



PERFORMANCE VERIFICATION STATEMENT for the WET Labs ECO-BB-SB 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 WET Labs ECO-BB-SB 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 WET Labs ECO-BB-SB 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.

WET Labs provided an ECO-BB-SB optical backscattering sensor for the ACT turbidity evaluation. This sensor uses an LED light source at 660 nm and measures scattered light at a mean angle of 117 degrees. For determination of the turbidity level, the sensor was calibrated against a Formazin based standard, and provided output directly proportional to NTUs. The turbidity measurement is sensitive to within 0.01 NTU, and the standard range supplied from the factory extends to 25 NTU. For the ACT evaluation, sensitivity was set to approximately 0.025 NTU and the full scale range was set to 100 NTU. Designed for unattended deployments from weeks to months in duration, the ECO-BB-SB is a self-contained device, possessing its own batteries and storage of data. An integrated bio-wiper and copper faceplate on the optical head reduce the effects of bio-fouling accumulation on the sensor. The device is housed in a 6.3 cm diameter acetyl-co-polymer/ABS pressure housing and is rated to 300 m operating depth with the bio-wiper. The device communicates and downloads data through a RS232 serial data port and also supports a 0-5 VDC analog output. Sampling rate is user selectable to 8 Hz. AN ECO-BB-SB is capable of recording up to 65000 samples before requiring download and battery replacement.

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 was set to record 10 burst samples per minute. Following a 10 minute equilibration period at least 150 measurements were recorded at each test condition to assess instrument performance. Instrument response was linear over at least 0-85 NTU, and exhibited similar response factors for formazin- and SDVB-induced turbidity. However, even the small differences (ca. 2%) 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 300 consecutive burst measurements versus the mean signal for a selected subset of test conditions. For the SDVB test, the signal noise ranged from 5% to <0.1% of the measured signal across the turbidity test range (Fig. 1B). Absolute noise was not dependent on either temperature or the turbidity over the range of test conditions. For the formazin test, the relative signal noise ranged from 4% to <0.1% 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.

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.

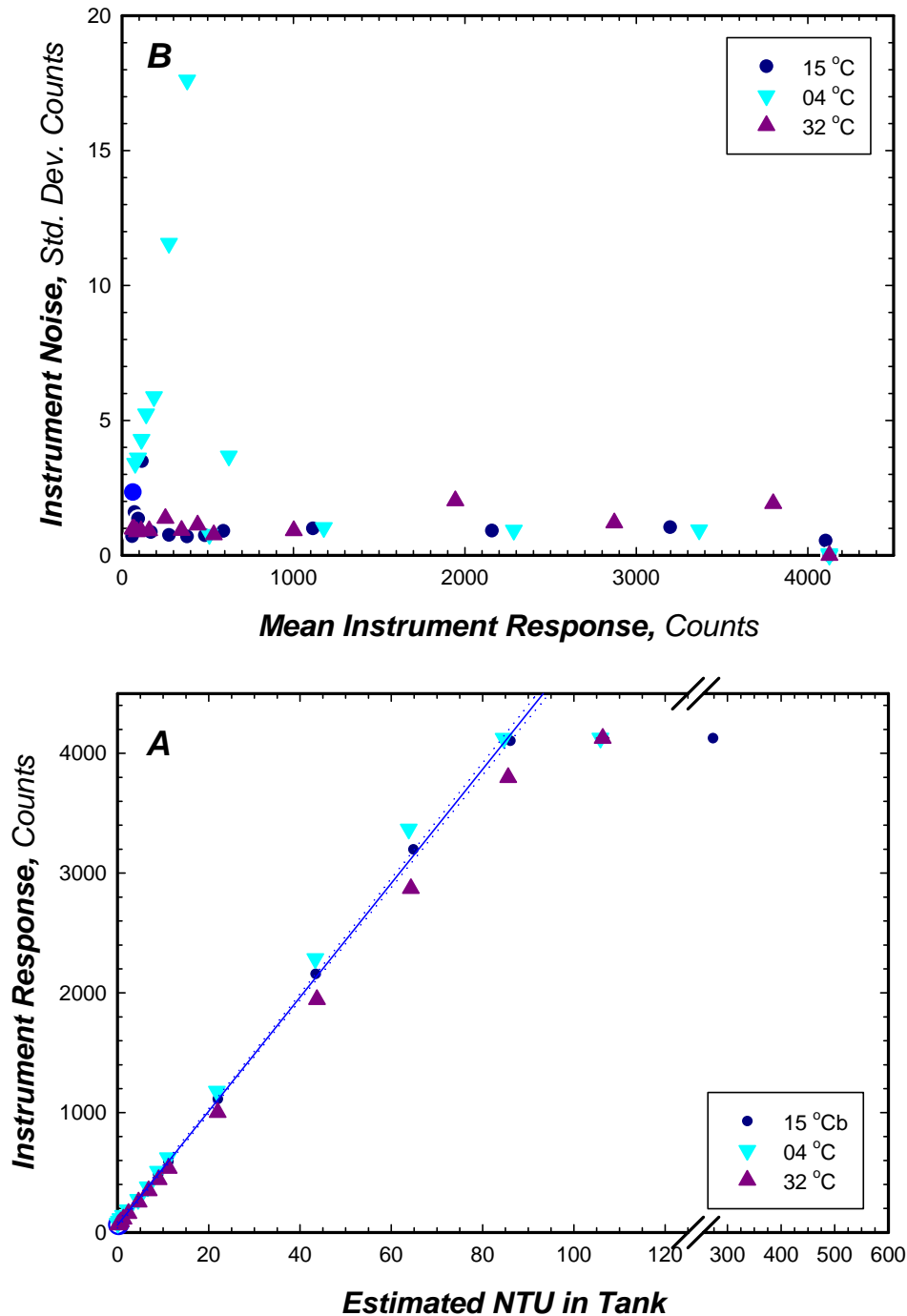


Figure 1. WET Lab's BBSB signal and instrument noise in response to increasing turbidity derived from SDVB added to filtered deionized water at three test temperatures. (A) Mean detector response to sequential additions of known SDVB concentrations. Instrument response over a turbidity range normally observed in natural waters (0-85 NTU) was modeled by linear regression. Modeled response at 15°C, with 99% confidence intervals (dotted lines): $\text{Counts} = 47.569\text{NTU}_{\text{SDVB}} + 61.686$, $r^2 = 0.999$, demonstrates response is linear up to 85 NTU SDVB. Detector response was lower at the highest temperature tested. (B) Signal noise (s.d.) ranged from <0.1 to 5% of measured signal in the presence of SDVB and no consistent temperature or turbidity dependence was detected.

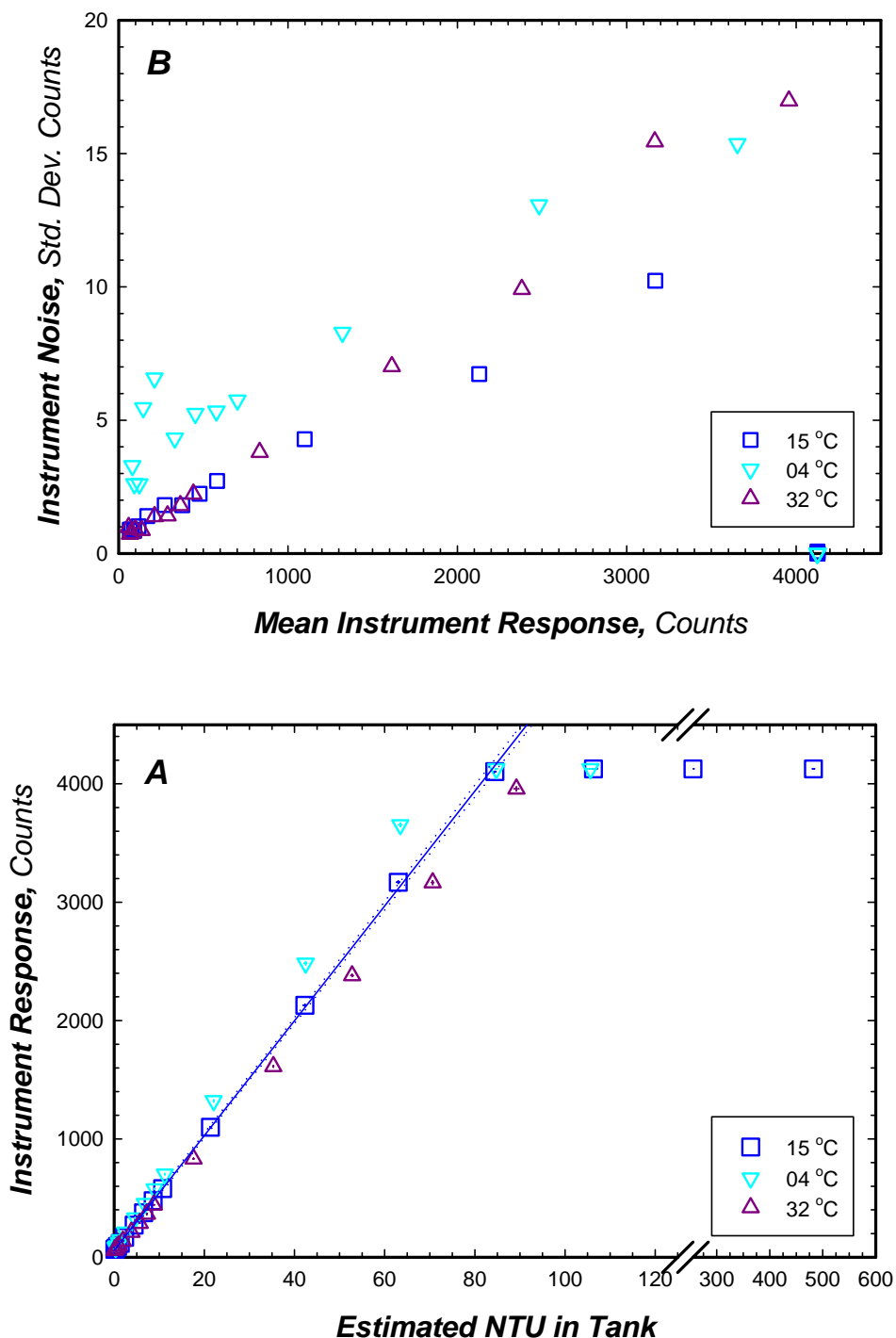


Figure 2. WET Labs' BBSB signal and instrument noise in response to increasing turbidity derived from Formazin added to filtered deionized water at three test temperatures. **(A)** Mean detector response to sequential additions of known Formazin concentrations. Instrument response over a turbidity range normally observed in natural waters (0-85 NTU) was modeled by linear regression. Modeled response at 15°C, with 99% confidence intervals (dotted lines): $\text{Counts} = 48.491\text{NTU}_{\text{FRMZ}} + 58.904$, $r^2 = 0.999$, demonstrates response is linear up to 85 NTU Frmz. Detector response was temperature dependent. **(B)** Signal noise (s.d.) ranged from <0.1 to 4% of measured signal, measured noise was highest at 4°C. The monotonic increase in signal s.d. with Formazin turbidity, likely results from detection of particle aggregates in suspension.

