



PERFORMANCE VERIFICATION STATEMENT for the In-Situ Troll 9500 Turbidity Probe

TECHNOLOGY TYPE:	Optical Turbidity Sensor
APPLICATION:	<i>In situ</i> estimates of turbidity for moored deployments
PARAMETERS EVALUATED:	Response linearity, precision, range, and reliability
TYPE OF EVALUATION:	Laboratory and Field Performance Verification at seven ACT Partner sites
DATE OF EVALUATION:	Testing conducted from May through October 2006
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This document has been peer reviewed by ACT Partner Institutions and a technology-specific advisory committee and was recommended for public release. Mention of trade names or commercial products does not constitute endorsement or recommendation by ACT for use.

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EXECUTIVE SUMMARY:

Instrument performance verification is necessary so that effective existing technologies can be recognized and so that promising new technologies can become available to support coastal science, resource management, and ocean observing systems. The Alliance for Coastal Technologies (ACT) has therefore completed an evaluation of *in situ* turbidity sensors. Turbidity is a property commonly used to describe water clarity in both marine and freshwater environments, providing a gross assessment of the amount of suspended material. Differences in methods of measurement and their individual responses to varying types of suspended material have made the measurement of turbidity difficult to perform in a consistent and standardized way. This has necessitated many public-service agencies to define turbidity in very specific terms based on optical methods of measurement. Despite these limitations, a variety of *in situ* instruments that provide some measure of turbidity are commonly and successfully used in many researcher and monitoring settings as a relative measure of suspended sediment concentration.

As described below in more detail, field tests that examine manufacturers' turbidity values against simultaneously determined measurements of transmissivity, total suspended solids, and particulate organic carbon were designed only to examine an instrument's ability to track changes in water clarity through time and NOT to determine how well the instrument's values directly correlated with the ancillary measurements. The use of turbidity sensors to estimate a specific parameter (such as TSS) in nature requires local calibration to take into account many factors including particle composition, size and shape, along with other any other light scattering influences from dissolved organic compounds.

In this Verification Statement, we present the performance results of the In-Situ Troll 9500 Turbidity Probe evaluated in the laboratory and under diverse environmental conditions in moored field tests. A total of seven different field sites were used for testing, including tropical coral reef, high turbidity estuary, open-ocean, and freshwater lake environments. Because of the complexity of the tests conducted and the number of variables examined, a concise summary is not possible. We encourage readers to review the entire document for a comprehensive understanding of instrument performance.

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BACKGROUND:

Instrument performance verification is necessary so that effective existing technologies can be recognized and so that promising new technologies can be made available to support coastal science, resource management and ocean observing systems. To this end, the NOAA-funded Alliance for Coastal Technologies (ACT) serves as an unbiased, third party testbed for evaluating sensors and sensor platforms for use in coastal environments. ACT also serves as a comprehensive data and information clearinghouse on coastal technologies and a forum for capacity building through workshops on specific technology topics (visit www.act-us.info).

This document summarizes the procedures used and results of an ACT Evaluation to verify manufacturer claims regarding the performance of the In-Situ Troll 9500 Turbidity Probe. Detailed protocols, including QA/QC methods, are described in the *Protocols for the ACT Verification of In Situ Turbidity Sensors* (ACT PV06-01), which can be downloaded from the ACT website (www.act-us.info/evaluation_reports.php). Appendix 1 is an interpretation of the Performance Verification results from the manufacturer's point of view and is available at www.act-us.info/evaluation_reports.php.

TECHNOLOGY TYPE:

Turbidity is a property commonly used to describe water clarity in both marine and freshwater environments, providing a gross assessment of the amount of suspended material and dissolved substances. However, turbidity is often not a direct measure of the quantity of interest, such as suspended sediment or living particles, but rather a measure of the effect of the desired quantity on a specific optical property of the water. At present, there are numerous methods for quantifying turbidity (e.g., light attenuation, optical scatter, acoustic back-scatter, etc.). Differences in methods of measurement and their individual responses to varying types of suspended material have made the measurement of turbidity difficult to perform in a consistent and standardized way. This has necessitated many public-service agencies (e.g., USGS, US EPA, ISO, ASTM, etc.) to define turbidity in very specific terms based on optical methods of measurement, since optically-based approaches have conventionally been the most used. Although such standards and definitions were created to be both technically and legally specific (thereby minimizing the ambiguity in interpreting what turbidity is and how it is measured), it is still not possible to create an absolute standard that is applicable for different natural water types and different instrument designs employing the exact same principles of measurement. Despite these limitations, a variety of *in situ* instruments that provide some measure of turbidity are commonly and successfully used in many research and monitoring settings as at least a relative measure of water clarity.

The In-Situ turbidity sensor for the Troll 9500 sonde is designed for general purpose monitoring of turbidity in water. It conforms to the design specifications of ISO 7027. The emitter is a near-infrared LED with a peak wavelength of 860 nm. Light scattered by suspended particles in the water is measured by a photodiode. The light beam is pulsed and the measurement results are synchronously detected in order to remove interference from both natural and artificial light sources. The emission and sensing beams pass through abrasion-resistant sapphire optical windows to intersect at a 90 degree angle in the water. An available wiper accessory is used to keep the windows free of fouling effects. The default reporting unit of measure is FNU, or Formazin Nephelometric Units. The sensor is factory calibrated against AMCO-Clear suspended polymer turbidity calibration standards. The operating range is 0-2000 FNU with an accuracy specification of +/-5% of reading or 2 FNU whichever is greater, and a resolution of 0.1. A "user" calibration can be performed using from one to four reference points. The sensor accuracy after performing such a calibration is often limited primarily by the accuracy of the standards. The user calibration can also be used to reference the calibration against formazin standards, or within a particle suspender to calibrate directly against total suspended solids (mass/volume). The sensor is factory-installed and can be combined with pressure sensors ranging from 5 through 300 PSI full-scale ranges, with absolute or gauge sensing. More information can be found at www.in-situ.com.

OBJECTIVES OF THE TURBIDITY SENSOR VERIFICATION:

The basic application and parameters evaluated were determined by surveying users of *in situ* turbidity sensors. Most surveyed users deploy instruments on remote platforms in estuarine and near shore environments, in relatively shallow waters. Therefore, the performance verification focused on this application. It was also clear from the survey that reliability, accuracy, range/detection limits, precision, and calibration life are the most important parameters guiding instrument selection decisions. Furthermore, based on recommendations from the September 2005 ACT Workshop on “Measures of Turbidity in Coastal Waters” (www.act-us.info/workshops_reports.php), it was decided that while laboratory tests can evaluate instrument performance against known turbidity reference standards, there is no true standard (or single quantifiable variable) to measure instrument performance against when tested in the field. Therefore, a suite of appropriate environmental parameters at the field test sites to characterize conditions that may influence turbidity measurements (see below). Instrument performance will not be compared directly to any particular parameter.

PARAMETERS EVALUATED:

Because of the inherent limitations of *in situ* turbidity sensors and the inability to control various factors that can impact the data during field tests, accuracy, response linearity, and range was determined in the laboratory only. Furthermore we were only able to provide a qualitative estimate of precision during this evaluation because we did not feel the test solutions provided a consistent or guaranteed level of homogeneity to conduct a more rigorous statistical analysis. Field tests focused on reliability/stability and the ability of the instrument to track natural changes in the environment. The following definitions were agreed upon with the manufacturers as part of the verification protocols.

- **Accuracy** – combination of bias and precision of an analytical procedure, which reflects the closeness of the measured value to the true value. Accuracy will be determined in the laboratory by allowing test instruments to record at least 10 consecutive measurements when exposed to a set concentration of formazin or submicron styrene divinyl benzene polymer beads (SDVB; GFS Chemicals, Inc.). At least five concentrations of each reference particle type were tested.
- **Response Linearity** – Reliability (accuracy) of instrument response was determined by linear regression of recorded instrument response versus turbidity resulting from additions of formazin or SDVB at different temperature and light conditions.
- **Precision** – Precision is a measure of the repeatability of a measurement. Instrument precision was assessed by visualizing the relationship between the standard deviation of a measurement relative to the mean instrument response at a range of fixed turbidity levels.
- **Range** – Range is a measure of the minimum (or detection limit) and maximum concentration of specific formazin and SDVB concentration the instrument can accurately (see definition above) measure under total darkness.
- **Reliability** – Reliability is the ability to maintain integrity or stability of the instrument and data collections over time. Reliability of instruments was determined in two ways. In both laboratory and field tests, comparisons were made of the percent of data recovered versus percent of data expected. In field tests, instrument stability was determined by pre- and post-measures of blanks and reference standards (formazin and SDVB) to quantify drift during deployment periods. Comments on the physical condition of the instruments (e.g., physical damage, flooding, corrosion, battery failure, etc.) were also recorded.

SUMMARY OF VERIFICATION PROTOCOLS:

The protocols used for this verification were developed in conference with ACT Technical Coordinators, the participating instrument manufacturers and an external Technical Advisory Committee. It was determined collectively that the verification protocols would: (A) employ both formazin and SDVB as standards for determining instrument performance characteristics in controlled laboratory tests, and (B) include field tests to evaluate performance under a variety of environmental conditions. All personnel involved in this verification were affiliated with ACT and properly trained on the use of instruments by manufacturer representatives and trained to use standardized methods of water sampling, processing, storage, shipping and analysis. A brief synopsis of the protocols is provided below and a **complete copy can be downloaded at: www.act-us.info/evaluation_reports.php**.

All laboratory tests of accuracy, response linearity, precision, range, and reliability were conducted at Moss Landing Marine Laboratories (MLML) in well-mixed (submersible circulating pumps), temperature controlled water baths. Although field tests included instrument deployments under varying salinity conditions, it was decided that salinity would not be tested as a variable in the laboratory evaluations. Therefore, all laboratory tests were conducted in filtered, bubble-free, deionized water. For the accuracy and linearity/stability tests, instruments were set to record measurements at a minimum frequency of 1 min⁻¹, and equilibrated at the test temperature for at least 30 minutes and at each turbidity level for 10 minutes. Following equilibration at each turbidity level, the mean and standard deviation of instrument response was derived from a minimum of 10 measurements. In separate trials, the test instrument was exposed to formazin or SDVB with concentration targets of: 0.2, 0.5, 1, 2, 4, 6, 8, 10, 50, 100, 250, and 500 NTU (Nephelometric Turbidity Units) achieved by sequential additions of known concentrations of particle stock solutions. A range of concentrations from 0.2 to 100 NTU was also examined at 4 and 32 °C to produce a matrix with approximately 80 independent conditions for evaluating response linearity. Precision tests were conducted simultaneously by monitoring the variance of instrument signal over 30 consecutive measurements at 1 minute intervals in a selected subset of test conditions. Results from the experimental matrix above were used to determine the linear detection ranges at each test temperature. For instruments with programmable scale factors, the test instrument was set to measure turbidity for an expected range of 0 – 100 NTU/FTU for all tests. Instrument sensitivity to ambient irradiance was assessed at select turbidity levels over the range 0 – 500 NTU at 15°C by illuminating the test tanks with a bank of 500W halogen worklights providing approximately 400 - 500 $\mu\text{mole quanta m}^{-2} \text{s}^{-1}$ PAR at the surface, and comparing these readings against those made immediately beforehand in dark conditions. This light intensity is approximately equivalent to a mid-morning value of PAR for incoming solar radiation.

Moored field tests were conducted by each of the seven ACT Partner Institutions with test sites representing a range of water quality conditions within diverse coastal environments throughout North America (see Table 1). Field sites included Chesapeake Bay (Solomons, MD), Winans Lake (Ann Arbor, MI), Damariscotta River Estuary-Gulf of Maine (Walpole, ME), Moss Landing Harbor (Moss Landing, CA), western shore of Skidaway Island (Skidaway, GA), Kaneohe Bay Barrier Reef (Kaneohe Bay, HA), and offshore of Tampa Bay (St. Petersburg, FL). Instruments were deployed at a fixed depth of 1 meter for continuous time periods ranging from four to eight weeks. A total of four identical instruments were provided by the manufacturers, so two sets of field tests were conducted. Instrument packages were returned to manufacturers for reconditioning and calibration in between the two sets of field tests. Prior to deployment, all instruments were set up and calibrated at the field sites as suggested by the manufacturer and the turbidity sensors programmed to record data every 15 minutes during the entire field deployment. All turbidity sensors were exposed to certified 0 and 5 NTU turbidity standards (GFS Chemicals Lot P674097) both before and after deployment. An aliquot of initial stock solutions and final test solutions from each site were sent to MLML for analysis on a Hach 2100AN Turbidimeter calibrated with StableCal (Hach) certified formazin reference standards to assess changes in reference solutions due to age or contamination from handling. Complete results and explanation of the turbidity standards comparison can be found in Appendix 4, *Discussion of Turbidity Calibration Standards* at www.act-us.info/evaluation_reports.php.

A photograph of each individual sensor and the entire instrument rack was taken just prior to deployment and just after recovery to provide a qualitative estimate of biofouling during the field tests. Additionally, a series of growth substrates (glass and PVC plates) were deployed as close as possible to the test instruments to help assess the rate at which biofouling occurred. Each week, one of each substrate type was removed from the water and photographed, and a description of the fouling community recorded. All of the photographic records and descriptions from each site are presented in Appendix 2, *Results of Biofouling Plates for the ACT 2006 Turbidity Sensor Verification* and may be downloaded at www.act-us.info/evaluations_reports.php.

ANCILLARY ENVIRONMENTAL DATA:

A series of ancillary data sets were collected during field deployments to characterize fully the variation in water quality conditions during testing and to provide a qualitative analysis of how particular environmental parameters are correlated to instrument turbidity values. A calibrated CTD package was deployed as close as possible to the instrument mooring and programmed to provide an independent record of conductivity and temperature at the same depth and same 15-minute intervals as the test instrument. In addition, a calibrated *in situ* fluorometer and transmissometer (wavelength 660 nm) were connected to a datalogger and placed into the water (as close as possible to the test instrument) to collect ancillary data on relative fluorescence and beam attenuation, respectively, at corresponding 15 minute intervals. Because these optical instruments were also prone to biofouling, they were cleaned daily during the work week. After the daily cleaning, one in-air value was recorded for both the fluorometer and transmissometer to assure that the instruments were performing consistently throughout the test period.

Water samples were collected and analyzed for total suspended solids (TSS) and particulate organic carbon (POC) throughout the deployment to characterize the type and quantity of particulate matter in the test environment. Each sampling was timed to exactly correspond to the instrument sampling time and took place as close as physically possible to the test sensor. At the initiation of deployment, three consecutive water samples were taken at one-hour intervals. During the remainder of the moored deployments, two water samples were collected every weekday. In addition, a minimum of two intensive sample sets (consisting of six consecutive samples taken at no more than one hour apart) were collected sometime during the first two weeks of deployment. This basic sampling schedule was amended for the USF offshore test site because of limited access; however, a similar number of samples were collected at each test site. Sampling and filtration gear were cleaned between each sampling event and procedural blanks (field blanks) processed weekly.

TSS was determined in triplicate for every sampling event. TSS was determined gravimetrically for material retained on 47mm Whatman GF/F filters after the filtration and drying of a well-mixed sample of water following APHA Method 208D (1975), USEPA Method 160.2 (1979), and Etcheber, H. (1981). The mean value of the triplicates was taken as the best timepoint estimate and each of these TSS values was subsequently corrected using derived estimates from procedural blanks intended to serve as a measure of mass loss of filter material combined with mass carry over due to potential cross-contamination. Analyses for TSS were done independently at each Partner test site.

