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Spatially Intensive Water Quality Monitoring of the Maryland Coastal Bays

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Spatially Intensive Water Quality Monitoring of the Maryland Coastal Bays April – November 2003

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1.0 Introduction

Maryland's Coastal Bays stretch from the barrier islands of Fenwick in the north, to Assateague in the south. A socially significant and unique ecosystem, Maryland's Coastal Bays watershed is composed of a variety of land use types including urban, agricultural, and wetland areas. Rapid development within the northern portions of the watershed (around Ocean City) has left just 25% of this area as wetlands or in agricultural usage. The Lower Bay watersheds are substantially less developed consisting primarily of agriculture, forests, and wetlands (Boynton 1993; Jacobs 1993). As a result of changing land use, Maryland's Coastal Bays are now listed on the Maryland 303(d) Impaired Surface Water List for the nutrients nitrogen and phosphorus that cause excessive algal blooms and subsequent violations of established dissolved oxygen criterion. The St. Martin River was first listed in 1994, while Assawoman Bay and Isle of Wight Bay were listed in 1996. The Newport Bay system, partitioned into five sub-watersheds (Ayer Creek, Kitts Branch, Marshall Creek, Newport Creek and Newport Bay [including Trappe Creek]) were also listed in 1996 (Maryland Dept. of the Environment, 2002).

The Coastal Bays are generally shallow and typically well-mixed, with freshwater inputs and ocean exchange both relatively low. Significant influences by storm events and prevailing winds are also common (Boynton et al. 1996). According to Pritchard (1960) it can take 63 days for 99% of Chincoteague Bay's water volume to be exchanged. Tidal heights in the Coastal Bays range from 1 meter at the Ocean City Inlet to approximately 0.1 meter in the upper reaches of the Bays (Allison, 1974). Traditional water quality monitoring has been typically limited to a few stations, located almost exclusively in deeper channel waters. This type of monitoring has limited use for identifying spatial gradients and processes occurring in shallow water. Therefore, in order to better understand the temporal and spatial dynamics of water quality in these systems we conducted a series of water quality mapping cruises in 2003 using our DATAFLOW 5.5 water quality mapping system in order to help characterize the scale of spatial gradients and potential degraded areas.

With this system, water quality data was collected with very high spatial resolution in both near-shore and open water areas, throughout Newport, Sinepuxent, and Assawoman Bays as well as within several tributaries of these systems. DATAFLOW 5.5 allowed us to measure the following parameters: temperature, salinity, dissolved oxygen, pH, fluorescence, and turbidity. Measurements were made biweekly from April through October in order to capture relatively short-lived re-suspension or algal bloom events compared to what would be captured in more typical monthly sampling programs. In addition, whole water samples were collected at several fixed stations within each region to provide additional information on nutrient concentrations in the region. Finally, for purposes of clarity and brevity in this report, the phrase "Upper Bays" is meant to encompass Isle of Wight and Assawoman Bays, and associated tributaries, in particular St. Martin River; the phrase "Lower Bays" represents the Northern portion of Chincoteague Bay, Sinepuxent and Newport Bays, and associated tributaries.

A discussion of surface water quality of the Maryland Coastal Bays should not exclude at least a cursory examination of streamflow into the Upper and Lower estuarine systems. Birch Branch on the St. Martin River (Showell, MD) had a nine month (Jan-Sept) average stream flow of 15.6 cubic feet per second in 2003, compared with Bassett Creek on Newport Bay (Ironshire, MD)

which averaged 2.9 cubic feet per second for the same period (USGS, 2004). Flow records were mentioned because diffuse inputs to the Maryland Coastal Bays represent a significant source of nutrients, but more data must be evaluated to understand the cause of the conditions encountered during the 2003 surface water quality mapping season.

2.0 Methods, Locations, and Sampling Frequency

The water quality mapping of Maryland's Coastal Bays consisted of two discrete but complementary field activities. The first was the collection of high-resolution spatial data with the DATAFLOW 5.5 water quality mapping system. A full description of this system is provided below. The second activity was the collection of data and water samples at fixed sampling stations during each mapping cruise. The purpose of the fixed station sampling was twofold. First, to collect auxiliary water quality data that was used to translate DATAFLOW sensor output into universally recognized units. The second, to collect whole water samples that were analyzed for nutrient concentrations as well as chlorophyll concentrations, and total suspended solids (TSS). These latter parameters were also used to translate DATAFLOW sensor output to universally recognized, lab-based units.

2.1 DATAFLOW 5.5

DATAFLOW 5.5 is a compact, self-contained surface water quality mapping system, suitable for use in a small boat operating at speeds of up to 20 knots. A schematic of this system is shown in Fig 1-1. Surface water (0.6m deep) was collected through a pipe ("ram") deployed from the transom of the vessel. Assisted by a high speed pump, water passed through a hose to a flow meter and then to an array of water quality sensors which record the water quality variables, time, and geographic position. The total system water volume was approximately 3.0 liters.

Dataflow surveys were conducted from a CBL vessel and typically involved two field technicians to perform sampling operations and safe navigation. The Dataflow package consisted of a water circulation system that is sampled at a prescribed rate by a Yellow Springs, Inc. 6600 DataSonde combined with a YSI 650 Datalogger. This sensor provided data on dissolved oxygen, temperature, conductivity and salinity, as well as turbidity and fluorescence (from which we derived chlorophyll-a concentration).The 650 also recorded positional data with an accuracy of approximately 10 meters from a Garmin e-Trex GPS unit utilizing an NMEA 0183 v. 2.0 data format. Depth data were collected with an auxiliary Garmin 168 global positioning system with a built-in depth sounder. The Garmin 168 GPS transmitted NMEA 0183 version 2.3 formatted data to a Wescor RDT 3200 portable computer using Procomm Plus communication software. Data files were merged by time stamp at a later date using a SAS software routine. Although the flow rate does not affect any of the sensor readings, decreased flow is an indication of either a partial blockage or an interruption of water flow to the instrument and affects the water turnover rate of the system. An inline flow meter wired to a low-flow alarm alerted the operators of potential problems as they occurred. The low-flow alarm was set to 3.0 liters per minute. A single 1100 gallon per hour "Rule Pro Series" bilge pump provided approximately 20-25 liters per minute of flow to the system. During the course of a cruise, the crew stopped at established, individual calibration stations located along the cruise track where the vessel was anchored and whole water samples were taken from the water circulation system.

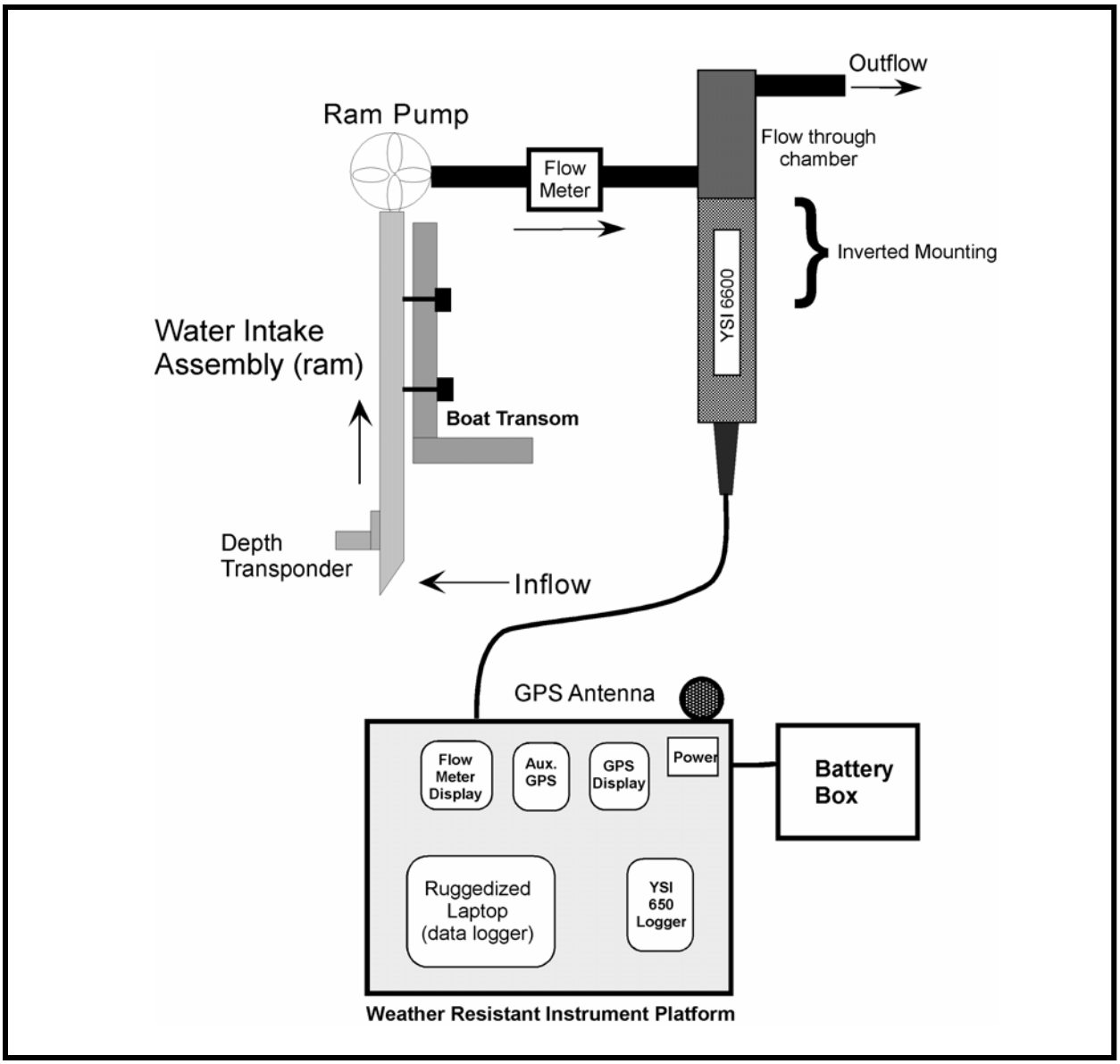

Figure 2-1. Schematic diagram of DATAFLOW 5.5 illustrating the path of water through the instrument.