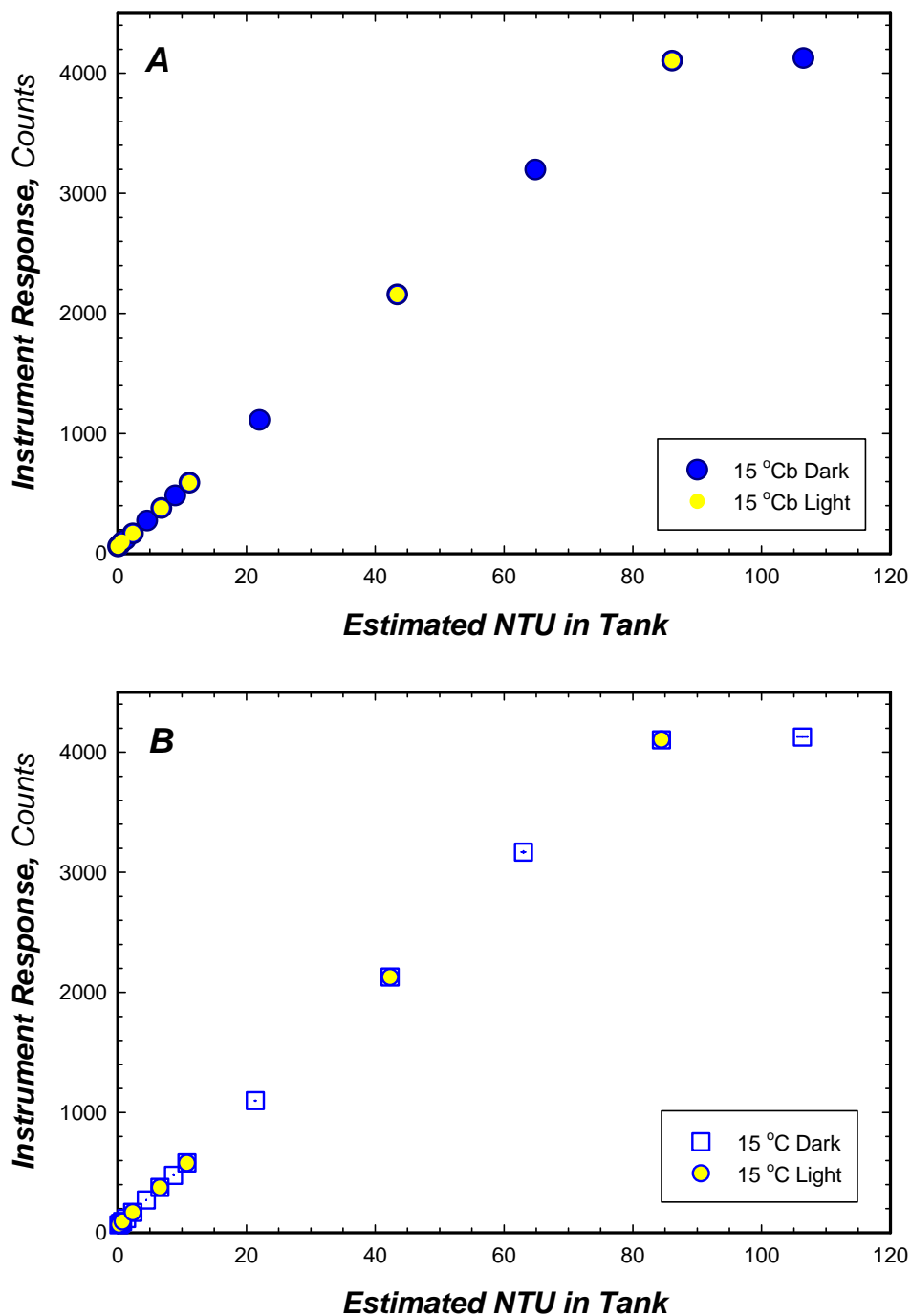


Figure 3. Effects of downwelling irradiance on turbidity measurement by the *WET Labs BBSB*. Surface irradiance applied at each indicated test concentration using a bank of three 500W halogen lamps. E_0 : 400-500 $\mu\text{mol quanta m}^{-2} \text{s}^{-1}$ measured using a Licor 190S detector. **(A)** 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 WET Labs BBSB 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 0.1 – 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.

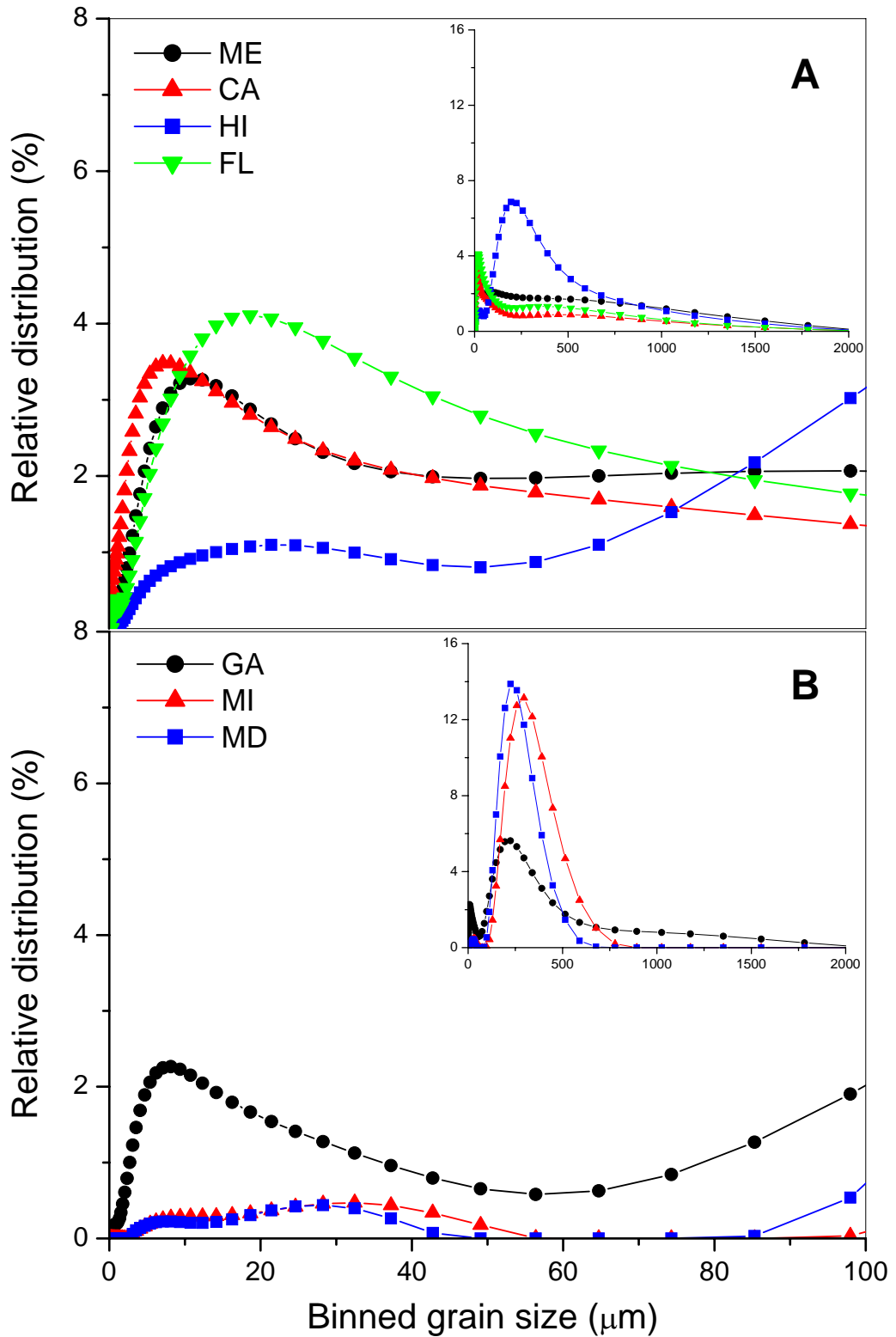


Figure 4. Normalized volume concentrations (%) of the benthic sediment grain size distribution collected at each site during the field test period. The size distribution (not corrected for bin size) was measured by Laser Light Scattering (ASTM D4464-00) at STL Burlington (Colchester, VT) on sediment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

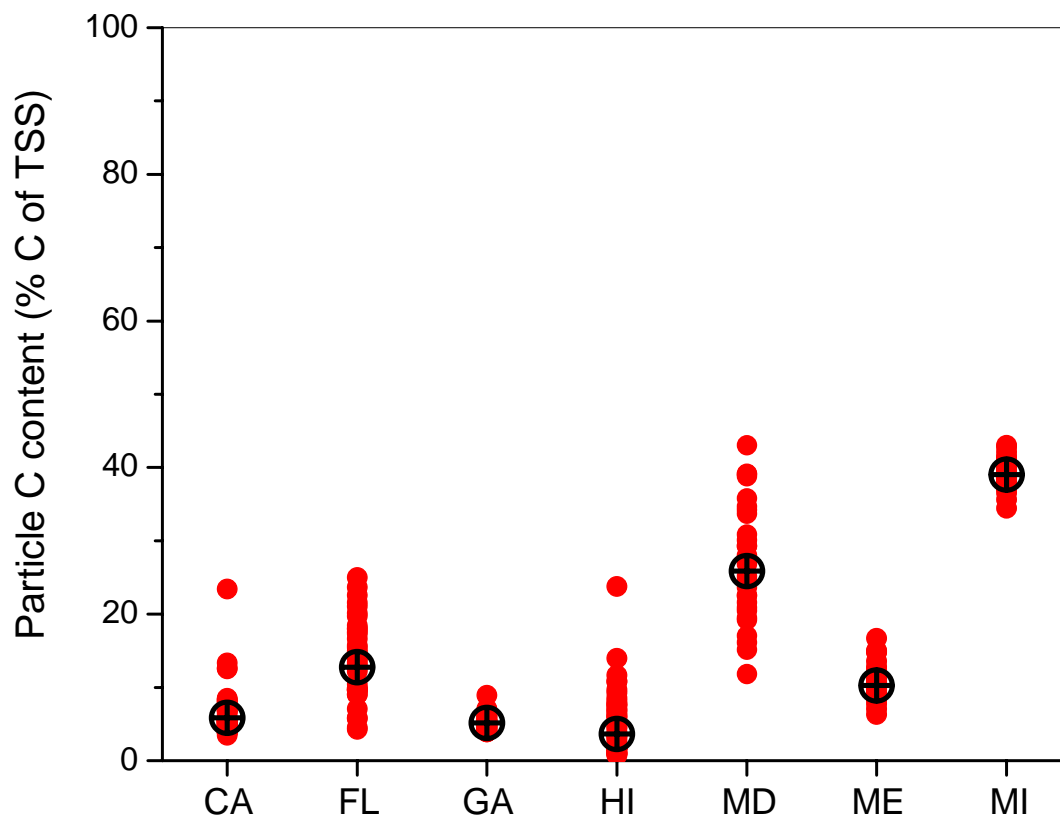


Figure 5. Particulate organic carbon (C) calculated as a percentage of total suspended solids (TSS) at each field site. At each site, particle C content was generated for each sampled time point (red dots) and the most frequent value (the mode) was also calculated (black crosshairs).