POC samples were determined in triplicate for all intensive sampling events but only once per day during normal sampling. POC samples were collected on pre-combusted 25 mm Whatman GF/F filters and the elemental composition of the organic matter (weight percent of carbon, hydrogen, and nitrogen) was determined using an Automated Organic Elemental Analyzer following the Dumas combustion method. Each week triplicate dry and wet blanks were collected and processed as separate samples. All POC samples were analyzed at University of California at Santa Barbara, Marine Science Institute's Analytical Laboratory. All POC concentrations were corrected using derived estimates from procedural 'wet' blanks intended to quantify carbon contamination present in the glass fiber filter, as well as, from any dissolved organic carbon (DOC) that potentially adsorbed to the filter during sample filtration.

QUALITY ASSURANCE/QUALITY CONTROL:

This performance verification was implemented according to the test/QA plans and technical documents prepared during planning of the verification test. Prescribed procedures and a sequence for the work were defined during the planning stages, and work was performed following those procedures and sequence. Technical procedures included methods to assure proper handling and care of test instruments, samples, and data. Performance evaluation, technical system, and data quality audits were performed by QA personnel independent of direct responsibility for the verification test. All implementation activities were documented and are traceable to the test/QA plan and to test personnel.

The main component to the QA plan included technical systems audits (TSA), conducted by ACT Quality Assurance Specialists at two of the ACT Partner test sites (CILER/University of Michigan, and University of South Florida) selected at random. These audits were designed to ensure that the verification test was performed in accordance with the test protocols and the ACT *Quality Assurance Guidelines*. (e.g., reviews of sample collection, analysis and other test procedures to those specified in the test protocols, and data acquisition and handling). During the verification tests, no deviations from the test protocols were necessary.

The environmental samples used for the determination of TSS and POC were subject to several levels of quality assurance control including analytical and field trip blanks, as well as, control charts for blanks and replicate analysis. All analytical measurements were performed using materials and/or processes that are traceable to a Standard Reference Material. Standard operating procedures (SOPs) are utilized to trace all quantitative and qualitative determinations to certified reference materials. Lastly, ACT's Quality Assurance Specialists audited approximately 10% of the verification data acquired in the verification test to determine if data had been collected in accordance to the Protocols with respect to compliance, correctness, consistency, and completeness.

It should be noted that while ACT takes every precautionary measure to ensure the highest quality data and appropriate training and handling of the test equipment, that instances may arise where an unforeseen problem occurs with the test equipment during its evaluation. Constraints in both the testing protocols and available resources do not allow us to easily repeat the verification study if an instrument failure occurs at any given site. In part, that is why we conduct independent verifications at all seven Partner Institution sites.

VERIFICATION RESULT, LABORATORY TESTS:

A series of laboratory test were conducted to examine the performance characteristics (linearity and precision), of the test sensor in varying concentrations of two different reference turbidity standards (SDVB and formazin), at varying temperature and ambient light conditions. Concentrations of the reference solution were measured by independent analysis on a Hach 2100AN Turbidimeter using US EPA Method 180.1 and formazin standards. Tests were performed over a concentration range of approximately 0 - 500 NTU for both SDVB (Fig. 1) and formazin (Fig. 2) solutions. Tests were conducted at three different temperatures, 4, 15, and 32 °C, with two independent tests being conducted at 15 °C as an additional test of precision. The instrument sample rate was set to 1 per minute and following a 10 minute equilibration period at least 15 measurements were recorded at each test condition to assess instrument performance. Instrument response was linear over at least 0-100 NTU, with similar response factors to both formazin- and SDVB-induced turbidity. However, even the small (ca. 4%) differences in detector response to standard particles should be taken as an end-user caution; the relative NTU value reported by an instrument will depend on what reference particles were used for calibration. Users are encouraged to conduct rigorous field calibrations appropriate for the local system being monitored.

Variation in measurement precision was assessed by cross plotting the calculated standard deviation of 30 consecutive measurements versus the mean signal for a selected subset of test conditions. For the SDVB test, the signal noise ranged from 10% to < 0.1% of the measured signal across the turbidity test range (Fig. 1B). Absolute noise was not dependent on either temperature or the magnitude of turbidity over the range of test conditions. For the formazin test, the signal noise ranged from 7% to 0.2% of the measured signal across the turbidity test range and no dependence on temperature was apparent (Fig. 2B). However, there was a monotonic increase in the variance with increasing formazin turbidity. It is likely that this increased variance was due to the presence of particle aggregates in the test solution as more formazin was added. As this variance was still very small compared to the measurement signal, the instrument still accurately measured the high turbidity test concentrations (Fig. 2A).

The influence of ambient light to instrument response was evaluated by comparing instrument response under complete darkness versus response measured under light intensities of approximately 400-500 $\mu\text{mol quanta m}^{-2} \text{s}^{-1}$ over a range of 0 – 110 NTU for both the SDVB and formazin solutions (Fig. 3). The dark and light measurements were conducted back to back once the instrument was equilibrated for 10 minutes at the new test conditions. Data points represent the mean and standard deviation (indistinguishable on plots at size scale of symbols) of at least 15 minutes of measurements following equilibration at each test condition. There was no measurable difference in instrument response between light and dark test conditions over the complete range of concentrations tested.

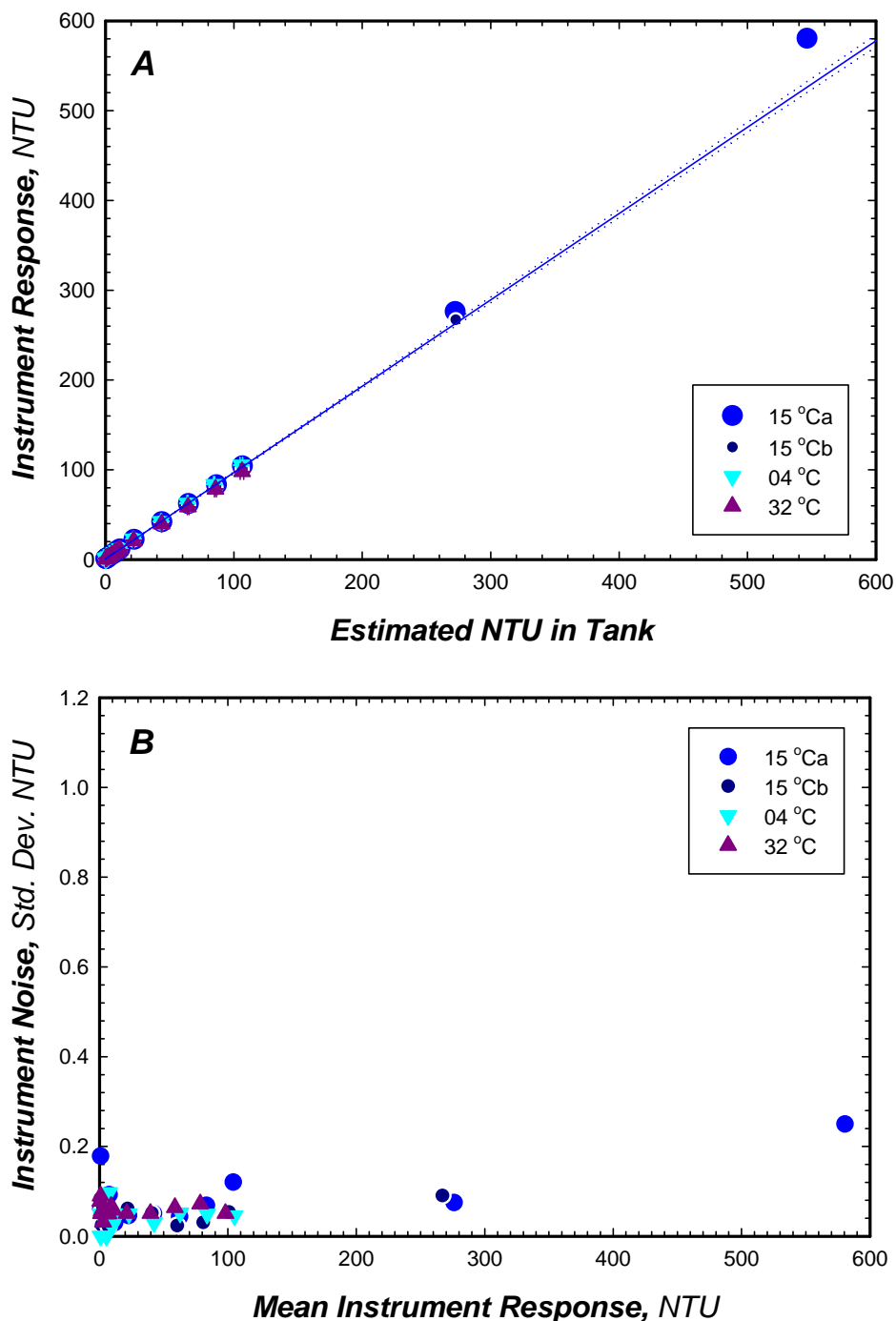


Figure 1. In-Situ's Troll 9500 signal and instrument noise in response to increasing turbidity derived from SDVB added to filtered deionized water at three test temperatures. **(A)** Mean detector response to sequential additions of known SDVB concentrations. Instrument response over a turbidity range normally observed in natural waters (0-100 NTU) was modeled by linear regression. Modeled response at 15°C, with 99% confidence intervals (dotted lines): $NTU_{instru} = 0.962NTU_{SDVB} + 0.691$, $r^2 = 0.999$, demonstrates response is linear through 280 NTU SDVB. Detector response was unaffected by the ambient temperatures tested. **(B)** Signal noise (s.d.) ranged from <0.1 to 10% of measured signal in the presence of SDVB and no consistent temperature or turbidity dependence was detected.

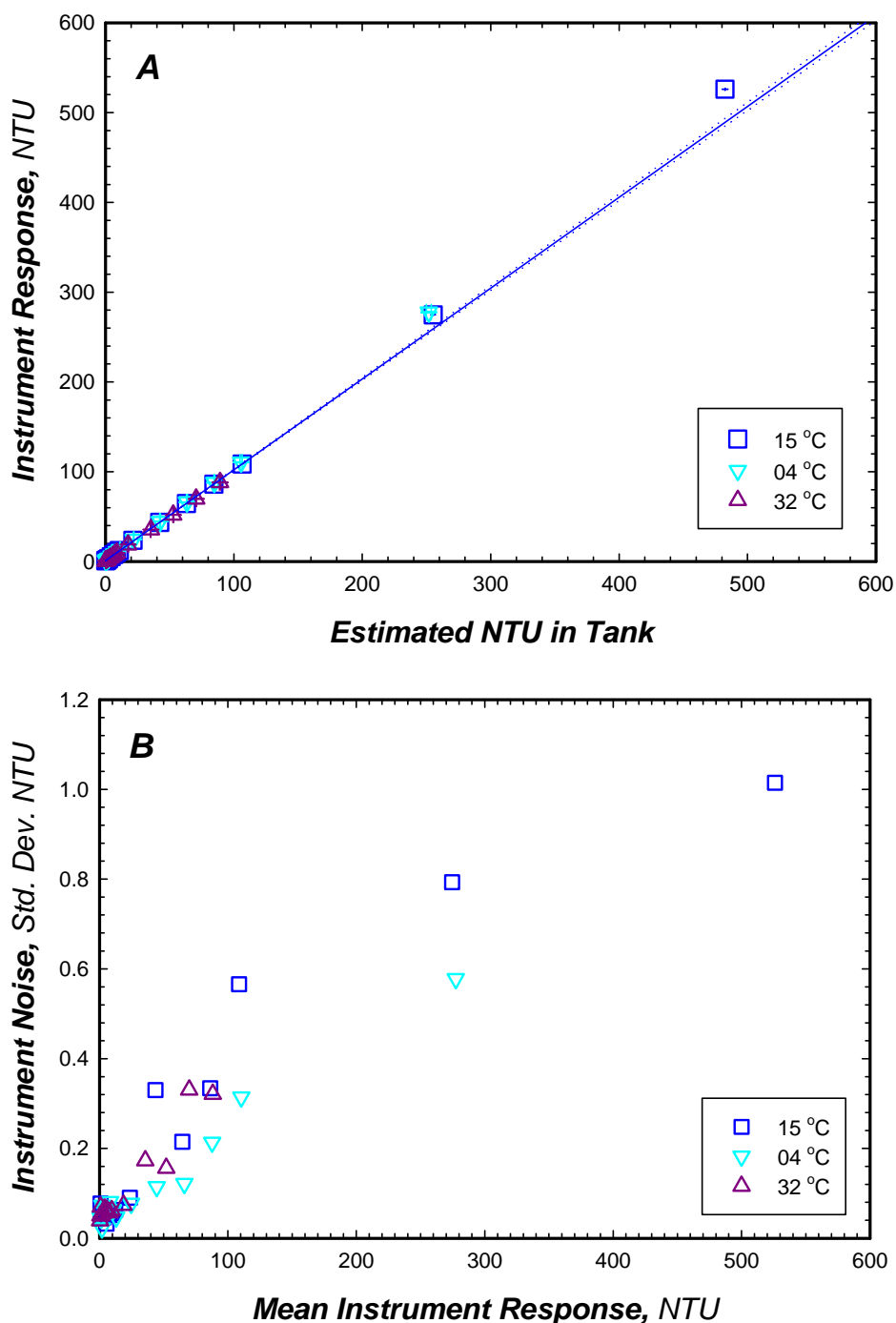


Figure 2. In-Situ's Troll 9500 signal and instrument noise in response to increasing turbidity derived from Formazin added to filtered deionized water at three test temperatures. **(A)** Mean detector response to sequential additions of known Formazin concentrations. Instrument response over a turbidity range normally observed in natural waters (0-100 NTU) was modeled by linear regression. Modeled response at 15°C, with 99% confidence intervals (dotted lines): $NTU_{instru} = 1.012NTU_{FRMZ} + 1.004$, $r^2 = 0.999$, demonstrates response is linear through at least 260 NTU Frmz. Detector response was unaffected by the ambient temperatures tested. **(B)** Signal noise (s.d.) ranged from 0.2 to 7% of measured signal and was independent of temperature. The increase in signal s.d. with Formazin turbidity, likely results from detection of particle aggregates in suspension.