Seawater is drawn up through the ram behind the transom of the research vessel. A centrifugal pump mounted on the ram (ram pump) boosts the flow. The water flows through a paddle-wheel type flow meter that triggers a horn if the flow rate falls below 3 l min-1, and then to an inverted flow-through chamber where it is sampled by the YSI 6600 datasonde sensors. The inverted mount is used in order to evacuate any air bubbles in the system. After sampling, the water is discharged overboard. The displays for the instruments, including the YSI 650 Datalogger, Garmin 168 GPS/Depthsounder, Garmin e-Trex GPS unit, flow meter display, and RDT 3200 are located on the instrument platform.

2.2 Sampling locations and frequency

Dataflow cruises were performed on a bi-weekly basis on the Northern and Southern sections of the Maryland Coastal Bays, for a total of eleven sampling cruises during 2003. The cruise dates are listed in Table 1-1. Cruise tracks were chosen to provide a reasonable coverage of each water body while sampling both near-shore and off-shore areas (Fig. 2-2). No data were collected from the middle of August until late September due to a combination of mechanical problems and hazardous weather.

Table 2-1. DATAFLOW cruise dates in 2003. *Highlighted dates indicate a single cruise split into two days (upper and lower segments).*

Region	**Spring**	**Summer**	**Fall**
Coastal Bays	4/23, 5/15, **5/29, 5/30**, **6/11, 6/12**, 6/23	7/07, 7/31, 8/13	9/23, 10/08, 10/22

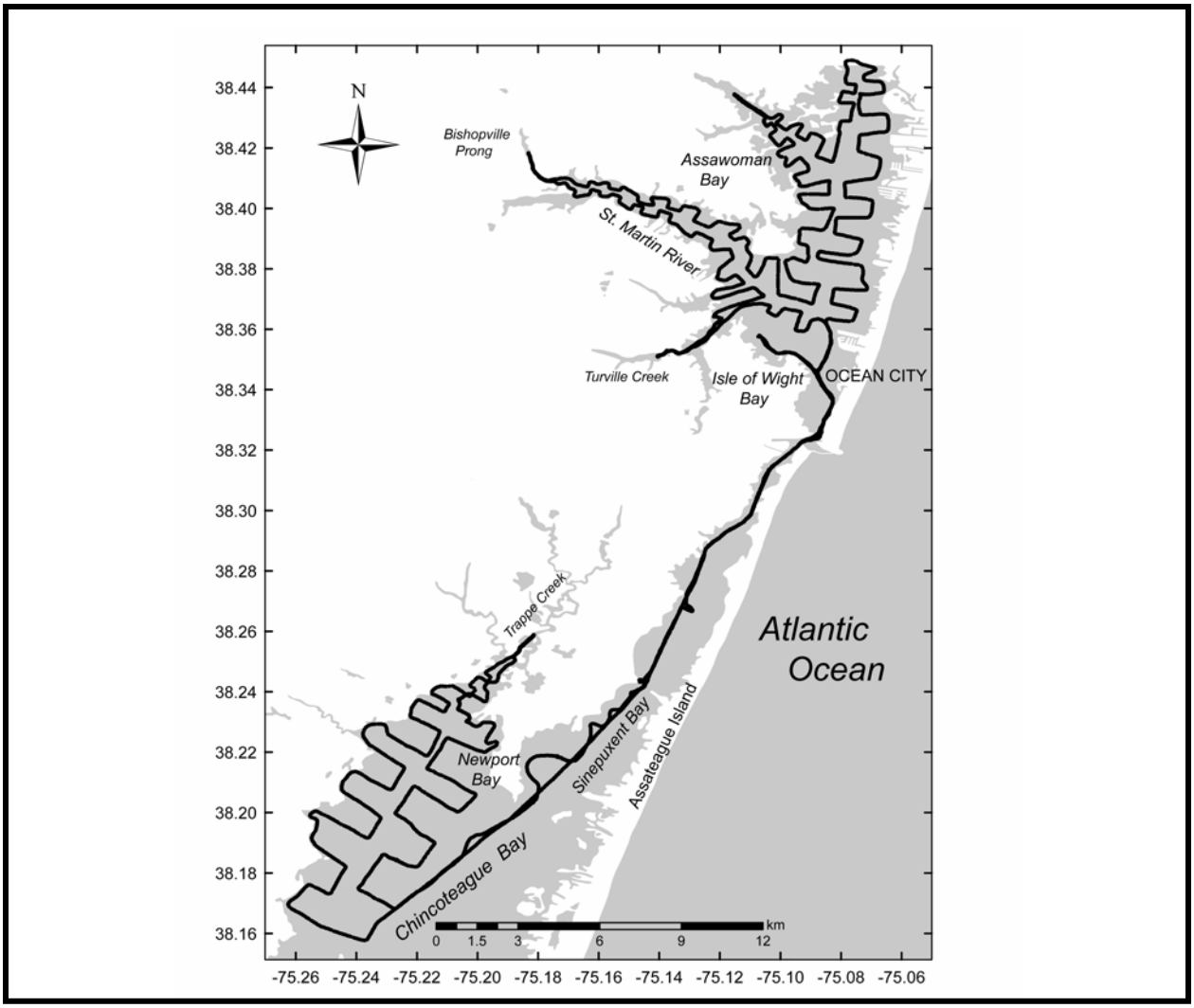

Figure 2-2. Typical DATAFLOW cruise track for the Maryland Coastal Bays, October 8, 2003. This cruise track covered approximately 105 nautical miles.

2.3. Fixed Station Sampling

The selection of fixed station locations in each region was made to sample the greatest possible range of water quality conditions found during each cruise and to sample a broad spatial area. Every effort was made to maintain the same location of calibration stations between cruises. The location of several calibration stations were also chosen to correspond to Maryland DNR Coastal Bays Program water quality monitoring stations within each segment, and these stations were sampled during each cruise. The coordinates for those stations are listed in Table 1-2, while geographic positions are shown in Fig. 1-3.

At each fixed station, whole water samples were collected and placed in a cooler for transport back to the laboratory. In the laboratory these samples were filtered according to Maryland DNR protocols and frozen prior to analysis. Upon transport to the Nutrient Analytical Services Laboratory (NASL) at the Chesapeake Biological Laboratory, they were analyzed for the following parameters: total suspended solids (TSS), total volatile solids (TVS), ammonium (NH4+), nitrite (NO2-), nitrate (NO3-), dissolved inorganic phosphorus (PO4), dissolved organic carbon (DOC), particulate carbon (PC), particulate phosphorus (PP), particulate inorganic phosphorus (PIP), total dissolved nitrogen (TDN), total dissolved phosphorus (TDP), and silicate (Si). Samples for analysis of water column chlorophyll-*a* concentrations were sent to the Maryland Department of Health and Mental Hygiene. A limited number of water samples were also analyzed for total and active chlorophyll-*a* samples by NASL to use in sensor data translation. This supplemental sampling was discontinued in June, 2003, due to budgetary constraints. In addition, a subset of the full suite of nutrients were collected during the April cruise before the 'full-suite' policy was implemented. A detailed explanation of all field and laboratory procedures is given in the annual CBL QAPP documentation (Rohland, 2003).

Table 2-2. Location of DATAFLOW fixed stations.
∗ Coincident with DNR long-term fixed station water quality monitoring stations.
† Coincident with DNR continuous monitoring instrument stations.

