cases possibly up to one minute for better results (Swift, 2010; Kawano, 2010), these cautions are often neglected either from ignorance, or in cases where current shears preclude the rosette from maintaining its position in the water column. The experiments presented here indicate that these soak times can be too short under some circumstances, sometimes requiring in excess of two minutes.

The motivation for this study arises from real-world experiences on expeditions such as the U.S. Joint Global Ocean Flux Study (JGOFS) and from the analysis of data from the Arctic. The Arctic data are from one particular Shelf Basin Interactions Project (SBI) cruise, HLY-03-03, that emphasized rapid carousel deployments. I provide an example (Fig. 3) of four CTD vertical profiles that show differences between the measured bottle salinity (using a salinometer) and the CTD electronic profile. These data from a strongly salt-stratified Arctic water column suggest that tripping bottles on a carousel after insufficient "soak times" can lead to bottle salinities that do not represent conditions at the bottle tripping depths. Note that on the up portion of the casts (Fig. 3), bottle salinities can be much higher than the corresponding CTD salinities. Conversely (and as would be expected) the deepest bottles tripped after the CTD has stopped descending sometimes yield salinity values that tend to be lower than the CTD salinities despite reduced winch speeds as the carousel approaches the bottom of the cast and the need to pause to undertake data entry tasks.

Weiss (1971) evaluated the flushing characteristics of several types of oceanographic sampling bottles, including Nansen and NMS series (General Oceanics, Miami), ranging in size from 1.3 to 30 L. Weiss developed an idealized flushing model:

$$ln(c/c_0) = - (a/v) \cdot z, \qquad (1)$$

where c_0 is the initial concentration, c is the final concentration, a is the opening area of the bottle, v is the bottle volume, and z is the distance traveled. Weiss described a/v as the reciprocal of the idealized flushing length, which is the distance the bottle would have to travel to reduce the original concentration in the bottle by a factor of $1/e$. He conducted experiments to validate the model and found that characteristic (actual) flushing lengths were generally within 20% of the idealized model. For example, a 1.3 L Nansen bottle with "normal" valves had a v/a ratio of 3.23 and a characteristic flushing length of 2.80 meters. The worst agreement between the idealized and characteristic flushing length was with the 30 L Niskin bottle with an opening diameter of 7.2 cm and a v/a ratio of 7.37 and a characteristic flushing length of 12.7 meters.

In addition to bias due to bottle flushing characteristics, entrainment of water during the carousel ascent can also introduce bias. An example is given in figure 4, which shows a two-layer system with a more saline bottom boundary layer and a less saline surface mixed layer. The downcast CTD salinity (blue) displays a sharp gradient between 50 and 60 dbar. During the ascent (red) through the gradient, the CTD salinities display bias over a length of about 30 dbar. Sometimes such results are imputed to sensor hysteresis, but the ensemble of results presented here demonstrates that entrainment is also an important factor. The deviation shown in figure 3 at the bottom of the CTD casts also suggest entrainment. The impact of ship drift (Fig. 5) on the position of the entrainment plume relative to the carousel can help explain the variations in bottle “soak” times mentioned above (~ 20s to > 2min). Entrainment causes density inversions in the water column. Experimental data suggest that initial sinking and dispersion of the entrainment plume plus bottle flushing times dominate the signals in our experiments, but there are suggestions of subsequent rebound in the form of internal gravity waves. The period of these oscillations may be described using Brunt- Väisälä frequencies.

Intra-bottle stratification can also bias results. Little research has been done to identify best practices to reduce this source of bias, but Smethie and Buchholtz (1980) investigated intra-bottle stratification for dissolved oxygen when developing a procedure to sample microscale (~2 m) gradients. They deployed 30 L Niskin bottles directly on a hydrowire every 2 meters over a 10-meter length. They then oscillated the hydrowire (yo-yoed) with the bottles open at an amplitude of 2 to 4 meters with an oscillation period of 10 s, for a total of about 100 seconds before tripping the bottles. After retrieval, five oxygen samples were taken from each bottle. They found no evidence of intra-bottle stratification. Their experimental procedure simulated rougher sea states causing the bottles to flush more rapidly. Their scenario did not take into account bottle flushing dynamics in quiescent waters. The results presented here demonstrate that intra-bottle stratification can be present in bottles tripped under quiescent conditions (see Results and Discussion sections).

This work undertook flushing/entrainment experiments to better quantify the impact of recent oceanographic practices on the quality of bottle data, and to suggest protocols that can alleviate these problems. Bottle flushing experiments were conducted during two field expeditions (Fig. 6). One suite of experiments was conducted in the Chukchi Sea aboard the *USCGC Healy* during the 2013 field season (cruise HLY1301, 29 July to 15 August 2013). A second suite of experiments was conducted in the Bering Sea on the *RV Sikuliaq* (cruises SKQ2015-04T and SKQ2015-05s, 19 March to 7 April 2015).

METHODS

During the *USCGC Healy* and *RV Sikuliaq* experiments, Sea-Bird SBE 32 carousels were employed. The carousel frames were similar except for a conical extension on the *RV Sikuliaq's* frame to accommodate a snubbing apparatus. The frames' horizontal diameters were ~ 150 cm, and their heights were ~180 cm, absent the extension on the *RV Sikuliaq*. The *USCGC Healy's* carousel was equipped with twenty-four 12 L Niskin bottles (Fig. 7) fitted with external springs. The carousel on the *RV Sikuliaq* was equipped with twenty-four 10 L Niskin bottles from Ocean Test Equipment (Fig. 8) fitted with internal springs. Both CTD/rosette systems employed Sea-Bird SBE 911plus CTDs equipped with dual temperature and conductivity sensors, a dissolved oxygen sensor, and various other sensors (e.g. chlorophyll fluorometers).

EXPERIMENT TYPES

Three different types of experiments to evaluate the effect of current sampling practices in different sea state conditions were conducted to assess the potential impacts of entrainment and insufficient flushing. The first type (Type I) was designed to evaluate the soaking time procedure during which the rosette is stopped for a period of time at the desired sampling depth before the bottles are tripped. The second type (Type II) was similar to the first in that the rosette was stopped before the bottles were tripped, but after reaching the desired depth a "yo-yo" motion was added after each bottle trip, to mimic the motion of the ship in rougher seas. The target bottle tripping times for experiment types I and II conducted on the *USCGC Healy* are shown in Table 1. The third type (Type III) represented the "tripping on the fly" method, where the rosette is not stopped when tripping a bottle. Five separate casts were conducted for this experiment type each at differing ascent speeds (Table 2).

It is important to note that the sea states were relatively calm during the *USCGC Healy* and *RV Sikuliaq* cruises and that the ships were often in ice, meaning ship motion - both linear (i.e. heave) and rotational (i.e. pitch and roll) - had a negligible role in any vertical oscillations of the carousel during the experiments.

For stations at which data were collected at multiple depths, we employ the following terminology to describe position within the water column. The upper halocline is defined as a zone with a relatively weak gradient above and a stronger gradient below. The mid halocline is defined as a zone with relatively strong gradients above and below. The lower halocline is defined as a zone with relatively strong gradients above and weak gradient below. A bottom boundary layer is defined as a zone that abuts the bottom and is uniform with respect to salinity.

Each downcast, regardless of the experiment type, was deployed similarly. The carousel was submerged to 10 m below the surface for about a minute and then brought back up to one meter below the surface and then immediately lowered to the sea floor at about 25 dbar/min.

Differences between the salinities recorded by the CTD at the time a Niskin bottle was closed, and the salinity of the water within the bottle while the CTD was immersed in a significant salinity gradient were the metric employed to assess the degree of bottle flushing.

WATER SAMPLES

During both cruises, salinity samples were collected from the carousel sampling bottles using 250 mL clear glass bottles with plastic screw tops with conical inserts (*RV Sikuliaq*) or plastic caps and separate inserts (*USCGC Healy*). Duplicates were always collected during the *USCGC Healy* cruise. Salinities were determined on-board with Guildline salinometers (8400B Autosal on the *USCGC Healy*; 8410A Portasal on the *RV Sikuliaq*). International Association for the Physical Sciences of the Oceans (IAPSO) seawater standard was used to calibrate both salinometers; for the *RV Sikuliaq* - batch P155, expiration date = Sept 2015, K^{15} = 0.99981, and salinity = 34.993; for the *USCGC Healy* - P series batch, K^{15} = 0.99984.

Salinity bottles were rinsed at least three times before collecting a sample, which were subsequently filled to the bottle neck. They were generally the first samples drawn, but in the experiments that explored the possibility of stratification within oceanographic sampling bottles, an initial sample was followed by a sample drawn when the bottles were almost empty. On the *RV Sikuliaq*, two samples were drawn only when examining intra-bottle stratification. The salinity samples were then stored in wooden crates for up to 3 days before analysis. Crate temperatures were monitored with digital thermometers to ensure that sample temperatures were close to the Autosal or Portasal water bath temperatures (21° C on the *USCGC Healy* and 23 or 25° on the *RV Sikuliaq*) before testing. Once equilibrated, the salinity samples were analyzed. The salinometers were calibrated before and at the end of each run (no more than 24 samples) with IAPSO Seawater Standard on the *USCGC Healy* and before each run on the *RV Sikuliaq* (no more than 16 samples). The salinometers on both ships were connected to computers that employed Scripps Institution of Oceanography's Ocean Data Facility software to guide and prompt the analyst.

CTD SALINITY CORRECTIONS

The SBE 911plus CTD, Guildline Autosal, and Guildline Portasal have stated salinity accuracies of ±0.003 (Sea-Bird, 2016), ±0.002 (Guildline, 2006), and ±0.003 (Guildline, 2002), respectively. Thus, the salinity differences between a well calibrated CTD and well calibrated Salinometer sample from a well flushed bottle should be within ±0.005 for the *USCGC Healy* data and ±0.006 for the *RV Sikuliaq* data. CTD salinity values can, however, start to drift after a factory calibration, which for the *USCGC Healy* was reportedly done four months before the cruise leading to the possibility of larger drift. To harmonize the *USCGC Healy* CTD and Autosal salinities for their inherent accuracies and for any instrument drift, the salinity difference, Δs, between each CTD sensor package and well-flushed bottle samples from mixed bottom layers were compared (Eq. 1).

$$\Delta s = s_b - s_c, \quad (2)$$

Where s_b is the bottle salinity value and s_c is the CTD salinity value. There were five *USCGC Healy* stations where CTD and well-flushed (180 second soak times) bottle salinity values were collected in mixed bottom layers at least 10 dbar thick (Table 3). *USCGC Healy* CTD sensor package I had a mean salinity 0.014 lower than the Autosal salinities, suggesting significant post calibration shift. CTD sensor package II had a mean salinity 0.007 lower than the Autosal values, just outside of the expected range. Therefore, the salinity values from CTD sensor package II were used in the comparisons of bottle and CTD salinities from the *USCGC Healy*. Furthermore, we uniformly adjusted the CTD sensor package's values to eliminate the mean differences that we observed between the CTD sensor packages and bottle salinities (Table 3) in these mixed bottom layers.

Two tests on the *RV Sikuliaq* cruise suggested that Portasal salinities averaged 0.002 higher than CTD salinities. Since this difference is well within the stated accuracies of the CTD and the Portasal salinometer, no corrections for CTD vs. salinometer salinities were made for *RV Sikuliaq* samples.

Although all data are presented and described, data collected at or shallower than 12 dbar are included only in the analysis of intra-bottle stratification. This is because of indications that the results relative to entrainment and flushing were significantly impacted by ship discharges (e.g. bilge water) and turbulence from the ship's propulsion system at depths ≤ 12 dbar.

RESULTS

Results of each experiment, organized by experiment type, are described below. Following each experimental result, a brief summary is also provided of the commonalities among experiments. In general, entrainment (Fig. 3) and flushing cause initial salinities to be biased low when the carousel is traveling downwards in an increasing gradient and to be biased high when the package is traveling upwards (see Introduction). Also note that since the bottles take longer to flush than the CTD sensors, they can act like low-pass filters and dampen oscillatory signals that can be more pronounced in the electronically collected CTD data.

To help normalize the results for gradients of different strength during experiment types I and II, the percent of undisturbed ambient water at a given depth present in each bottle sample was calculated as follows:

$$p = 1 - (s_b - s_a) / (s_s - s_a), \quad (3)$$

where s_b is the bottle salinity, s_a is the ambient salinity - with the assumption that the CTD salinity is closest to this value - and s_s is the ambient salinity of the prior depth where the carousel stopped.

The ambient salinity (s_a) is defined as the last CTD salinity reading at the conclusion of each time series. These calculations come with two caveats. The first is that it is presumed the last CTD salinity reading is a good estimate of the ambient value. This assumption is supported by the experimental data that suggests the CTD is *relatively* quick at equilibrating to the ambient value. The second caveat has to do with the vertical displacement between the bottles and CTD on the carousel; the bottles being located ~ 1 dbar above the CTD. Thus, in relatively large salinity gradients, real salinity differences between the bottles and CTD can exist even after equilibration. Therefore, equilibrated bottle salinities can be significantly less saline than CTD salinity values when salinities increase strongly with depth, which will give percent values over 100%.

Experimental conditions necessitated somewhat "rough and ready" subjective criteria for choosing the prior depth salinities that provided the baseline for estimating percent bottle flushing over time. These calculations, nevertheless, proved useful for visualizing bottle flushing progress in the face of varying salinity gradients. The ambient salinity of the prior depth (s_s) was estimated in three different ways. If there was only one bottle tripping depth at a given station at or near the halocline, s_s is the CTD salinity from the deepest part of the profile. If the first sampling depth in a series is at the bottom of the profile (i.e. in the mixed bottom layer), s_s is the CTD salinity at 10 dbar from the carousel downcast. For the rest of the sampling depths in a series, s_s is the CTD salinity for the last bottle trip at the prior sampling depth.

Table 4 summarizes the Type I and Type II experiments with respect to the pressure range, salinity gradient, and estimated CTD and bottle salinity stabilization times.

TYPE I EXPERIMENTS

USCGC Healy Station 00501

For the first cast in this series, the carousel was stopped mid halocline, at about 15 dbar with an ambient salinity of 32.000 and the salinity gradient was 0.140 /dbar (Fig. 9). Twelve bottles were sequentially tripped at predetermined increments over a period of 281 seconds to determine optimal equilibration time for the given conditions. The bottle at t = 60s malfunctioned when tripped, therefore no water was collected for analysis. The initial bottle salinity was 32.589 (p = 31.4%), whereas the corresponding CTD salinity was 32.042. The CTD and bottle salinity values seem to stabilize between 120 and 150 seconds - bottle salinity was 31.9 (p = 114.2%) - suggesting that it took this long to equilibrate with ambient seawater. The CTD salinity was close to the ambient salinity at t = 0s, but this may be an artifact because an apparent water mass oscillation, possibly induced by settling of relatively dense water entrained by the carousel, may have increased equilibration time. Intra-bottle salinity stratification was examined on this cast.

The upper salinity values tended to be less saline than the bottom salinity values in the Niskin bottle with a mean salinity difference of 0.016.

RV Sikuliaq Station 001, Cast 01

Nine bottles were tripped over 141 seconds in the middle of a local halocline, at about 83 dbar with an ambient salinity of 32.524 and the salinity gradient was 0.050 /dbar (Fig. 10). The initial CTD and bottle salinities were 32.638 and 32.658 (p = 66.3%), respectively. The Niskin bottle at t = 141s malfunctioned at some point during the deployment and was only half full upon retrieval. Therefore, the data from this bottle are not included in any analysis. The CTD salinities appeared to stabilize at t = 75s and the bottle salinities appeared to stabilize at 32.519 (p = 101.3%) by t = 98s. There was a tendency for bottle salinities for samples in the upper portion of the bottles to have lower values than samples from the lower portion of the bottle suggesting within bottle stratification. The mean salinity difference between the bottom and top bottle sample for each bottle was 0.003. Note that this station was taken in open water and there was significant ship motion.

RV Sikuliaq Station 007, Cast 07

Eleven bottles were tripped over a period of 250 seconds near the boundary of the surface mixed layer and the local salinity halocline, at about 57 dbar with an ambient salinity of 31.736 and the salinity gradient was negligible at 0.002 /dbar (Fig. 11). The initial CTD and bottle salinities were 31.741 and 31.848 (p = 29.5%). The CTD salinities stabilized to ambient by t = 41s at 31.680, whereas the bottle salinity stabilized by t = 192s at 31.777 (p = 97.9%).

RV Sikuliaq Station 008, Cast 08

Four bottles were tripped over a period of 117 seconds in the surface mixed layer just above the boundary with the bottom boundary layer (~3 dbar) at about 42 dbar with an ambient salinity of 31.736 and a negligible salinity gradient (Fig. 12). The initial CTD and bottle salinities were 31.896 and 31.905 (p = 61.4%). There was still a significant difference between CTD and bottle salinities after t = 117s when CTD and bottle salinities were 31.736 and 31.790 (p = 87.7%). If one assumes a slight increase in salinities in the upper layer with time due to currents or ship drift, the CTD salinities may have been free of entrainment artifacts within 30s. This experiment aimed to investigate the possibility of stratification within Niskin bottles, and only four Niskin bottles were tripped over a period of 117s. The data clearly indicate within Niskin bottle stratification with the salinities from the upper portion of the Niskin bottles being lower than the salinities from the water in the lower portion of the bottle, even though ship maneuvering caused the carousel to vibrate. The mean salinity difference was 0.023. Bottle salinities did not stabilize during the time (t = 117s) of this experiment.

USCGC Healy Station 06101

Four bottles were planned to be sequentially tripped at each of three distinct depths, however only the bottom boundary layer was sampled (Fig. 13) due to sea ice conditions.

The bottom boundary layer was about 9 dbar thick. Four samples were taken near the bottom of the mixed layer at about 44 dbar, having an ambient salinity of 32.749. The initial CTD and bottle salinities were 32.729 and 32.702 (p = 98.9%), respectively. The CTD salinity stabilized before t = 50s. Even though the carousel traveled about 9 dbar through the mixed layer, it took between 90 and 180 seconds for the bottle salinity to stabilize at 32.745 (p = 99.9%).

USCGC Healy Station 06201

Samples were collected at 8, 14, and 47 dbar. Four bottles were sequentially tripped at each depth (Fig. 14).

At 8 dbar in the upper portion of the local halocline, ambient salinity was 26.723. The initial CTD and bottle salinities were 27.209 and 28.666 (p = 57.1%), respectively. Both the CTD and bottle salinities stabilized between t = 90s and t = 180s - possibly around 120 seconds - with a bottle salinity of 26.096 (p = 113.6%) at 180s. As stated previously, although we present these data from less than 12 dbar, they are only included in our analysis of intra-bottle stratification. Upper bottle salinity values were consistently less saline than bottom bottle salinity values with a mean difference of 1.216.