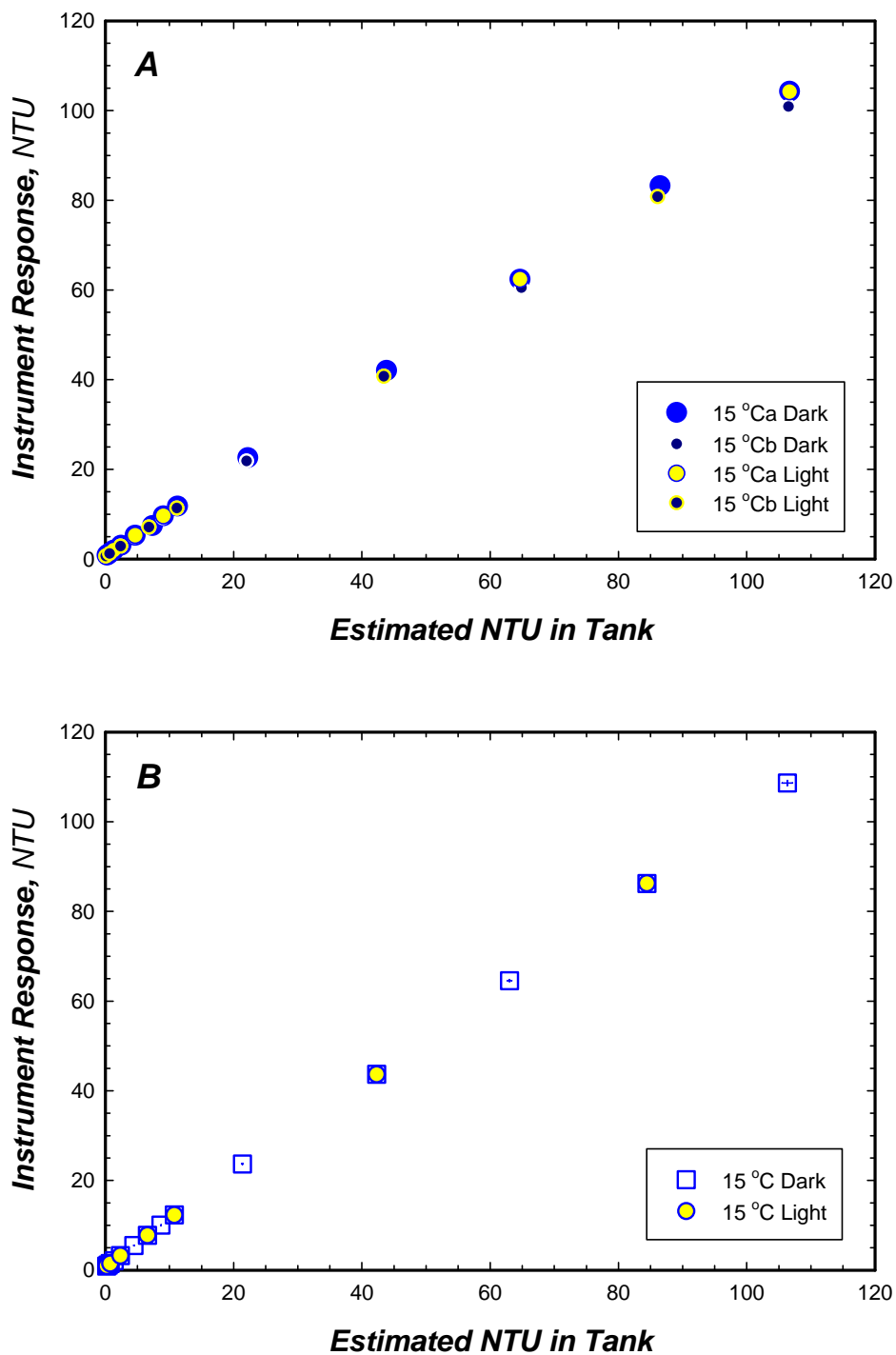


Figure 3. Effects of down-welling irradiance on turbidity measurement by the In-Situ Troll 9500 turbidity sensor. Surface irradiance applied at each indicated test concentration using a bank of three 500W halogen lamps. E_0 : 400-500 $\mu\text{mol quanta m}^{-2} \text{s}^{-1}$ measured using a Licor 190S detector. **(A)** Mean detector response to sequential additions of known *SDVB* concentrations. **(B)** Mean detector response to sequential additions of known *Formazin* concentrations. Exposure to down-welling irradiance did not have a significant impact on instrument response under these test conditions.

VERIFICATION RESULT, MOORED FIELD TESTS:**Field Site Characterization**

The performance of the In-Situ Troll 9500 Turbidity Probe was examined in field deployment tests at each of seven Partner Institution test sites. The deployment duration ranged from 4 – 8 weeks depending on the expected rate of biofouling and the frequency of water quality sampling. The range and mean for temperature, salinity, TSS, and duration for the deployment at each test site is given in Table 1. Across sites, temperature ranged from 10 – 32 °C, salinity from 0.2 – 39, and TSS from 0.4 – 82 mg L⁻¹.

Table 1. Range and average for temperature, salinity, and total suspended solids at each of the test sites during the sensor field deployment, and the duration of the deployment in days.

SITES		Temperature (°C)	Salinity	TSS (mg.L ⁻¹)
Moss Landing Harbor, CA (n = 44 days)	Min.	11.9	30.4	10.4
	Max.	16.8	33.4	82.4
	Mean	14.4	32.5	29.1
Offshore Tampa Bay, FL (n = 77 days)	Min.	26.5	36.8	1.1
	Max.	31.5	38.9	8.5
	Mean	29.1	38.1	3.4
Skidaway Island, GA (n = 30 days)	Min.	26.8	23.3	10.6
	Max.	31.2	32.8	80.7
	Mean	29.3	27.7	27.0
Kaneohe Bay, HI (n = 41 days)	Min.	23.7	33.5	1.4
	Max.	29.1	35.0	25.1
	Mean	26.7	34.6	10.2
Chesapeake Bay, MD (n = 30 days)	Min.	23.6	10.9	5.1
	Max.	30.8	14.5	23.2
	Mean	27.3	13.2	10.0
Damariscotta Estuary, ME (n = 37 days)	Min.	10.1	26.4	2.5
	Max.	17.8	30.3	6.6
	Mean	13.7	28.7	4.0
Winans Lake, MI (n = 31 days)	Min.	15.7	0.2	1.2
	Max.	23.2	0.2	2.3
	Mean	19.0	0.2	1.8

Benthic sediment size grain analysis and site specific carbon content

A general characterization of the grain size distribution for surface sediments at each of the mooring locations was performed just prior to the field tests. The particle size distribution of each sediment sample (range 0 – 2 mm) was analyzed by the laser light scattering method (ASTM D4464). Four of the sites (HI, MI, MD and GA) had peak particle composition in the size range 200-350 μm (Fig. 4), with GA having a secondary peak of sediment particle sizes around 7 μm . The remaining sites (CA, FL and ME) had their main particle size range at or below 20 μm . Two of these sites (CA and ME) peaked in the 7-10 μm range, while FL showed a maximum at 20 μm . Visual inspection of the samples also revealed that two of the sites (FL and HI) had a great numbers of shell fragments > 2mm. Due to the size limitation on the laser light scattering method however, these were not included in particle size distribution given here.

Lastly, an analysis of the percent C content of total suspended solids was performed on all of data collected by each test site to help distinguish the range of particulate matter composition present for these field tests (Fig. 5). This ratio provides a coarse measure of the importance of allochthonous inputs or resuspension versus contributions from algal abundance since pure organic matter would have roughly 50% of its dry weight mass as carbon. Most of the sites (CA, FL, GA, HI, ME) had an average carbon (C) content in the range of 3 – 12% of total suspended solids, while the remaining two sites had 25% (MD) and 39 % (MI).

Total Suspended Solids and Particulate Organic Carbon

While ACT makes no claim that data derived from *in situ* turbidity sensors should directly correlate with total suspended solids (TSS) or particulate organic carbon (POC), these parameters were designated as useful ancillary data to characterize the abundance, and to some extent, the type of particulate matter present in the test environments. Considerable effort was made to ensure and report the highest quality TSS and POC data. ACT applied site specific blank corrections to the raw data for both parameters in order to adjust the values to reflect truer, mean values. Details about these correction procedures are provided in the turbidity sensor verification protocols and in Appendix 3, *Determination of TSS and POC Blank Corrections for the ACT 2006 Turbidity Sensor Verification* and may be downloaded at www.act-us.info/evaluations_reports.php.

In brief, each mean TSS value was corrected using derived estimates from procedural blanks intended to serve as a measure of mass loss of filter material combined with mass carry over due to potential cross-contamination. All sites maximized the volume they could filter within the 30 minute time allotted for sample processing in an effort to maximize signal to noise ratios. Overall, blanks at ACT's seven Partner sites were -0.0001 ± 0.0006 g with a median of -0.0002 g ($n = 128$) (Fig. 6A). This blank represents a very small negative offset, but was important to consider in samples with very low TSS. Although blanks from all seven test sites fell within the same confidence belt, blank corrections were applied independently at each site to incorporate any subtle between-site differences in particle characteristics, equipment, and processing.

Similarly, all POC concentrations were corrected using derived estimates from procedural blanks intended to quantify both carbon contamination present in the glass fiber filter, as well as from any dissolved organic carbon (DOC) that may potentially adsorb to the filter during sample filtration. All POC concentrations were therefore corrected by a wet-blank that consisted of dunking pre-combusted 25 mm Whatman GFF filters in sample filtrate processed during our standard POC collection. Final corrections were made using a site-specific average of the 4 – 8 blanks generated by each site. The site-specific averaged blank, ranged from 0.01 – 0.06 mg (Fig. 6B). On most occasions, the POC blanks were substantially less than the field samples, but were important to consider when low POC concentrations are present.

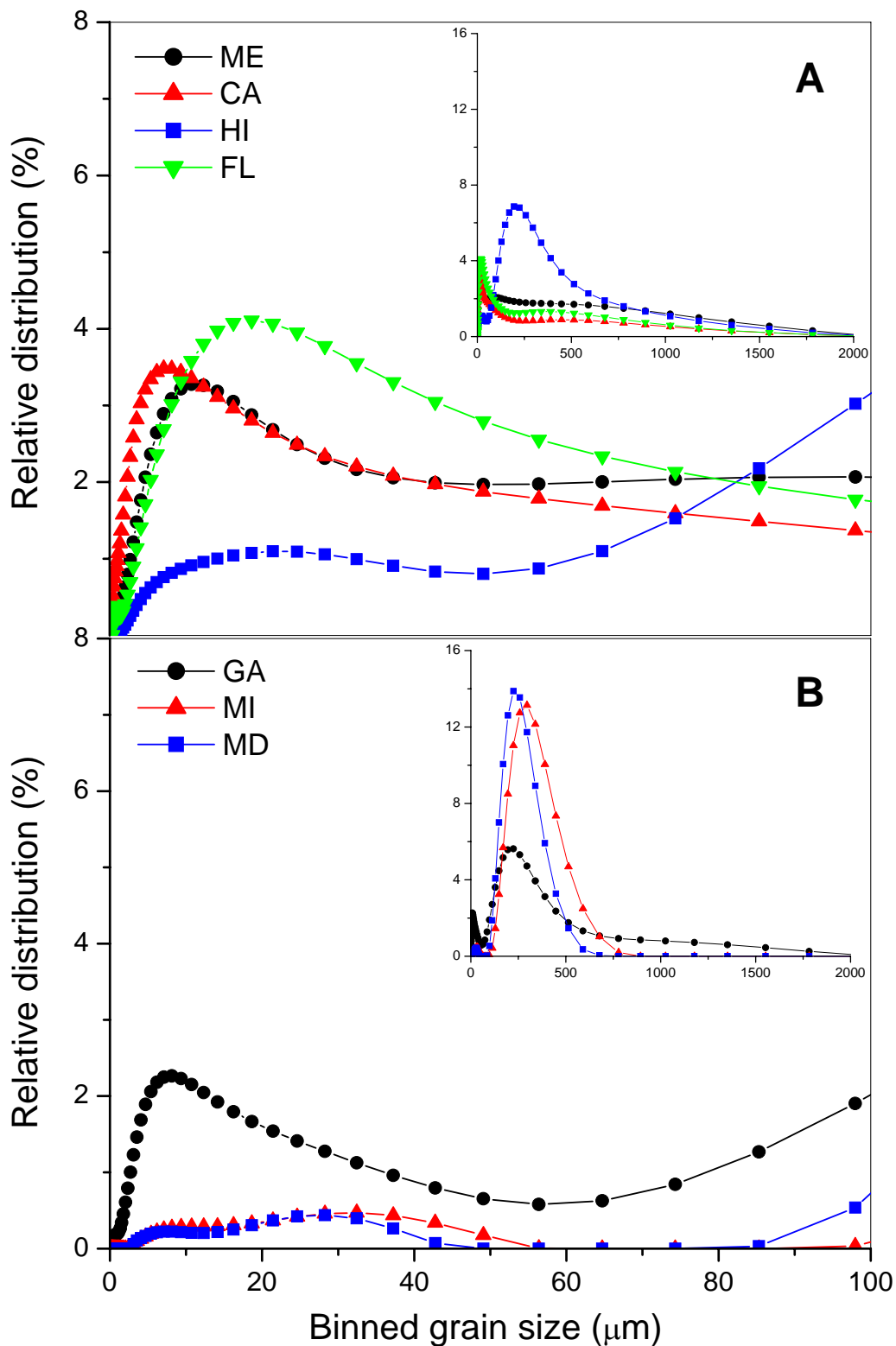


Figure 4. Normalized volume concentrations (%) of the benthic sediment grain size distribution collected at each site during the field test period. The size distribution (not corrected for bin size) was measured by Laser Light Scattering (ASTM D4464-00) at STL Burlington (Colchester, VT) on sediment particles < 2 mm.

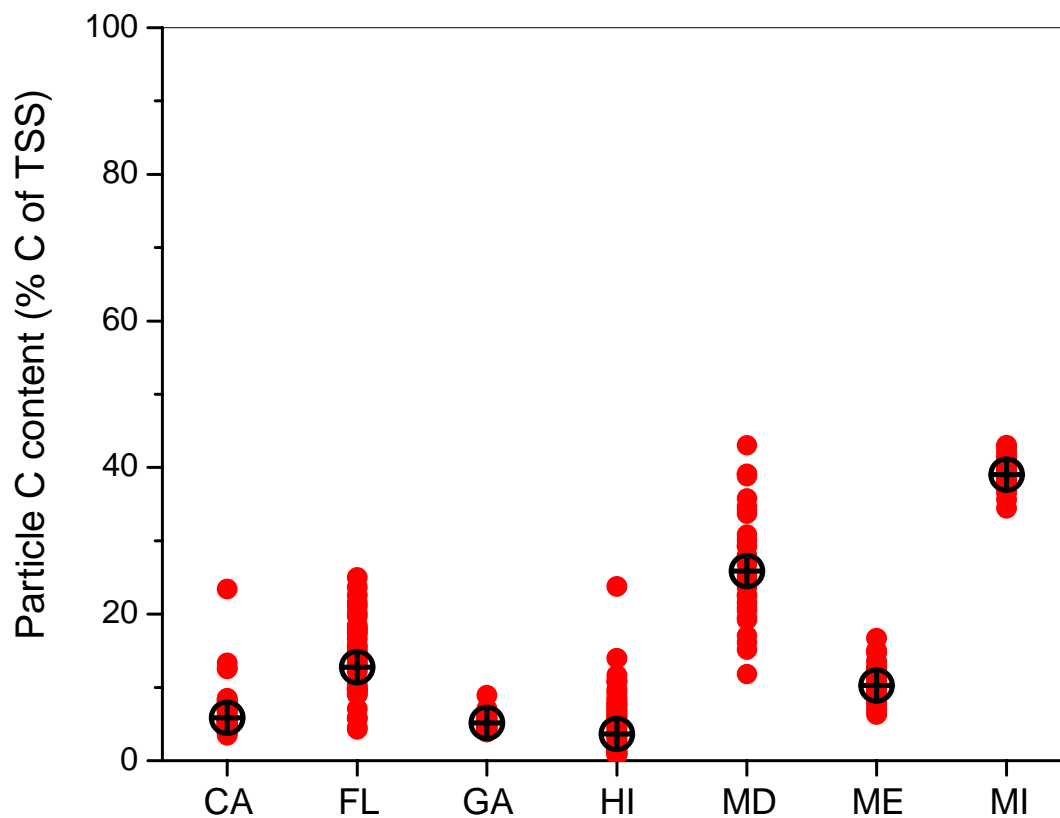


Figure 5. Particulate organic carbon (C) calculated as a percentage of total suspended solids (TSS) at each field site. At each site, particle C content was generated for each sampled time point (red dots) and the most frequent value (the mode) was also calculated (black crosshairs).