Section	Station (CBL)	Station (DNR)	Latitude (deg mins)	Longitude (deg mins)
Upper Bays	CBDF01*	XDN0146	38° 20.054' N	75° 05.386' W
	CBDF02*	XDN3445	38° 23.348' N	75° 05.521' W
	CBDF03*	XDN6454	38° 26.500' N	75° 04.650' W
	CBDF04*	XDN4312	38° 24.327' N	75° 08.786' W
	CBDF05†	XDM4486	38° 25.438' N	75° 11.318' W
	CBDF06†	TUV0021	38° 21.322' N	75° 08.992' W
	CBDF09	XDN6528	38° 26.492' N	75° 07.164' W
Lower Bays	CBDF07*	XCM1562	38° 11.300' N	75° 13.887' W
	CBDF08*	XCM4878	38° 14.475' N	75° 12.647' W
	CBDF10	XCN6219	38° 16.245' N	75° 08.032' W
	CBDF11	XCM3393	38° 13.340' N	75° 10.667' W
	CBDF12	XCM6193	38° 16.140' N	75° 10.674' W

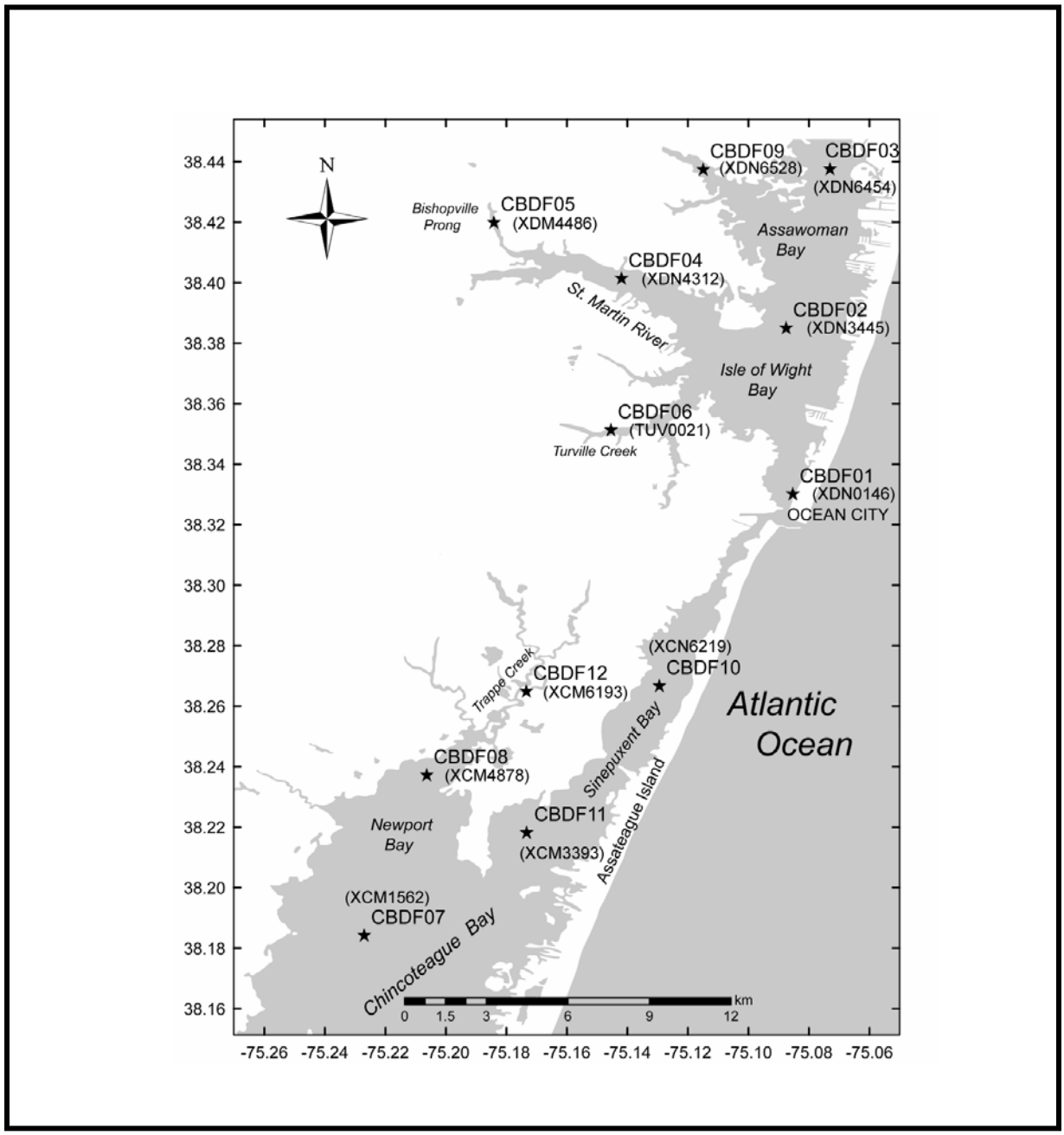

Figure 2-3. Calibration Stations on the Maryland Coastal Bays, 2003. DNR Station names are in parentheses.

2.4. Contour Maps

Contour maps were generated using the ESRI ArcGIS 8.3 software suite to assist in the interpretation of spatial patterns of different water quality parameters. Interpolation was accomplished using the Inverse Distance Weighting routine in the Spatial Analyst extension within the ArcGIS software. Interpolation technique is subject to much discussion regarding effectiveness and veracity of representation, so these maps are provided to illustrate only one method used to visualize patterns found in the Coastal Bays during 2003.

Each map was created by an inverse distance weighted interpolation technique using discrete data collected during an individual cruise. The interpolation was constrained by a boundary polygon, the geometry of which was determined by each cruise track. This method allows for improved accuracy in the representation of interpolated surface water quality data since it prohibits points from having artificial influence on one another if they are separated by a land mass or other physical barrier.

The data from which these figures were devised underwent QA/QC processes approved by managers and researchers from Maryland and Virginia through Chesapeake Bay Program Tidal Monitoring and Analysis Workgroup meetings. The QA/QC process ensured that extreme values resulting from data concatenation error (a function of how the instrument data are logged) or turbidity spikes resulting from operating a vessel in shoal areas could be eliminated or at least sequestered from the proofed dataset. Data are also visually inspected using ArcGIS where specific values can be compared with calibration data and the cruise log in order to eliminate similar obvious erroneous values.

We continue to explore different interpolation techniques available to us in commercial GIS software packages, and also plan to explore different ways to visualize the spatially intensive data gathered during the course of DATAFLOW cruises. Issues regarding data interpolation have yet to be resolved by a consortium of Chesapeake Bay managers and scientists, and it remains our intent to explore different methods while also presenting such data in a straightforward fashion in reports such as this one. In any case, the figures provide a snapshot of surface water quality for a selection of cruises.

2.5 Data translations and regressions

In order to properly compare the YSI turbidity (NTU) and chlorophyll (*in-situ* $\mu g\ l^{-1}$) sensor output to established habitat standards we performed a variety of linear regression analyses of these data versus data collected using established laboratory and field standards. For estimates of chlorophyll concentrations we regressed YSI sensor output, recorded at fixed station locations, versus total chlorophyll-*a* concentrations (fluorescence before acidification) from whole water samples collected at those stations. The Nutrient Analytical Services Laboratory (NASL) at the Chesapeake Biological Laboratory performed a limited number of these analyses in 2003. Regression results were compared using data from a single cruise, for several cruises on the Coastal Bays, and for Patuxent River and Coastal Bays cruises together in order to find the most robust relationship.

For estimates of water clarity, we regressed YSI turbidity output (NTU) recorded at each fixed station versus the mean water column light attenuation coefficient (Kd) calculated from replicate water column profiles at each station. These regressions were performed using data from a single cruise as well as from data collected during the entire season. Because secchi depth is also a widely used standard for measuring water clarity, we regressed Kd versus 1/secchi, as well as YSI (NTU) versus 1/secchi using data from the entire season.

3.0 Results

Datasets were also plotted using ArcGIS software to reveal route events during individual cruises. Since each sample from the Dataflow system is recorded as a discrete point in space and time, this proved to be a useful quality assurance tool to remove erroneous data (e.g. extreme turbidity values due to vessel grounding or propeller wash).

3.1 Fixed Calibration Station Nutrient Concentrations

Overall there was substantial temporal and spatial variation in dissolved nutrient concentrations across all stations sampled in 2003 (Tables 3-1, 3-2, Figs. 3-1-3-4). Temporal changes in concentrations throughout the sampling season resulted in non-normally distributed frequency distributions for dissolved inorganic nutrients increasing the variability within stations and regions. Spatially, as a group, the median concentrations at stations located in upstream positions (CBDF04-06, 09, and 12) were significantly higher compared to open water stations for every nutrient parameter sampled (Sign Rank test, $P < 0.05$). Even among the tributary stations, CBDF05 (Bishopville Prong of the St. Martin River) was unique in that many of the most extreme values encountered during the 2003 field season were found at that site. For example, the highest dissolved inorganic nitrogen (DIN), dissolved organic carbon (DOC), and particulate carbon (PC) concentrations (1.51 mg l^{-1}, 25.77mg l^{-1}, and 25.30 mg l^{-1} respectively) were recorded at this station. In comparison, the next highest DIN concentration (1.30 mg l^{-1}) was found just downstream at station CBDF04. The next highest DOC and PC concentrations (11.75 mg l^{-1}, 8.7 mg l^{-1} respectively) were recorded at station CBDF12 which is also a tributary station. In addition, CBDF05 also exhibited the lowest overall salinity and most variable pH, presumably due to high metabolic activity and lack of buffering found in higher salinity waters.

With the tributary stations excluded there was no significant difference in dissolved inorganic nitrogen (DIN) concentrations between the upper and lower bay regions (ANOVA on log transformed data, $P>0.05$). In addition, there was no significant difference in dissolved inorganic phosphorus (DIP) between the upper and lower bay regions (ANOVA on log transformed data, $P>0.05$). Finally, there were no significant differences between the upper and lower Bays for any of the remaining nutrient parameters (t-test, $P>0.05$) with the exception of total dissolved phosphorus (TDP) which was significantly higher in the lower Bays region (t-test, $P<0.05$). The magnitude of this difference was quite small but was detected due to a very small variance in these samples.

Table 3-1. Mean, median, minimum, and maximum for Dissolved Inorganic Nitrogen (DIN) and Dissolved Inorganic Phosphorus (DIP) concentrations on Upper Bays over during the 2003 sampling season.