At 14 dbar, in the lower portion of the local halocline the ambient salinity was 31.249 and the salinity gradient was 0.558 Δs/dbar. Initial CTD and bottle salinities were 31.156 and 32.390 (p = 22.5%), respectively. The CTD salinity stabilized by t = 90s, whereas the bottle salinity seemed to stabilize by t = 180s - possibly soon after the CTD at about 120 seconds - with a value of 31.241 (p = 100.6%). Intra-bottle stratification was examined during this experiment. Upper bottle salinity values were consistently less saline than bottom bottle salinity values with a mean difference of 0.390.

The 47 dbar sample was located in a bottom boundary layer, approximately 14 dbar below its upper boundary with an ambient salinity was 32.722. Initial CTD and bottle salinities were 32.722 and 32.718 (p = 99.9%). After traveling through the mixed layer, CTD and bottle salinity differences were near or at detection limits. The CTD salinity seemed to stabilize instantaneously, and the same can be said for bottle salinities. Nevertheless, if significance is imputed to the small differences, inspection of the data suggests that it took about 90 seconds for the bottle salinity, 32.721 (p = 100.0%), to equilibrate and that there was within bottle salinity stratification. Upper bottle salinity values were consistently less saline than bottom bottle salinity values with a mean difference of 0.006, which is slightly larger than the instrument accuracy.

USCGC Healy Station 006901

Samples were collected at 11, 16, and 40 dbar. Four bottles were sequentially tripped at each depth (Fig. 15).

The 11 dbar samples were located in the upper portion of the local halocline where the ambient salinity was 28.233. The initial CTD and bottle salinities were 30.148 and 30.474 (p = 36.5%), respectively. The CTD salinity values appeared to oscillate during the time series with an overall decrease in salinity. The bottle salinity steadily decreased over time. Neither the bottle or CTD data displayed noticeable stabilization during the time series. The bottle salinity at t = 180s was 29.121 (p = 74.9%). The oscillation period of the salinity recorded by the CTD is roughly in line with the calculated Brunt-Väisälä period.

At 16 dbar in the lower portion of the local halocline, ambient salinity was 31.764 and the salinity gradient was 0.562/dbar. The initial CTD salinity was 32.344. The bottle at t = 0s misfired and therefore no salinity value was recorded, however the bottle salinity at t = 45s was 32.252 (p = 49.9%). The CTD salinity values displayed a similar, less dramatic oscillation to that of the 11 dbar plot during the time series with an overall decrease in salinity. The bottle salinity steadily decreased over time. Neither instrument displayed stabilization by the end of the time series (180s), possibly due to the relatively large salinity gradient. The final bottle salinity was 31.798 (p = 96.5%).

The 40 dbar experiment was located in a bottom boundary layer, with an ambient salinity of 32.738 and located 11 dbar below the upper limit of the mixed layer, the initial CTD and bottle salinities were 32.734 and 32.737 (p = 100.0%), respectively. The bottle salinity displayed stabilization near instantly with negligible change during the time series - save the t = 90s salinity of 32.734 (p = 99.9%) - whereas the CTD salinity stabilized by t = 45s. The range of values were near detection limits, which could explain why the bottle values seemed to stabilize before the CTD values.

USCGC Healy Station 07001

Samples were collected at 15, 20, and 38 dbar. Four bottles were sequentially tripped at each depth (Fig. 16).

At 15 dbar, in the middle of the local halocline ambient salinity was 30.699 and the salinity gradient was 0.499/dbar. The initial CTD and bottle salinities were 32.023 and 32.071 (p = 26.0%), respectively. Both the CTD and bottle salinity values decreased over the time series at similar rates. Neither instrument displayed stabilization over the time period, possibly due to the relatively high salinity gradient. The bottle salinity at t = 180s was 30.603 (p = 105.1%).

At 20 dbar, in the lower halocline the ambient salinity was 32.553 and the salinity gradient was 0.268/dbar. The bottle at t = 0s mis-tripped, therefore no water was available to sample. The initial CTD salinity was 32.621 and the second bottle salinity value at t = 45s was 32.583 (p = 81.1%). The CTD salinity appeared to oscillate during the entire time period, and therefore it is not apparent that complete stabilization was achieved by t = 180s. The bottle salinity slowly decreased over the entire time series (i.e. the salinity values did not oscillate similar to the CTD salinity), which is most likely due to the "low-pass" filter characteristics of the bottle relative to the CTD. The bottle salinity at t = 180s ended up being significantly less saline than the CTD salinity at 32.408 (p = 192.5%), displaying a lack of stabilization relative to the CTD. The CTD salinity oscillation throughout the time series makes the experiment challenging to interpret.

At 38 dbar, in a bottom boundary layer, with an ambient salinity of 32.710 and located 13 dbar below the upper limit of the mixed layer, the initial CTD and bottle salinity values were 32.710 and 32.709 (p = 100.0%), respectively. Both the CTD and bottle salinity values displayed stabilization near instantly with negligible change during the time series.

USCGC Healy Station 07901

Samples were collected at 9, 17, and 49 dbar. Four bottles were sequentially tripped at each depth (Fig. 17).

At 9 dbar, in the upper portion of the local halocline, ambient salinity was 27.167. Initial CTD and bottle salinities were 29.168 and 30.275 (p = 13.6%), respectively. The bottle salinity displayed a steady decrease until apparent stabilization between t = 90s and t =180s at 27.131 (p = 101.0%). The CTD salinity oscillated, but was close to the bottle salinity by t = 180s.

At 17 dbar, in the lower portion of the halocline, ambient salinity was 30.765 and the salinity gradient was 0.165/dbar. Initial CTD and bottle salinities were 31.230 and 31.240 (p = 76.1%), respectively. CTD and bottle salinity values steadily decreased. CTD salinity suggested stabilization by t = 90s, whereas the bottle salinity displayed stabilization between t = 90s and t =181s at 30.852 (p = 95.6%).

At 49 dbar, in the bottom boundary layer with an ambient salinity of 32.749 and located 3 dbar below the upper limit of the mixed layer, the initial CTD and bottle salinities were 32.661 and 32.676 (p = 98.1%), respectively. The CTD displayed stabilization by t = 45s, whereas the bottle salinity appeared to stabilize between t = 90s and t = 180s at 32.726 (p = 99.4%). The long equilibration time for the bottle salinity is most likely due to traveling through the thin mixed layer for a relatively short period of time before stopping.

Summary for type I experiments

The Type I experiments suggest that the time it takes for bottle samples to replicate ambient salinity values in the presence of the gradients that we encountered usually exceeds 1 minute and can often exceed two minutes (Fig. 18). Equilibration times appeared to increase with increasing salinity gradients as would be expected since the number of *e*-foldings - the time interval in which a relict water mass is removed from the bottle by a factor of *e* - required for bottle and CTD values to approach ambient values within the accuracy of the instruments would increase with increasing salinity differences. Anecdotal evidence suggests a relationship between CTD salinity oscillations that were, at times, significant and their local Brunt-Väisälä periods.

Thirty-three observations (Fig. 19) were obtained during this study for intra-bottle stratification. Twenty of these observations displayed significant stratification. Twelve of the resultant salinity differences were within the instrument's accuracy, but still tended to display stratification where the upper bottle salinities were less saline than the lower bottle salinities. Data also suggest that larger intra-bottle salinity differences are present in relatively larger ambient salinity gradients, as would be expected.

TYPE II EXPERIMENTS

These experiments were similar to Type I experiments, except for the addition of a yo-yo motion between each bottle triggering to simulate sample collection during rough seas. The yo-yo motion was obtained by raising the carousel roughly one decibar followed by lowering it one decibar using the carousel winch immediately after each bottle trip. The manual yo-yo motion may not have been precise enough to move the carousel exactly one dbar up and down each time, therefore, the salinity values reported are from a depth range (Table 4). A difference between the interpretation of Type I and Type II experiments is that yo-yoing through a salinity gradient means that a number equal to the salinity gradient times 1 decibar has to be added to the instrumental accuracy when assessing whether or not CTD and bottle salinities are significantly different.

USCGC Healy Station 00701

For the first cast in this series, the carousel was stopped mid halocline, at about 10 dbar (actual sample range was 9.18 to 10.50 dbar) with an ambient salinity value of 30.876 (Fig. 20). Twelve bottles were then tripped sequentially at predetermined temporal increments up to a period of 283 seconds, similar to *USCGC Healy Station 00501*. The initial CTD and bottle salinities were 31.955 and 32.704 (p = 9.1%), respectively. The CTD salinity seemed to equilibrate with the ambient water by t = 50s, whereas the bottle salinity equilibrated by t = 123s at 30.462 (p = 120.6%). However, due to the constant fluctuation of the measured salinity values, it is difficult to estimate the time of stabilization for either instrument. Two issues that may have contributed to the constant fluctuation include yo-yo motion protocol relative to bottle trip timing and the shallow depth at which the experiment was conducted. These data were removed from final analysis, because they were collected from shallower than 12 dbar.

USCGC Healy Station 03802

The carousel was deployed and bottles were tripped similar to *USCGC Healy Station 00701,* however, the bottle tripping depth was at about 20 dbar (actual range was 19.71 to 19.97 dbar), which reduced any possible ship influence (Fig. 21). The ambient salinity was 30.810 with a salinity gradient of 0.188/dbar. The initial CTD and bottle salinities were 31.289 and 32.440 (p = 29.5%), respectively. The CTD salinity displayed stabilization by t = 34s, whereas the bottle displayed stabilization by t = 56s at 30.813 (p = 99.9%). Deviation of the CTD and bottle salinities from ambient water after stabilization was evident, but it was significantly less than that of *USCGC Healy Station 00701*. This deviation is presumed to be caused mainly by the oscillation of the water column due to the yo-yo motion of the carousel.

USCGC Healy Station 06701

Samples were collected at 10, 21, and 43 dbar. Four bottles were sequentially tripped at each depth (Fig. 22).

At 10 dbar (actual sample range was 9.99 to 10.11 dbar), classified as upper halocline water with an ambient salinity of 28.681. Initial CTD and bottle salinities were 29.900 and 29.607 (p = 69.8%), respectively. The CTD displayed stabilization with a salinity of 28.729 by t = 46s, whereas the bottle displayed stabilization with a salinity of 28.571 (p = 103.6%) by t = 90s. These data were not used in the final analysis, because they were collected shallower than 12 dbar.

At 21 dbar (actual sample range was 20.46 to 20.58 dbar), classified as lower halocline water, with an ambient salinity of 31.751 and a salinity gradient of 0.293/dbar. Initial CTD and bottle salinities were 31.956 and 32.303 (p = 47.3%), respectively. Both the CTD and bottle salinities displayed stabilization by t = 46s with a bottle salinity of 31.485 (p = 125.4%).

At 43 dbar (actual sample range was 43.26 to 43.53 dbar), classified as bottom boundary layer with an ambient salinity of 32.799 and located 10 dbar below the upper limit of the mixed layer. The initial CTD and bottle salinities were 32.799 and 32.769 (p = 99.0%). The CTD salinity displayed stabilization near instantaneously, whereas the bottle salinity stabilized by t = 90s at 32.799 (p = 100%).

Summary for type II experiments

The Type II experiments suggest that the time it takes for bottle samples to replicate ambient salinity values in the presence of the gradients that we encountered usually took no more than 90 seconds (Fig. 23). The CTD salinities generally equilibrated to ambient water within 45 to 50 seconds. As with the Type I experiments, equilibration times appeared to increase with increasing salinity gradients. Overall, equilibration times for the type II experiments are shorter than the type I experiments, because of the induced yo-yo motion.

TYPE III EXPERIMENTS

Because some research programs (e.g. Cutter and Bruland, 2012; Measures et al, 2008) collect water samples from continuously ascending carousels in order to minimize contamination, etc., we ran a series of five experiments, during which the carousel was raised at a steady pace while the bottles were tripped "on the fly". This means that the "soak" time of each bottle at the tripping depth was approximately 0 seconds. During the *USCGC Healy* experiments, ascent rates for each subsequent cast were systematically reduced in speed (Table 2): full (25 dbar/min), half (12 dbar/min), quarter (6 dbar/min), and eighth (3 dbar/min) during the upcast. The bottles were tripped in sequence once the carousel reached the bottom of a halocline to amplify the salinity difference. The ascent rate for the *RV Sikuliaq* experiment about 10 dbar/min. The bottles were tripped in sequence - about once per minute - starting in the bottom boundary layer, through the boundary layer, and into the surface mixed layer.

To minimize the influence of ship induced turbulence and ship induced discharges, data from the upper 12 dbar were discarded in the analysis of the "on the fly" data. Simple type I linear regressions were calculated for each cast (assuming that the downcast CTD salinities could be treated as an independent variable) that correlated salinity differences (*cu-cd* and *bo-cd*) to the downcast CTD salinity gradient.

USCGC Healy Station 00801

The carousel ascended at full speed while tripping 12 bottles over a period of 52 seconds (Fig. 24). The first bottle was tripped at 24.8 dbar in a salinity gradient of 0.007/dbar and a speed of 27 dbar/min. The salinity gradient gradually increased, and the carousel ascent speed gradually decreased. The final bottle was tripped at a depth of 3.6 dbar and a speed of 24 dbar/min in a salinity gradient of 0.561/dbar. The ascent speed was reduced, because the carousel was getting close to the surface. The data displayed an increasing salinity difference between both the CTD upcast minus downcast salinities and the bottle minus CTD downcast salinities as the salinity gradient increases, with the latter displaying the greater difference at each bottle tripping depth.

The results from bottle trips 10 - 12 were removed from the analysis, because they were collected at a depth shallower than 12 dbar. The result of the linear regressions for this experiment are as follows: for *cu-cd* versus the salinity gradient, the slope = 1.331 and R^2 = 0.93, and for *bo-cd* versus the salinity gradient, the slope = 3.922 and R^2 = 0.28. The slope for cu-cd plus the low *bo-cd* R^2 value are significantly different from the bulk of the results. The relatively small gradients and the first three anomalous bottle salinities may have contributed to this situation.

USCGC Healy Station 00901

The carousel ascended at half speed while tripping 12 bottles over a period of 51 seconds (Fig. 25). The local halocline occurred between 9 dbar to 12 dbar. Starting the bottle sampling procedure at 12 dbar was too shallow for the time needed to trip 12 bottles and avoid ship influence. Therefore, the first bottle in the series was tripped at 20.2 dbar in a salinity gradient of 0.022/dbar and a speed of 14.3 dbar/min. The salinity gradient increased as the carousel ascended while the speed remained relatively constant. The final bottle was tripped at 8.2 dbar in a salinity gradient of 0.069/dbar, which was not representative of the trend. The previous bottle (number 11) tripped in a salinity gradient of 0.500/dbar. The data display an increasing salinity difference between both the CTD upcast minus downcast salinities and the bottle minus CTD downcast salinities as the salinity gradient increases, with the latter displaying a greater difference at each bottle tripping depth, but not as significant as the full speed cast. The results from bottle trips 9 - 12 were removed from the analysis, because they were collected in the upper 12 dbar. The CTD salinity measured at bottle trip 8 was also rejected from analysis, because the value fell far outside the range of the other data. The result of the linear regressions for this experiment are as follows: for *cu-cd* versus the salinity gradient the slope = 4.714 and R^2 = 1.00, and for *bo-cd* versus the salinity gradient the slope = 5.086 and R^2 = 1.00.

RV Sikuliaq Station 021, Cast 22

The carousel ascended ~10 dbar/min while tripping 8 bottles about every minute over a period seven and a half minutes (Fig. 26). The water column at this station consisted of a mixed surface layer and mixed bottom layer separated by a sharp boundary. The overall salinity difference between the two layers was modest (~0.5). The first bottle was tripped at 80.2 dbar and a speed of 10 dbar/min in a negligible salinity gradient. The salinity gradient increased to 0.036/dbar as it passed through the sharp boundary, and decreased to a negligible salinity gradient as the final bottle was tripped at 10.6 dbar and a speed of 5.5 dbar/min. These data display - similar to the other “on the fly” stations - an increasing salinity difference between both the CTD upcast minus downcast salinities and the bottle minus CTD downcast salinities as the salinity gradient increases. The salinity difference between the bottle and CTD downcast were greater than between the CTD upcast and downcast. The result of the linear regressions for this experiment are as follows: for *cu-cd* versus the salinity gradient the slope = 2.965 and R^2 = 0.99, and for *bo-cd* versus the salinity gradient the slope = 5.012 and R^2 = 0.91.

USCGC Healy Station 02101

The carousel ascended at one-quarter speed while tripping 12 bottles in 8 to 10 second intervals over a period of 99 seconds (Fig. 27). The local halocline occurred between 13 and 26 dbar. The first bottle was tripped at 23.8 dbar in a salinity gradient of 0.070/dbar and at a speed of 6.5 dbar/min. The salinity gradient fluctuated between 0.070 and 0.166/dbar for the duration of the experiment. The final bottle was tripped at 12.8 dbar and at a speed of 6.4 dbar/min with a salinity gradient of 0.153/dbar. These data display an increasing salinity difference between both the CTD upcast minus downcast salinities and the bottle minus CTD downcast salinities as the salinity gradient increases. However, the former displayed the greater salinity difference relative to the latter. All of the data from this cast were removed from the analysis because there were inexplicable differences between the upcast and downcast CTD profiles. Specifically, the upcast CTD values were lower than the downcast values which is a logical impossibility absent a significant water mass change during the experiment or instrument malfunction. No linear regressions were calculated for these data.

USCGC Healy Station 02201

The carousel ascended at one-eighth speed (~3 dbar/min) while tripping 12 bottles at 20 second intervals over a period of 199 seconds (Fig. 28). The local halocline occurred between 15 and 25 dbar. The first bottle was tripped at 21.9 dbar and a speed of 3.2 dbar/min in a salinity gradient of 0.130/dbar. The salinity gradient fluctuated between 0.111 and 0.708/dbar during the sampling period. The final bottle was tripped at 10.9 dbar at a speed of 3.7 dbar/min with a salinity gradient of 0.188/dbar. These data display, similar to the other "on the fly" stations, an increasing salinity difference between both the CTD upcast minus downcast salinities and the bottle minus CTD downcast salinities as the salinity gradient increases. While the salinity difference between the bottle and CTD downcast were greater than between the CTD upcast and downcast, the difference was minimal. The results from the last two bottles, 11 and 12, were removed from the analysis, because they were collected in the upper 12 dbar. The result of the linear regressions for this experiment are as follows: for *cu-cd* versus the salinity gradient the slope = 4.041 and R^2 = 0.91, and for *bo-cd* versus the salinity gradient the slope = 4.639 and R^2 = 0.97.