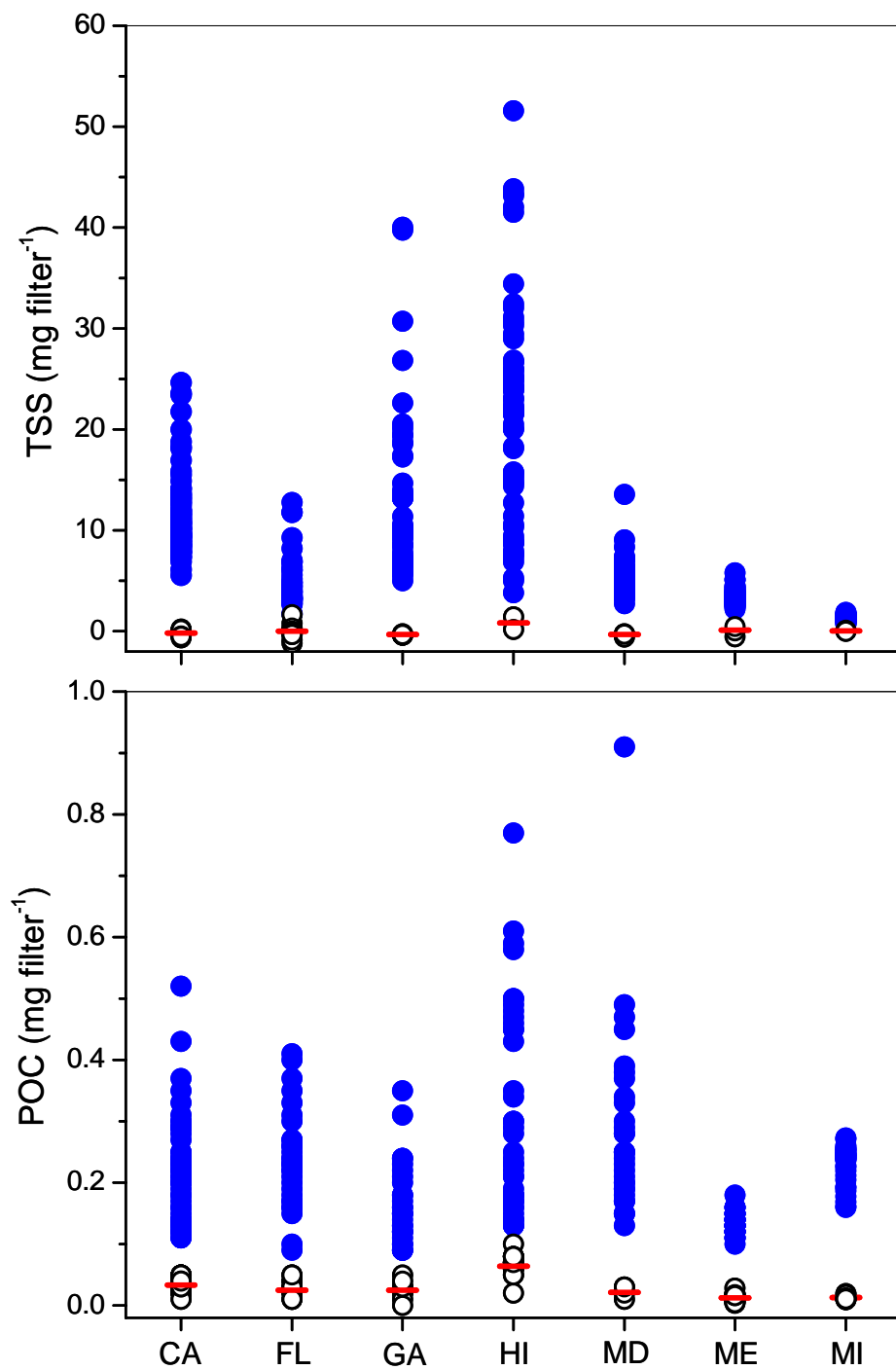


Figure 6. Total suspended solids (TSS; A) and particulate organic carbon (POC; B) collected at each study site. Field samples are shown as total amount of TSS and POC collected per filter (blue dots; mg filter⁻¹). The average blanks (red bars) were calculated from the field blanks (TSS; open circles) and the wet blanks (POC; open circles) used in the calculation of TSS and POC per liter.

Field Deployment Results

Results of the field tests from each of the seven sites are presented on the following pages in figures 7 – 20. The data from each site are presented in two consecutive figures followed by a table of results for pre- and post-readings of reference standards and photographs of the sensor. Panel A of the first figure for each site (7A, 9A, 11A, 13A, 15A, 17A and 19A) displays the time series of the turbidity sensor measurements for the entire deployment. Panel B of these figures displays a time series of beam attenuation (BAC) with units of m^{-1} derived from the SeaTech transmissometer (blue line) overlain with TSS values (black dots) taken from discrete water samples throughout the test. TSS samples were collected and the transmissometer cleaned each day of the work-week, but not on weekends. The effect of the extra time between cleaning can be seen as apparent increases in BAC at some of sites where biofouling was extensive. Panel A of the second figure for each site (8A, 10A, 12A, 14A, 16A, 18A and 20A) displays corresponding temperature (black line) and salinity (red line) at field sites collected by the independently deployed CTD. Panel B of these figures displays a time series of an independently moored *in situ* fluorometer (green line) overlaid with POC values (black dots) taken from discrete water samples throughout the test. Again, POC samples were collected and the fluorometer cleaned each day of the work-week, but not on weekends. The lack of transmissometer and fluorometer data at the USF test site (Figs. 9 & 10) is due to instrument damage resulting from a storm surge at the test site during Tropical Storm Alberto.

Pre and Post-deployment tests

Results of the pre- and post readings of reference standards by the test sensor and by the lab-based Hach 2100AN Turbidimeter are given for each site in Tables 2 – 8. The values represent the average of three independent readings collected using the same sampling set-up used in the field. Instruments were cleaned and wipers removed before dunking the sensor in the test solution for the post-reading to prevent contamination. The post Hach2100AN reading is from an aliquot of the test solution measured by the sensor and indicates whether any contamination resulted from the exposure of the test instrument or sample handling.

Comparisons across all field sites

Given that all instruments tested at the seven different field sites were programmed and calibrated under identical procedures and that all ancillary data was processed the same, it was possible to examine how the test instrument responded over the complete range of environmental conditions to which it was exposed. To that end we plotted instrument readings against estimated values for transmissometer beam attenuation, TSS, and POC collectively from all sites (Fig. 21). In general, there was a strong linear relationship between the instrument response and measured beam attenuation coefficient over the observed range of 0.5 – 30 BAC. However, the plot clearly reveals that the instrument response is very site specific and reflective of differences in the types and sizes of the particles generating the turbidity. In particular, instrument response was much more variable relative to TSM at the Hawaii test site and exhibited a much different slope for the range of TSM at the Maine test site. The relationship to POC was generally more variable across sites as well as within individual sites and seemed to exhibit much less influence on measured turbidity.

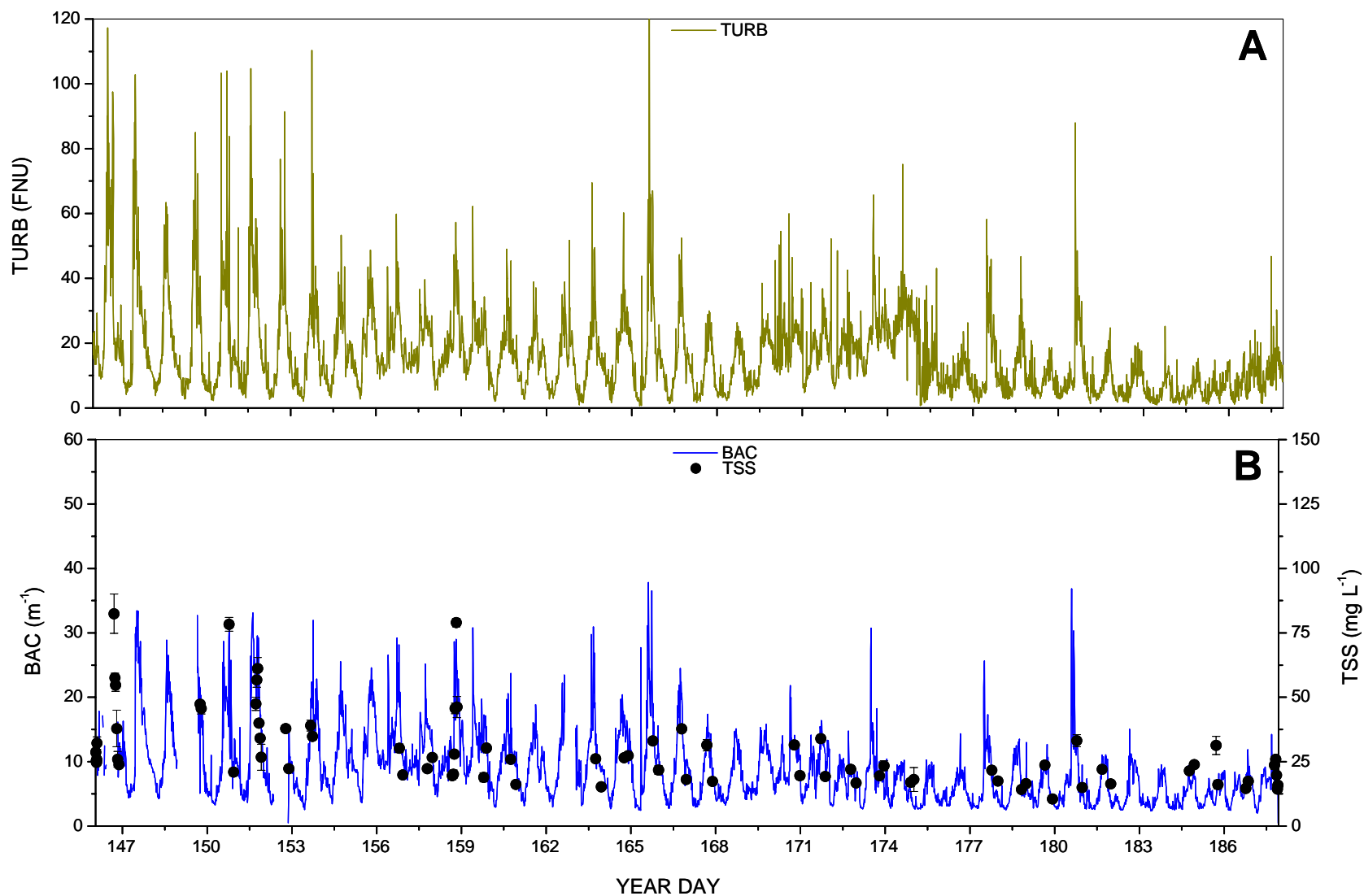


Figure 7. Moss Landing Harbor, CA. A) Turbidity (TURB; Formazin Nephelometric Units) measured by the In-Situ Troll 9500; B) Beam Attenuation Coefficient (BAC) measured by an in situ transmissometer, and total suspended solids (TSS).

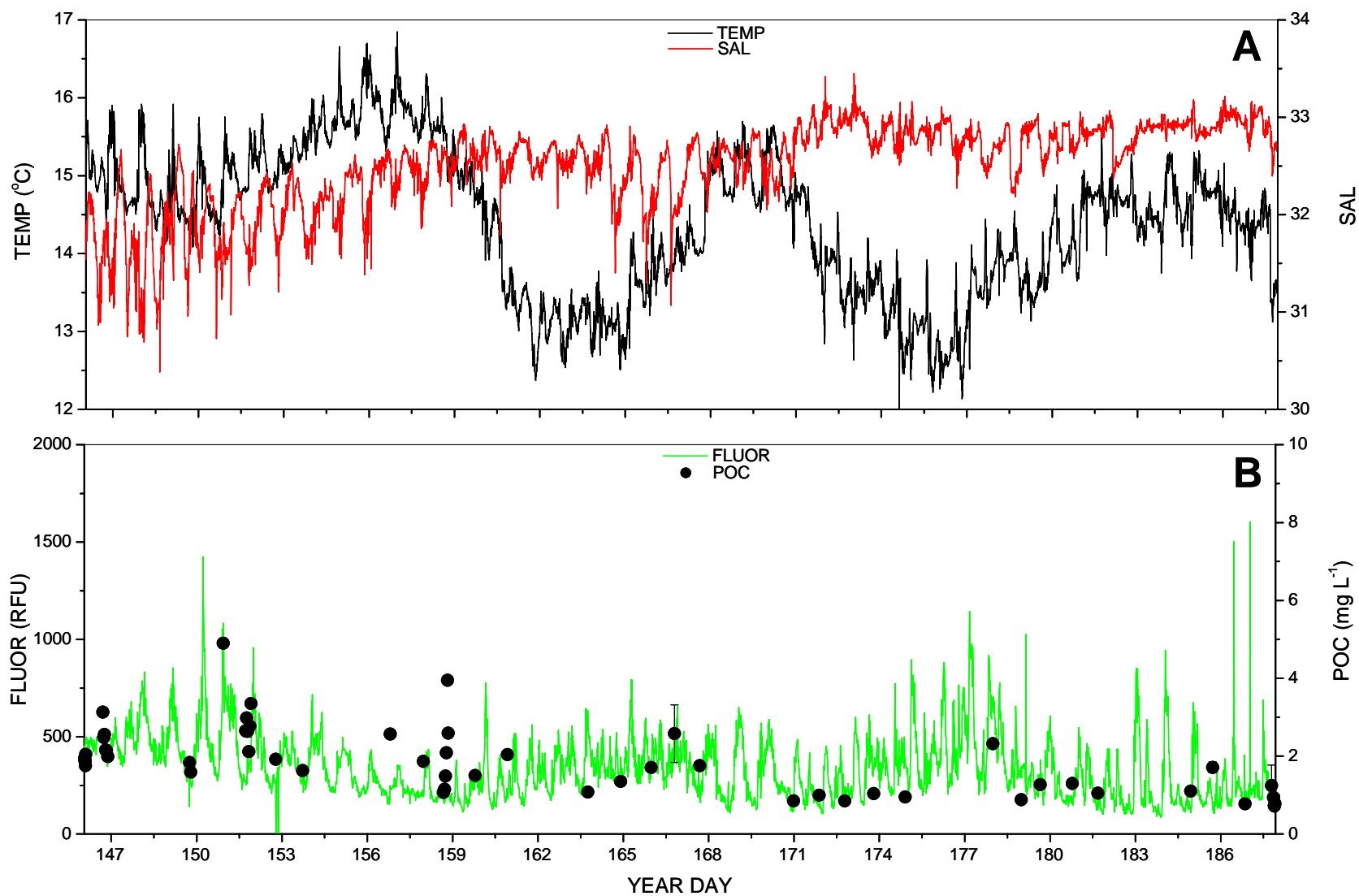


Figure 8. Moss Landing Harbor, CA. A) Temperature (TEMP) and salinity (SAL); B) Fluorescence (FLUOR in Relative Fluorescence Units) measured by an in situ fluorometer, and particulate organic carbon (POC).

Table 2. Instrument readings of reference turbidity standards before (PRE) and after (POST) the field deployment at the Moss Landing, California test site. Sensor readings are the average of three independent readings taken at 15-minute intervals. The two reference standards were designed to be essentially clear water (nominal 0 NTU) and a light to moderate turbidity level (nominal 5 NTU). PRE and POST values that are the same or similar demonstrates little or no instrument drift over time. However, it is important to note that instrument drift is only one possible explanation for PRE and POST values that differ. Factors such as imperfect post-deployment cleaning or standard solution contamination may also result in measured differences.

Reference Standard	PRE sensor value	POST sensor value
Nominal 0 NTU	-3.2	-3.0
Nominal 5 NTU	2.2	2.0

Sensor Photographs

Photographs of the In-Situ Troll 9500 turbidity sensor immediately prior to the field deployment and immediately after recovery. Images are intended to document the total extent of biofouling experienced by the sensor during the deployment. A weekly, photographic, time-series of biofouling plates was also produced from the site to qualitatively document the rate at which the biofouling occurred (see Appendix 2).