Upper Bays		**CBDF01**	**CBDF02**	**CBDF03**	**CBDF04**	**CBDF05**	**CBDF06**	**CBDF09**
Dissolved Inorganic Nitrogen	Mean	2.12	2.55	3.94	24.72	20.71	6.08	10.55
(μM N)	Median	1.38	2.30	3.56	12.79	7.78	3.84	5.84
	Min	0.49	0.79	0.91	1.09	1.91	1.21	1.54
	Max	5.31	5.66	11.64	93.07	108.07	15.29	37.57
Dissolved	Mean	0.21	0.14	0.21	1.57	0.49	0.23	0.45
Inorganic Phosphorus	Median	0.19	0.11	0.15	1.12	0.27	0.21	0.50
(μM P)	Min	0.06	0.08	0.08	0.10	0.08	0.08	0.08
	Max	0.43	0.49	0.54	6.87	2.23	0.53	0.71

Table 3-2. Mean, median, minimum, and maximum for dissolved Inorganic Nitrogen (DIN) and Dissolved Inorganic Phosphorus (DIP) concentrations on Lower Bays during the 2003 sampling season.

Lower Bays		**CBDF07**	**CBDF08**	**CBDF10**	**CBDF11**	**CBDF12**
Dissolved	Mean	2.64	5.86	4.63	4.41	4.83
Inorganic Nitrogen	Median	1.15	3.76	2.53	2.86	1.54
(μM N)	Min	0.79	0.99	1.11	0.67	0.57
	Max	12.19	13.93	12.84	16.90	18.57
Dissolved	Mean	0.15	0.11	0.31	0.15	0.33
Inorganic Phosphorus	Median	0.13	0.10	0.29	0.11	0.32
(μM P)	Min	0.06	0.06	0.09	0.07	0.07
	Max	0.22	0.17	0.64	0.37	0.76

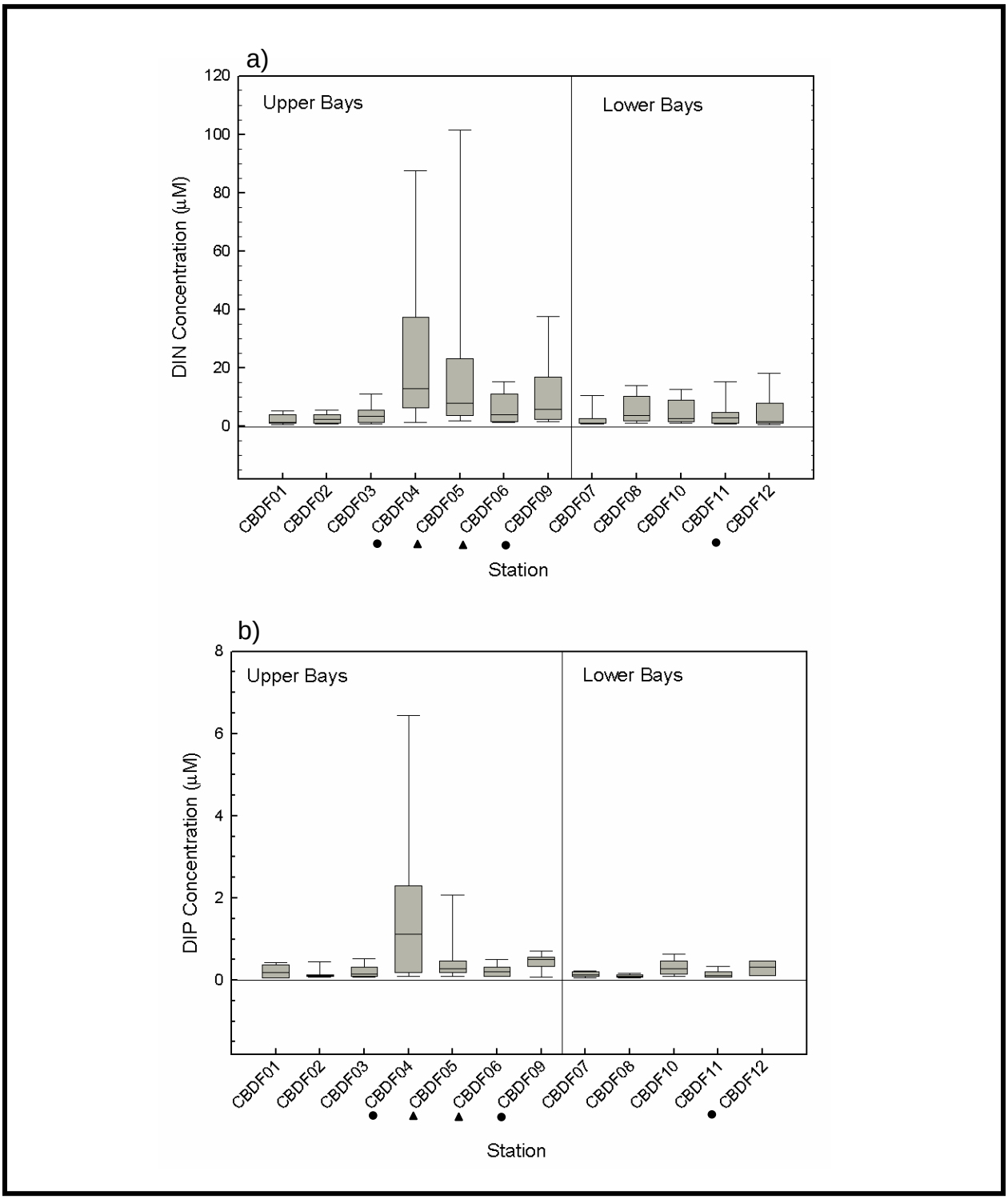

Figure 3-1. a) DIN and b) DIP water column concentrations at calibration stations during the 2003 sampling period. Horizontal lines indicate median values, upper and lower box boundaries represent 75th and 25th percentiles, respectively. Upper and lower whiskers represent 5th and 95th percentiles, respectively. The stations marked with circles are located in tributaries, and those marked with triangles are Continuous Monitoring sites (also located in tributaries).

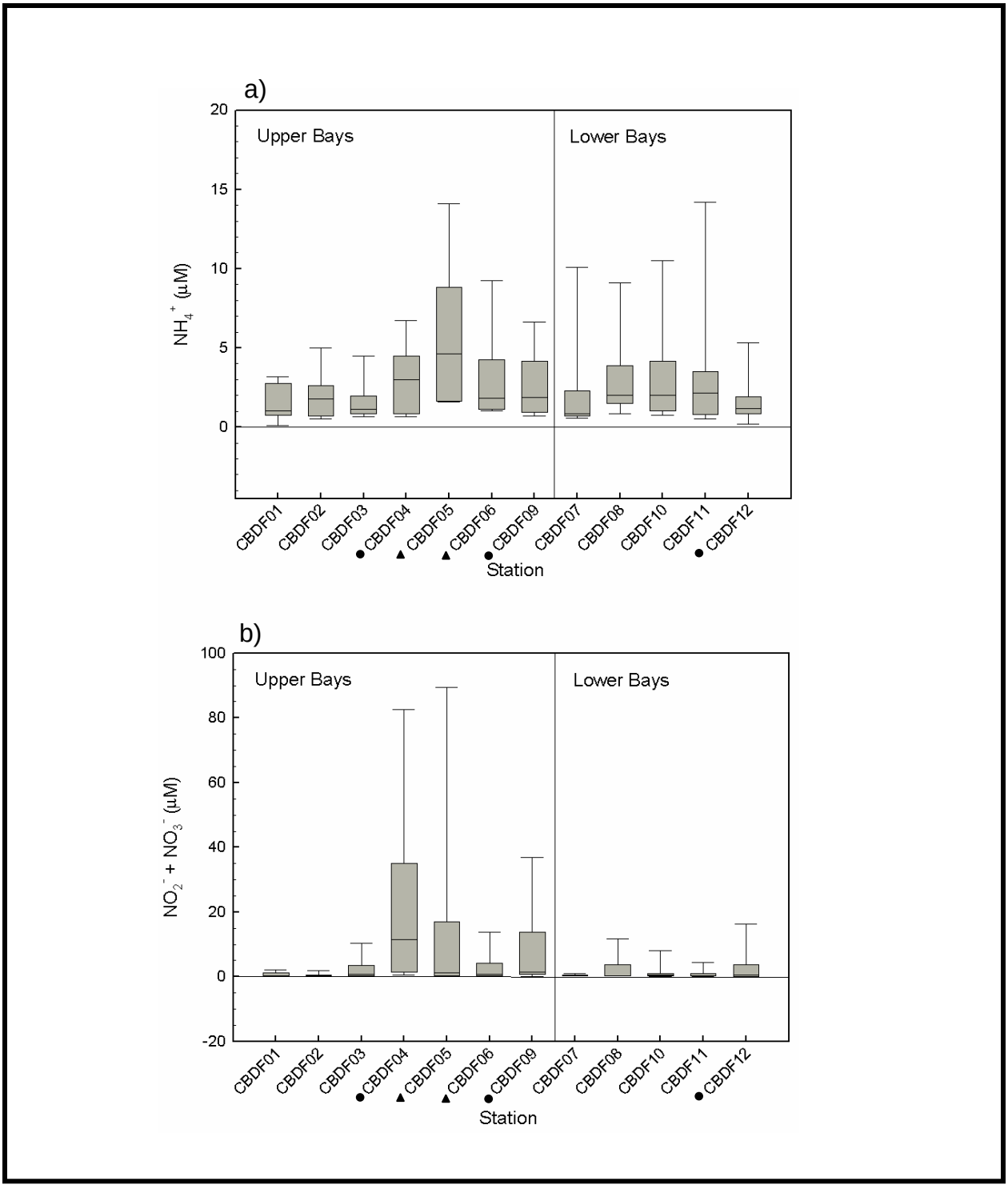

Figure 3-2. a) Ammonium and b) Nitrite + Nitrate water column concentrations at each calibration station in 2003. Horizontal lines indicate median values, upper and lower box boundaries represent 75th and 25th percentiles, respectively. Upper and lower whiskers represent 5th and 95th percentiles, respectively. The stations marked with circles are located in tributaries, and those marked with triangles are Continuous Monitoring sites (also located in tributaries).