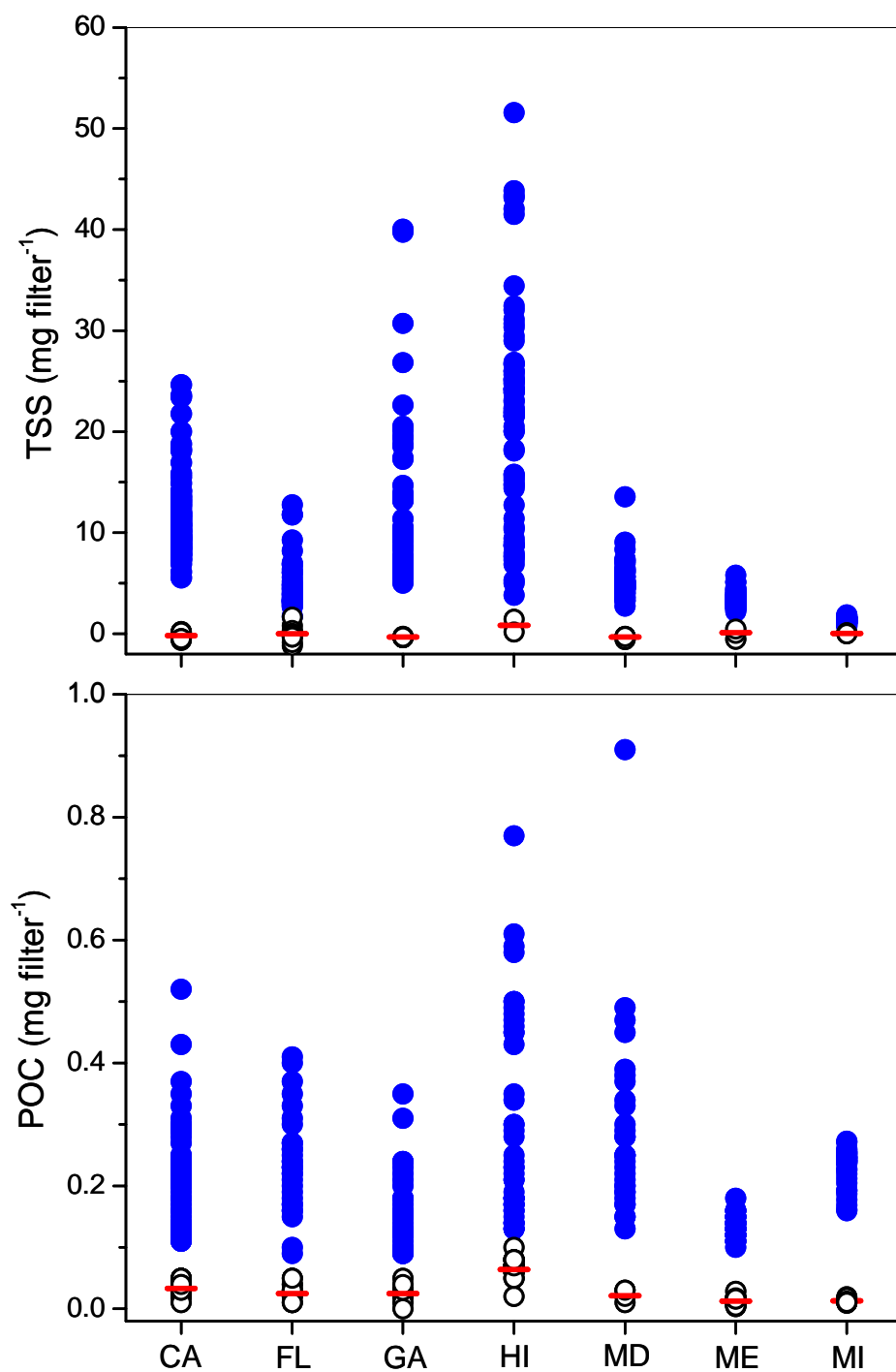


Figure 6. Total suspended solids (TSS; A) and particulate organic carbon (POC; B) collected at each study site. Field samples are shown as total amount of TSS and POC collected per filter (blue dots; mg filter⁻¹). The average blanks (red bars) were calculated from the field blanks (TSS; open circles) 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 six of the seven sites are presented on the following pages in figures 7 – 18. Results from the field test Offshore Tampa Bay, FL were omitted from the report as the test was compromised during the evaluation. The data from the remaining sites 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, and 17A) 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, and 18A) 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.

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 – 7 and Appendix 4, respectively. 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 the five field sites where complete test data was obtained (Fig. 19). There was a strong linear relationship between instrument response and beam attenuation coefficient over the observed range of 0.5 – 30 BAC. However, the plots of NTU against TSM and POC reveal 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, the instrument response relative to TSM was much more variable at the HI 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. In particular, the test instrument was not very responsive to variation in POC concentrations at the Maryland test site.

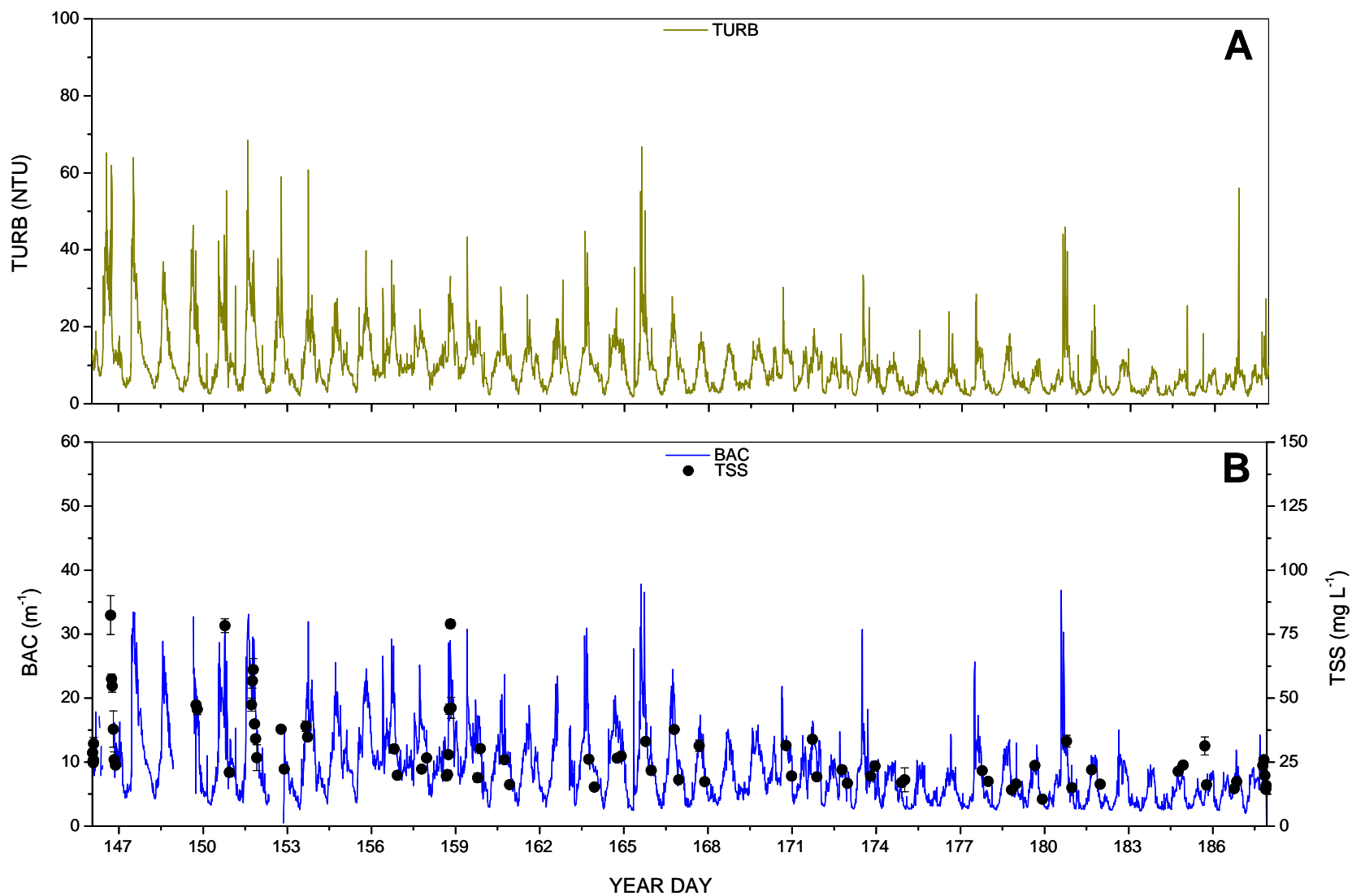


Figure 7. Moss Landing Harbor, CA. A) Turbidity (TURB; Nephelometric Turbidity Units) measured by the WET Labs BBSB; B) Beam Attenuation Coefficient (BAC) measured by an in situ transmissometer, and total suspended solids (TSS).