Summary for type III experiments

As stated in the individual descriptions, some data - mainly samples collected above 12 dbar and all of *USCGC Healy Station 02101* - were removed from analysis. The remaining data were split into three parts: 1. the CTD salinity collected during the downcast, 2. The CTD salinity collected during the upcast, and 3. the bottle salinity collected during the upcast. The data from each deployment were analyzed by calculating 1. the bottle salinity and the downcast CTD salinity differences (*bo-cd*), 2. the salinity differences between the upcast CTD salinity and the downcast CTD salinity at bottle tripping pressures (*cu-cd*), and 3. the salinity gradient at each bottle tripping pressure (Table 5). The gradient is calculated from the following equation,

$$\Delta s / \Delta p = s_{p+5} - s_p / 5, \tag{4}$$

where s_p is the CTD downcast salinity value at a bottle tripping depth and s_{p+5} is the downcast salinity 5 dbar below the tripping depth. Unlike the gradient calculations from Type I and II experiments, the gradient in this series is calculated from the water column below the bottle tripping point. Since the carousel is always ascending, even during bottle trips, the water above the carousel never has a chance to rebound downward, as it would when the carousel is stopped.

The combined results (Fig. 29) for *cu-cd* linear regression gave a slope of 4.101 and an R^2 of 0.95. The combined results for *bo-cd* linear regression gave a slope of 4.736 and an R^2 of 0.99. Overall, these results indicate a significant positive relationship between the magnitude of a salinity gradient and the bias of the related data. The *bo-cd* salinity differences are consistently greater than the *cu-cd* salinity differences. The difference between *bo-cd* and *cu-cd* was small relative to the overall signal suggesting that entrainment could be a larger factor than bottle flushing.

DISCUSSION

Weiss (1971) showed that bottle flushing can be an issue for individually deployed bottles (not part of a carousel). This study shows that the employment of large carousel systems can exacerbate the flushing problem initially explored by Weiss in four ways: 1. The modern design of bottles employed often are of large volumes and have relatively small openings resulting in relatively large flushing lengths (*V/A*); 2. The bottles are often cocked in inconsistent ways (e.g. Fig. 30 and 31) that result in even longer flushing lengths; and very importantly, 3. The bottles are often tripped with minimal soak times, sometimes as soon as the carousel reaches the desired depth, not allowing the entrained water to subside, which is a major source of sample bias.

At first glance, the CTD and bottle results of the “on-the-fly” experiments (Type III experiments) sometime display a relatively minimal difference that could, in some cases, be attributed to their relative locations on the carousel and the degree of the ambient salinity gradient. However, if the reasonable assumption is made that the downcast CTD salinities are as accurate as technology permits, comparison of the upcast and downcast CTD salinity readings almost always suggest that the upcasts entrain deeper water, biasing both the CTD and bottle salinity values in relation to the water at the sampling depth. Since both the upcast bottle and CTD values are sometimes closer to each other than to the downcast CTD salinities, it is reasonable to infer that the upcast bias in both bottle and CTD salinities is dominated by entrainment. The ensemble of the results indicate that bottle flushing characteristics cause observable bias in addition to the bias introduced by entrainment. The results also suggest that the local gradient may be more important than carousel ascent speed when tripping on the fly. Therefore, tripping bottles on the fly during the carousel ascent is not a preferred method for collecting representative water samples in any gradient unless avoiding contamination - for example by trace metals - is of paramount concern.

The overall results of Type I and II experiments display similar biases in the CTD and bottle data at t = 0s, which should be expected, because conditions at t = 0s approach mimicking an "on the fly" experiment. In other words, although the carousel has experienced deceleration and a short stoppage before tripping the t = 0s bottle, there has not been much time for the entrainment plume to dissipate. Type I and II experiments sample the same depth for a period of time, therefore, these data provide an indication of the time scale over which the impact of the entrainment plumes and internal gravity waves are important. It is reasonable to assume that an entrainment plume's effect ends when the upcast CTD salinities are indistinguishable from the downcast CTD salinities. Generally, it took less than 100s for CTD values to reach this state, but bottle salinities frequently took much longer and sometimes did not become indistinguishable from the "true" salinities over the entire experimental lifetime of Type I experiments. Although the data are limited, the Type II yo-yo experiments, meant to reflect a rougher sea state, display a relatively faster approach to the "true" salinity (Table 4), which is to be expected since yo-yoing should promote bottle flushing (e.g. Smethie and Buchholtz, 1980) and might help to dissipate the entrainment plume. Whereas the initial amplitude of any CTD salinity oscillations during the time series experiments relates to the entrainment plume characteristics, the period of subsequent and presumably smaller CTD salinity oscillations relates to the stability of the water column as identified by Brunt-Väisälä. It is possible, therefore, that once the CTD reaches apparent ambient salinity, there are subsequent smaller oscillations in the CTD signal. Our data suggest that adequate bottle flushing is generally achieved within 3 minutes, but the possibility of small oscillations that could have small effects on our signals over 10s of minutes cannot be excluded.

Clearly these results indicate that carousel entrainment characteristics and sampling bottle flushing characteristics on a carousel can both contribute to sampling bias. The "on the fly" experiments suggest that if the package does not escape the entrainment plume, entrainment can often be the largest contributor to bias with insufficient bottle flushing often adding additional bias. The results of the first Type I experiment (*USCGC Healy* station 00501) also suggests an entrainment plume oscillation that could obscure entrainment plume effects, which can take longer to dissipate than expected. The time for the sampling bottles to reflect ambient conditions tended to be longer than the time for the entrainment plume to dissipate since CTD values normally obtained equilibrium before bottle values. This is presumably because the sampling bottles act like low-pass filters that are scaled to their mixing lengths. On occasion, equilibrium times for the bottle samples exceeded the entire length of the experiment. The Type II experiments suggest that under quiescent conditions, yo-yoing should shorten the time for bottle samples to approach ambient water values.

Smethie and Buchholtz (1980) showed that intra-bottle stratification is negligible - when sampling strong oxygen gradients - when the bottles were yo-yoed (to simulate ship motion), however, this does not address the issue as it relates to quiescent seas. Intra-bottle experiments conducted during the Type I experiments aboard the *USCGC Healy* and *RV Sikuliaq* tested this possibility. The results indicate internal stratification in calm seas, and in some cases, even after the bottle was left open to equilibrate over periods of up to 180 seconds. The results also display an increase in salinity differences with increased ambient gradients. It is, therefore, reasonable to conclude that the turbulence generated by the carousel itself contributes to internal bottle mixing.

Salinity was chosen for this bottle flushing study, because a secondary instrument with faster flushing characteristics – the CTD – was available for comparison. While salinity is a good proxy for describing the effects of carousel entrainment and bottle flushing, other variables, such as nutrient gradients, do not always parallel salinity gradients (Codispoti et al, 2005; Fig. 32). Thus, what appears to be acceptable flushing with respect to salinity may not always be sufficient for other variables. Consider, for example, the data in Fig. 30 that suggest silicate and nitrate values can vary considerably in the presence of weak salinity gradients.

Several recommendations follow from these results. Bottle sample collection using a carousel depends on the environmental conditions. When practical, the ship should always be allowed to drift downstream, moderately, as this allows the carousel to drift out of the entrainment plume and subsequent buoyancy oscillation, which leaves bottle flushing as the dominant cause of sample bias (Fig. 5).

According to Weiss's equations (1971), each mixing length movement removes 67% of relict water. After moving 5 mixing lengths, the amount of water from other depths in the bottle would be 00.33^5 or only about 0.4% relict water, which may be negligible in most open ocean gradients. Since 10-12 L Niskin type bottles have a mixing length of about two meters, and the carousel motion induced by ship roll is often on the order of two meters, this means that tripping bottles after three complete ship rolls may often be adequate. We note that Swift (2010) suggests waiting for two ship rolls before tripping, but the number of rolls to wait depends on how strong the rolls are, and the mixing lengths of the bottles that are being employed. Thus, there is no simple "rule of thumb", and a great dependence on actual conditions. Comparison of downcast and upcast CTD, and bottle salinities is a useful technique for estimating whether bottle flushing and entrainment effects have been appropriately minimized. Waiting for several ship rolls or longer to obtain a bottle sample would smear the signal a bit, but this bias would be more similar to that which occurs in historical data, which would hopefully average out to be close to the true value, as suggested by the work of Smethie and Bucholtz (1980).

If a ship maintains station location, either naturally or by dynamic positioning, and/or is a large ship in relatively quiescent waters, then this study shows that soak times required to obtain representative samples may exceed 180s.

Finally, with respect to intra-bottle stratification, understand that the value of any given variable may change vertically within the bottle under quiescent conditions. Thus, investigators, might be well advised to take samples from the bottom and top of a sampling bottle in strong gradients if they are interested in the exact values.

Future research considerations, given time and resources, would include closer investigation of mechanical and environmental factors that contribute to carousel entrainment and bottle flushing. This includes carousel designs, additional instrument placement/designs, and bottle designs. Weiss' (1971) study shows that bottles designed with large effective A/V ratios are preferred. There are other types of sampling devices that might be worthy of further development, such as the WOCE water sampler (Albro et al, 1990), the PRISTINE sampler (Rijkenberg et al, 2015), and pumping systems (Codispoti et al, 1991). Instruments such as a Lowered, or Shipboard, Acoustic Doppler Current Profiler, measuring current speed, could help to determine whether samples are collected in quiescent waters or in waters with rapid regime changes.

APPENDIX

TABLES

Table 1. Target bottle tripping times - in seconds - for Type I and Type II experiments conducted aboard the *USCGC Healy*.

Bottle	1	2	3	4	5	6	7	8	9	10	11	12
Time[1] (sec)	0	10	20	40	60	80	100	120	150	180	230	280
Time[2] (sec)	0	45	90	180	--	--	--	--	--	--	--	--

(1) Bottle tripping times for carousels when 12 bottles were tripped at a single depth.

(2) Bottle tripping times when 4 bottles were tripped at a single depth.

Table 2. Target ascent speeds (dbar/min) for Type Ⅲ experiments.

Station ID	HLY 00801	HLY 00901	SKQ 021, c022	HLY 02101	HLY 02201
Ascent Speed	25	12	10	6	3

Table 3. Salinity differences (bottle salinity minus CTD salinity) at t = 180s when the bottom boundary layer (BML) was at least 10 dbar thick from *USCGC Healy* stations. The mean differences for each sensor are also shown.

Station	**HLY 06101**	**HLY 06201**	**HLY 06701**	**HLY 06901**	**HLY 07001**	**mean**
BML thickness (dbar)	12	14	10	12	18	N/A
Sensor Package I	0.011	0.014	0.014	0.015	0.014	0.014
Sensor Package II	0.005	0.008	0.008	0.006	0.008	0.007

Table 4. Ensemble results for Type I and Type II experiments.

Station	Experiment	Pressure (dbar)	Salinity Gradient (Δs/dbar)	CTD stbl (sec)	Bottle stbl (sec)
hly00501	I	15	0.140	120	150
hly00701	II	10	N/A	50	120
hly03802	II	20	0.188	34	56
hly06101	I	44	~0	50	130
hly06201	I	8	N/A	120	120
hly06201	I	14	0.558	100	150
hly06201	I	47	~0	0	80
hly06701	II	10	N/A	45	90
hly06701	II	21	0.293	45	45
hly06701	II	43	~0	45	90
hly06901	I	11	N/A	180	180
hly06901	I	16	0.562	180	180
hly06901	I	40	~0	45	0
hly07001	I	15	0.499	180	180
hly07001	I	20	0.268	90 - 180	90 - 180
hly07001	I	38	~0	0	0
hly07901	I	9	N/A	90 - 180	90
hly07901	I	17	0.165	90	90 - 180
hly07901	I	49	~0	45	180
skq001	I	83	0.050	75	98
skq007	I	57	0.002	41	192
skq008	I	42	~0	>117	>117

Table 5. Ensemble results for Type III experiments. [1]

	HLY 00801			HLY 00901			HLY 02201			SKQ 021,c022		
Bot	**G**	**C**	**B**	**G**	**C**	**B**	**G**	**C**	**B**	**G**	**C**	**B**
12	0.561	1.065	0.715	0.069	0.545	0.236	0.188	1.670	1.823	N/A	N/A	N/A
11	0.371	0.982	0.330	0.500	0.375	0.566	0.577	2.843	3.125	N/A	N/A	N/A
10	0.105	0.835	0.348	0.268	2.076	0.405	0.601	2.871	2.937	N/A	N/A	N/A
9	0.106	0.141	0.325	0.590	1.964	2.559	0.601	2.633	2.658	N/A	N/A	N/A
8	0.065	0.099	0.219	0.492	0.409	2.452	0.708	2.987	3.054	0.000	0.000	0.003
7	0.028	0.037	0.065	0.463	2.228	2.313	0.406	1.321	1.431	0.000	0.001	0.004
6	0.020	0.059	0.058	0.096	0.363	0.505	0.271	0.668	0.816	0.000	0.001	0.003
5	0.010	0.013	0.023	0.051	0.197	0.239	0.233	0.464	0.635	0.000	0.002	0.008
4	0.008	0.007	0.009	0.046	0.196	0.208	0.181	0.352	0.535	0.036	0.107	0.143
3	0.007	0.014	0.014	0.042	0.191	0.180	0.150	0.326	0.561	0.004	0.021	0.025
2	0.007	0.012	0.014	0.030	0.113	0.118	0.111	0.283	0.374	0.002	0.008	0.012
1	0.007	0.011	0.016	0.022	0.063	0.069	0.130	0.240	0.289	0.000	0.003	0.006

1) Each cast contains three columns: *G* is the salinity gradient (Δs/m) for each bottle trip, *C* is the CTD upcast salinity minus CTD downcast salinity (Δs), and *B* is the bottle salinity minus the CTD downcast salinity (Δs). Data in grayed out cells were not included in the linear regression because of potential ship effects at depths <12 dbar.

FIGURES

Figure 1a.

Figure 1b.

Figure 2.

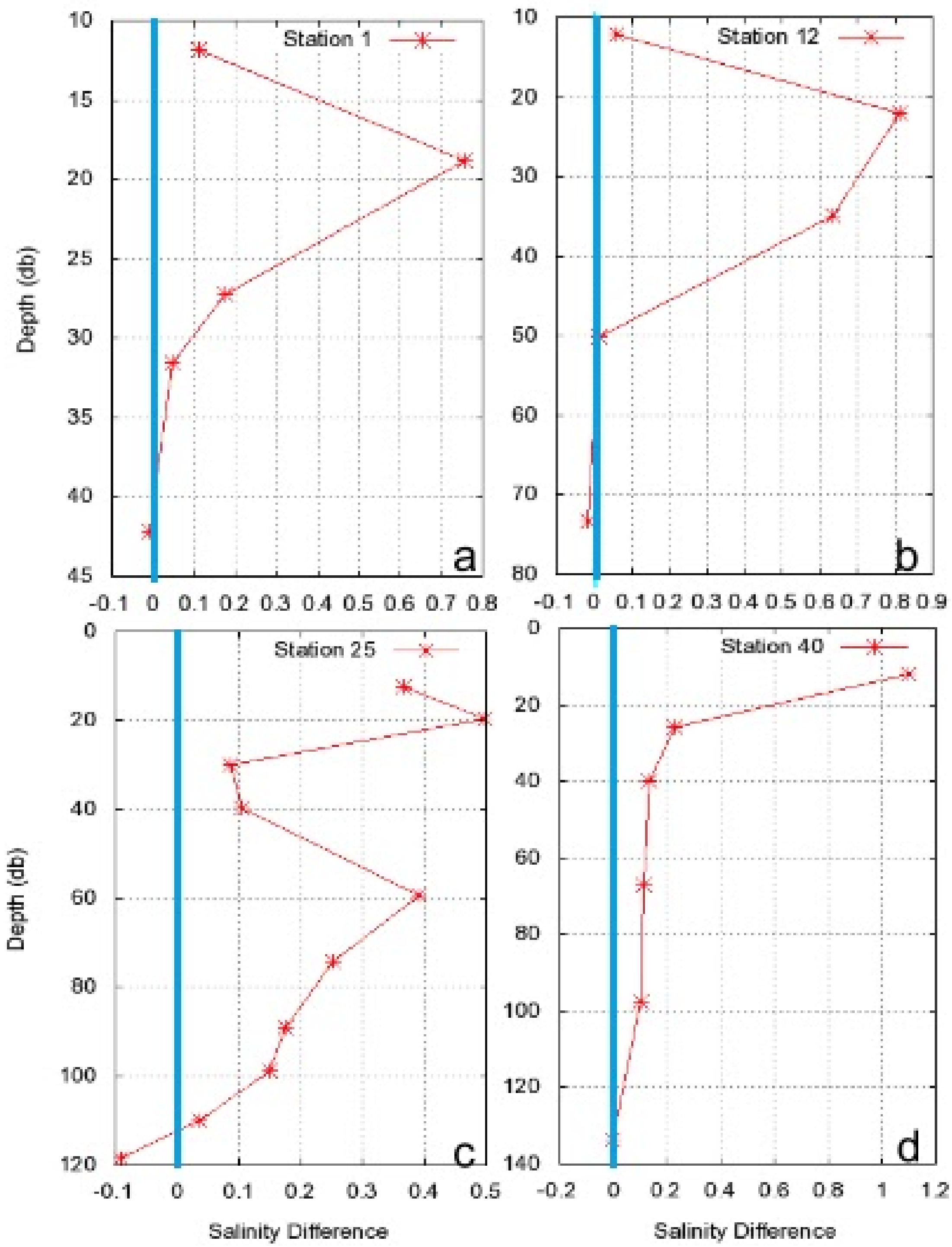

Station 1
Station 12
Station 25
Station 40
Depth (db)
Salinity Difference
a
b
c
d

Figure 3.