Pre-Deployment



Post-Deployment



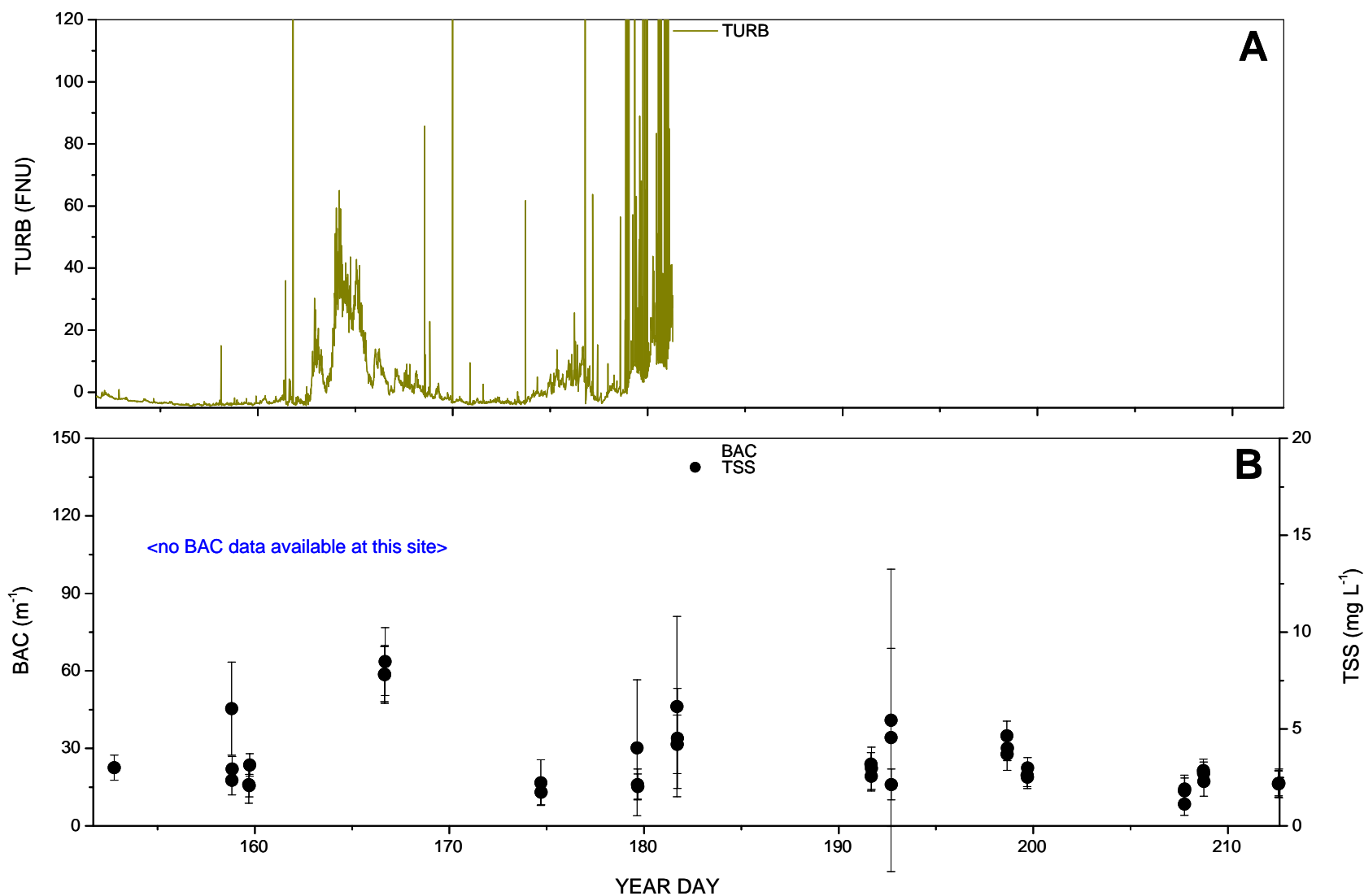


Figure 9. Offshore of Tampa Bay, FL. A) Turbidity (TURB; Formazin Nephelometric Units) measured by the In-Situ Troll 9500; B) Beam Attenuation Coefficient (BAC) measured by an in situ transmissometer, and total suspended solids (TSS).

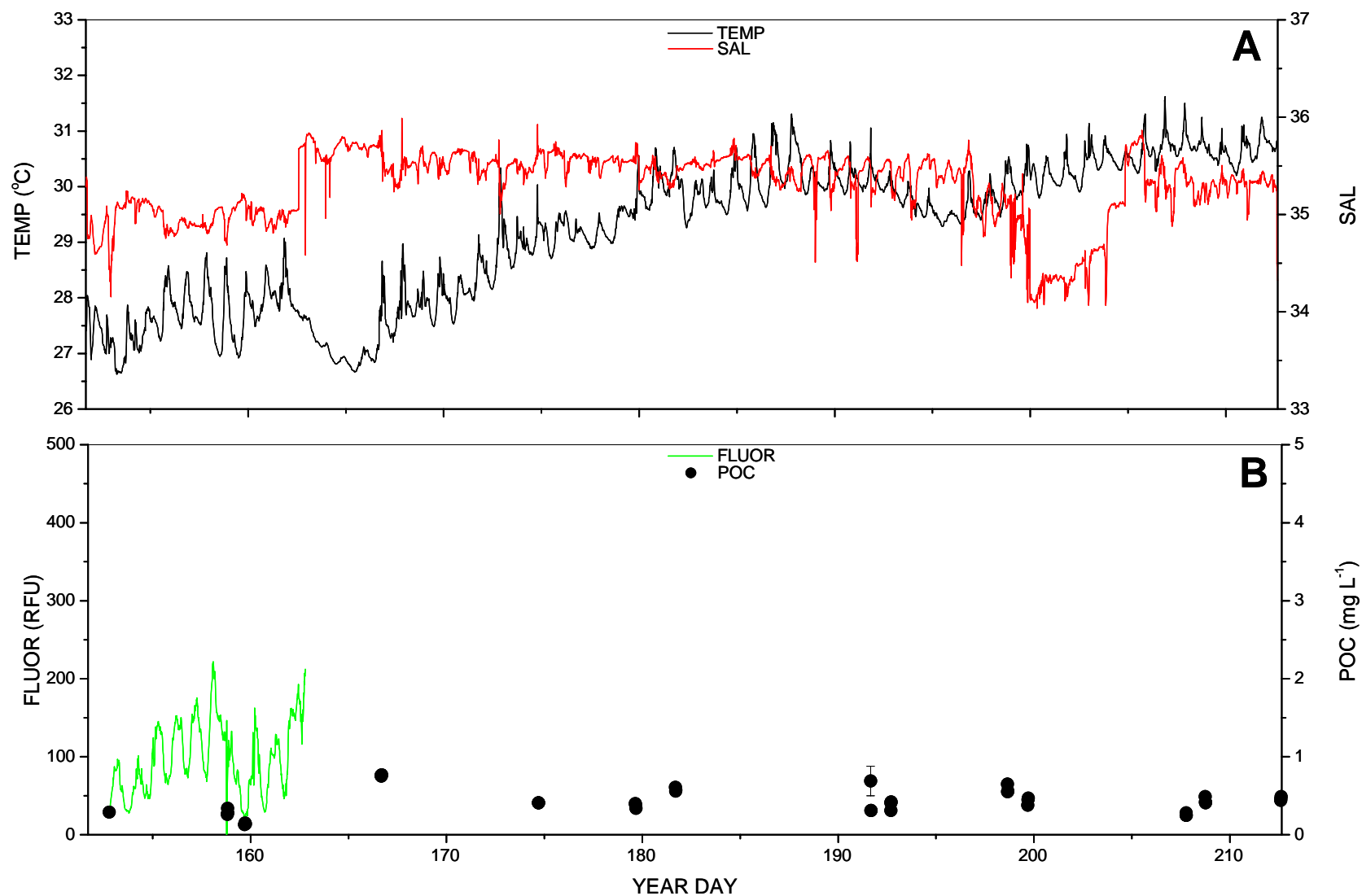


Figure 10. Offshore of Tampa Bay, FL. A) Temperature (TEMP) and salinity (SAL); B) Fluorescence (FLUOR in Relative Fluorescence Units) measured by an in situ fluorometer, and particulate organic carbon (POC).

Table 3. Instrument readings of reference turbidity standards before (PRE) and after (POST) the field deployment at the University of South Florida test site. Sensor readings are the average of three independent readings taken at 15-minute intervals. The two reference standards were designed to be essentially clear water (nominal 0 NTU) and a light to moderate turbidity level (nominal 5 NTU). PRE and POST values that are the same or similar demonstrates little or no instrument drift over time. However, it is important to note that instrument drift is only one possible explanation for PRE and POST values that differ. Factors such as imperfect post-deployment cleaning or standard solution contamination may also result in measured differences.

Reference Standard	PRE sensor value	POST sensor value
Nominal 0 NTU	-6.6	-4.1
Nominal 5 NTU	-1.1	-1.6

Sensor Photographs

Photographs of the In-Situ Troll 9500 turbidity sensor immediately prior to the field deployment and immediately after recovery. Images are intended to document the total extent of biofouling experienced by the sensor during the deployment. A weekly, photographic, time-series of biofouling plates was also produced from the site to qualitatively document the rate at which the biofouling occurred (see Appendix 2).

Pre-Deployment



Post-Deployment



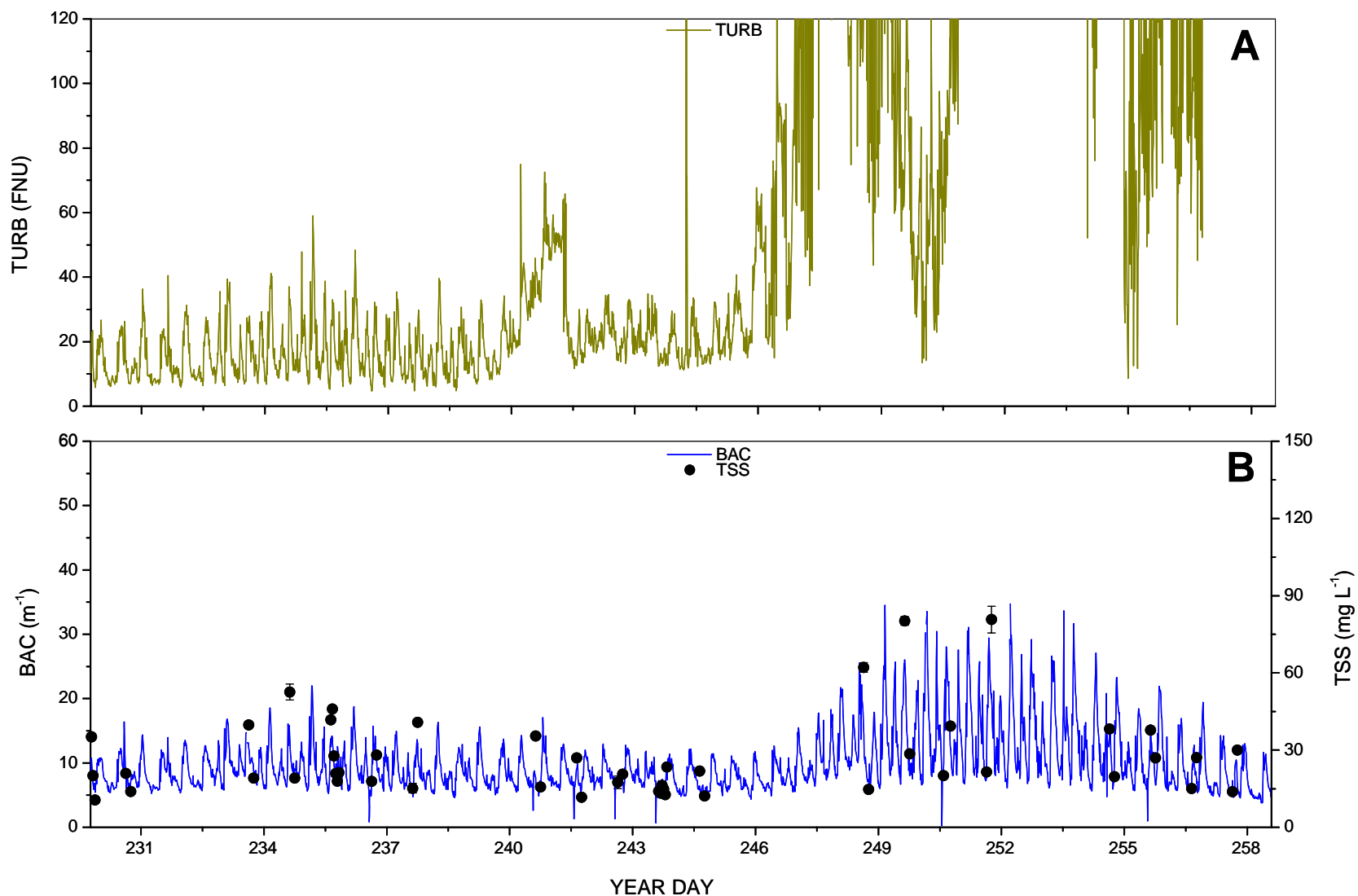


Figure 11. Skidaway Island, GA. A) Turbidity (TURB; Formazin Nephelometric Units) measured by the In-Situ Troll 9500; B) Beam Attenuation Coefficient (BAC) measured by an in situ transmissometer, and total suspended solids (TSS).

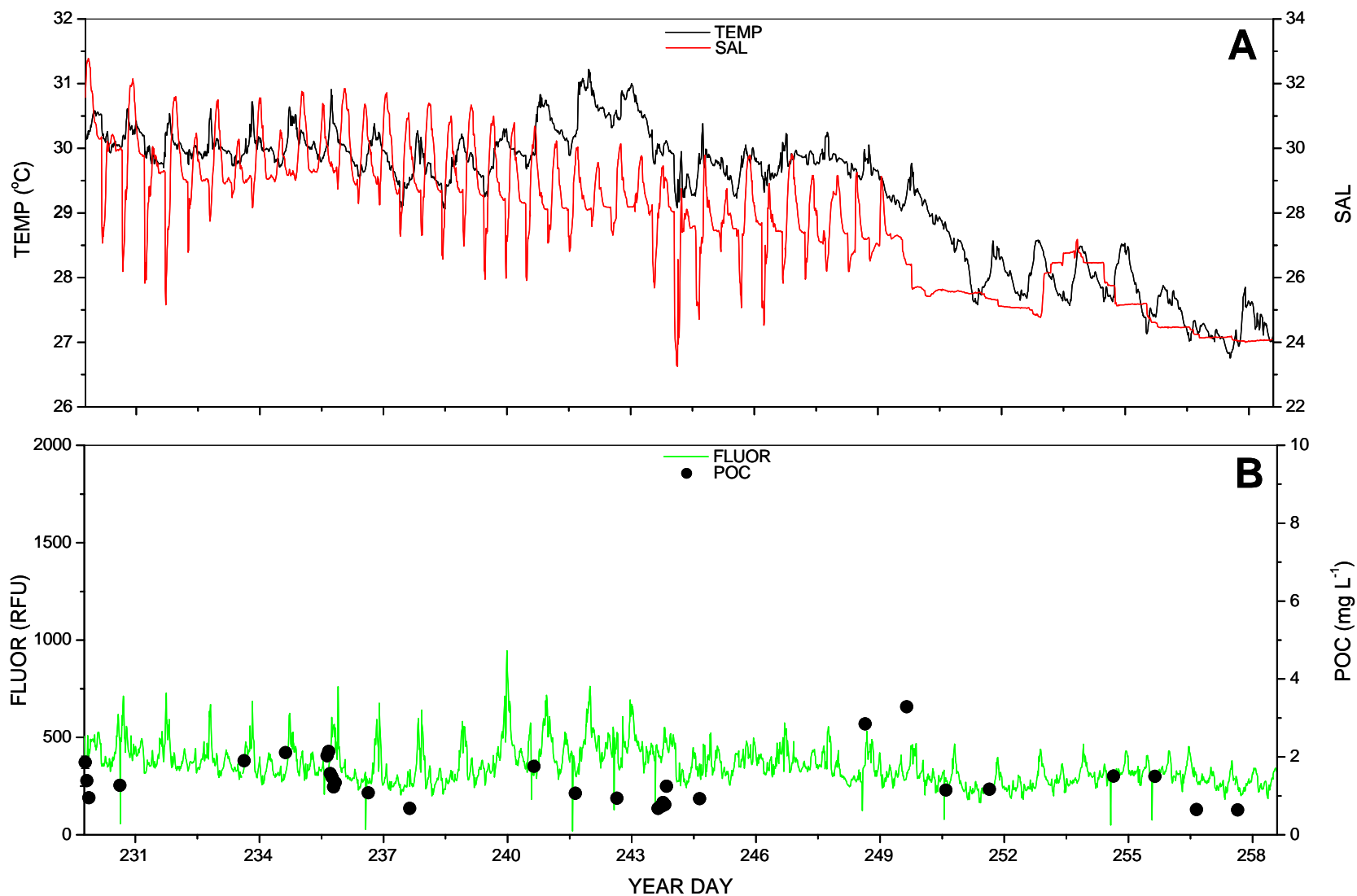


Figure 12. Skidaway Island, GA. A) Temperature (TEMP) and salinity (SAL); B) Fluorescence (FLUOR in Relative Fluorescence Units) measured by an in situ fluorometer, and particulate organic carbon (POC).