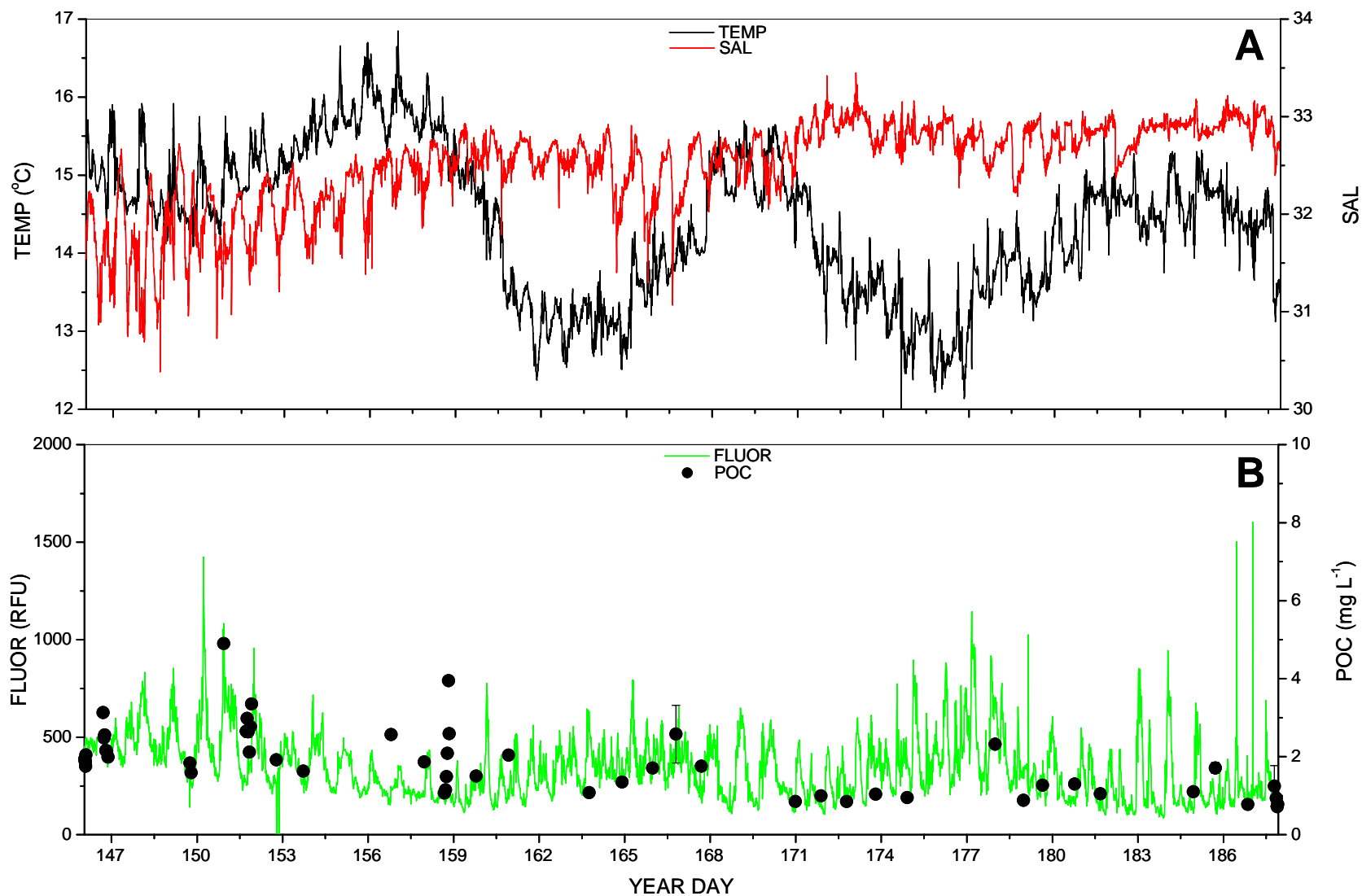


Figure 8. Moss Landing Harbor, CA. A) Temperature (TEMP) and salinity (SAL); B) Fluorescence (FLUOR in Relative Fluorescence Units) measured by an in situ fluorometer, and particulate organic carbon (POC).

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	0.3	0.5
Nominal 5 NTU	5.7	5.3

Sensor Photographs

Photographs of the WET Labs BBSB 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



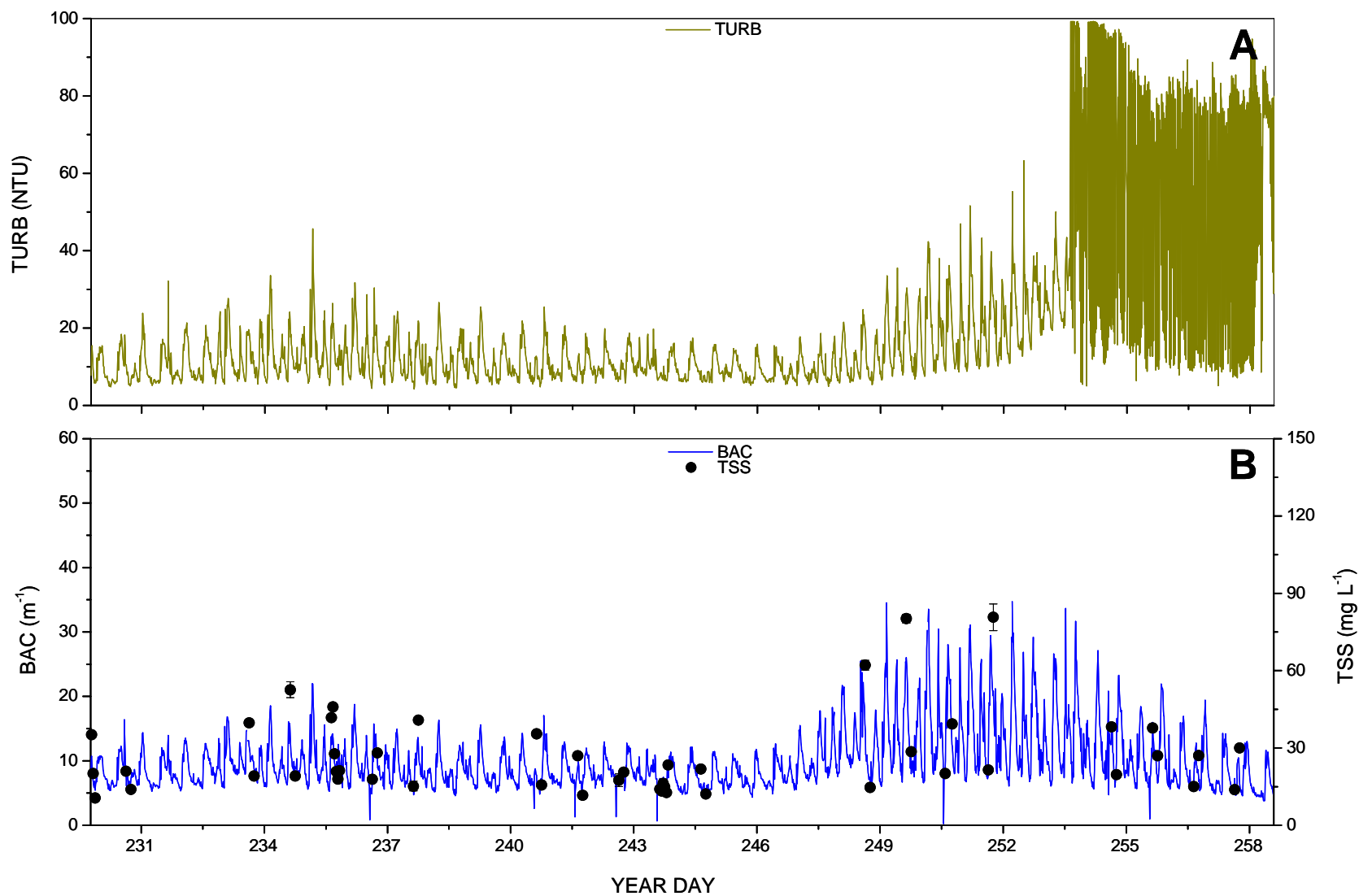


Figure 11. Skidaway Island, GA. A) Turbidity (TURB; Nephelometric Turbidity Units) measured by the WET Labs BBSB; B) Beam Attenuation Coefficient (BAC) measured by an in situ transmissometer, and total suspended solids (TSS).

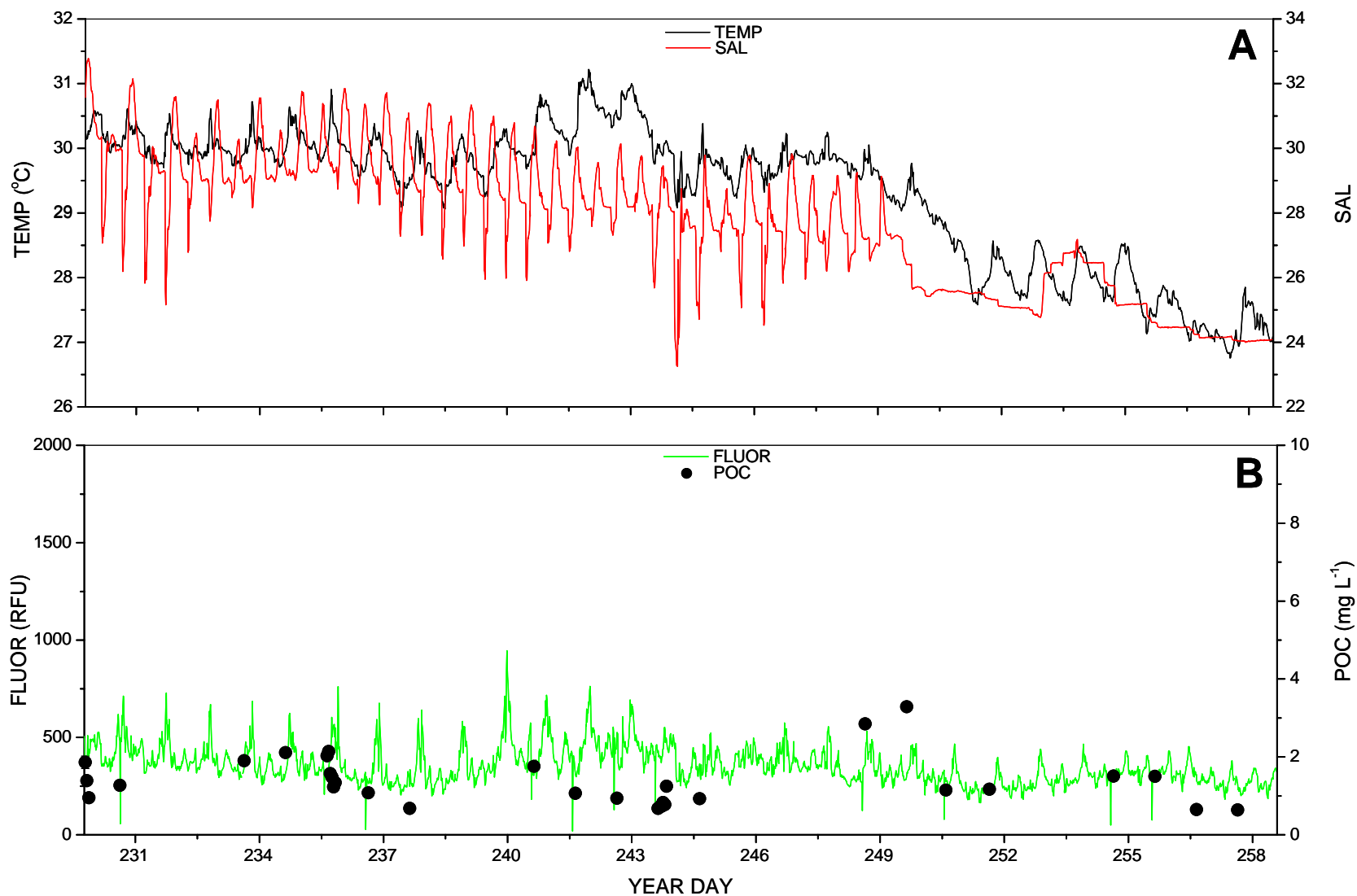


Figure 12. Skidaway Island, GA. A) Temperature (TEMP) and salinity (SAL); B) Fluorescence (FLUOR in Relative Fluorescence Units) measured by an in situ fluorometer, and particulate organic carbon (POC).