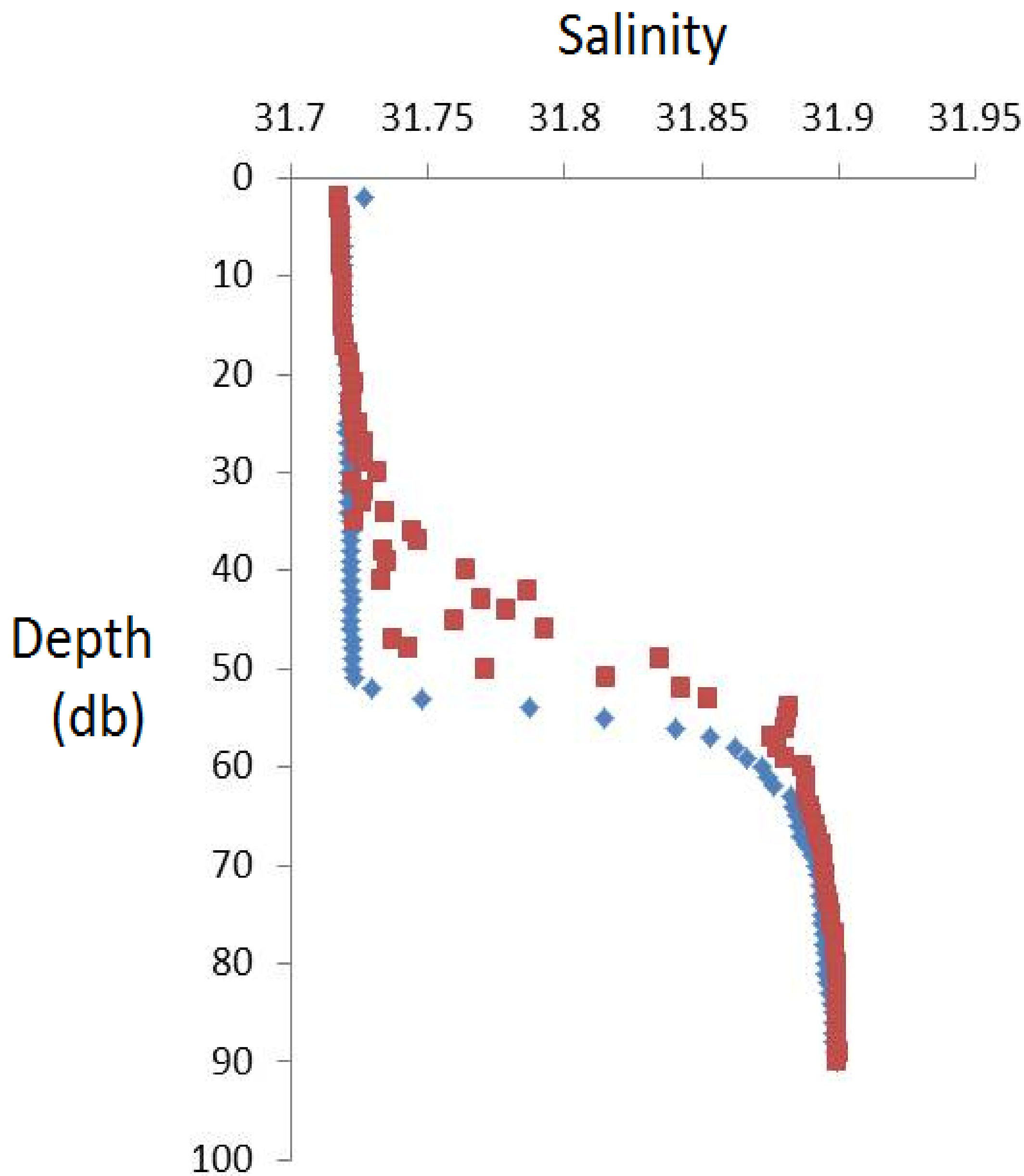

Salinity
31.7
31.75
31.8
31.85
31.9
31.95
0
10
20
30
40
50
60
70
80
90
100
Depth
(db)

Figure 4.

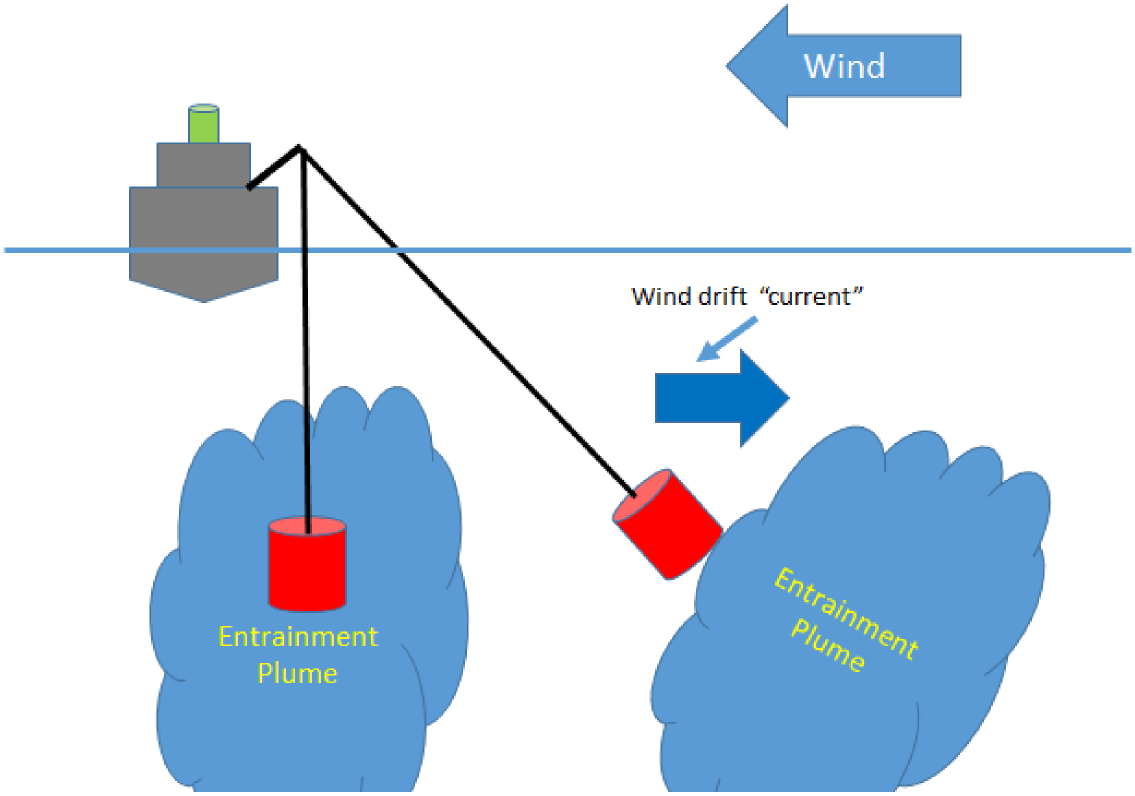

Wind
Wind drift "current"
Entrainment
Plume
Entrainment
Plume

Figure 5.

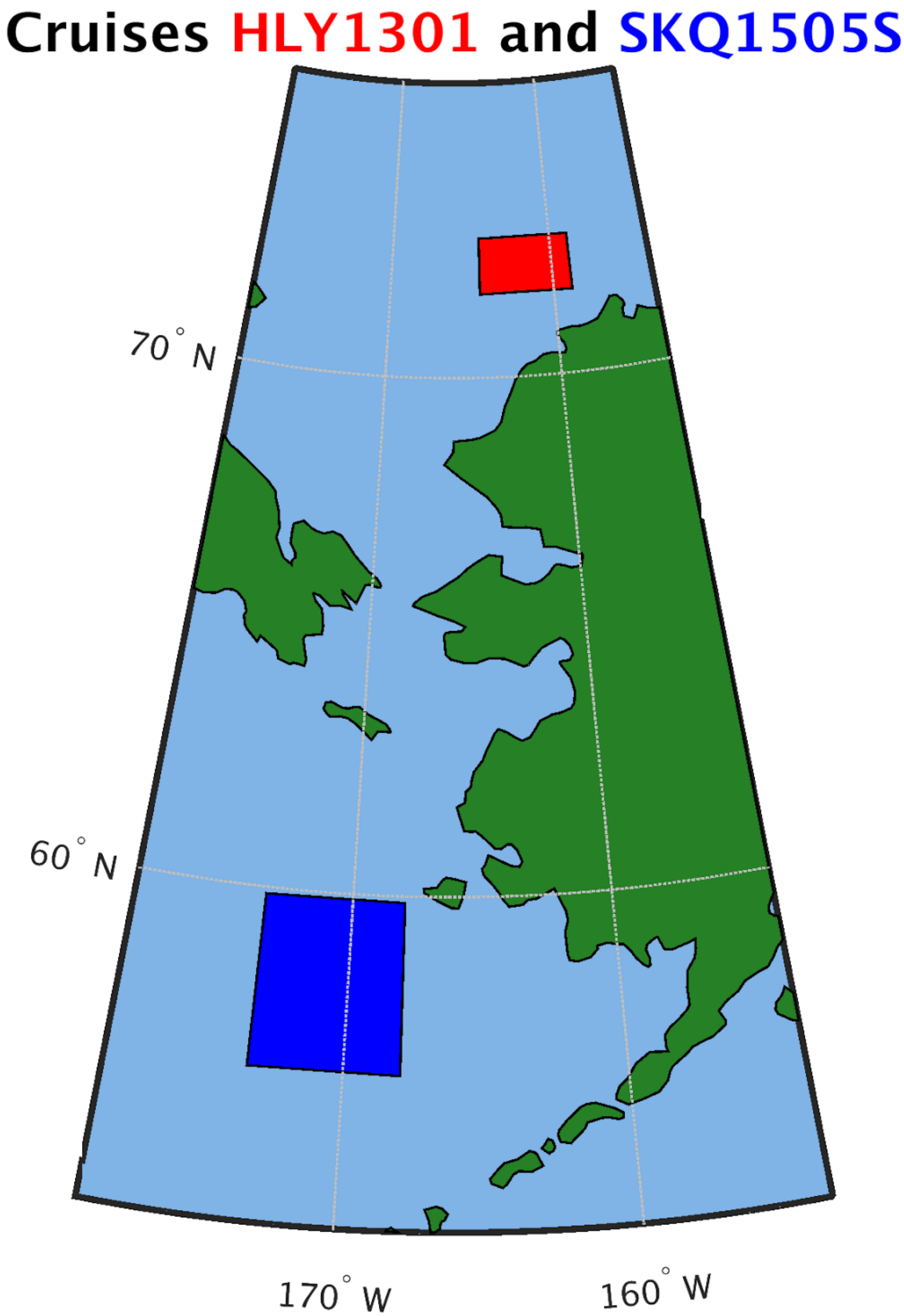


Figure 6.

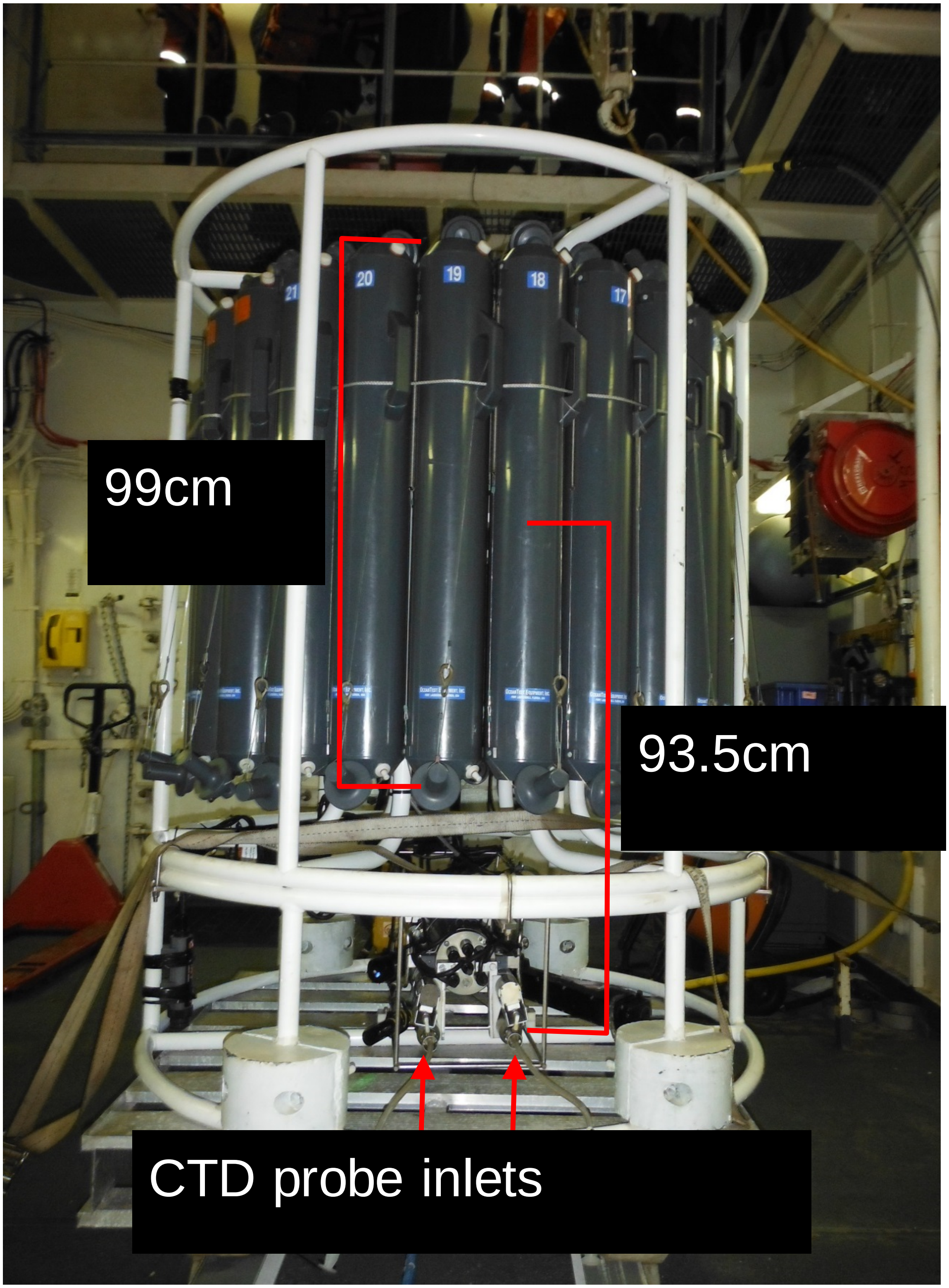


Figure 7.

Figure 8.

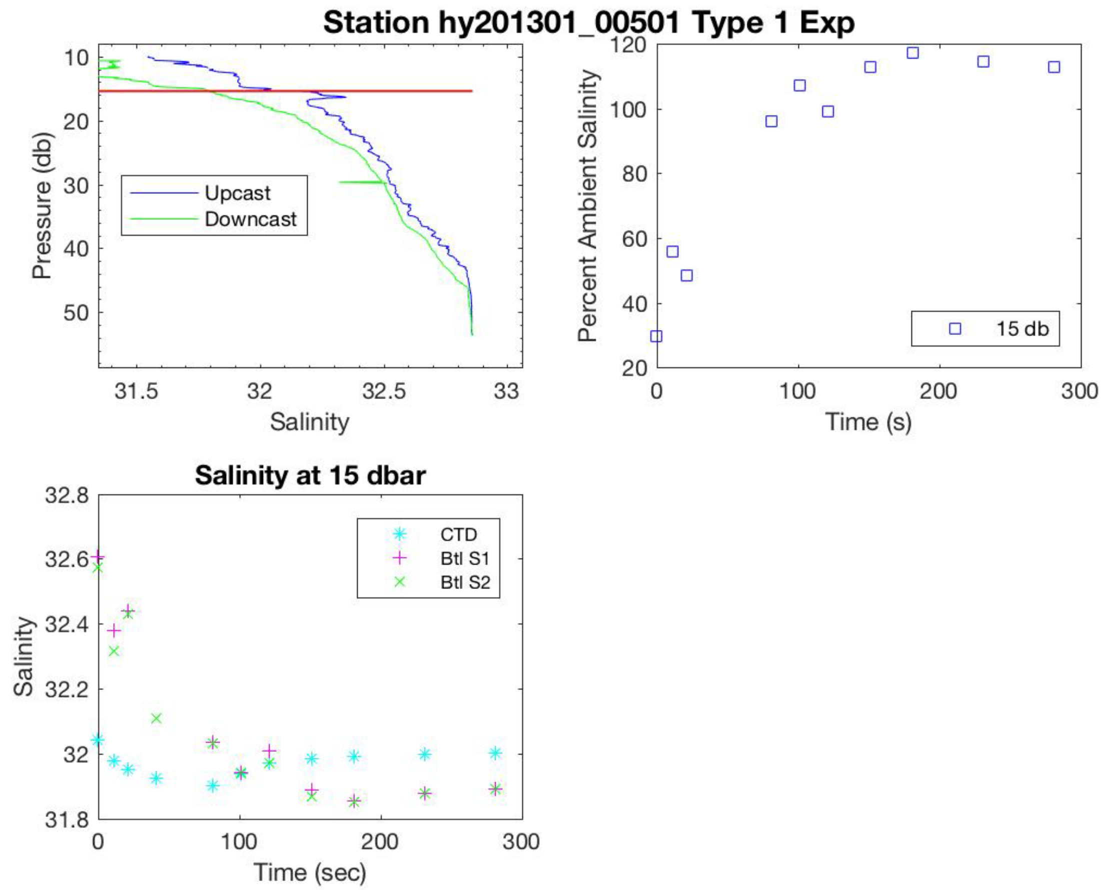

Station hy201301_00501 Type 1 Exp
Pressure (db)
Salinity
Upcast
Downcast
Percent Ambient Salinity
Time (s)
15 db
Salinity at 15 dbar
Salinity
Time (sec)
CTD
Btl S1
Btl S2

Figure 9.