Table 4. Instrument readings of reference turbidity standards before (PRE) and after (POST) the field deployment at the Skidaway Institute of Oceanography, Georgia test site. Sensor readings are the average of three independent readings taken at 15-minute intervals. The two reference standards were designed to be essentially clear water (nominal 0 NTU) and a light to moderate turbidity level (nominal 5 NTU). PRE and POST values that are the same or similar demonstrates little or no instrument drift over time. However, it is important to note that instrument drift is only one possible explanation for PRE and POST values that differ. Factors such as imperfect post-deployment cleaning or standard solution contamination may also result in measured differences.

Reference Standard	PRE sensor value	POST sensor value
Nominal 0 NTU	-0.6	-1.8
Nominal 5 NTU	5.6	4.8

Sensor Photographs

Photographs of the In-Situ Troll 9500 turbidity sensor immediately prior to the field deployment and immediately after recovery. Images are intended to document the total extent of biofouling experienced by the sensor during the deployment. A weekly, photographic, time-series of biofouling plates was also produced from the site to qualitatively document the rate at which the biofouling occurred (see Appendix 2).

Pre-Deployment



Post-Deployment



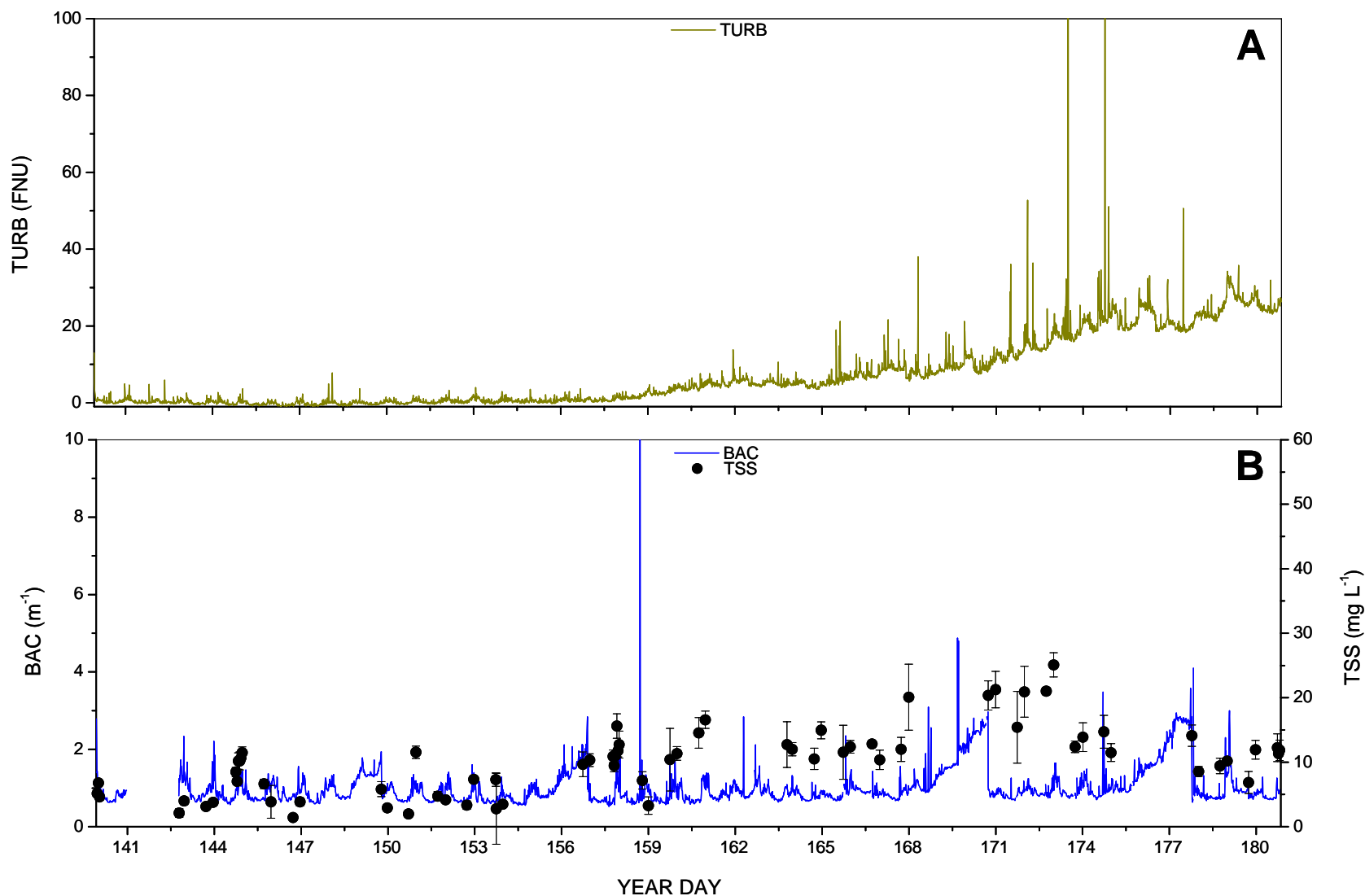


Figure 13. Kaneohe Bay, HI. A) Turbidity (TURB; Formazin Nephelometric Units) measured by the In-Situ Troll 9500; B) Beam Attenuation Coefficient (BAC) measured by an in situ transmissometer, and total suspended solids (TSS).

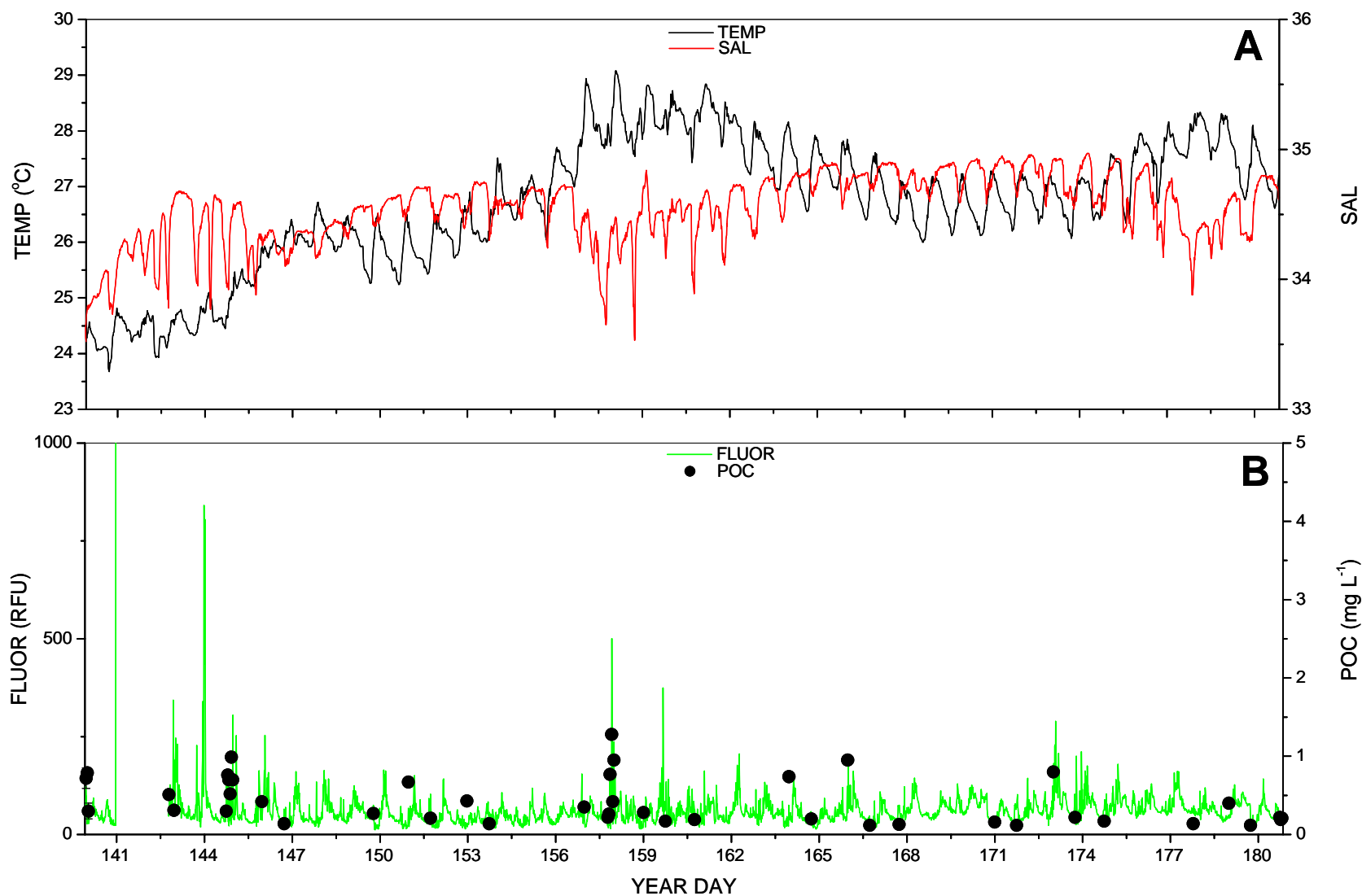


Figure 14. Kaneohe Bay, HI. A) Temperature (TEMP) and salinity (SAL); B) Fluorescence (FLUOR in Relative Fluorescence Units) measured by an in situ fluorometer, and particulate organic carbon (POC).

Table 5. Instrument readings of reference turbidity standards before (PRE) and after (POST) the field deployment at the University of Hawaii test site. Sensor readings are the average of three independent readings taken at 15-minute intervals. The two reference standards were designed to be essentially clear water (nominal 0 NTU) and a light to moderate turbidity level (nominal 5 NTU). PRE and POST values that are the same or similar demonstrates little or no instrument drift over time. However, it is important to note that instrument drift is only one possible explanation for PRE and POST values that differ. Factors such as imperfect post-deployment cleaning or standard solution contamination may also result in measured differences.

Reference Standard	PRE sensor value	POST sensor value
Nominal 0 NTU	-3.0	-2.9
Nominal 5 NTU	2.2	2.8

Sensor Photographs

Photographs of the In-Situ Troll 9500 turbidity sensor immediately prior to the field deployment and immediately after recovery. Images are intended to document the total extent of biofouling experienced by the sensor during the deployment. A weekly, photographic, time-series of biofouling plates was also produced from the site to qualitatively document the rate at which the biofouling occurred (see Appendix 2).

Pre-Deployment



Post-Deployment



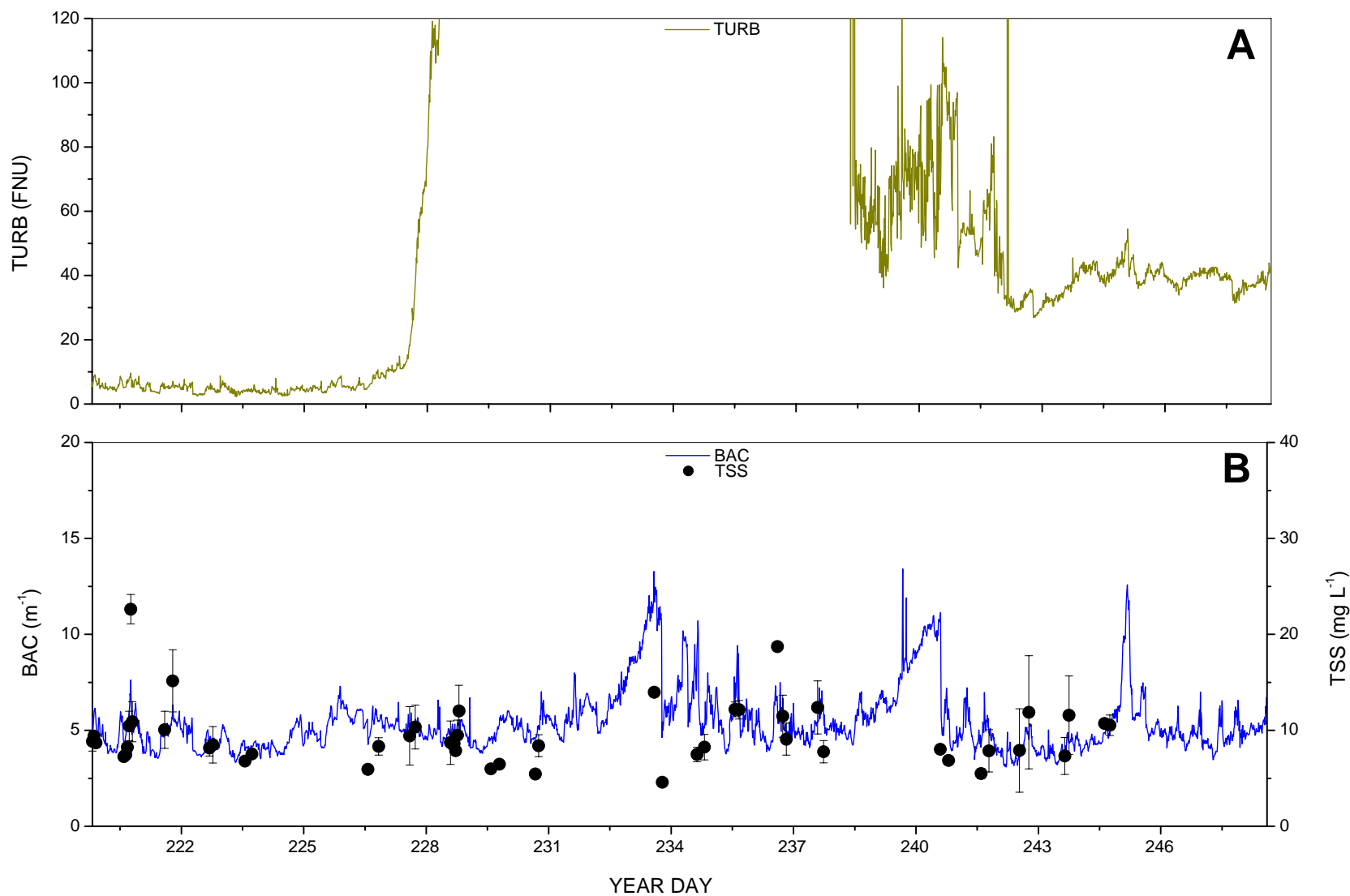


Figure 15. Chesapeake Bay, MD. A) Turbidity (TURB; Formazin Nephelometric Units) measured by the In-Situ Troll 9500; B) Beam Attenuation Coefficient (BAC) measured by an in situ transmissometer, and total suspended solids (TSS).