Table 3. 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	0.9	0.4
Nominal 5 NTU	7.6	7.5

Sensor Photographs

Photographs of the WET Labs BBSB 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



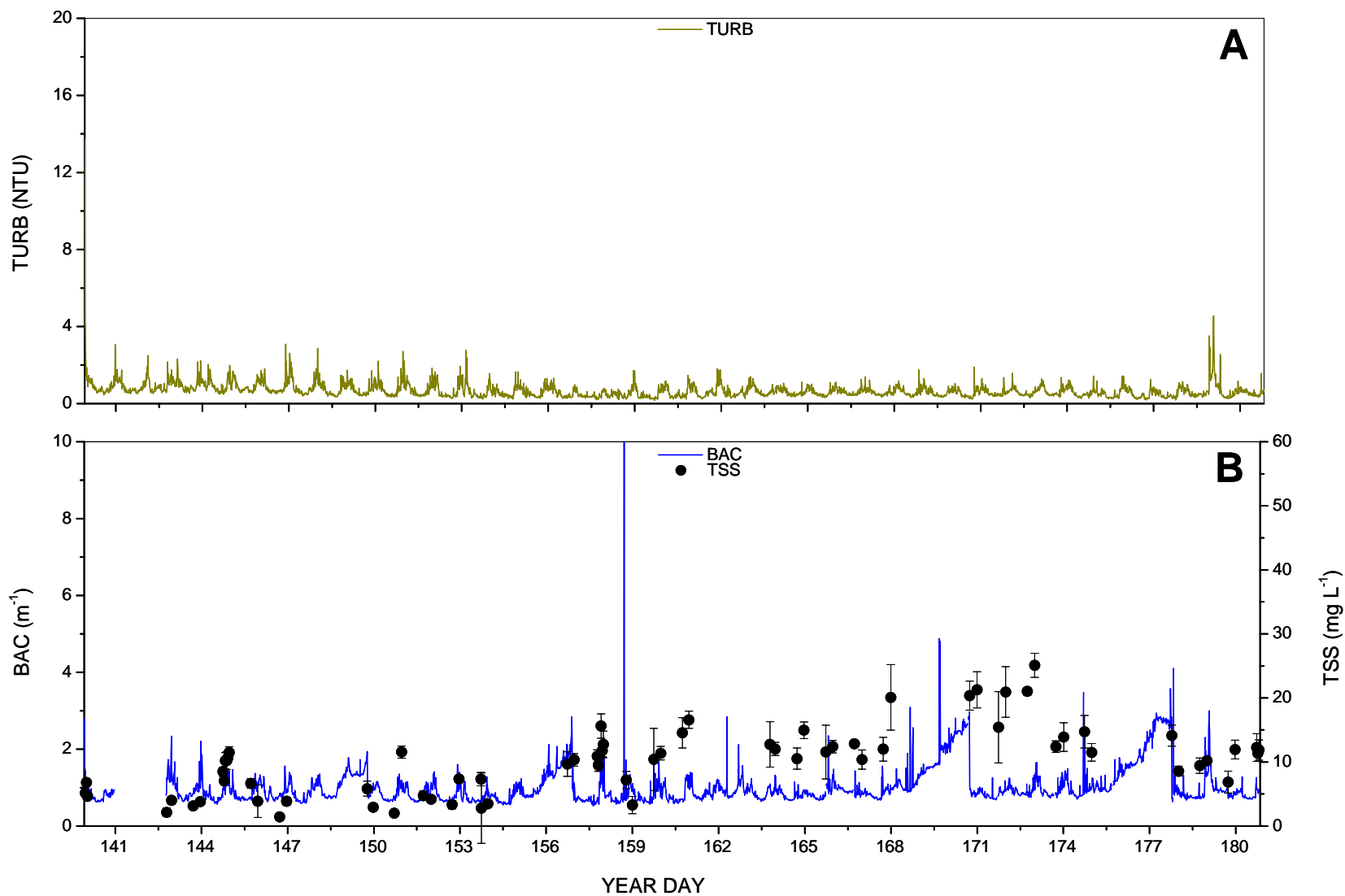


Figure 11. Kaneohe Bay, HI. A) Turbidity (TURB; Nephelometric Units) measured by the WET Labs BBSB; B) Beam Attenuation Coefficient (BAC) measured by an in situ transmissometer, and total suspended solids (TSS).

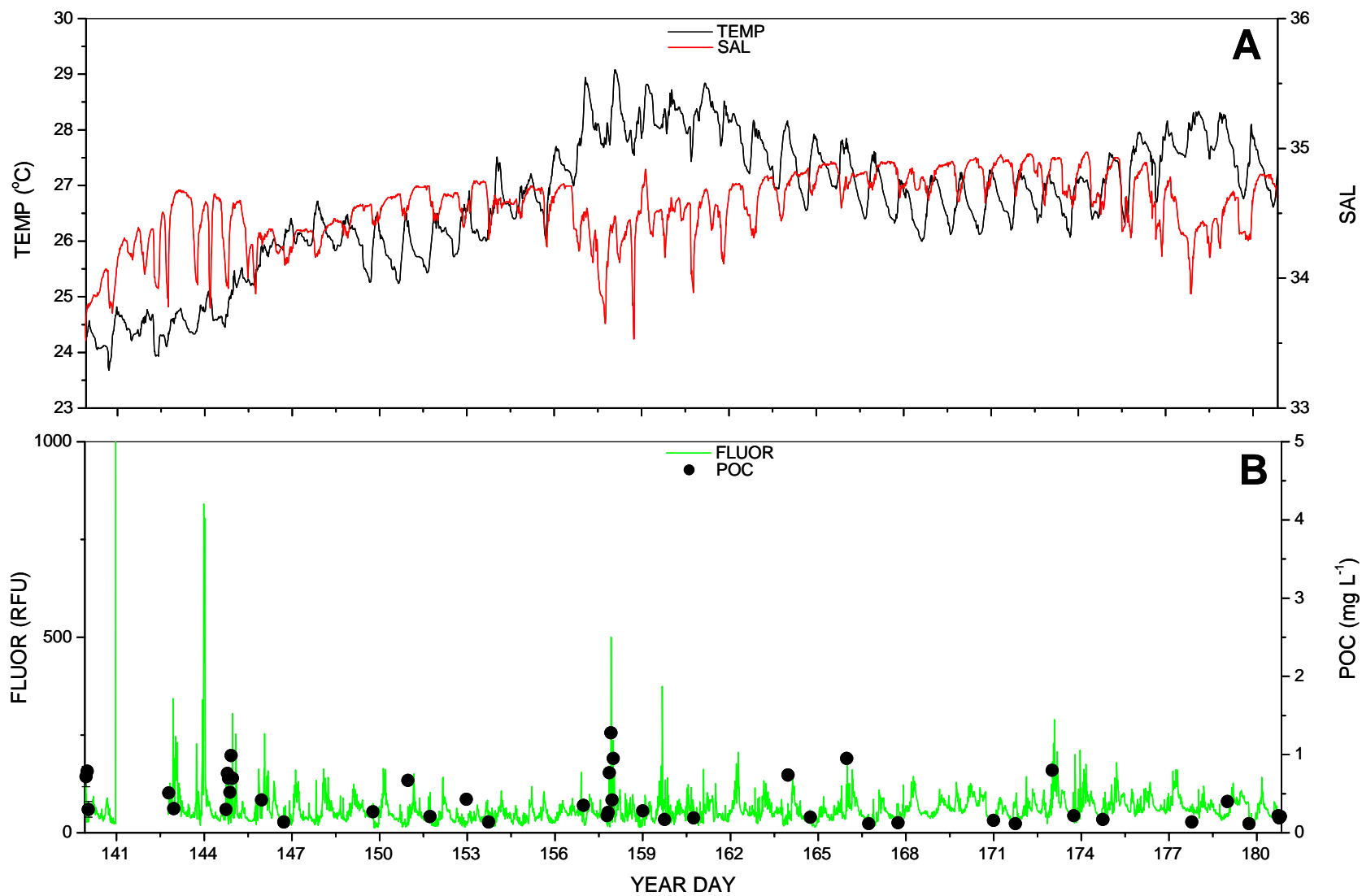


Figure 12. Kaneohe Bay, HI. A) Temperature (TEMP) and salinity (SAL); B) Fluorescence (FLUOR in Relative Fluorescence Units) measured by an in situ fluorometer, and particulate organic carbon (POC).

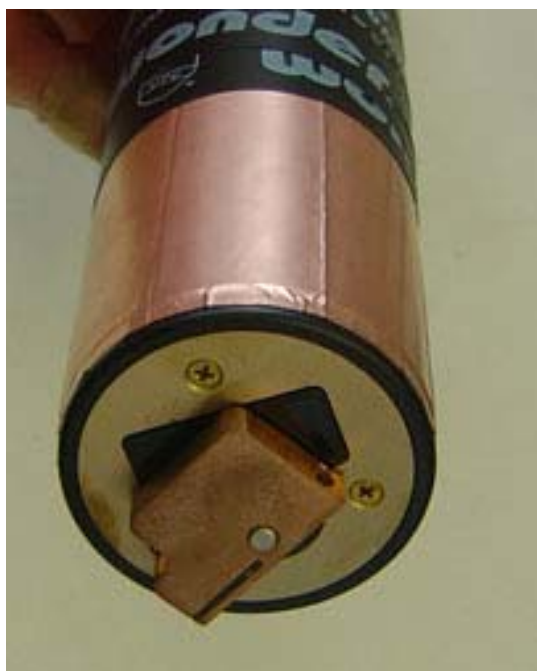
Table 4. Instrument readings of reference turbidity standards before (PRE) and after (POST) the field deployment at the University of Hawaii test site. Sensor readings are the average of three independent readings taken at 15-minute intervals. The two reference standards were designed to be essentially 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. (n.d. = not determined due to erratic sensor readings)

Reference Standard	PRE sensor value	POST sensor value
Nominal 0 NTU	n.d.	0.3
Nominal 5 NTU	6.5	5.4

Sensor Photographs

Photographs of the WET Labs BBSB 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