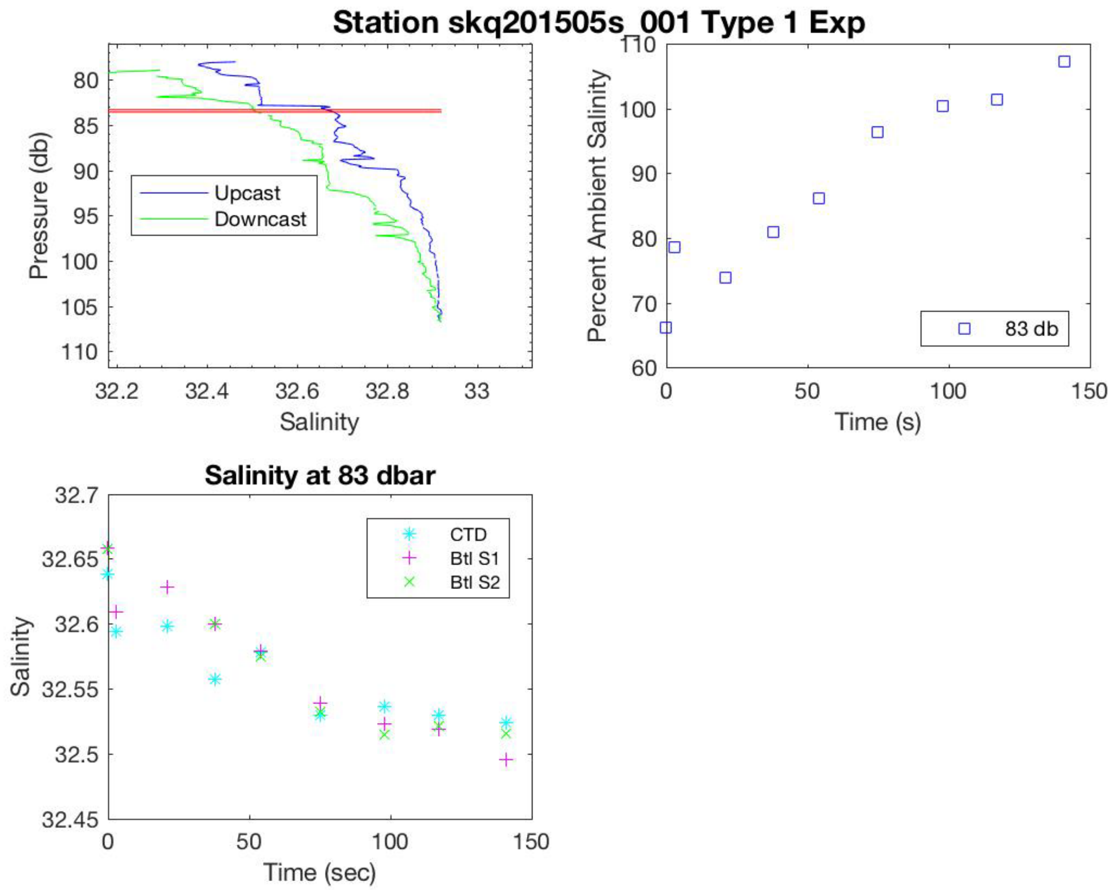

Station skq201505s_001 Type 1 Exp
Pressure (db)
Salinity
Upcast
Downcast
Percent Ambient Salinity
Time (s)
83 db
Salinity at 83 dbar
Salinity
Time (sec)
CTD
Btl S1
Btl S2

Figure 10.

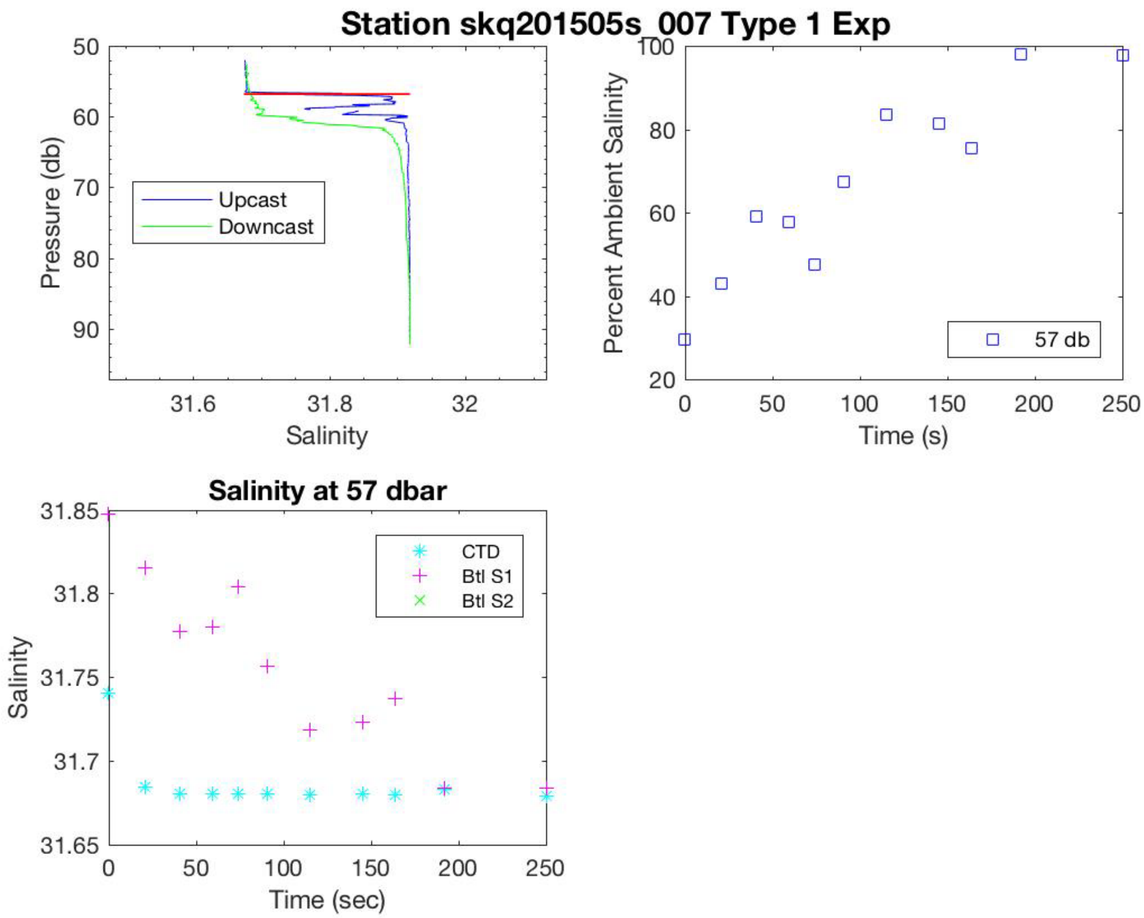
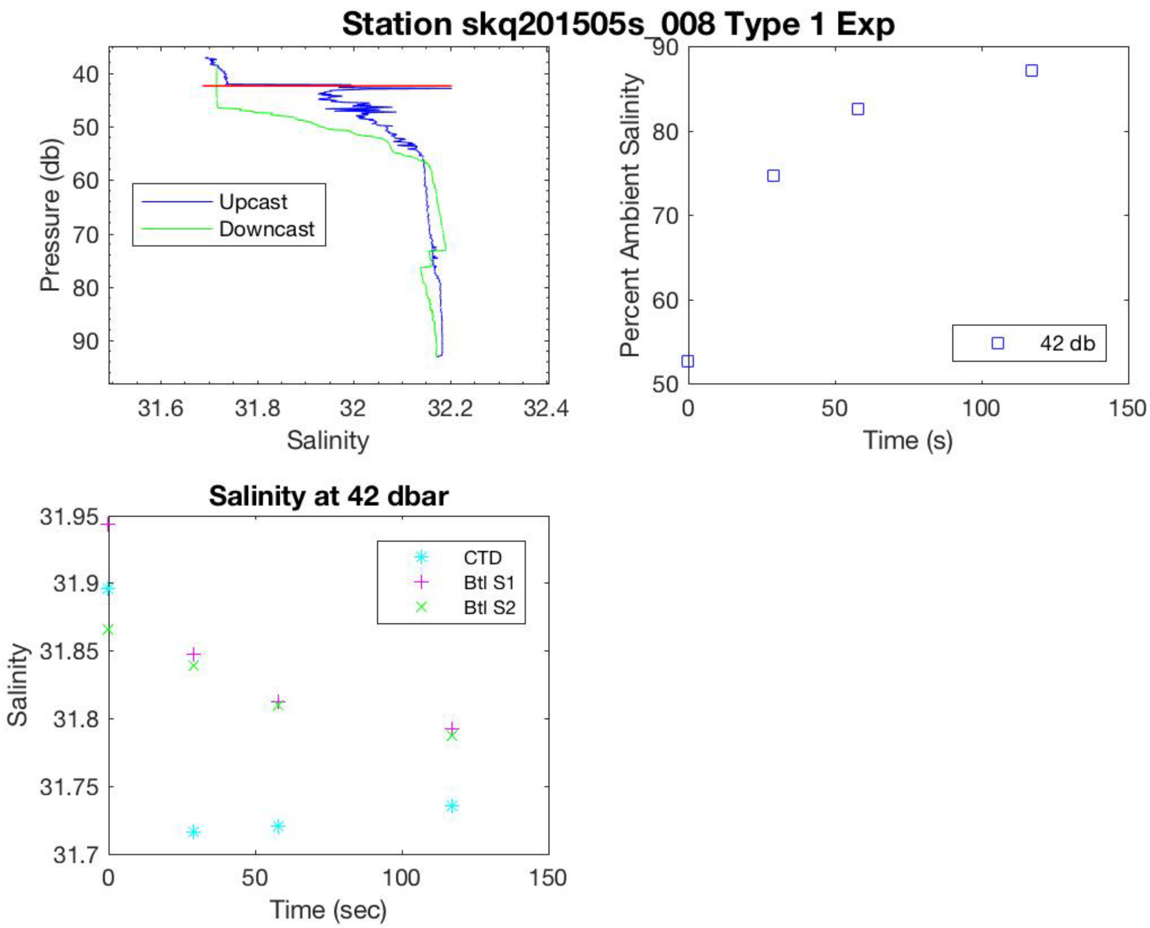

Station skq201505s_007 Type 1 Exp
Pressure (db)
Salinity
Upcast
Downcast
Percent Ambient Salinity
Time (s)
57 db
Salinity at 57 dbar
Time (sec)
CTD
Btl S1
Btl S2

Figure 11.



Station skq201505s_008 Type 1 Exp
Pressure (db)
Salinity
Upcast
Downcast
Percent Ambient Salinity
Time (s)
42 db
Salinity at 42 dbar
CTD
Btl S1
Btl S2
Time (sec)

Figure 12.

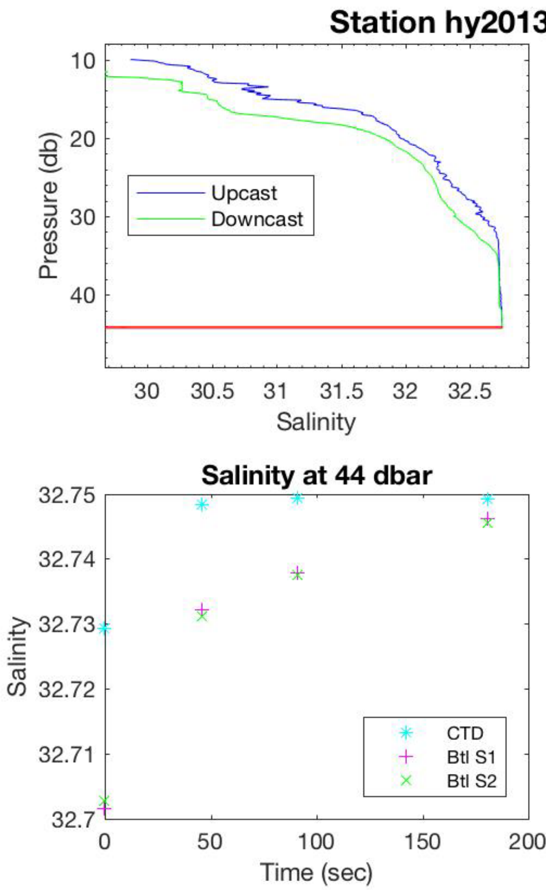

Station hy201301_06101 Type 1 Exp
Pressure (db)
Salinity
Upcast
Downcast
Percent Ambient Salinity
Time (s)
44 db
Salinity at 44 dbar
Salinity
Time (sec)
CTD
Btl S1
Btl S2

Figure 13.

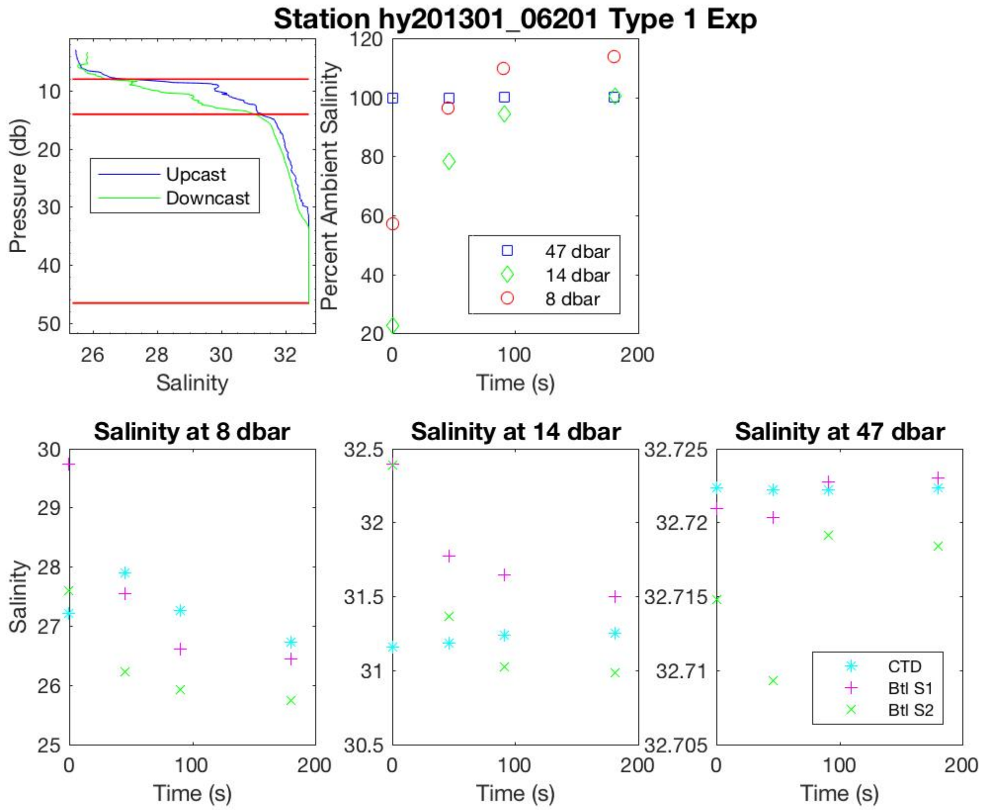

Station hy201301_06201 Type 1 Exp
Pressure (db)
Salinity
Upcast
Downcast
Percent Ambient Salinity
Time (s)
47 dbar
14 dbar
8 dbar
Salinity at 8 dbar
Salinity at 14 dbar
Salinity at 47 dbar
CTD
Btl S1
Btl S2

Figure 14.

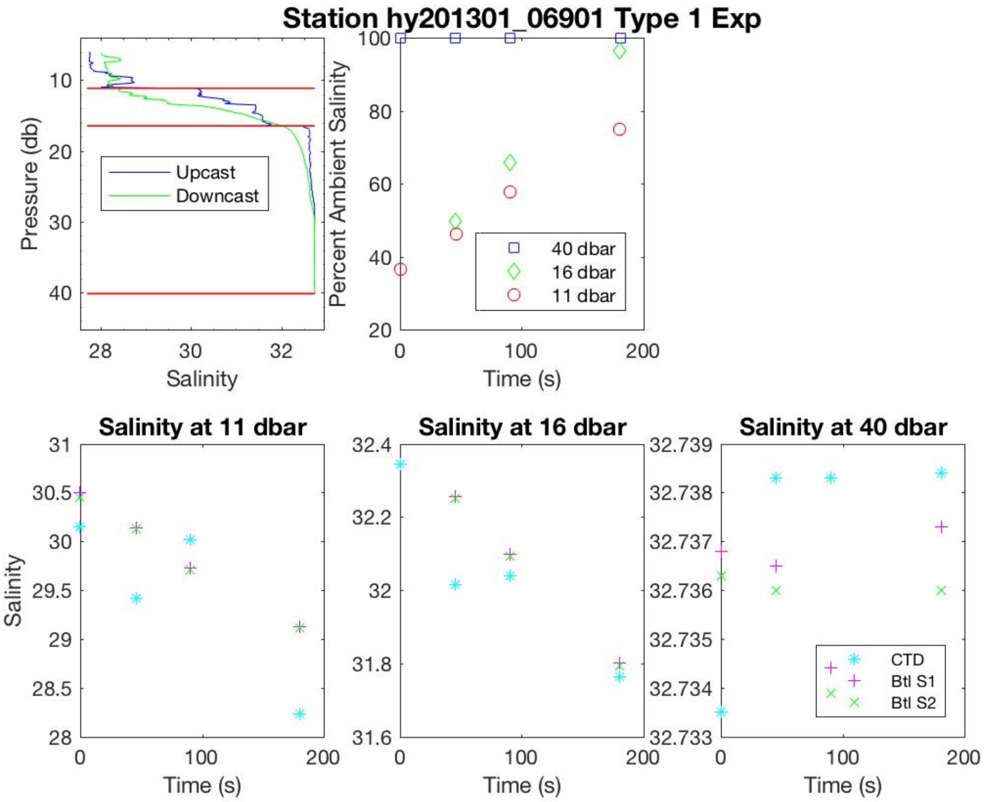
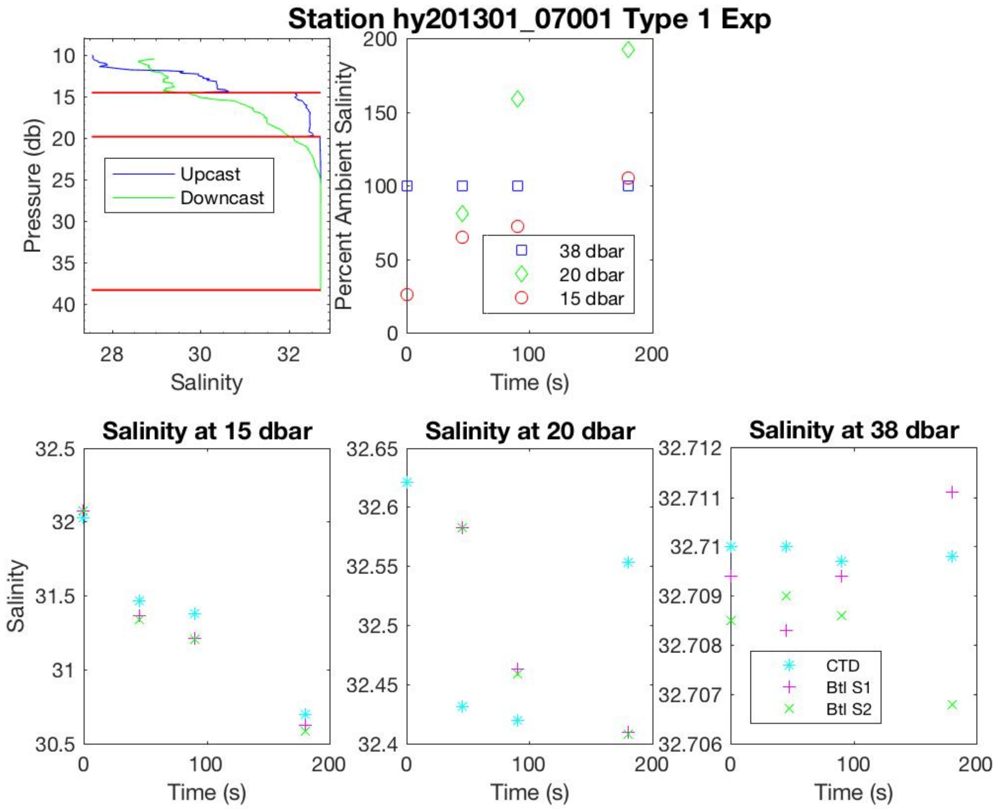
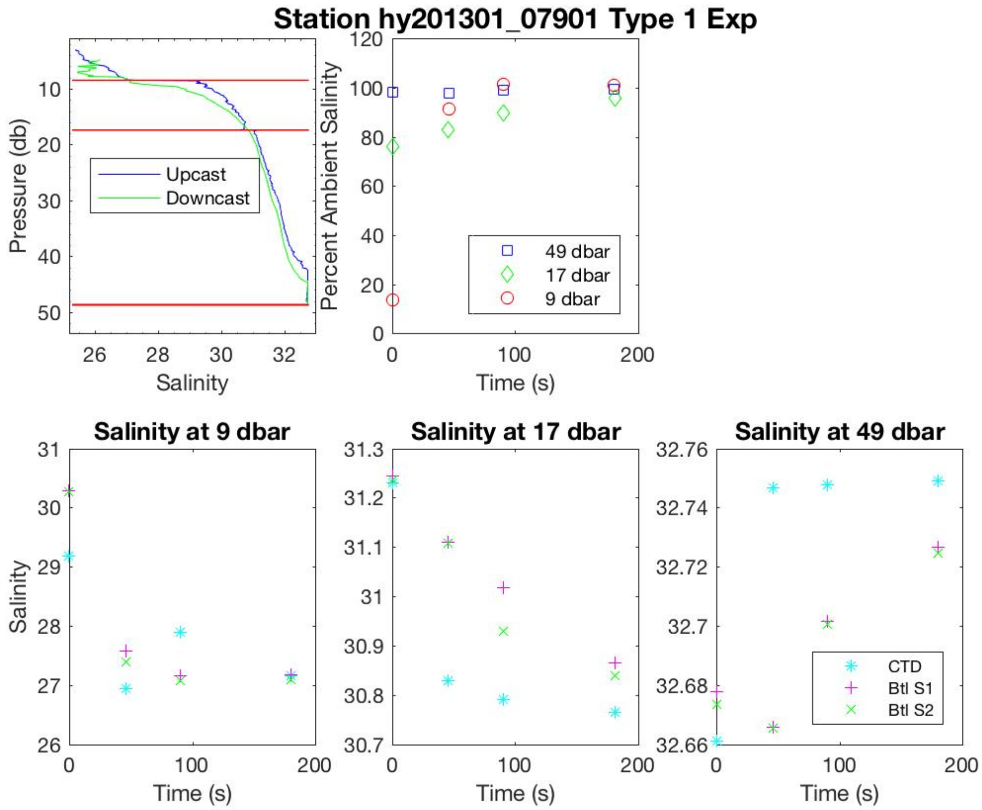