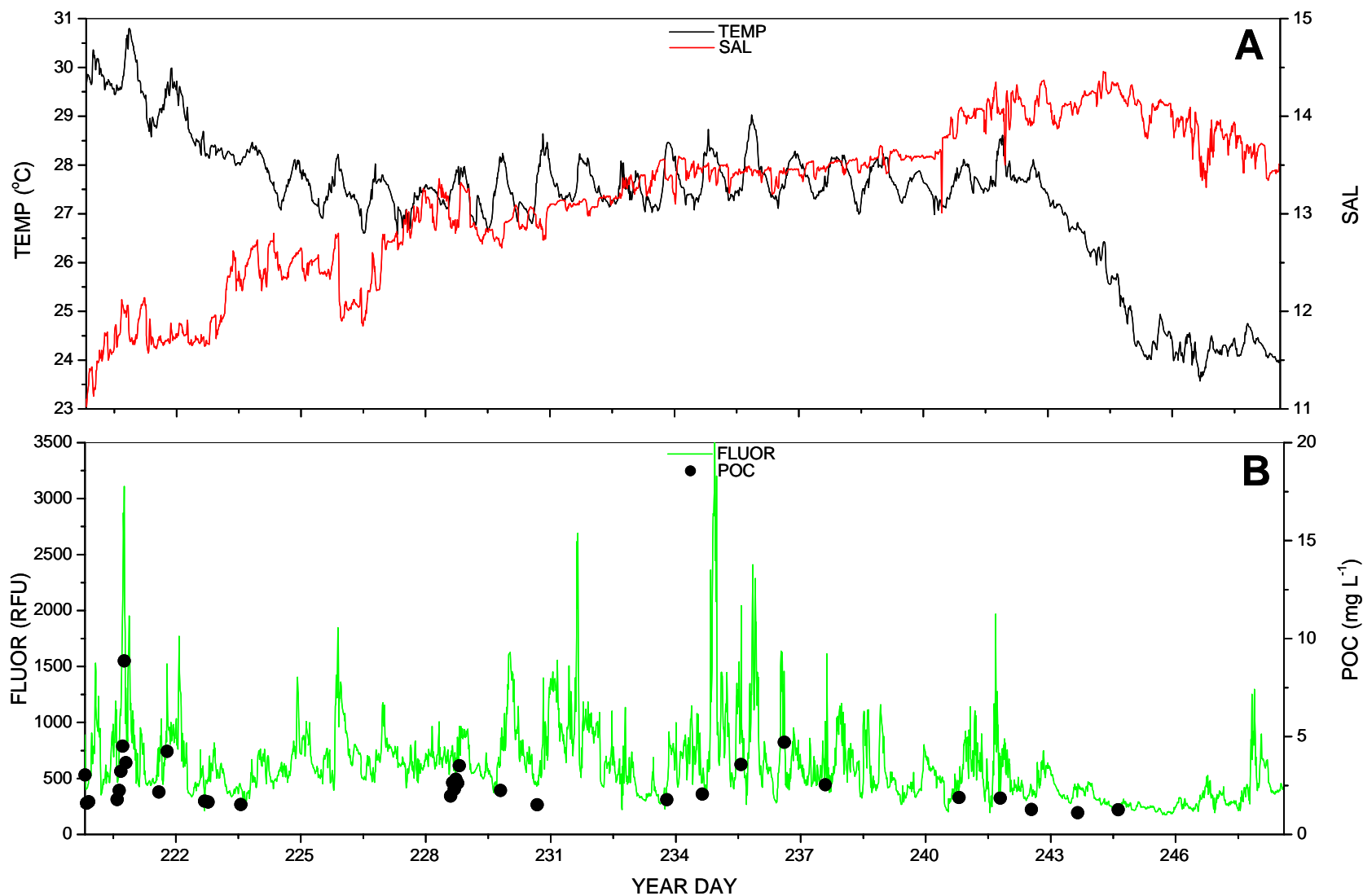


Figure 16. Chesapeake Bay, MD. A) Temperature (TEMP) and salinity (SAL); B) Fluorescence (FLUOR in Relative Fluorescence Units) measured by an in situ fluorometer, and particulate organic carbon (POC).

Table 6 Instrument readings of reference turbidity standards before (PRE) and after (POST) the field deployment at the Chesapeake Biological Laboratory test site. Sensor readings are the average of three independent readings taken at 15-minute intervals. The two reference standards were designed to be essentially clear water (nominal 0 NTU) and a light to moderate turbidity level (nominal 5 NTU). PRE and POST values that are the same or similar demonstrates little or no instrument drift over time. However, it is important to note that instrument drift is only one possible explanation for PRE and POST values that differ. Factors such as imperfect post-deployment cleaning or standard solution contamination may also result in measured differences.

Reference Standard	PRE sensor value	POST sensor value
Nominal 0 NTU	-3.6	-3.2
Nominal 5 NTU	2.5	2.9

Sensor Photographs

Photographs of the In-Situ Troll 9500 turbidity sensor immediately prior to the field deployment and immediately after recovery. Images are intended to document the total extent of biofouling experienced by the sensor during the deployment. A weekly, photographic, time-series of biofouling plates was also produced from the site to qualitatively document the rate at which the biofouling occurred (see Appendix 2).

Pre-Deployment



Post-Deployment



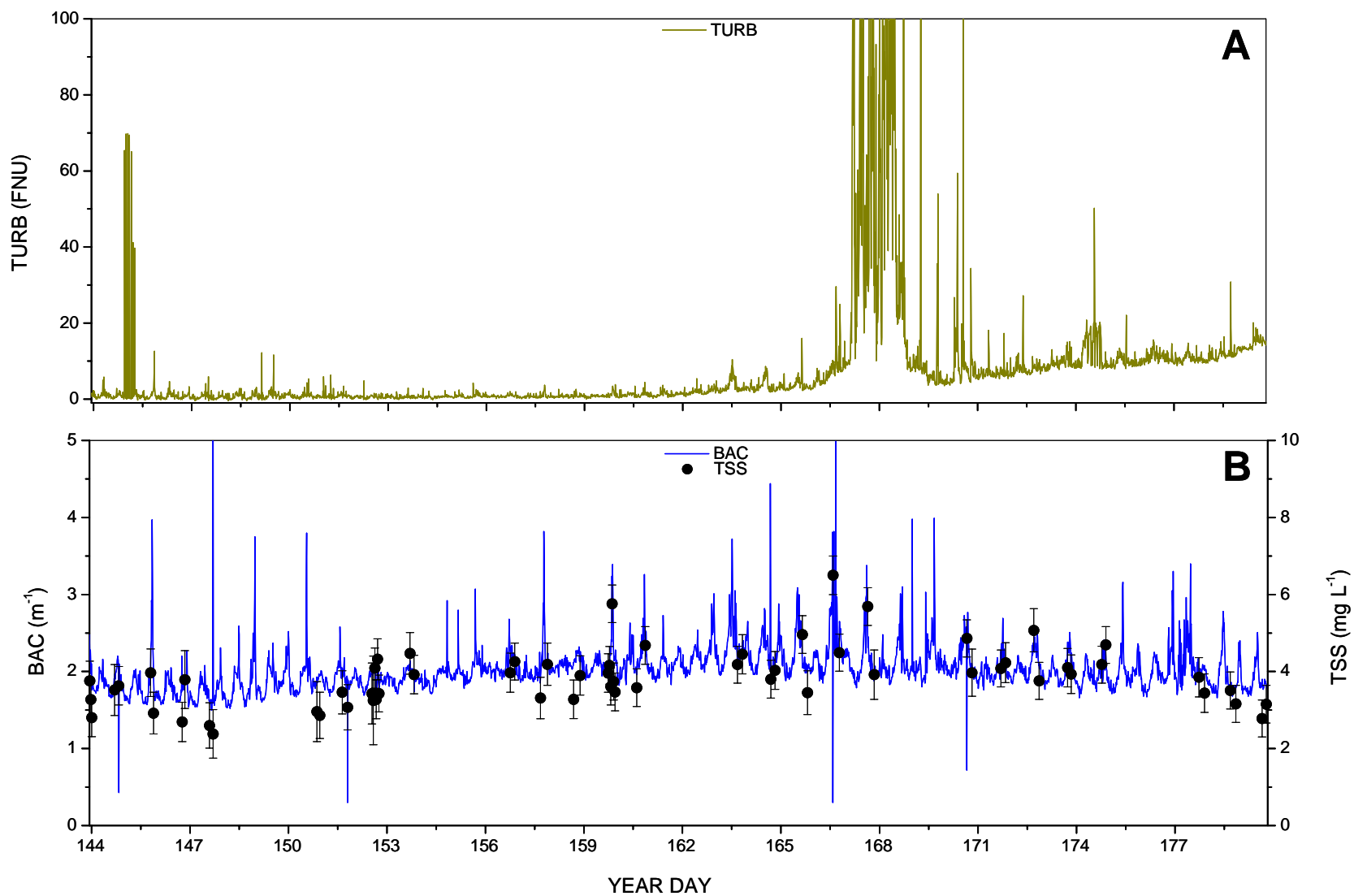


Figure 17. Damariscotta River Estuary, ME. A) Turbidity (TURB: Nephelometric Units) measured by the In-Situ Troll 9500; B) Beam Attenuation Coefficient (BAC) measured by an in situ transmissometer, and total suspended solids (TSS).

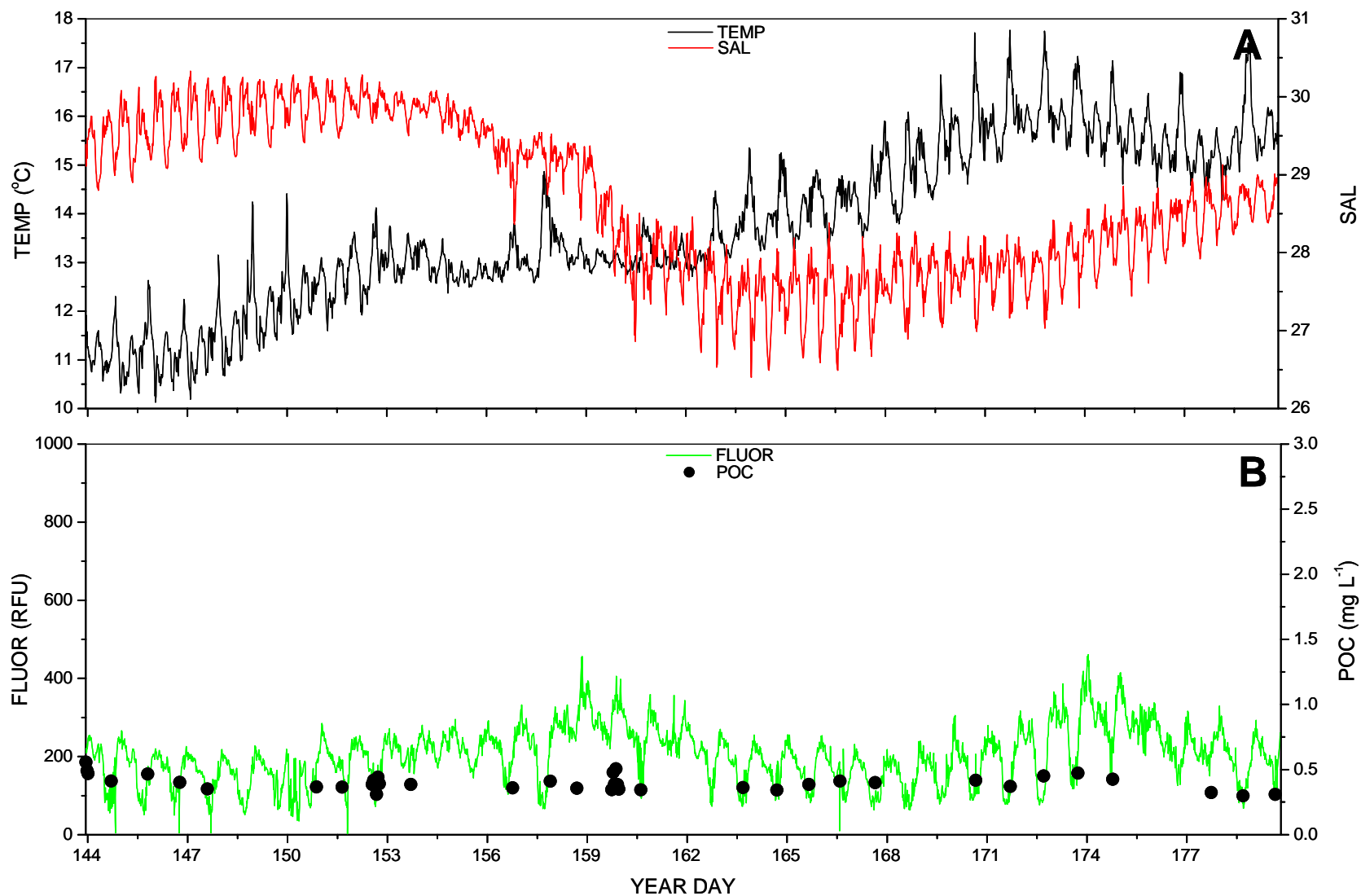


Figure 18. Damariscotta River Estuary, ME. A) Temperature (TEMP) and salinity (SAL); B) Fluorescence (FLUOR in Relative Fluorescence Units) measured by an in situ fluorometer, and particulate organic carbon (POC).

Table 7. Instrument readings of reference turbidity standards before (PRE) and after (POST) the field deployment at the Gulf of Maine Ocean Observing System test site. Sensor readings are the average of three independent readings taken at 15-minute intervals. The two reference standards were designed to be essentially clear water (nominal 0 NTU) and a light to moderate turbidity level (nominal 5 NTU). PRE and POST values that are the same or similar demonstrates little or no instrument drift over time. However, it is important to note that instrument drift is only one possible explanation for PRE and POST values that differ. Factors such as imperfect post-deployment cleaning or standard solution contamination may also result in measured differences.

Reference Standard	PRE sensor value	POST sensor value
Nominal 0 NTU	-2.8	-3.5
Nominal 5 NTU	2.2	2.4

Sensor Photographs

Photographs of the In-Situ Troll 9500 turbidity sensor immediately prior to the field deployment and immediately after recovery. Images are intended to document the total extent of biofouling experienced by the sensor during the deployment. A weekly, photographic, time-series of biofouling plates was also produced from the site to qualitatively document the rate at which the biofouling occurred (see Appendix 2).