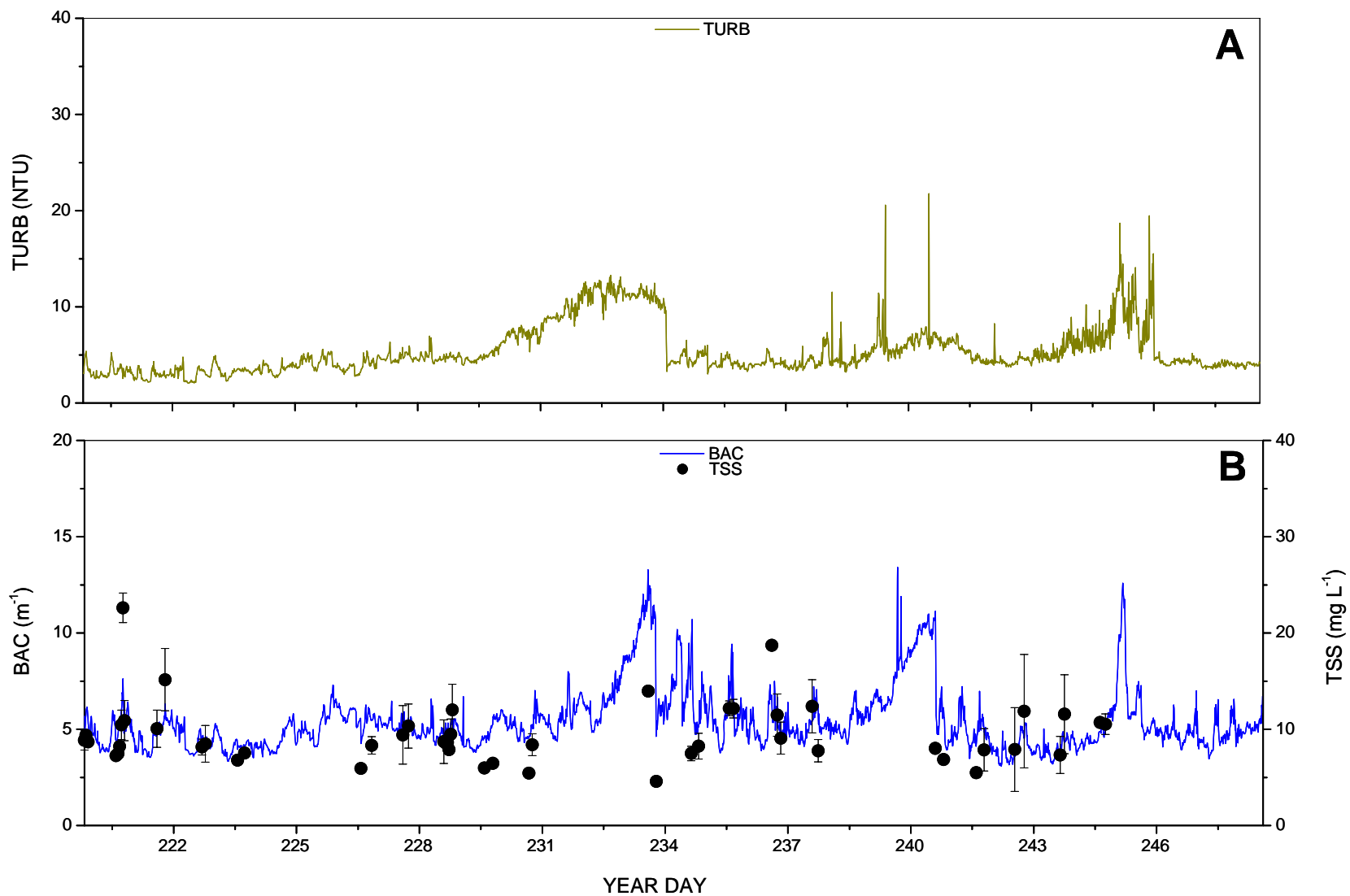


Figure 13. Chesapeake Bay, MD. A) Turbidity (TURB; Nephelometric Turbidity Units) measured by the WET Labs BBSB; B) Beam Attenuation Coefficient (BAC) measured by an in situ transmissometer, and total suspended solids (TSS).

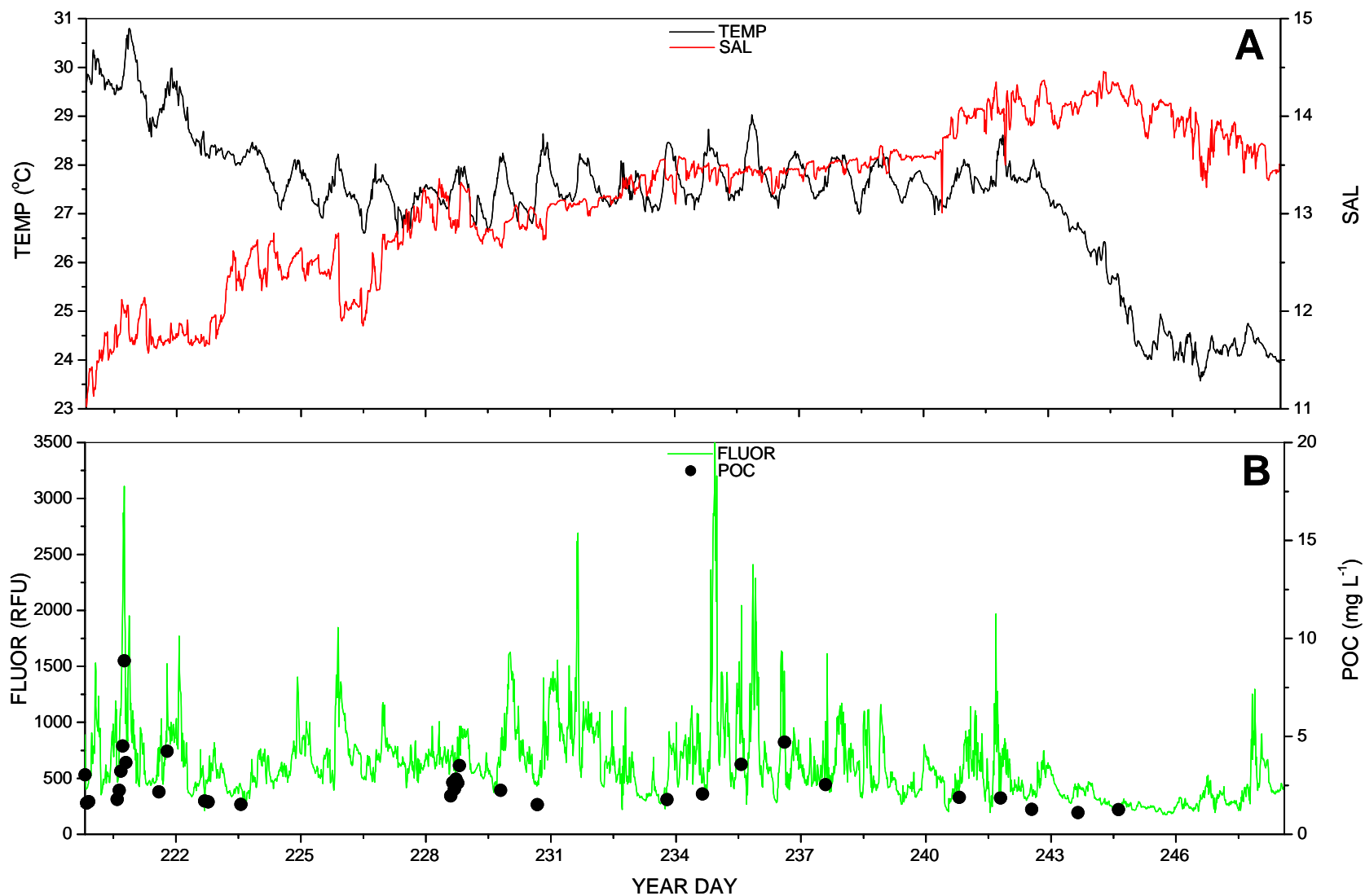


Figure 14. Chesapeake Bay, MD. A) Temperature (TEMP) and salinity (SAL); B) Fluorescence (FLUOR in Relative Fluorescence Units) measured by an in situ fluorometer, and particulate organic carbon (POC).

Table 5. 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	0.2	-0.1
Nominal 5 NTU	7.0	7.2

Sensor Photographs

Photographs of the WET Labs BBSB 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



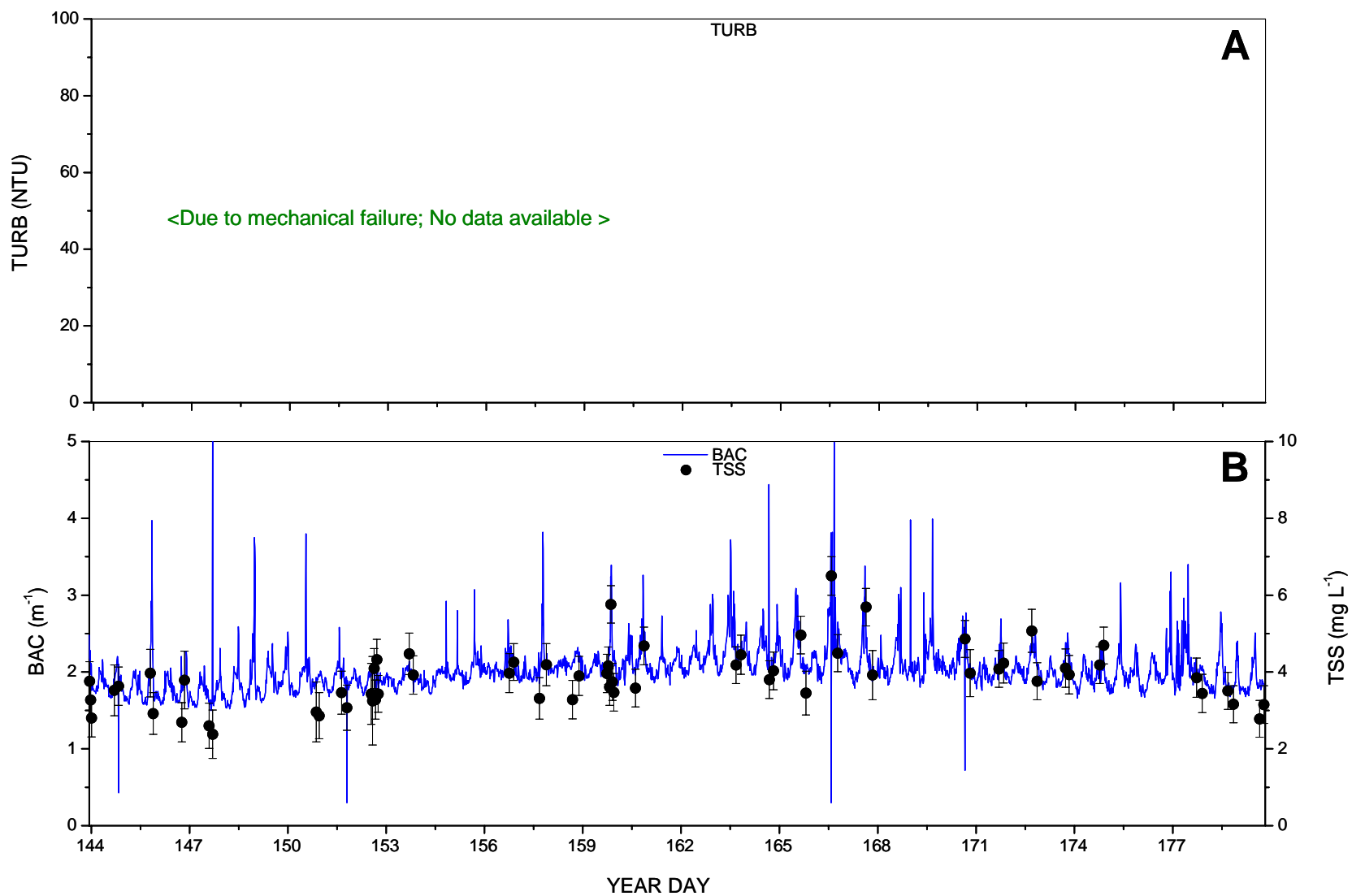


Figure 15. Damariscotta River Estuary, ME. A) Turbidity (TURB: Nephelometric Turbidity Units) measured by the WET Labs BBSB; B) Beam Attenuation Coefficient (BAC) measured by an in situ transmissometer, and total suspended solids (TSS).