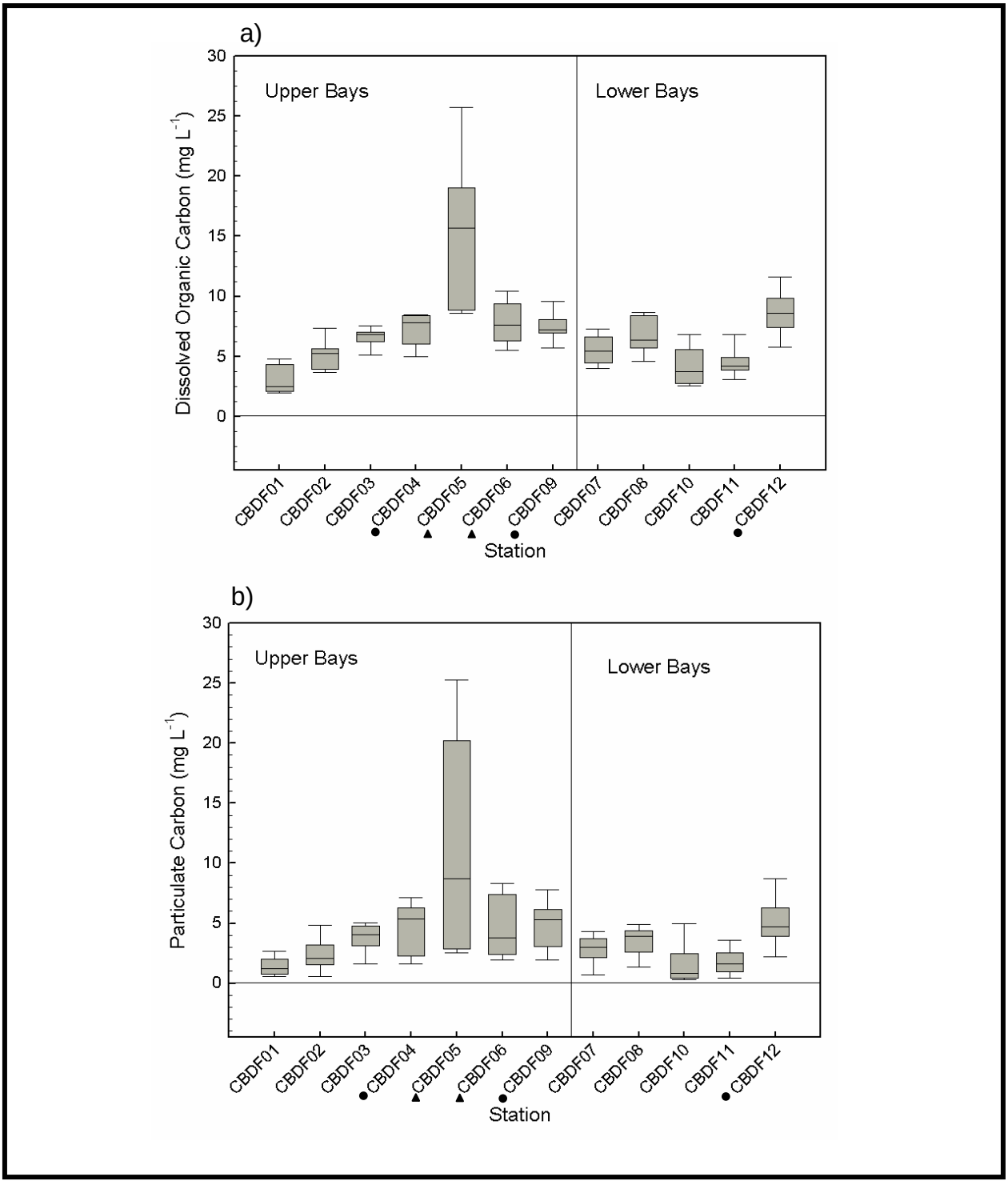

Figure 3-3. Distribution of a) water column dissolved organic carbon (DOC), and b) particulate carbon (PC) concentrations for DATAFLOW calibration stations in 2003. Box ends represent 25th and 75th percentiles, while horizontal lines represent median values. Upper and lower whiskers represent 5th and 95th percentiles, respectively. Stations marked with circles are located in tributaries, and those marked with triangles are Continuous Monitoring sites (also located in tributaries).

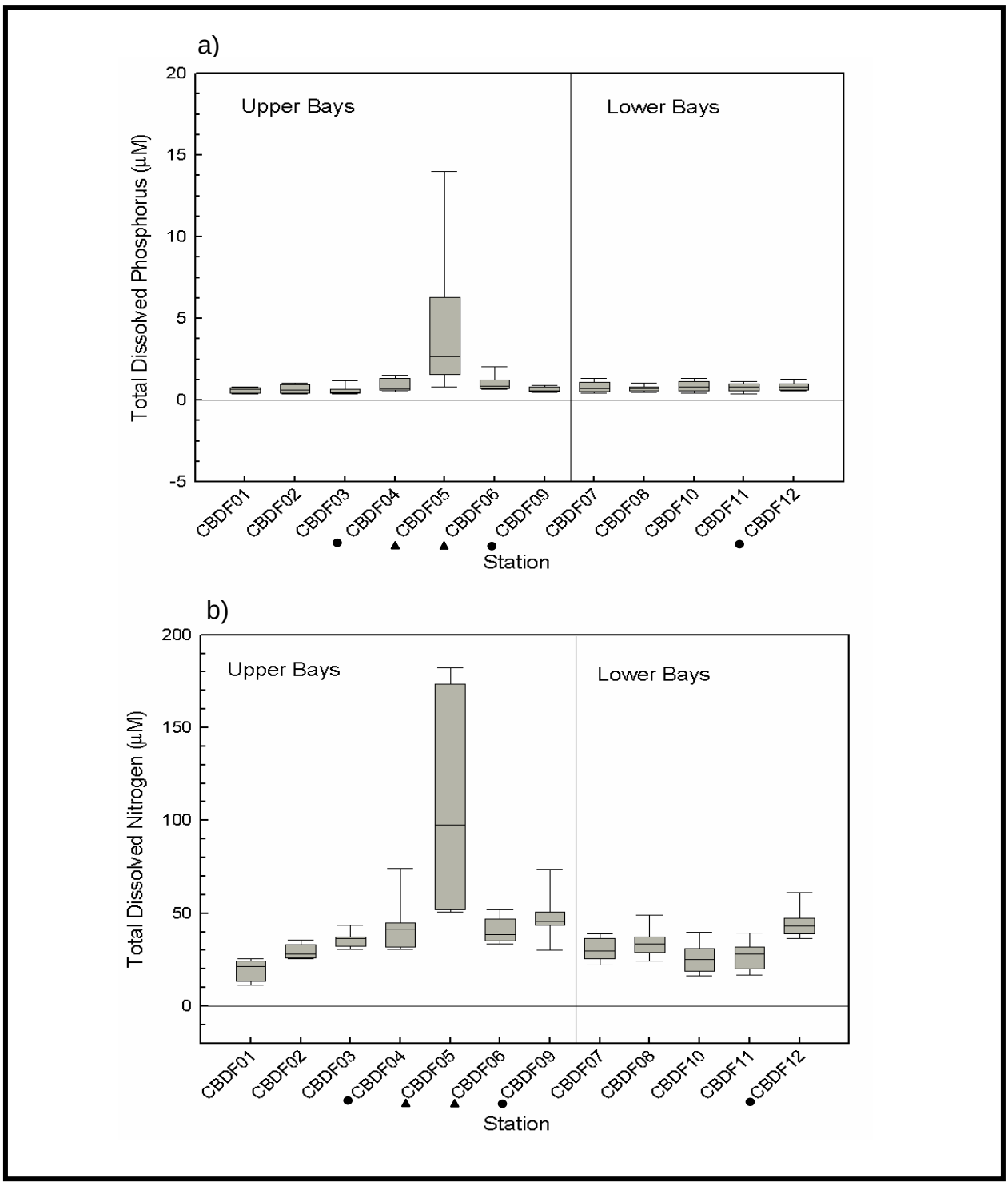

Figure 3-4. Distribution of a) total dissolved phosphorus (TDP), and b) total dissolved nitrogen concentrations for calibration stations in 2003. Box ends represent 25th and 75th percentiles, while horizontal lines represent median values. Upper and lower whiskers represent 5th and 95th percentiles, respectively. Stations marked with circles are located in tributaries, and those marked with triangles are Continuous Monitoring sites (also located in tributaries).