Station hy201301_06901 Type 1 Exp
Pressure (db)
Salinity
Upcast
Downcast
Percent Ambient Salinity
Time (s)
40 dbar
16 dbar
11 dbar
Salinity at 11 dbar
Salinity at 16 dbar
Salinity at 40 dbar
CTD
Btl S1
Btl S2

Figure 15.



Station hy201301_07001 Type 1 Exp
Pressure (db)
Salinity
Upcast
Downcast
Percent Ambient Salinity
Time (s)
38 dbar
20 dbar
15 dbar
Salinity at 15 dbar
Salinity at 20 dbar
Salinity at 38 dbar
CTD
Btl S1
Btl S2

Figure 16.



Station hy201301_07901 Type 1 Exp
Pressure (db)
Salinity
Upcast
Downcast
Percent Ambient Salinity
Time (s)
49 dbar
17 dbar
9 dbar
Salinity at 9 dbar
Salinity at 17 dbar
Salinity at 49 dbar
CTD
Btl S1
Btl S2

Figure 17.

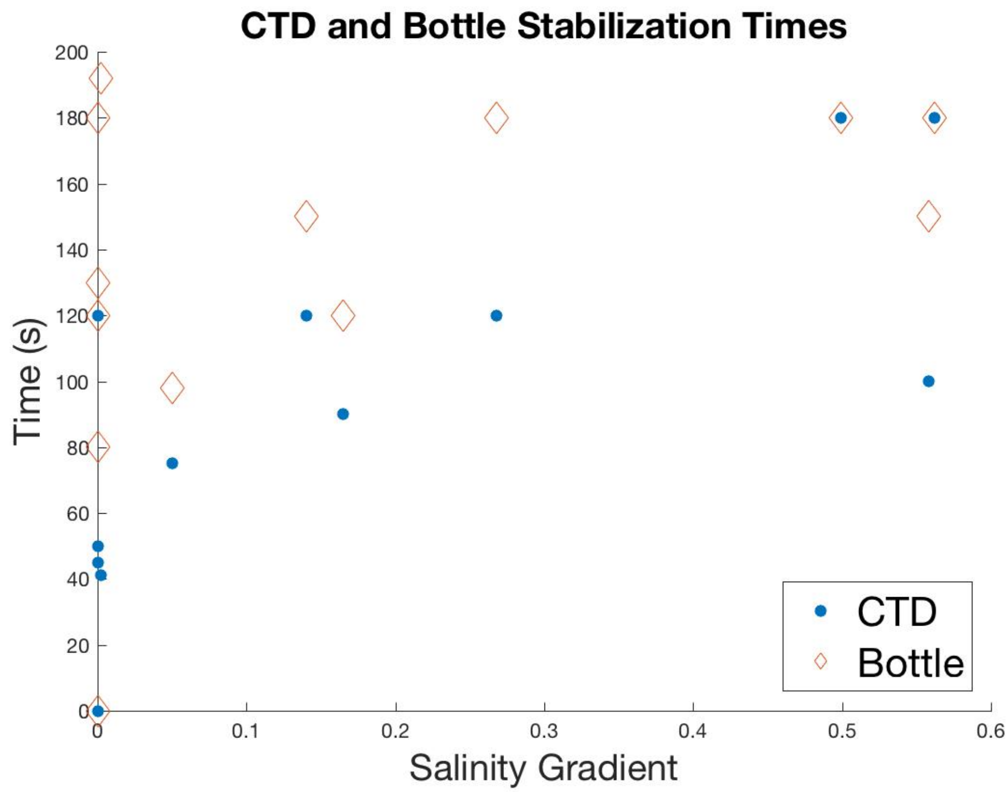

CTD and Bottle Stabilization Times
Time (s)
Salinity Gradient
200
180
160
140
120
100
80
60
40
20
0
0
0.1
0.2
0.3
0.4
0.5
0.6
CTD
Bottle

Figure 18.

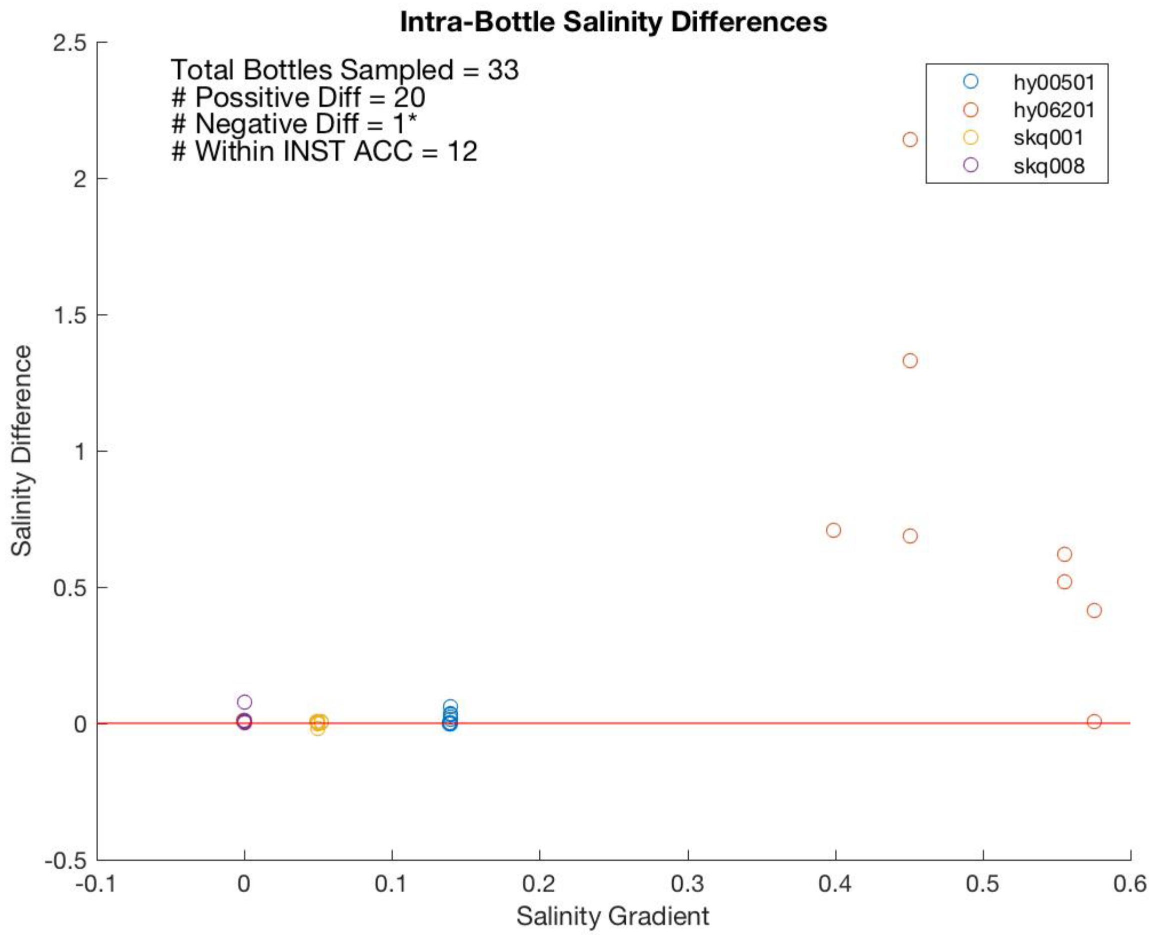

Intra-Bottle Salinity Differences
Total Bottles Sampled = 33
Possitive Diff = 20
Negative Diff = 1*
Within INST ACC = 12
hy00501
hy06201
skq001
skq008
Salinity Difference
Salinity Gradient
2.5
2
1.5
1
0.5
0
-0.5
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6

Figure 19.

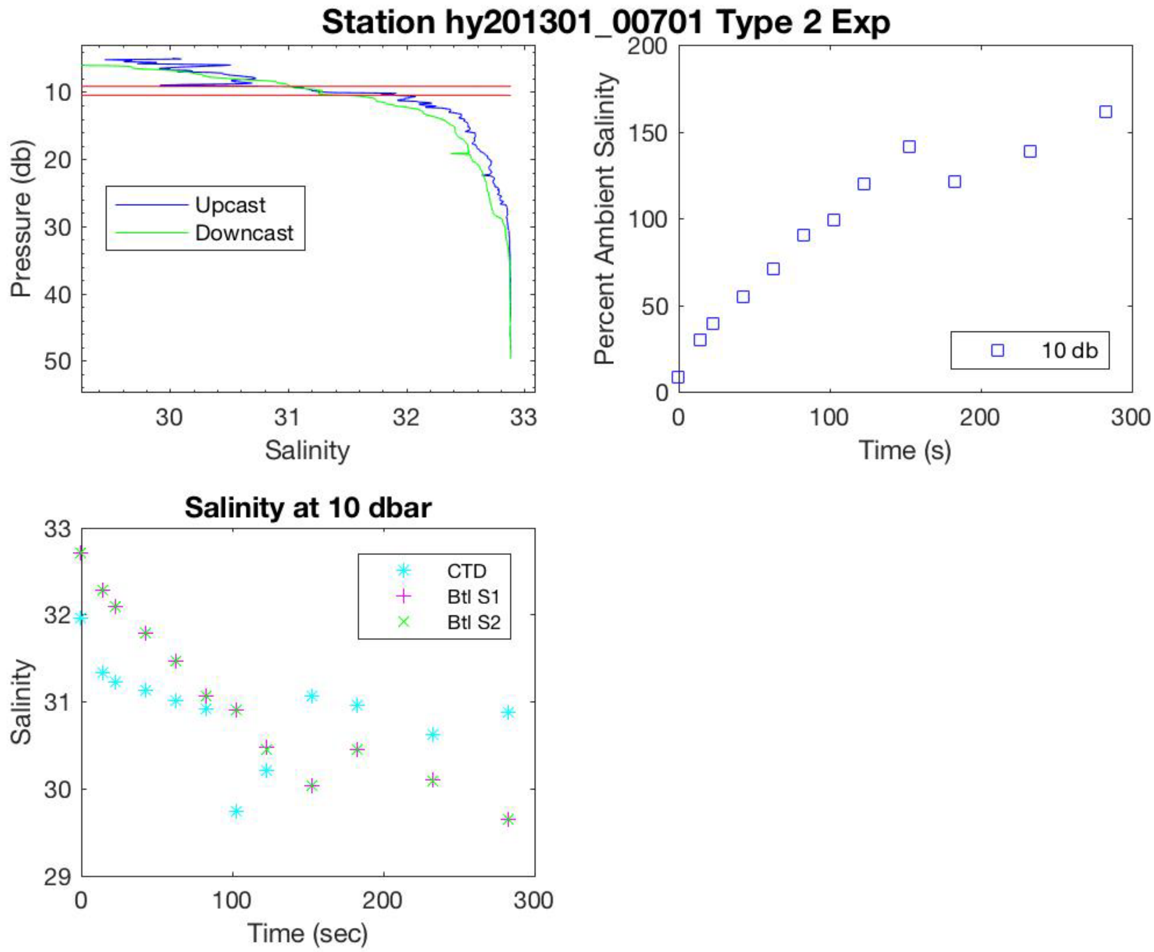

Station hy201301_00701 Type 2 Exp
Pressure (db)
Salinity
Upcast
Downcast
Percent Ambient Salinity
Time (s)
10 db
Salinity at 10 dbar
Salinity
Time (sec)
CTD
Btl S1
Btl S2

Figure 20.

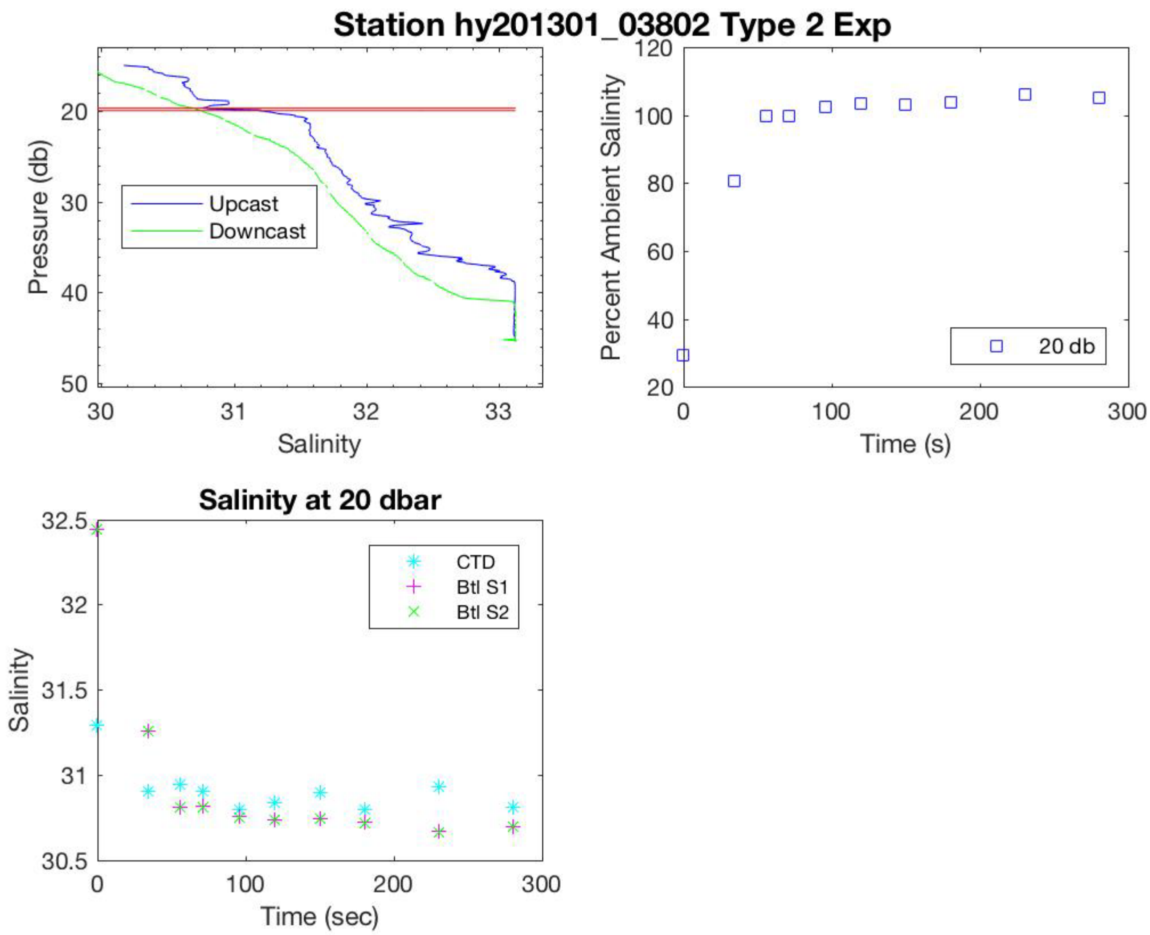
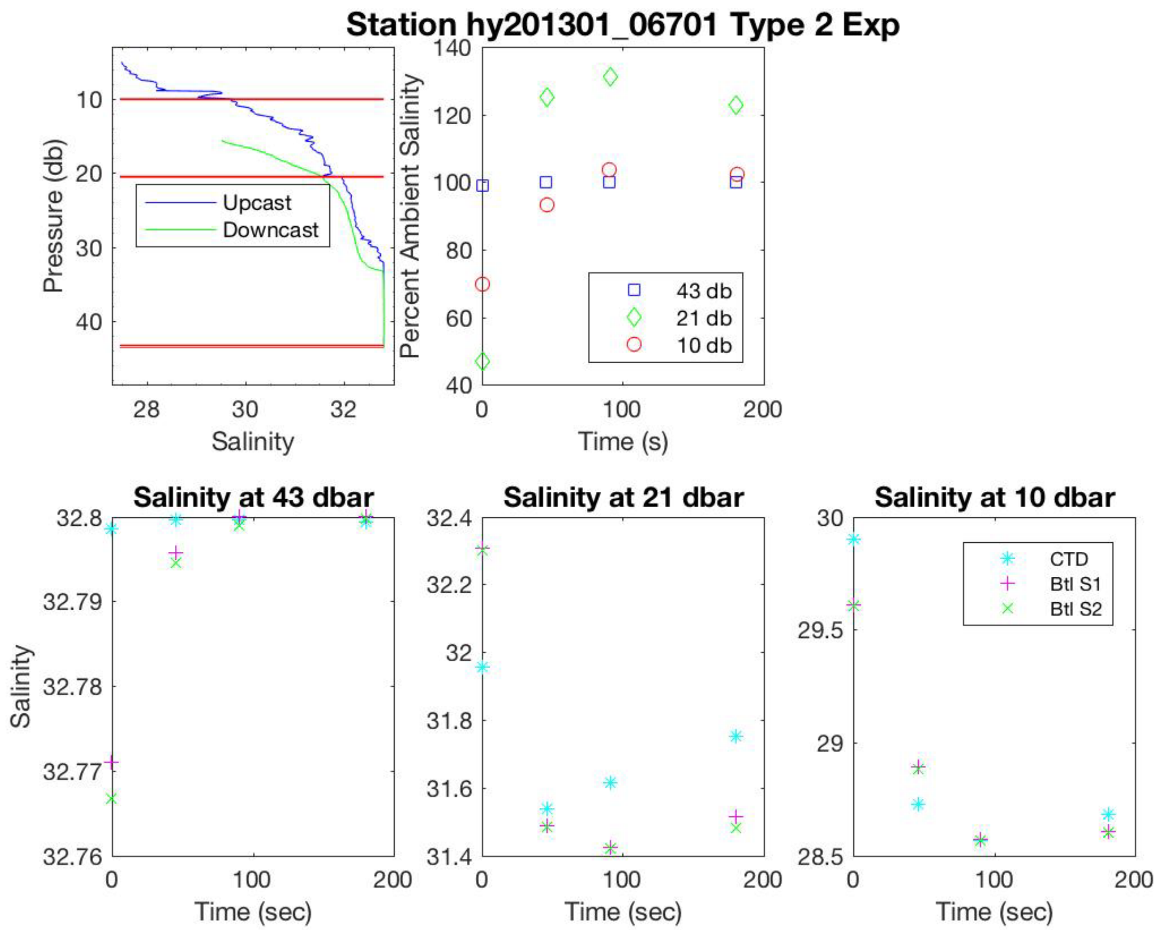