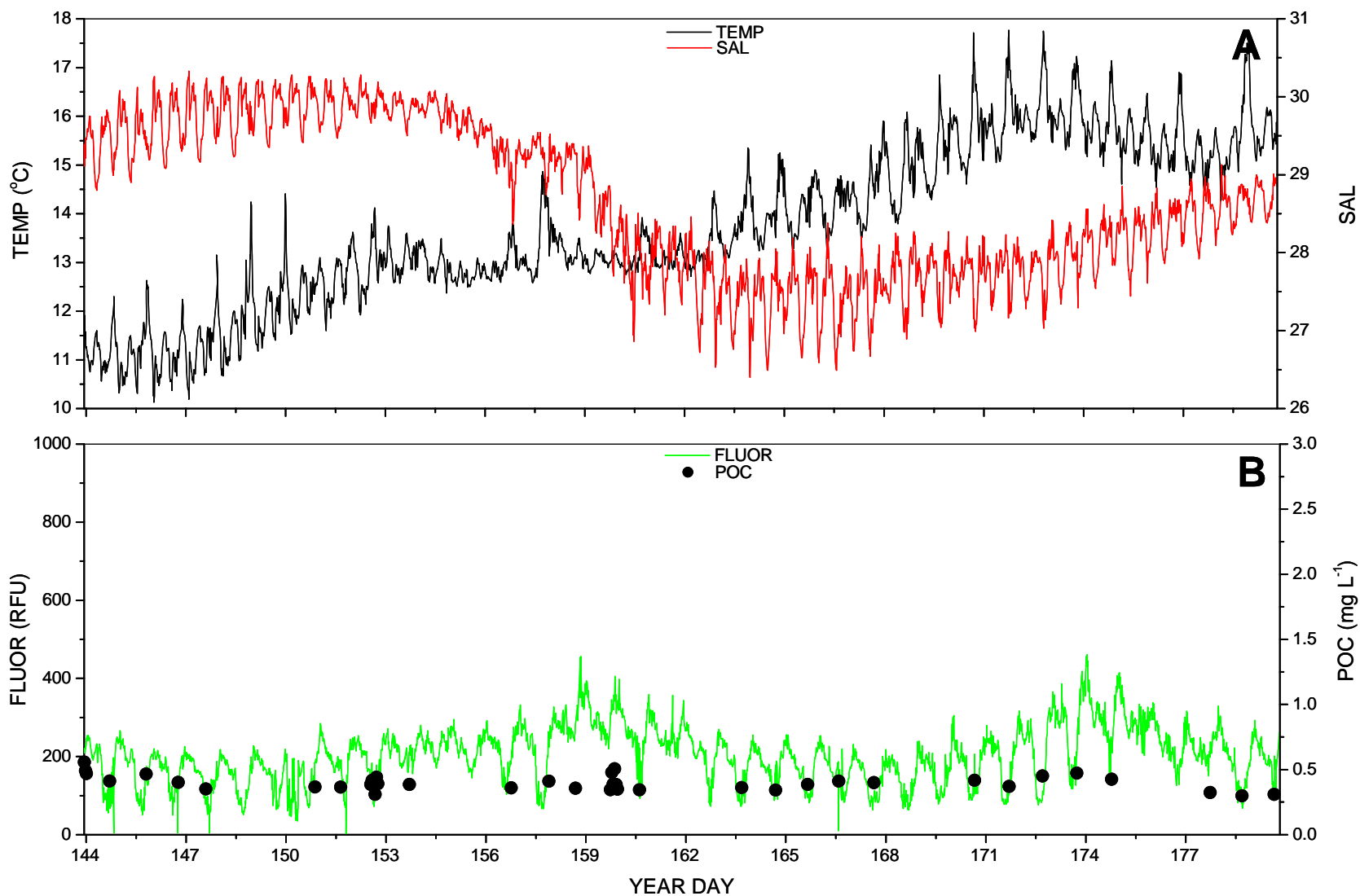


Figure 16. Damariscotta River Estuary, ME. A) Temperature (TEMP) and salinity (SAL); B) Fluorescence (FLUOR in Relative Fluorescence Units) measured by an in situ fluorometer, and particulate organic carbon (POC).

Table 6. 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	0.4	0.2
Nominal 5 NTU	5.9	7.3

Sensor Photographs

Photographs of the WET Labs BBSB 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



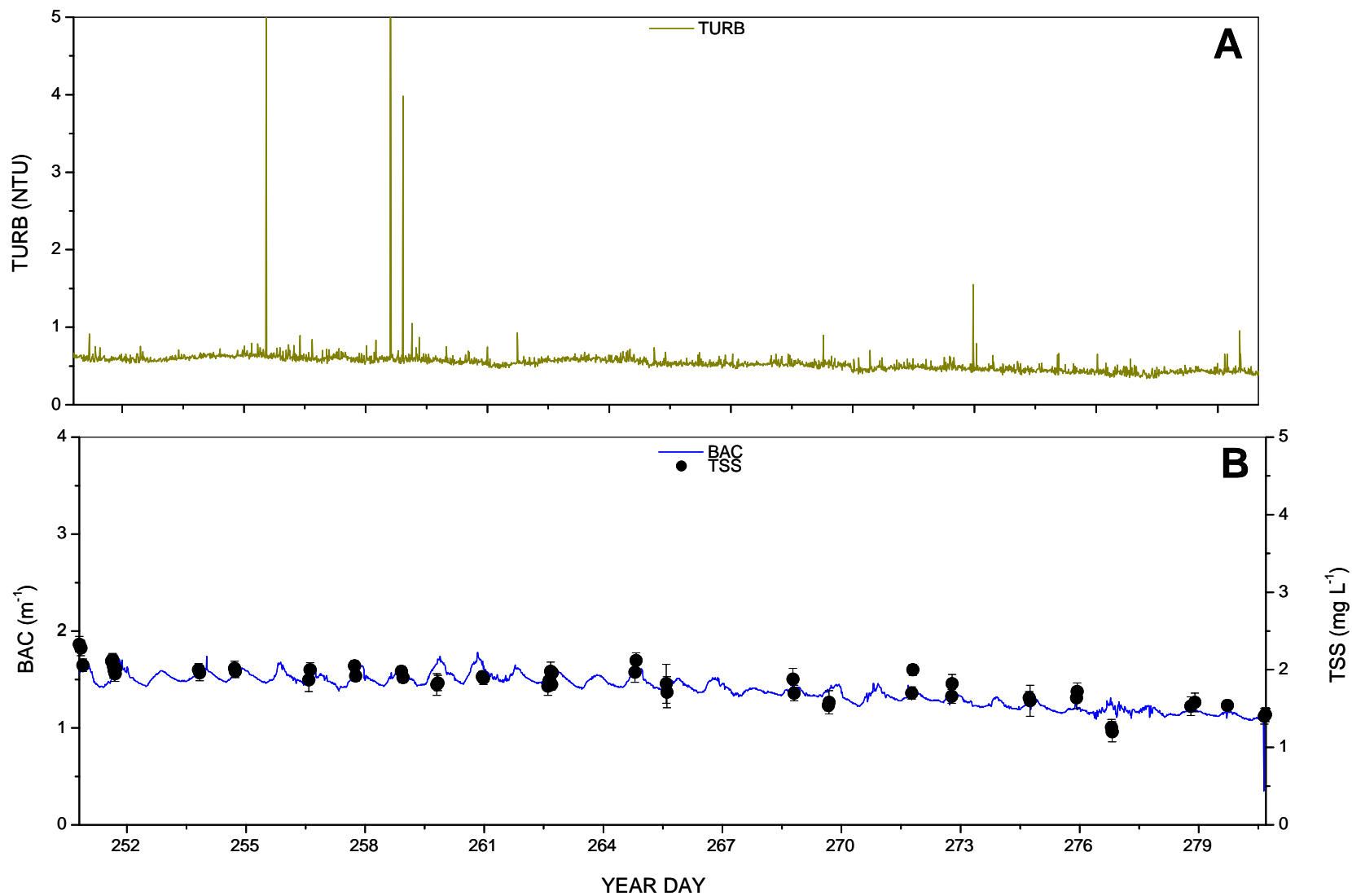


Figure 17. Winans Lake, Ann Arbor, MI. A) Turbidity (TURB; Nephelometric Turbidity Units) measured by the WET Labs BBSB; B) Beam Attenuation Coefficient (BAC) measured by an in situ transmissometer, and total suspended solids (TSS).

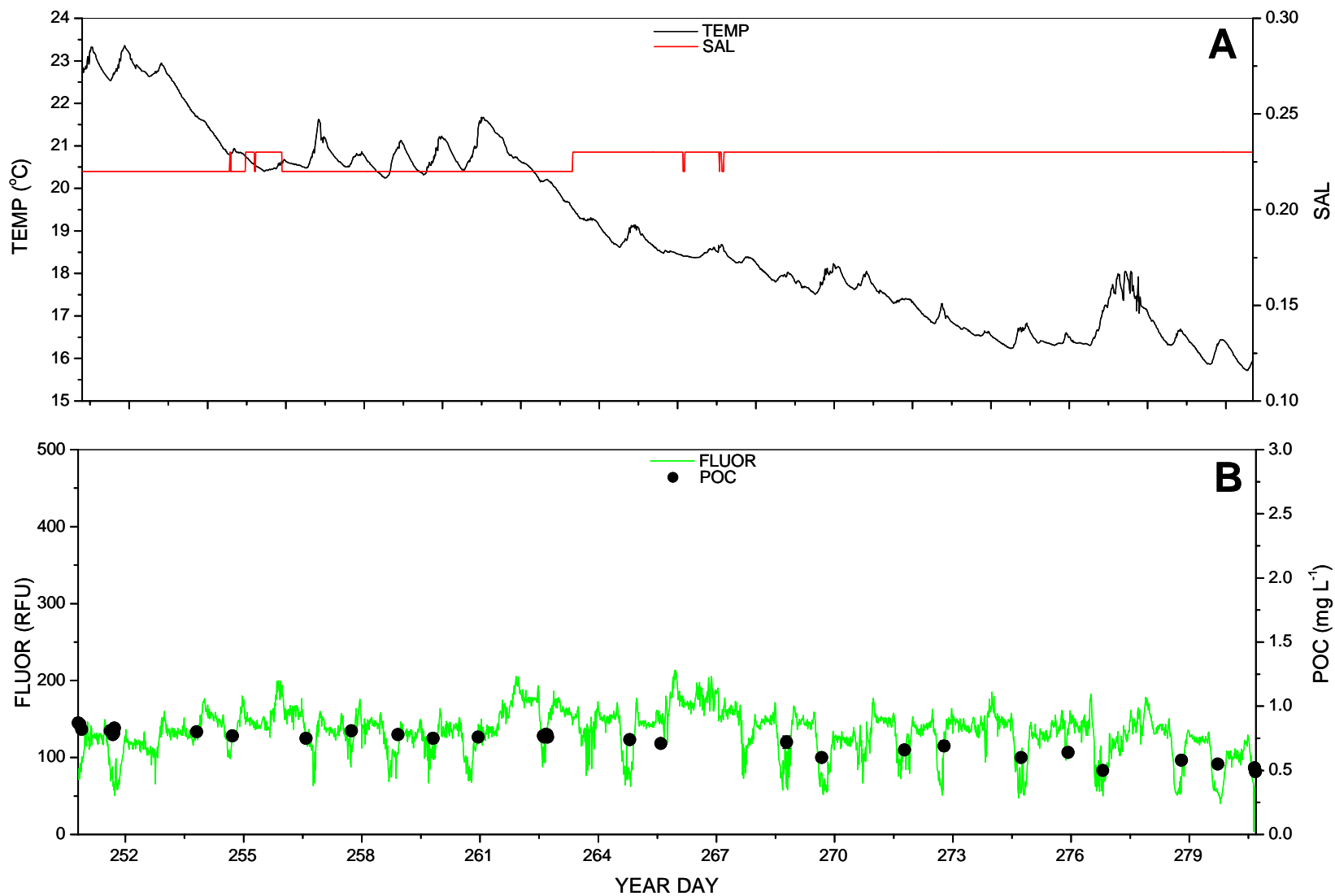


Figure 18. Winans Lake, Ann Arbor, MI. A) Temperature (TEMP) and salinity (SAL); B) Fluorescence (FLUOR in Relative Fluorescence Units) measured by an in situ fluorometer, and particulate organic carbon (POC).