3.1.2 Physical Conditions

Salinity values measured with the DATAFLOW system (> 70,000 observations) exhibited a substantial range of values. The minimum salinity recorded was 0.19 in Bishopville Prong, while the maximum was 32.44 near the Ocean City Inlet. The median salinity value for the whole dataset was 25.90. Salinity values recorded at the CBDF05 station in the Bishopville Prong also showed the highest variation of all fixed stations with values ranging from 0.19 to 19.1 (Fig. 3-5a). As a consequence, this variation in salinity was also likely responsible for high variation in pH values within this region. Overall, DATAFLOW surface water pH values ranged from a minimum 6.06 and a maximum of 9.14. However, both values were found in the vicinity of station CBDF05 in the Bishopville Prong of the St. Martin River. Consequently, the greatest variation in pH found at a single station was also found at station CBDF05. Median surface water pH for the entire dataset was 7.99. DATAFLOW surface water dissolved oxygen concentrations also varied substantially throughout the entire season with a minimum of 2.56 mg l^{-1} and maximum of 20.66 mg l^{-1}, both located in Bishopville Prong. Dissolved oxygen concentrations below 5.0 mg l^{-1} were found in a variety of locations ranging from the vicinity of the Isle of Wight, the Ocean City Inlet, to the overall length of Sinepuxent Bay and the open waters of Newport Bay. Median surface water dissolved oxygen concentration for the 2003 season was 6.70 mg l^{-1}. Surface water temperatures were also very high in tributaries, as would be expected. (Fig. 3-6b). DATAFLOW data showed a minimum surface water temperature was 7.97 degrees Celsius (at the Ocean City Inlet on April 23, 2003) and the maximum was 32.69 degrees Celsius (at CBDF08 in Bishopville Prong on July 7, 2003). DATAFLOW optical turbidity ranged from a low of 0.10 NTU in Sinepuxent Bay near the Verrazano Bridge and a maximum of 126.9 NTU in the open waters of Newport Bay. DATAFLOW sampling data for *in situ* chlorophyll had a minimum of instrument resolution of 0.1 µg l^{-1} in the open waters of Newport Bay and a maximum of 359.5 µg l^{-1} in Bishopville Prong near station CBDF05. The lowest recorded DATAFLOW *in situ* chlorophyll at a fixed station was 1.5 µg l^{-1} recorded at station CBFDF05.

The parameters total suspended solids (TSS), and light attenuation (Kd) were only measured at the fixed stations, therefore represent a much smaller dataset compared to DATAFLOW data. Stations CBDF05 and CBDF06 exhibited the highest range of TSS values (Fig. 3-7a). Turbidity at open water stations was consistent with the wind and wave exposure that contributes to mixing and sediment resuspension in a shallow system. The large range of light attenuation coefficient (Kd) values at open water stations was likely due to wind driven re-suspension of bottom sediments. Seasonal median Kd values typically increased at upstream stations, as illustrated by Fig. 3-7b. The highest Kd value was found at station CBDF05, and was the result of extremely high chlorophyll concentrations rather than suspended sediment. The lowest Kd value was recorded at station CBDF01 near the US 50 bridge and the Ocean City inlet. Kd derived from regression conversions of Secchi observations can be highly variable depending on the strength of the linear regression for each station. The variation is attenuated by the application of a linear equation derived from the regression of all calibration data for the system. This phenomenon is illustrated in Figure 3-8a and b. Compare these values converted from Secchi observations with the mean Kd values that were calculated for each calibration station through actual measurement of Photosynthetically Active Radiation (PAR) in Figure 3-7a.

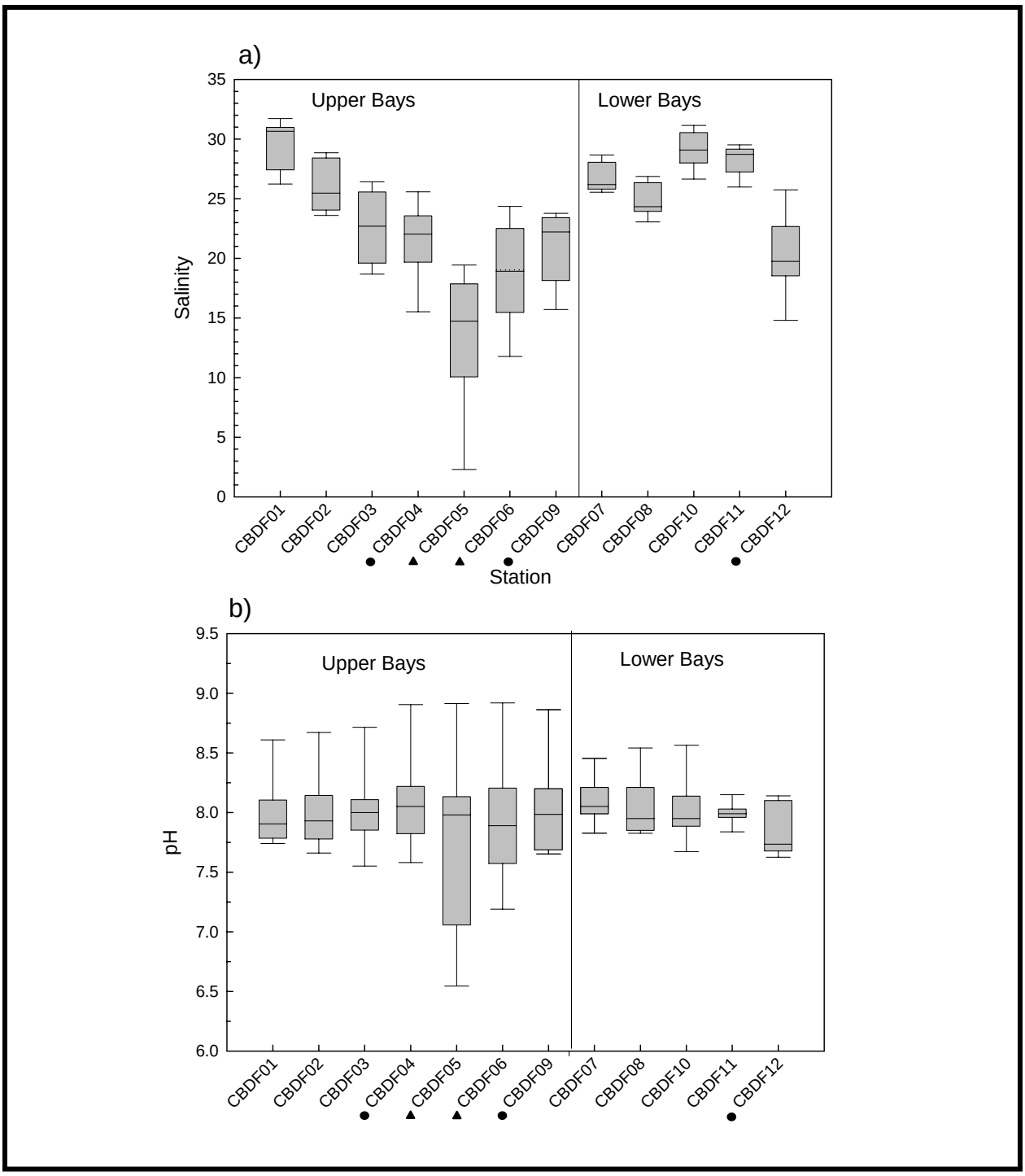

Figure 3-5. a) Range of salinity, and b) pH encountered during the 2003 sampling period. Horizontal lines indicate median values, and upper and lower box boundaries represent 75th and 25th percentiles, respectively. Upper and lower whiskers represent 5th and 95th percentiles, respectively. The stations marked with circles are located in tributaries, and those marked with triangles are Continuous Monitoring sites (also located in tributaries).