Station hy201301_03802 Type 2 Exp
Pressure (db)
Salinity
Upcast
Downcast
Percent Ambient Salinity
Time (s)
20 db
Salinity at 20 dbar
Salinity
Time (sec)
CTD
Btl S1
Btl S2

Figure 21.



Station hy201301_06701 Type 2 Exp
Pressure (db)
Salinity
Upcast
Downcast
Percent Ambient Salinity
Time (s)
43 db
21 db
10 db
Salinity at 43 dbar
Salinity at 21 dbar
Salinity at 10 dbar
Time (sec)
CTD
Btl S1
Btl S2

Figure 22.

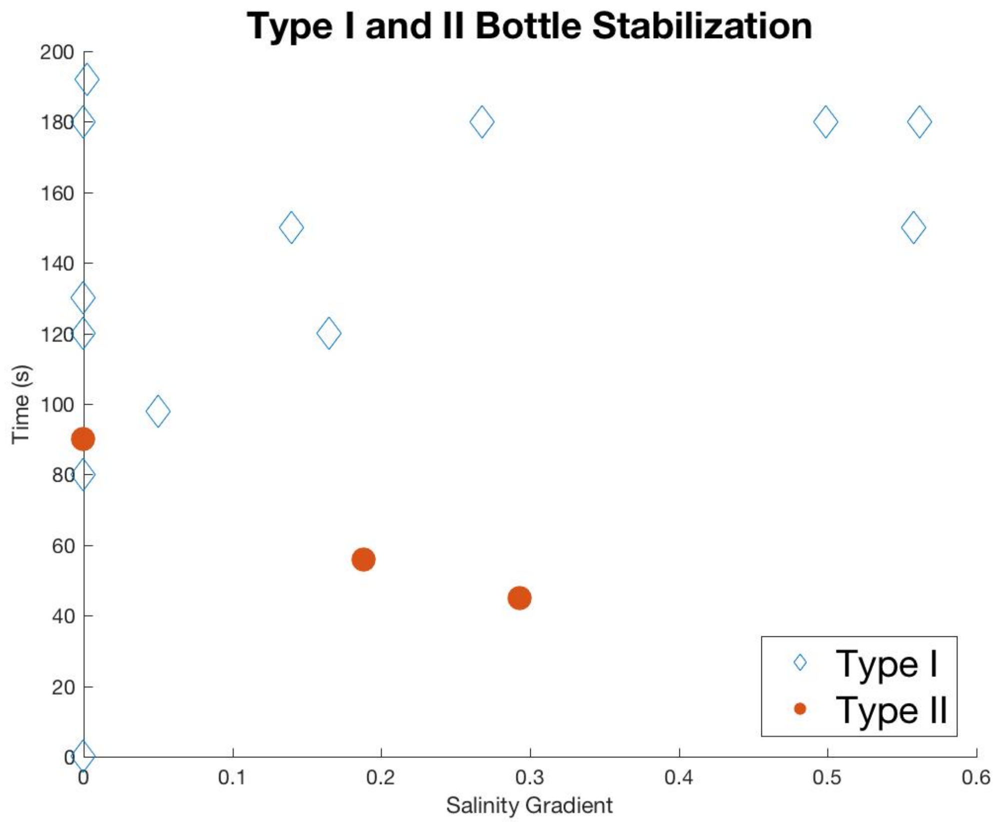

Type I and II Bottle Stabilization
Time (s)
Salinity Gradient
Type I
Type II
0
20
40
60
80
100
120
140
160
180
200
0
0.1
0.2
0.3
0.4
0.5
0.6

Figure 23.

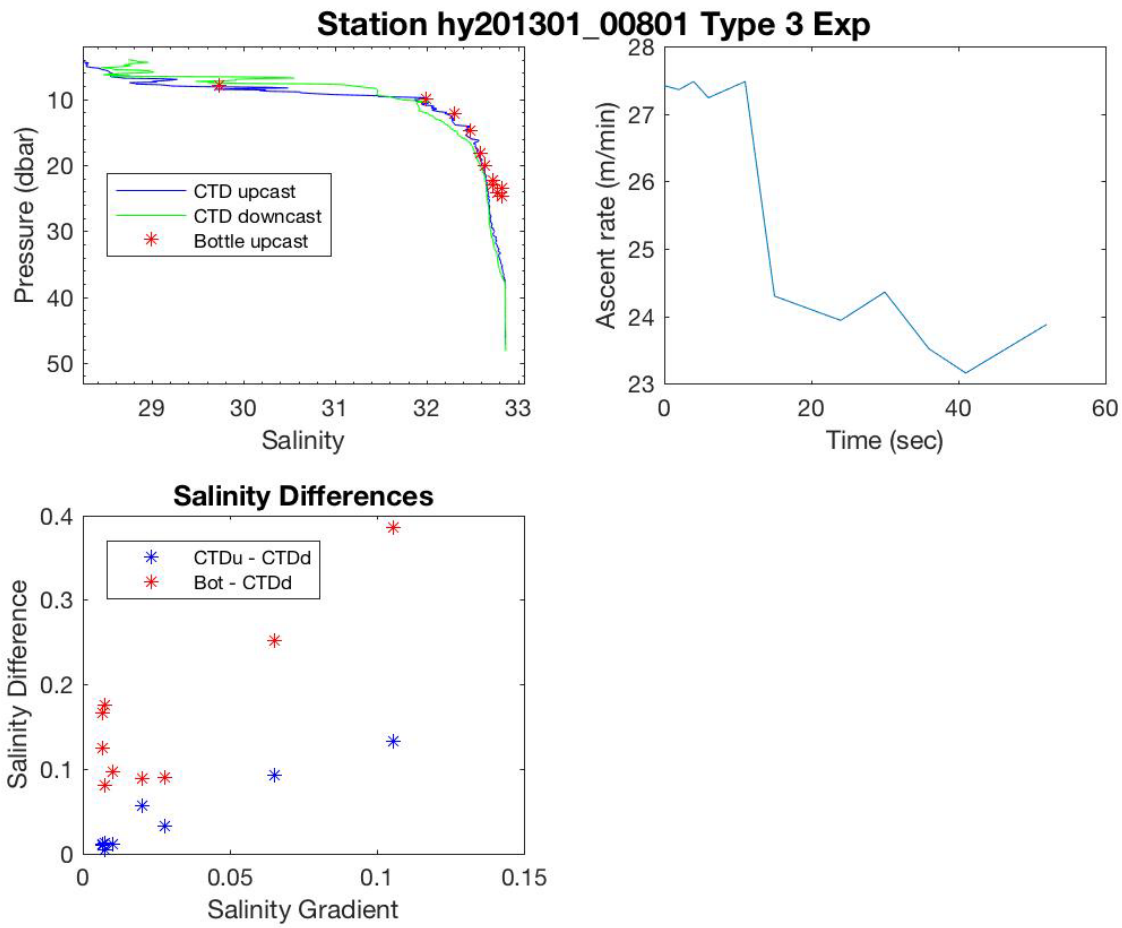
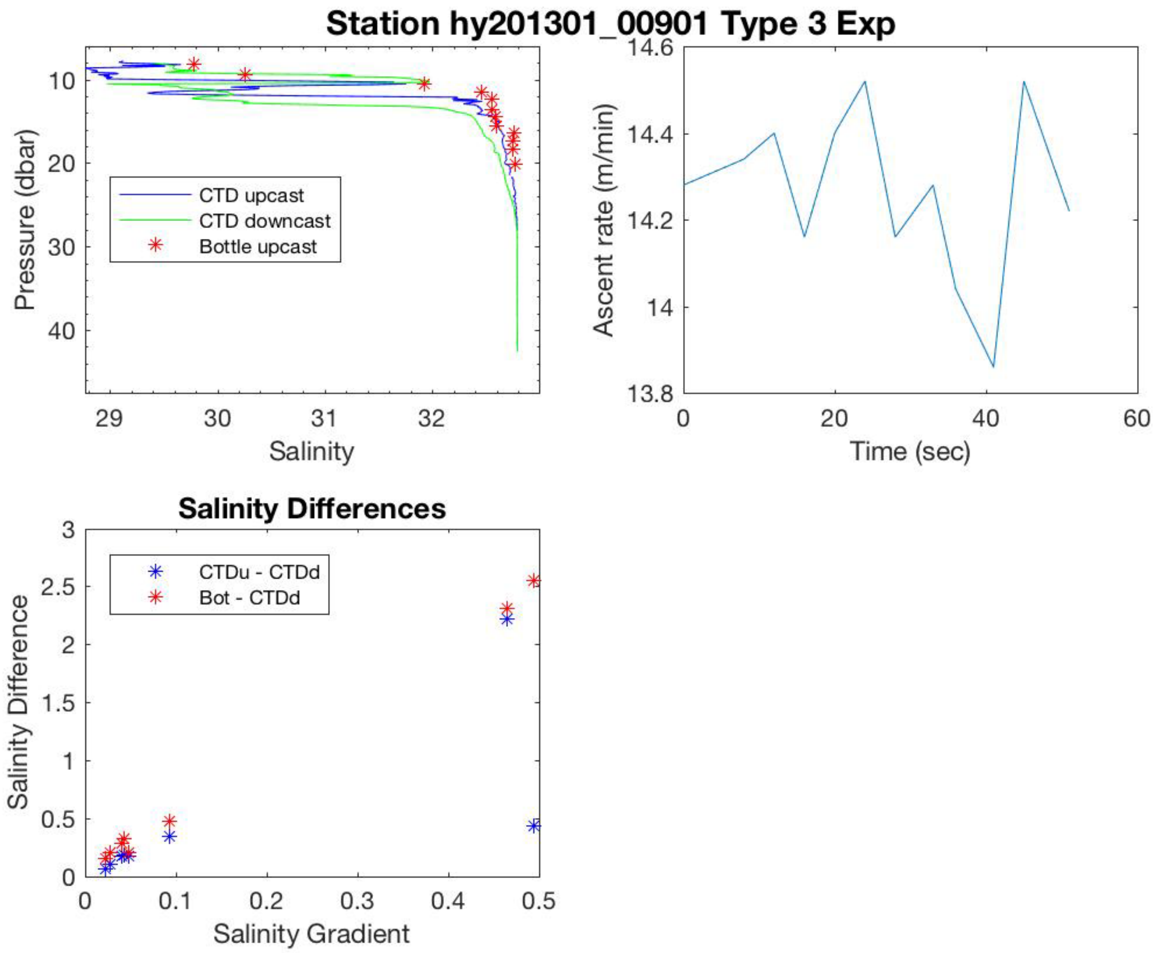

Station hy201301_00801 Type 3 Exp
Pressure (dbar)
Salinity
CTD upcast
CTD downcast
Bottle upcast
Ascent rate (m/min)
Time (sec)
Salinity Differences
Salinity Difference
Salinity Gradient
CTDu - CTDd
Bot - CTDd

Figure 24.



Station hy201301_00901 Type 3 Exp
Pressure (dbar)
Salinity
CTD upcast
CTD downcast
Bottle upcast
Ascent rate (m/min)
Time (sec)
Salinity Differences
CTDu - CTDd
Bot - CTDd
Salinity Difference
Salinity Gradient

Figure 25.

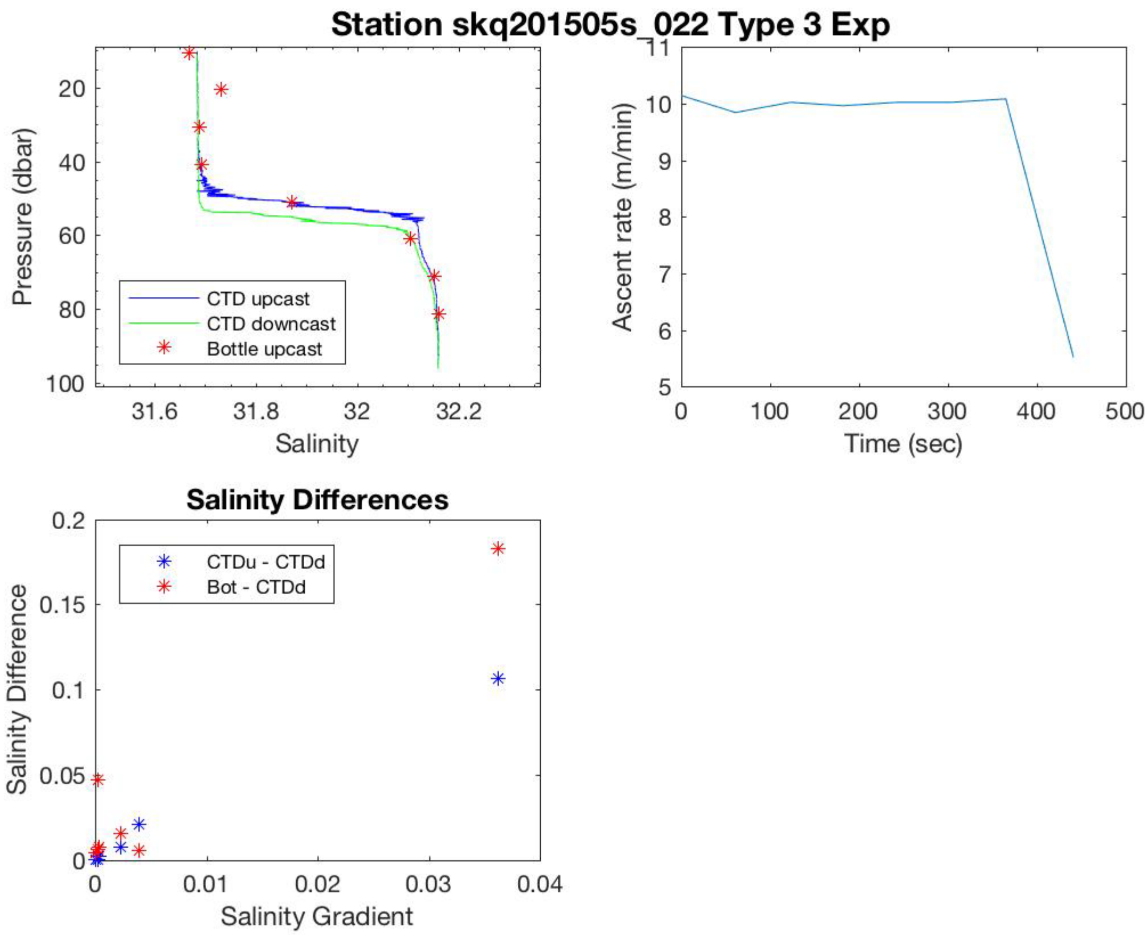
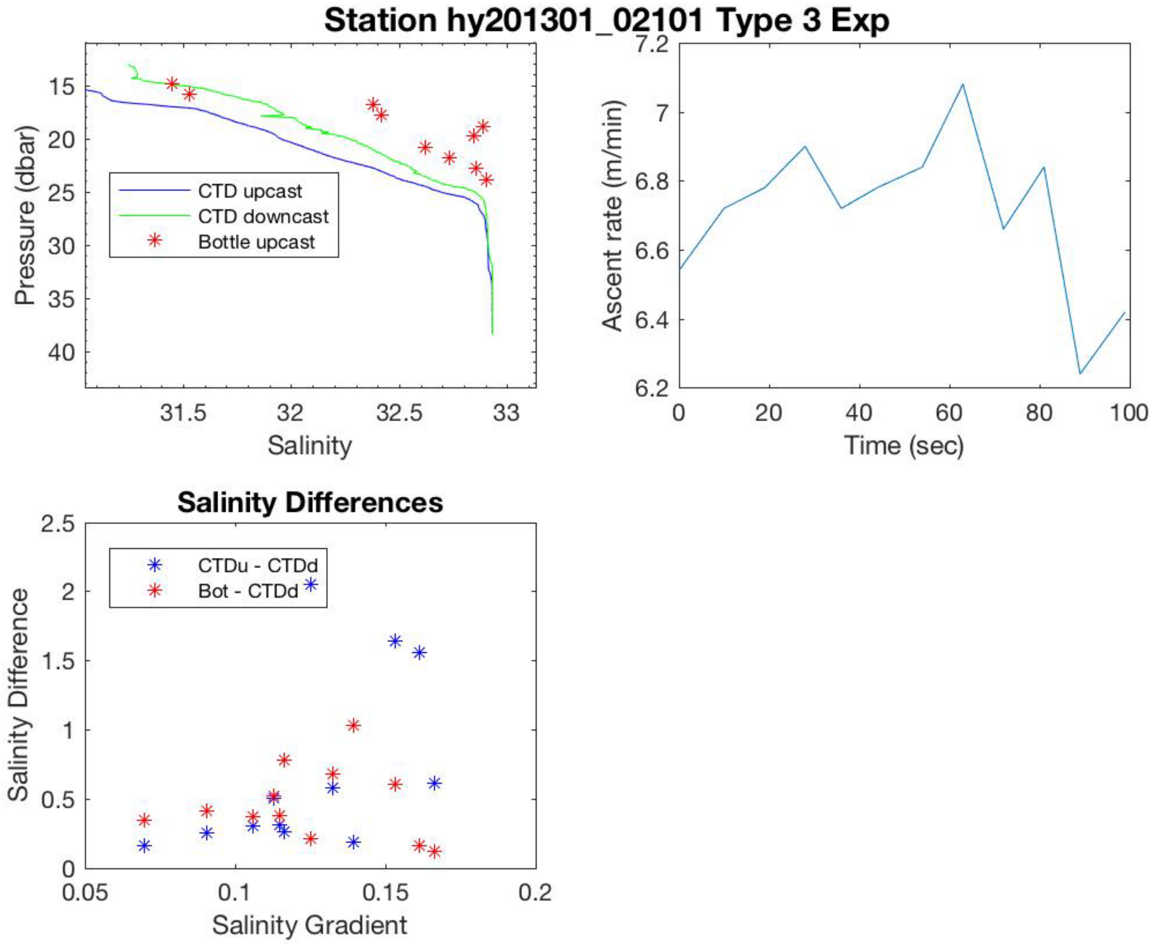