Pre-Deployment



Post-Deployment



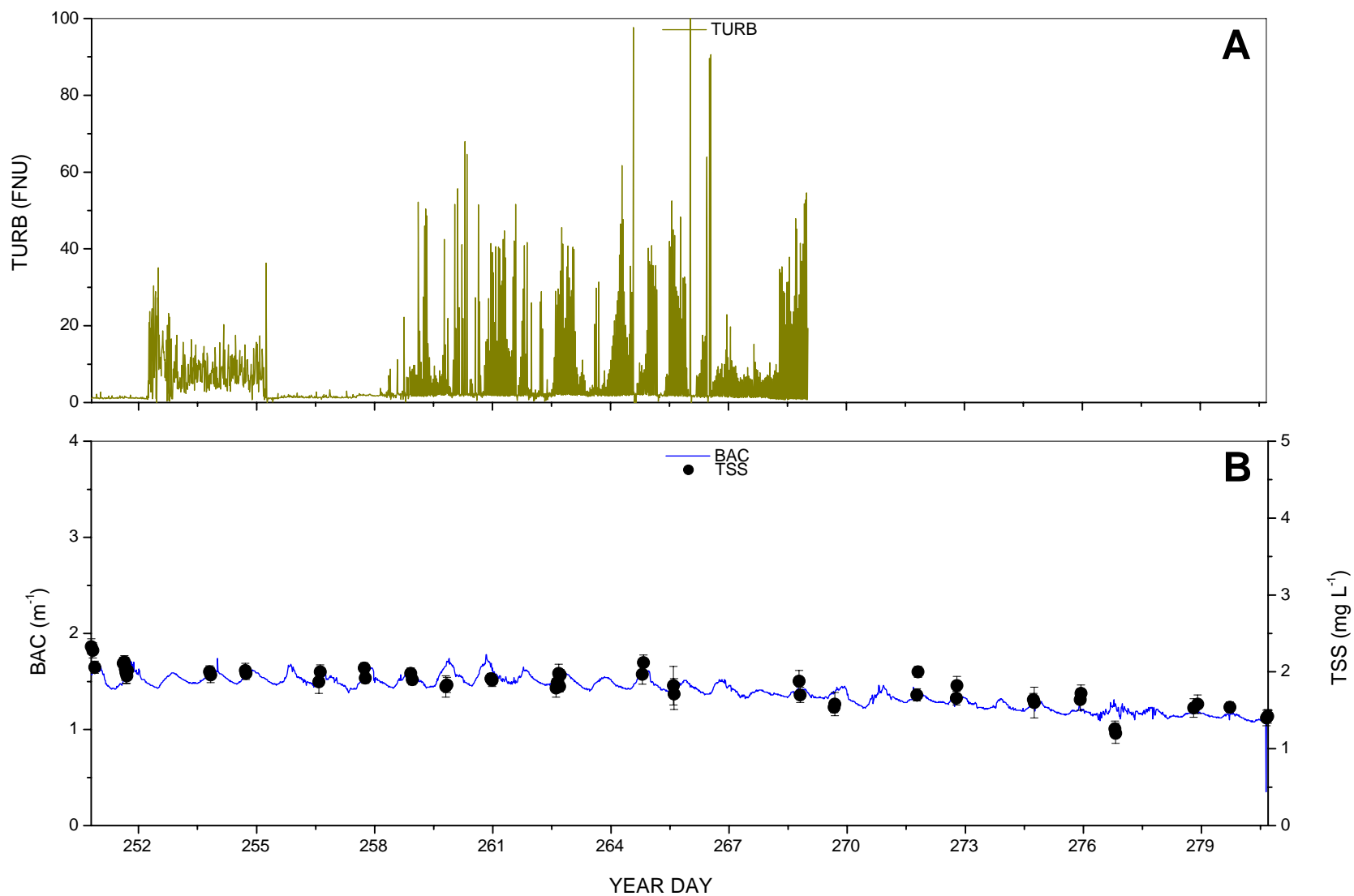


Figure 19. Winans Lake, MI. A) Turbidity (TURB; Formazin Nephelometric Units) measured by the In-Situ Troll 9500; B) Beam Attenuation Coefficient (BAC) measured by an in situ transmissometer, and total suspended solids (TSS).

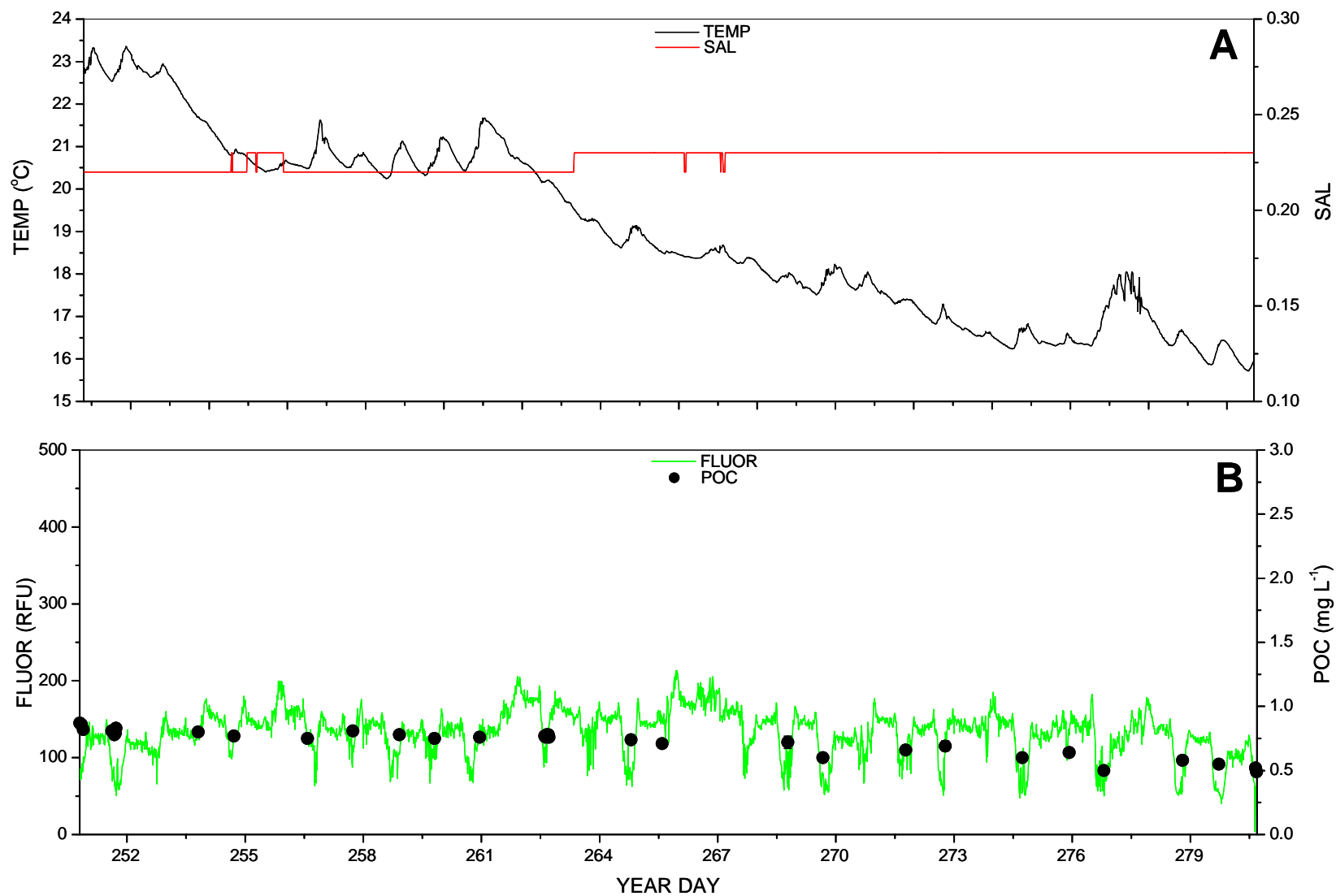


Figure 20. Winans Lake, MI. A) Temperature (TEMP) and salinity (SAL); B) Fluorescence (FLUOR in Relative Fluorescence Units) measured by an in situ fluorometer, and particulate organic carbon (POC).

Table 8. Instrument readings of reference turbidity standards before (PRE) and after (POST) the field deployment at the University of Michigan, Great Lakes test site. Sensor readings are the average of three independent readings taken at 15-minute intervals. The two reference standards were designed to be essentially clear water (nominal 0 NTU) and a light to moderate turbidity level (nominal 5 NTU). PRE and POST values that are the same or similar demonstrates little or no instrument drift over time. However, it is important to note that instrument drift is only one possible explanation for PRE and POST values that differ. Factors such as imperfect post-deployment cleaning or standard solution contamination may also result in measured differences. At this site, post deployment readings were obtained after new batteries were installed, as they had died during the deployment.

Reference Standard	PRE sensor value	POST sensor value
Nominal 0 NTU	-0.7	-5.0
Nominal 5 NTU	6.1	4.8

Sensor Photographs

Photographs of the In-Situ Troll 9500 turbidity sensor immediately prior to the field deployment and immediately after recovery. Images are intended to document the total extent of biofouling experienced by the sensor during the deployment. A weekly, photographic, time-series of biofouling plates was also produced from the site to qualitatively document the rate at which the biofouling occurred (see Appendix 2).

Pre-Deployment



Post-Deployment



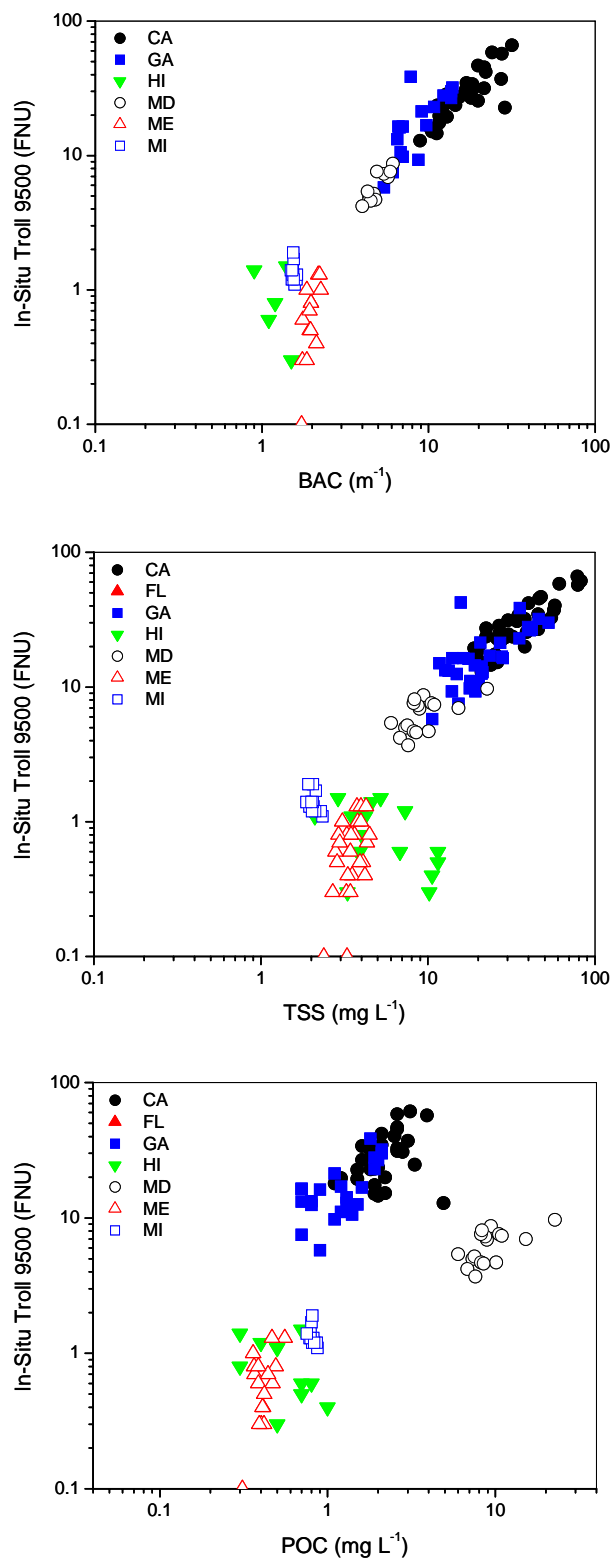


Figure 21. In-Situ Troll 9500 turbidity data (in Formazin Nephelometric Units) plotted against Beam Attenuation Coefficients (BAC), collected total suspended solids (TSS) and particulate organic carbon (POC).

INSTRUMENT RELIABILITY:**Laboratory**

We retrieved 100% of the expected data from the seven laboratory tests conducted with the In-Situ Troll 9500 Turbidity Probe.

Field Tests

Sensors were programmed to collect and record turbidity data every 15 minutes during the moored field deployments at each of the ACT test sites. The duration of deployments ranged from four – eight weeks. Four different instruments were used during this verification. During the test at Skidaway, GA it was noticed during the initial battery replacement that the battery compartment had previously experienced a leak and there was considerable corrosion, with the bottom spring actually corroded apart. After servicing the instrument ourselves, it functioned properly throughout the entire deployment. At the Michigan test site, the battery compartment flooded after 2 days into the deployment and the sensor stopped working. There was no obvious damage in the o-rings and the instrument had appeared to be sealed properly. Because we were not able to determine the cause of the leak we offered a repeat test of another instrument at a new test site. At the end of the re-test in Michigan the instrument was also not working upon retrieval, apparently due to a battery failure. The instrument functioned properly for 19 of the 31 days of the deployment. There was no sign of leakage, and the malfunctioned appeared to be a simple battery problem despite the fact that brand new batteries, from an unopened package, were put into the instrument prior to the deployment. The Florida test site also experienced a terminated test due to a battery failure. Part of the problem at this site was the extended length of time the instrument was logging prior to the actual deployment. Lithium batteries were used for this test to allow for the longer deployment interval, however a two week delay between when the instrument was calibrated and logging initiated and the actual field deployment, extended the duration beyond the battery capacity. The instrument actually ran for 46 days, which included 30 of the 77 days of the deployment. Lastly, at the Hawaii test site the instruments' wiper system failed sometime during the deployment and was not working upon retrieval.

ACKNOWLEDGMENTS:

We wish to acknowledge the support of all those who helped plan and conduct the verification test, analyze the data, and prepare this report. In particular we would like to thank our Technical Advisory Committee, E. Boss, J. Harrigan, N. Hawley, M. Luther, S. McLean, W.S. Pegau, and P. Pennington for their advice and direct participation in various aspects of this evaluation. E. Buckley also provided critical input on all aspects of this work and served as the independent Quality Assurance Manager. This work has been coordinated with, and funded by, the National Oceanic and Atmospheric Administration, Coastal Services Center, Charleston, SC.

March 30, 2007

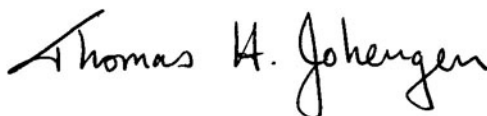
Date



Approved By: Dr. Mario Tamburri
ACT Executive Director

March 30, 2007

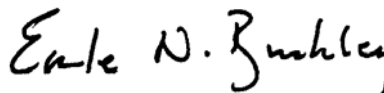
Date



Approved By: Dr. Tom Johengen
ACT Chief Scientist

March 30, 2007

Date



Approved By: Dr. Earle Buckley
Quality Assurance Supervisor



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Mario N. Tamburri, PhD, Executive Director
Alliance for Coastal Technologies

Dear Dr. Tamburri:

In-Situ was pleased to participate in the ACT Performance Verification of turbidity sensors.

As a matter of general advice, users should note that the sensor response depends on many properties of the sample including spectral reflectivity and particle size, as well as the optical design of the sensor. A correlation that was developed for one sample from a particular time and location may not hold for others. On the other hand, within its operating range a sensor will reliably detect changes in the concentration of scattering particles. Therefore turbidity is often employed as confirmation or a predictor of changes in other parameters, and as a trigger of sample collection events.

During the test program failures of the battery compartment seal occurred. These were traced to surface damage on the cover sleeves, allowing water intrusion into the battery compartment. This has been addressed at the factory in a corrective action.

The drift data includes an offset of approximately 3 NTU. This offset is a direct result of the instruction from In-Situ describing the sensor guard configuration to be used at each test stage. The intent was to allow a determination of drift of the sensor alone, without interference from accumulations of fouling on the guard. The difference between the pre- and post-deployment drift measurement figures therefore represent any changes in the sensor itself including accumulation of fouling on the optical windows. Drift experienced during the deployments was dominated by the accumulation of material on the sensor guard, and is evident in the signal traces.

Sincerely,

A handwritten signature in black ink, appearing to read "Tony Arnerich", written in a cursive style.

Tony Arnerich
Senior Chemist
In-Situ, Inc.