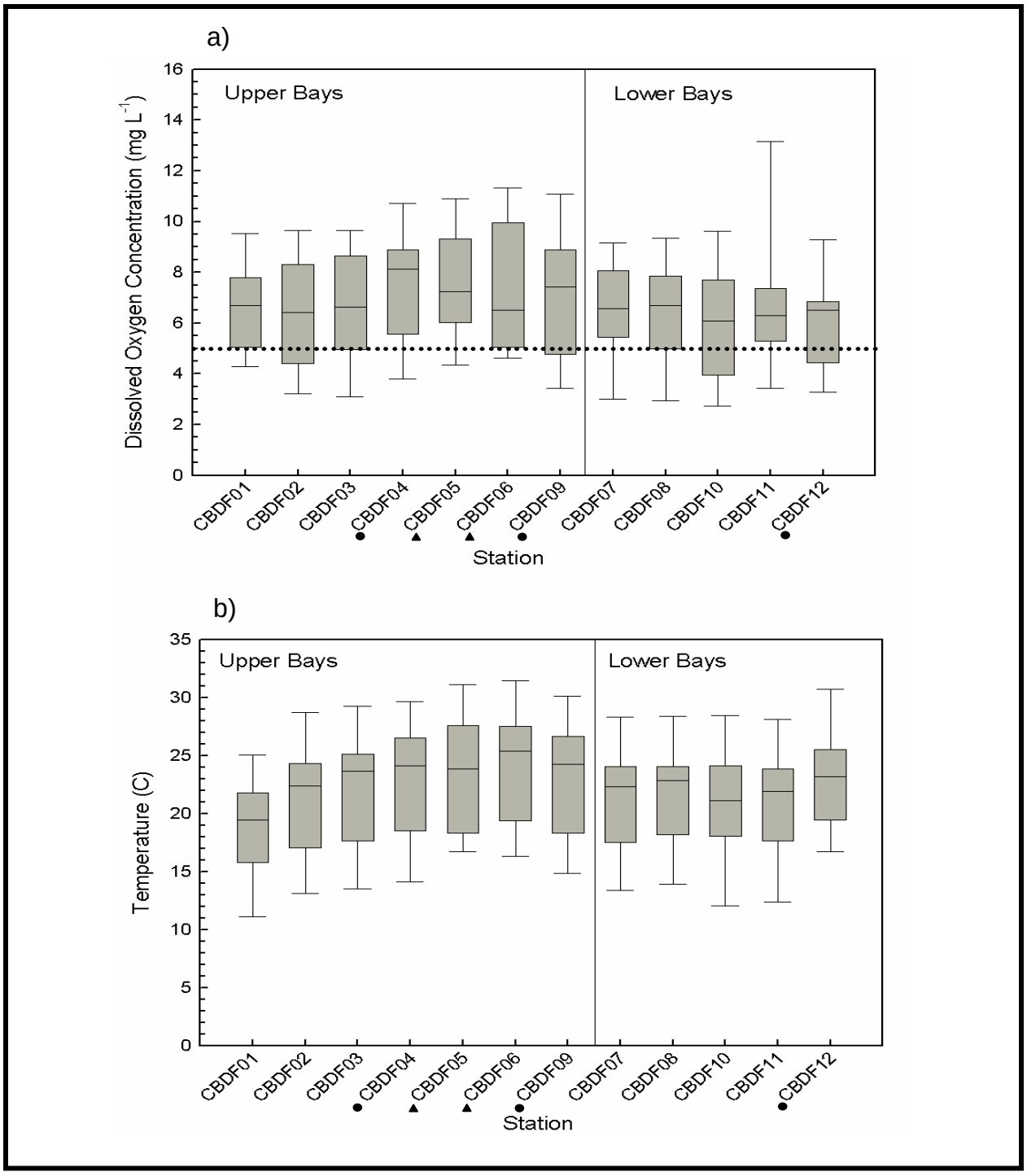

Figure 3-6. a) Dissolved oxygen concentrations (dashed line represents Chesapeake Bay Program habitat criteria), and b) Water Temperature during the 2003 sampling period. Horizontal lines indicate median values, and upper and lower box boundaries represent 75th and 25th percentiles, respectively. Upper and lower whiskers represent 5th and 95th percentiles, respectively. The stations marked with circles are located in tributaries, and those marked with triangles are Continuous Monitoring sites (also located in tributaries).

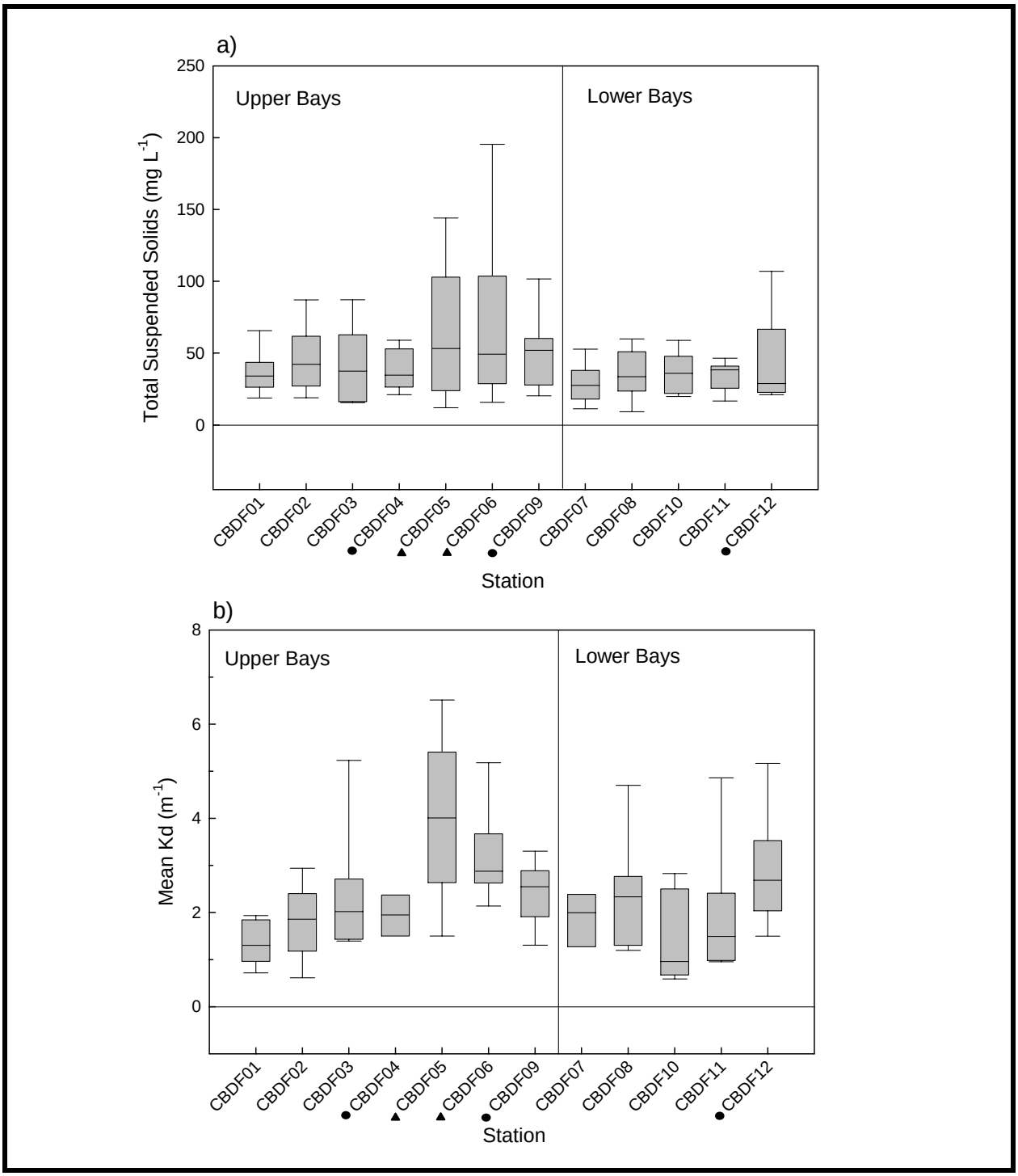

Figure 3-7. Box and whisker plots for a) total suspended solids, and b) light attenuation coefficient (Kd) for each calibration station during the 2003 sampling period. Horizontal lines indicate median values, and upper and lower box boundaries represent 75th and 25th percentiles, respectively. Upper and lower whiskers represent 5th and 95th percentiles, respectively. The stations marked with circles are located in tributaries, and those marked with triangles are Continuous Monitoring sites (also located in tributaries).