Station skq201505s_022 Type 3 Exp
Pressure (dbar)
Salinity
CTD upcast
CTD downcast
Bottle upcast
Ascent rate (m/min)
Time (sec)
Salinity Differences
Salinity Difference
Salinity Gradient
CTDu - CTDd
Bot - CTDd

Figure 26.



Station hy201301_02101 Type 3 Exp
CTD upcast
CTD downcast
Bottle upcast
Pressure (dbar)
Salinity
Ascent rate (m/min)
Time (sec)
Salinity Differences
CTDu - CTDd
Bot - CTDd
Salinity Difference
Salinity Gradient

Figure 27.

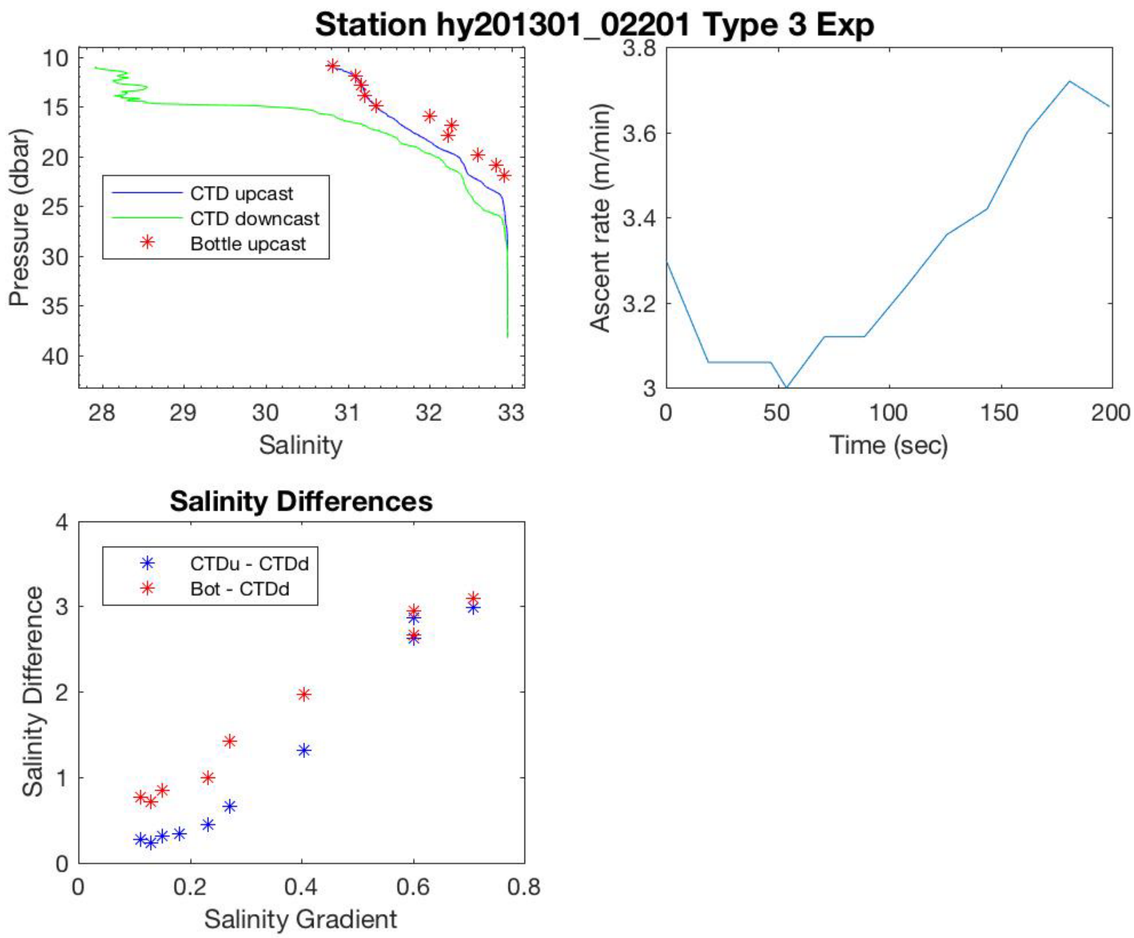

Station hy201301_02201 Type 3 Exp
CTD upcast
CTD downcast
Bottle upcast
Pressure (dbar)
Salinity
Ascent rate (m/min)
Time (sec)
Salinity Differences
CTDu - CTDd
Bot - CTDd
Salinity Difference
Salinity Gradient

Figure 28.

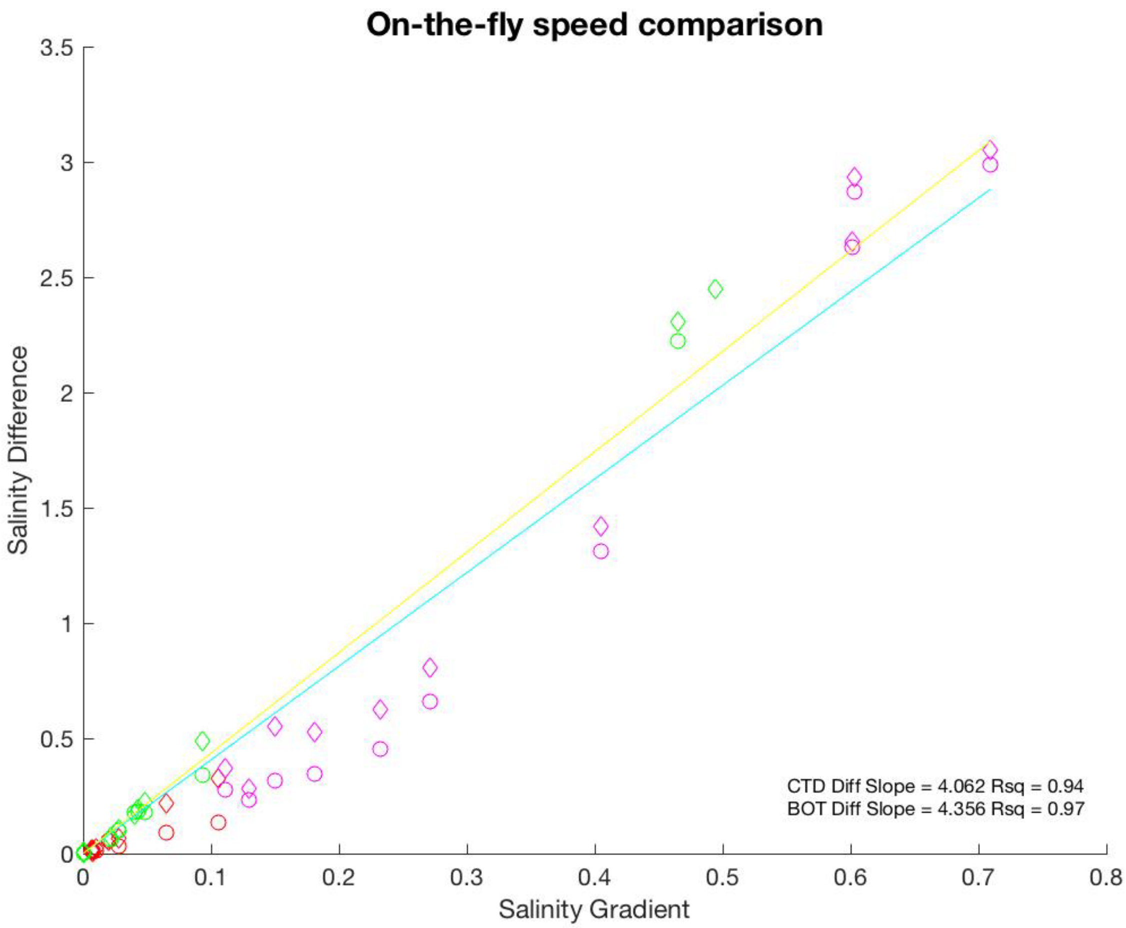

On-the-fly speed comparison
Salinity Difference
Salinity Gradient
CTD Diff Slope = 4.062 Rsq = 0.94
BOT Diff Slope = 4.356 Rsq = 0.97
0
0.5
1
1.5
2
2.5
3
3.5
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

Figure 29.

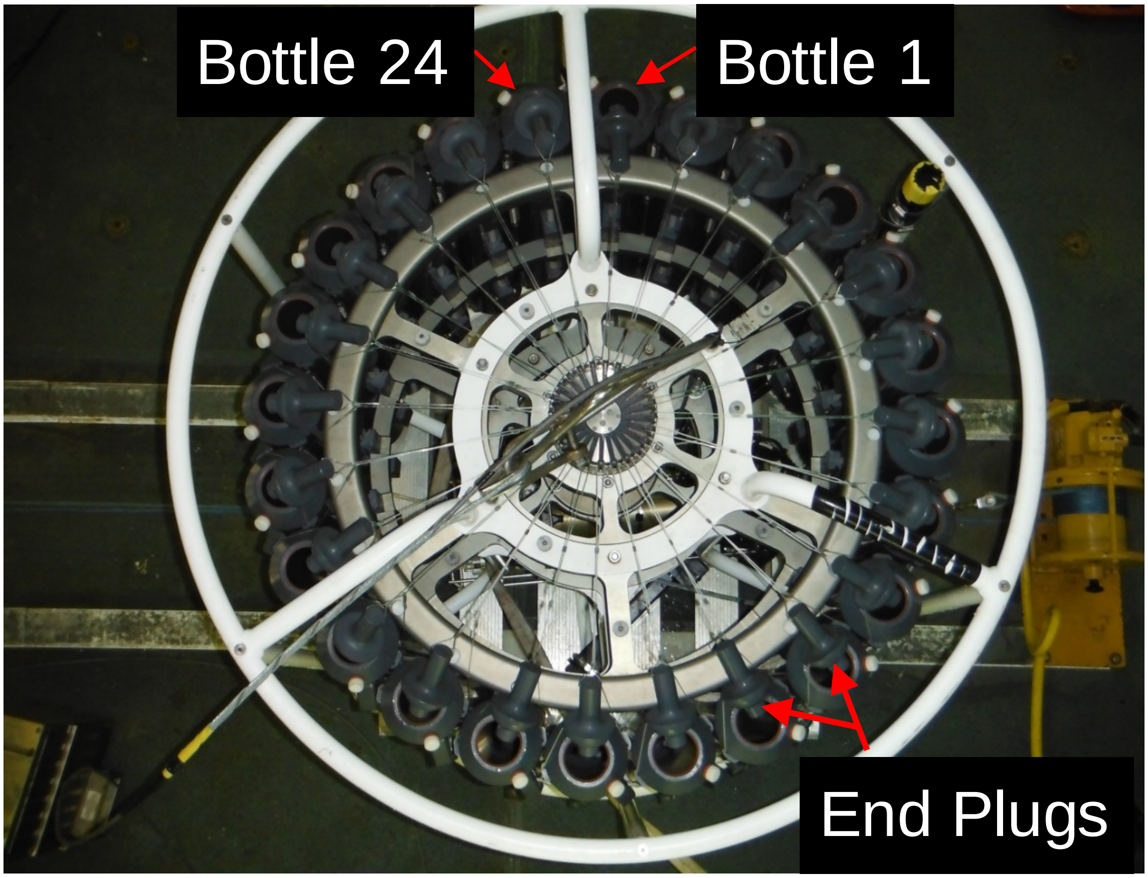


Figure 30.

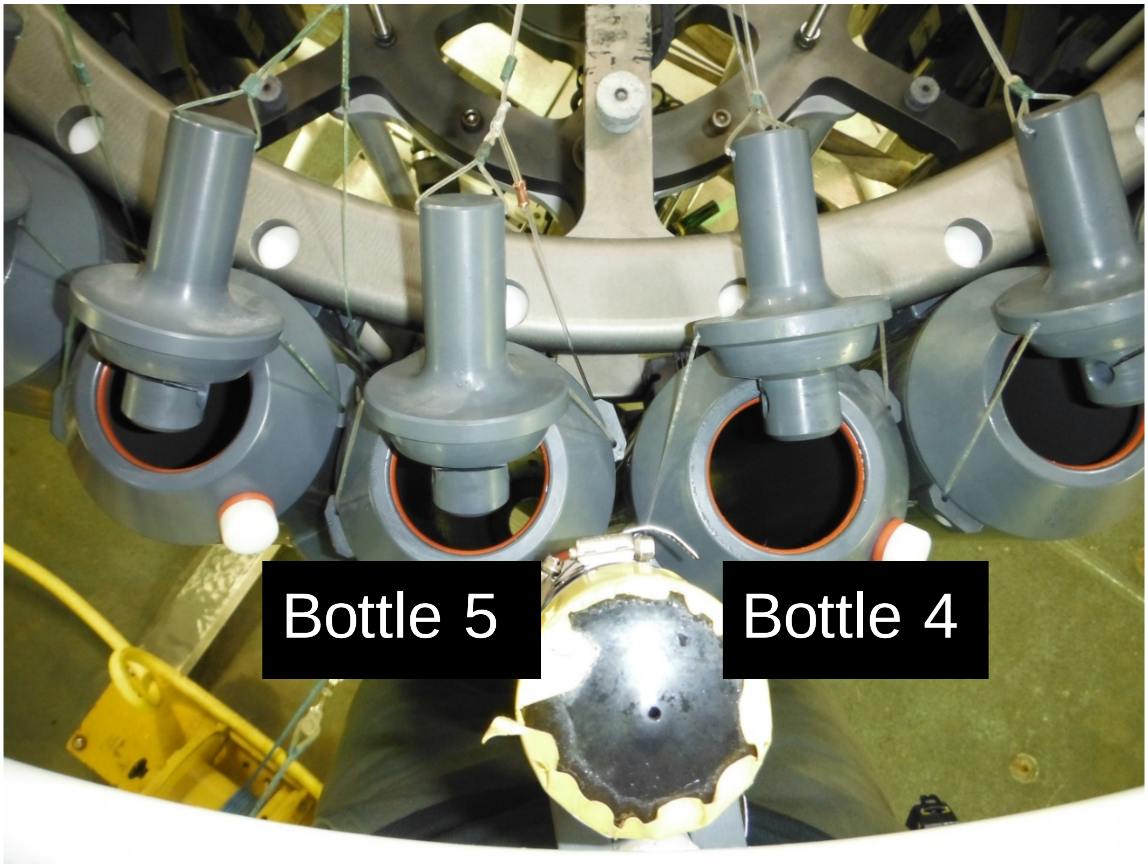


Figure 31.

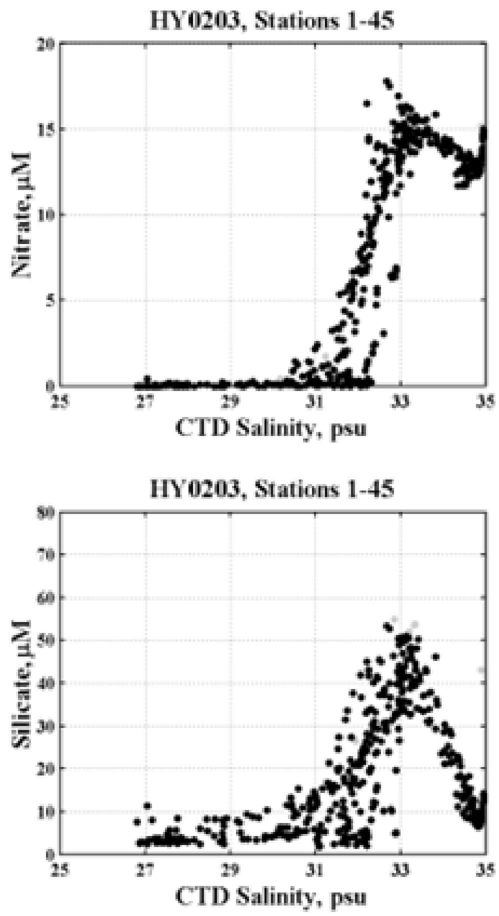

HY0203, Stations 1-45
Nitrate, µM
CTD Salinity, psu
HY0203, Stations 1-45
Silicate, µM
CTD Salinity, psu

Figure 32.

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