Table 7. 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.

Reference Standard	PRE sensor value	POST sensor value
Nominal 0 NTU	0.4	0.2
Nominal 5 NTU	7.1	7.4

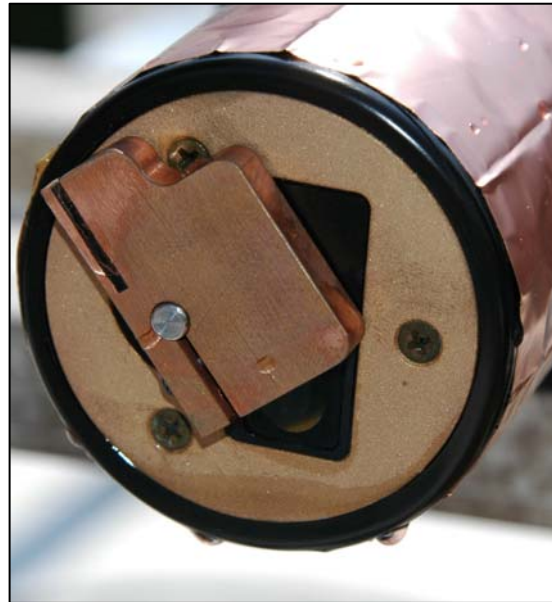
Sensor Photographs

Photographs of the WET Labs BBSB 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



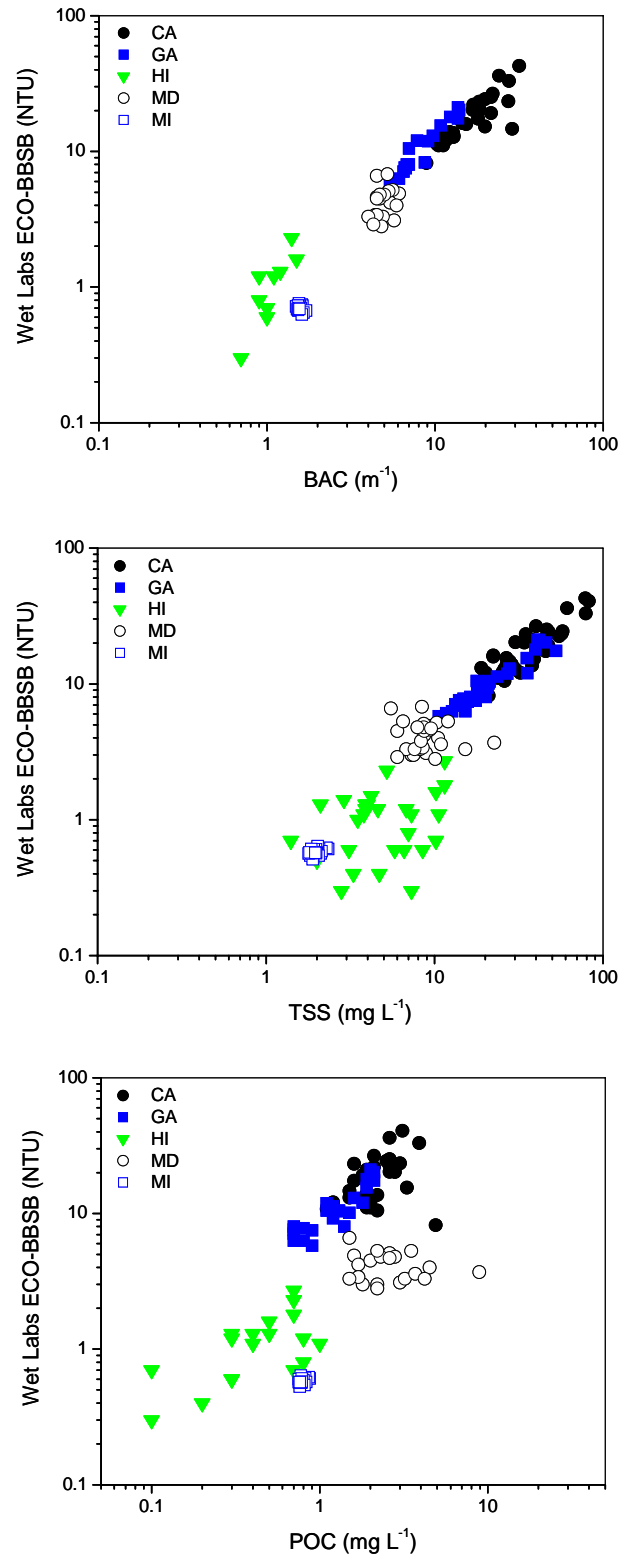


Figure 19. WET Labs BBSB turbidity data (in nephelometric turbidity units) plotted against Beam Attenuation Coefficients (BAC), collected total suspended solids (TSS) and particulate organic carbon (POC).

INSTRUMENT RELIABILITY:**Laboratory**

We retrieved 100% of the expected data from the seven laboratory tests conducted with the WET Labs ECO-BB-SB 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. All expected data were recovered from the sensors at each of the test sites.

For the Georgia test-site, the timing basis for the sensor appeared to run fast. The timestamps indicate that the clock was correct for the first week or so, but then, started to creep ahead a little on each subsequent sample. It gained about three minutes by the end of the deployment.

At the Maine test-site, prior to deployment, the wiper was noticeably loose and spinning on its axis. The wiper was realigned and tightened according to manufacturer's instructions. The instrument was then tested multiple times by turning it on and off to assure the wiper was installed correctly. It appeared to be working correctly when instrument deployed. After retrieval, it was noted that during sampling the wiper hardware was partially covering the window. Closer examination of the data indicated that 4 days after the instrument was deployed, the wiper started to at time partially cover the optical face, obscuring the readings. Several wiper cycles were watched in the lab, and sometimes the wiper covered the optics, and sometimes not. Closer inspection indicated the screw holding the wiper in place was not loose. The wiper was removed for post-standard checks, and instrument still read accurately. Subsequent trials at WET Labs suggested that the attachment pin protruding from the instrument casing moved out of alignment. The wiper hardware partially covered the sensor window after a number of readings, but the frequency and percentage coverage appeared to be at random. Finally, it was noted that the instrument was sampling 2 minutes sooner than the programmed sample time, again suggesting a slight timing issue with the internal clock.

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

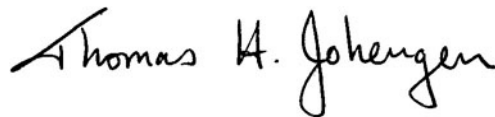
Date



Approved By: Dr. Mario Tamburri
ACT Executive Director

March 30, 2007

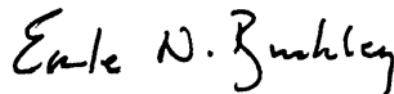
Date



Approved By: Dr. Tom Johengen
ACT Chief Scientist

March 30, 2007

Date



Approved By: Dr. Earle Buckley
Quality Assurance Supervisor

WET Labs' comments on the ACT turbidity meter verification statement

WET Labs wholeheartedly endorses the ACT goals and participated in the turbidity meter verification with pleasure. We think the community is well served by the ACT testing process.

WET Labs finds the ACT verification process an extremely useful feedback mechanism for our scientists and engineers. We use the results to gauge our effectiveness in making the best possible optical sensors for coastal systems. We know that biofouling will always win in the end: our job is to keep the data as good as possible for as long as possible. For example, following the ACT fluorometer testing in 2005 we added copper face plates to the ECO line of instruments to further decrease the impact of biofouling. Our experience since that design change and the results reported here indicate that the copper face plate does improve anti-biofouling performance. The ACT fluorometer test at Skidaway Island where biofouling is intense showed biofouling interference within two weeks. The results from the ECO turbidity sensor with the copper face plate reported here show good data for more than three weeks: an increase in the time to failure at that site of more than 50%.

Ref: http://www.act-us.info/Download/Fluorometer/ACT_TV06-07_Wet_Labs_Fluoro.pdf, page 24

We are very encouraged that biofouling did not apparently impact the data sets from the other sites reported here. Our goal is reliable data in the coastal zone for three to six months between servicing, about half as long as what our users in the open ocean have achieved. Our testing and the ACT results indicate that we have attained that measure in some environments. We continue to work to improve our anti-biofouling technology. Please see our website for the most recent results of this effort.

The instrument deployed in Maine had an o-ring failure on the seal around the shaft. While not serious enough to flood the instrument, the small amount of water that passed the o-ring dulled the shaft where the instrument records the position of the shaft relative to the motor. The instrument reported data for the entire time series and about half of the data appeared reasonable, but there is no reliable method to eliminate the data in which the bio-wiper interfered with the measurement and hence all the data is unreportable. This type of failure is fortunately rare, and serves to illustrate that even with the best quality control and manufacturing methods, putting mechanical instruments into the ocean will occasionally result in a failure.

Minor points:

Board level component changes since the instruments used in this testing were built have been instituted to reduce the temperature response of the instrument.

For the Hawaii site, the ECO data tracked the beam attenuation data very nicely. The TSS data (more properly TPM: total particulate matter) did not track either data set well. Hence, the lack of fit between the turbidity and TSS data is most likely due to variability in the TSS data.

In general, POC is a function of TPM only in blue water conditions where resuspension and detrital inputs can be assumed insignificant. A backscattering based instrument is not an effective method for measuring POC in coastal environments where resuspension and detrital inputs are inherent.

For long term monitoring programs the initial cost of an instrument is quickly dwarfed by the operational and maintenance costs, particularly in remote environments. It is paramount to be able to report good data for as long a period as possible. In the coastal environment where biofouling is extreme the cost of retrieving, refurbishing and replacing instruments is only exceeded by the cost of unreportable data due to poor data quality. In that respect, the ACT turbidity verification results are similar to the results our users are finding around the world: the ECO sensors are stable, correlatable with natural variability, and resistant to biofouling.