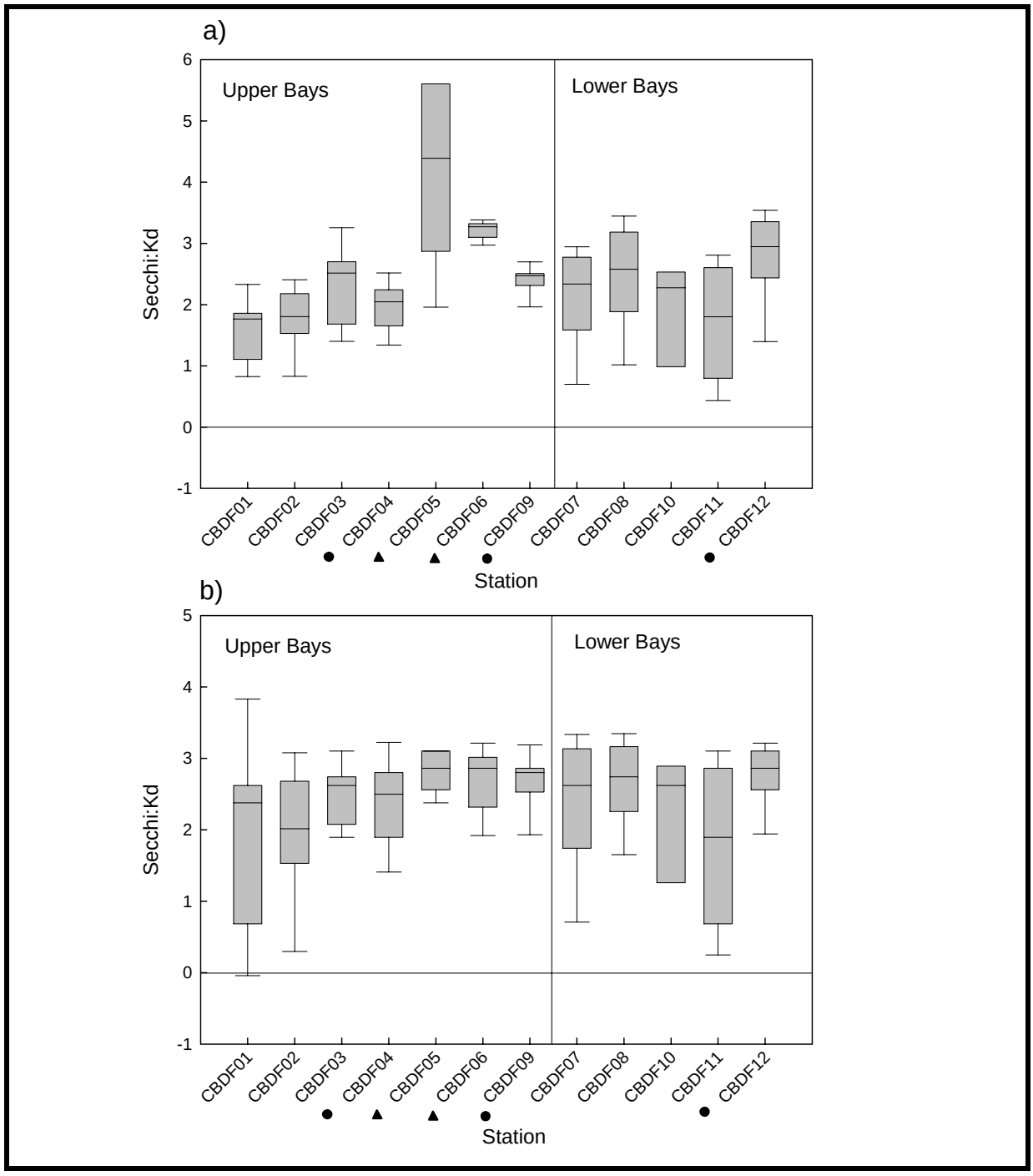

Figure 3-8. Box and whisker plots for a) converted Kd (from Secchi) through regression for each station, and b) converted Kd (from Secchi) using system wide regression for each calibration station during the 2003 sampling period. Negative values resulted from the calculations. Horizontal lines indicate median values, and upper and lower box boundaries represent 75th and 25th percentiles, respectively. Upper and lower whiskers represent 5th and 95th percentiles, respectively. The stations marked with circles are located in tributaries, and those marked with triangles are Continuous Monitoring sites (also located in tributaries).

3.2 Data Translations and Regressions

The usefulness of linear regressions to accurately translate YSI sensor output to universally recognized standards requires that a sufficient range of data be present in order to obtain a high correlation between the variables. This can be accomplished by using data collected from a single cruise, or by combining data from multiple cruises, and locations. The rationale for using data from a single cruise comes from the assumption that the specific components leading to water column light attenuation (or species if measuring chlorophyll) will be more similar within a single cruise compared to data collected over the entire season, resulting in a better fit of the data. In contrast, when data are combined over a whole season, or from different locations, there is a greater chance that the relationship between the two measurement variables will vary among cruises, thus leading to an overall lower correlation. However in circumstances where the observed gradient (turbidity or chlorophyll) within a single cruise is relatively small compared to the resolution and accuracy of the instruments, a higher correlation may be achieved by combining the data from multiple cruises. We present examples of these issues below.

The total dataset available for translation of YSI chlorophyll to laboratory based (NASL) total chlorophyll-*a* concentrations (T-chl-*a*) was somewhat more limited in 2003 (April – July) compared to what was available for turbidity. However several useful relationships were found. Unlike turbidity, the relationship between YSI sensor output and laboratory based values is a bit more complicated. Several issues must be considered before YSI sensor output is converted to laboratory standard chlorophyll-*a* concentrations. In order to use data from a single cruise, a sufficient range of values must be measured. However, because of the patchy nature of chlorophyll blooms there is the possibility that a single extremely high value will have a large influence on the relationship. As a result, care should be exercised when applying the results of these relationships to the data. An example of this is shown in Fig. 3-9a, where a single high observation will have a large influence on the relationship. In this case, the relationship between YSI sensor output and laboratory derived concentrations was very different from the bulk of the observations biasing the results. In addition, chlorophyll-*a* concentrations typically vary over the entire sampling season with overall lower concentrations found during certain times of the season. As a result, in most systems (including the Coastal Bays), correlations between YSI chlorophyll and laboratory derived values based upon a single cruise are not as high as with data from multiple cruises. This was true for the Coastal Bays in 2003. For example, on the June 11th cruise, with one outlier excluded, the range of total chlorophyll-*a* concentrations observed was approximately 30 μg l^{-1} T-chl-*a* (r^2 = 0.54, Fig. 3-8a) compared to more than 80 μg l^{-1} T-chl-*a* (r^2 = 0.63, Fig. 3.9b) for the entire available dataset. Further, when data from the lower Patuxent River was included, the overall correlation was improved (r2 = 0.83, Fig. 3-8c). Other methods for converting YSI chlorophyll to laboratory standards are being developed by Maryland DNR.

For turbidity measurements, correlation coefficients (r^2) obtained for single cruises were higher than that obtained using the entire combined dataset (r^2 = 0.42, Fig. 3-10b), for 6 of 10 total cruises. For example, there was a sufficient range of water clarity values on the June 23, 2003 cruise, that the regression of YSI turbidity (NTU) against water column light attenuation coefficient (Kd) produced a better fit (r^2 = 0.73, Fig. 3-10a) compared to the grouped data. As with chlorophyll, care should be taken when converting from one unit to another in order to obtain the best fit. Finally, because secchi depth is still regarded as a useful metric for estimating

water clarity, regressions of Kd against 1/secchi, and YSI turbidity (NTU) against 1/secchi were performed with correlation coefficients ($r^2 = 0.39$, and $r^2 = 0.28$ respectively, Fig. 3-11).

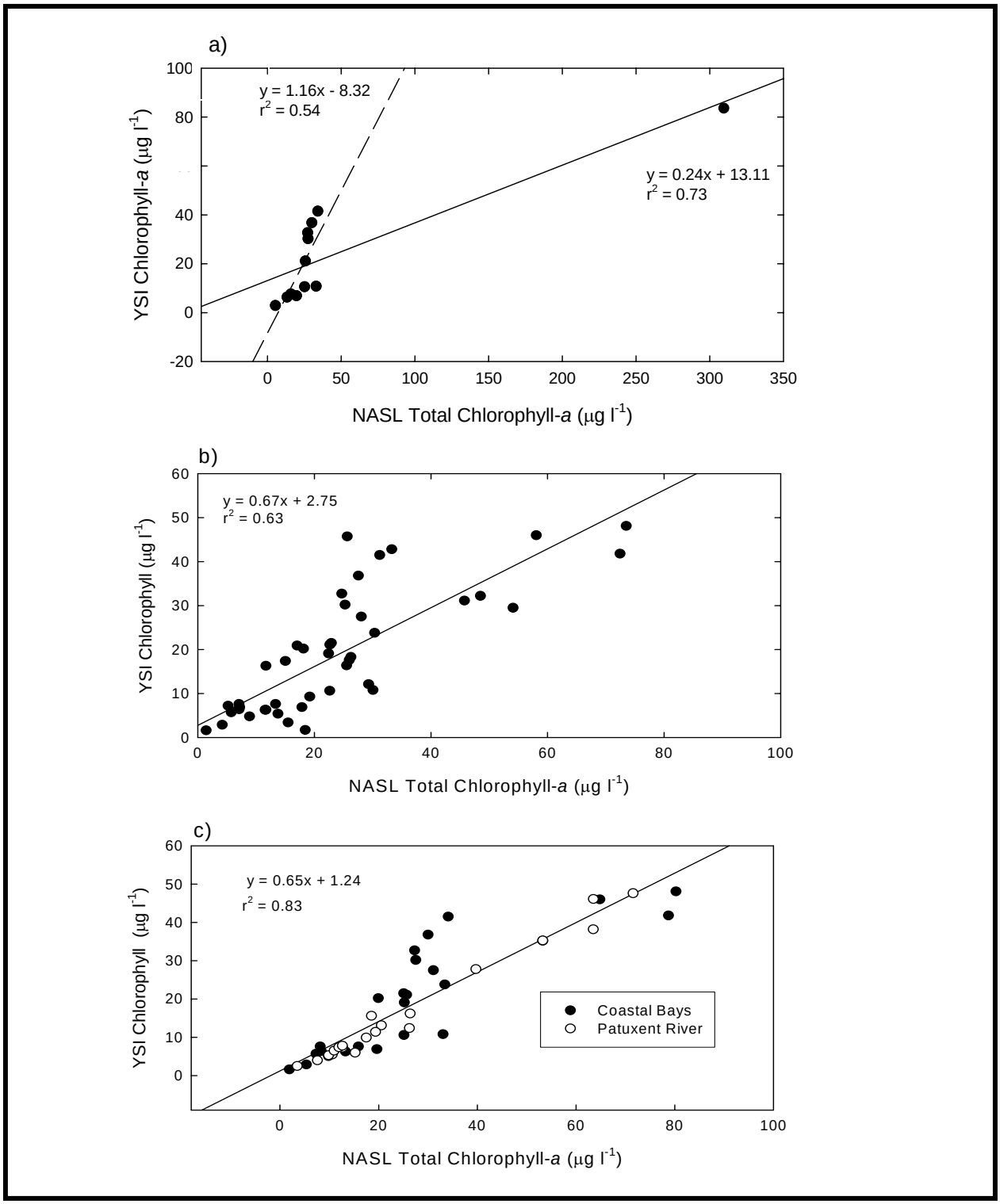

Fig. 3-9. Linear regression of YSI chlorophyll versus total chlorophyll-a based upon acetone extraction of water samples for a) a single cruise on the Coastal Bays June 11, 2003, regression lines calculated with and without extreme outlier, b) all cruises where NASL chlorophyll-a was measured (N=24), and c) Coastal Bays and Patuxent River data for several cruises in 2003.

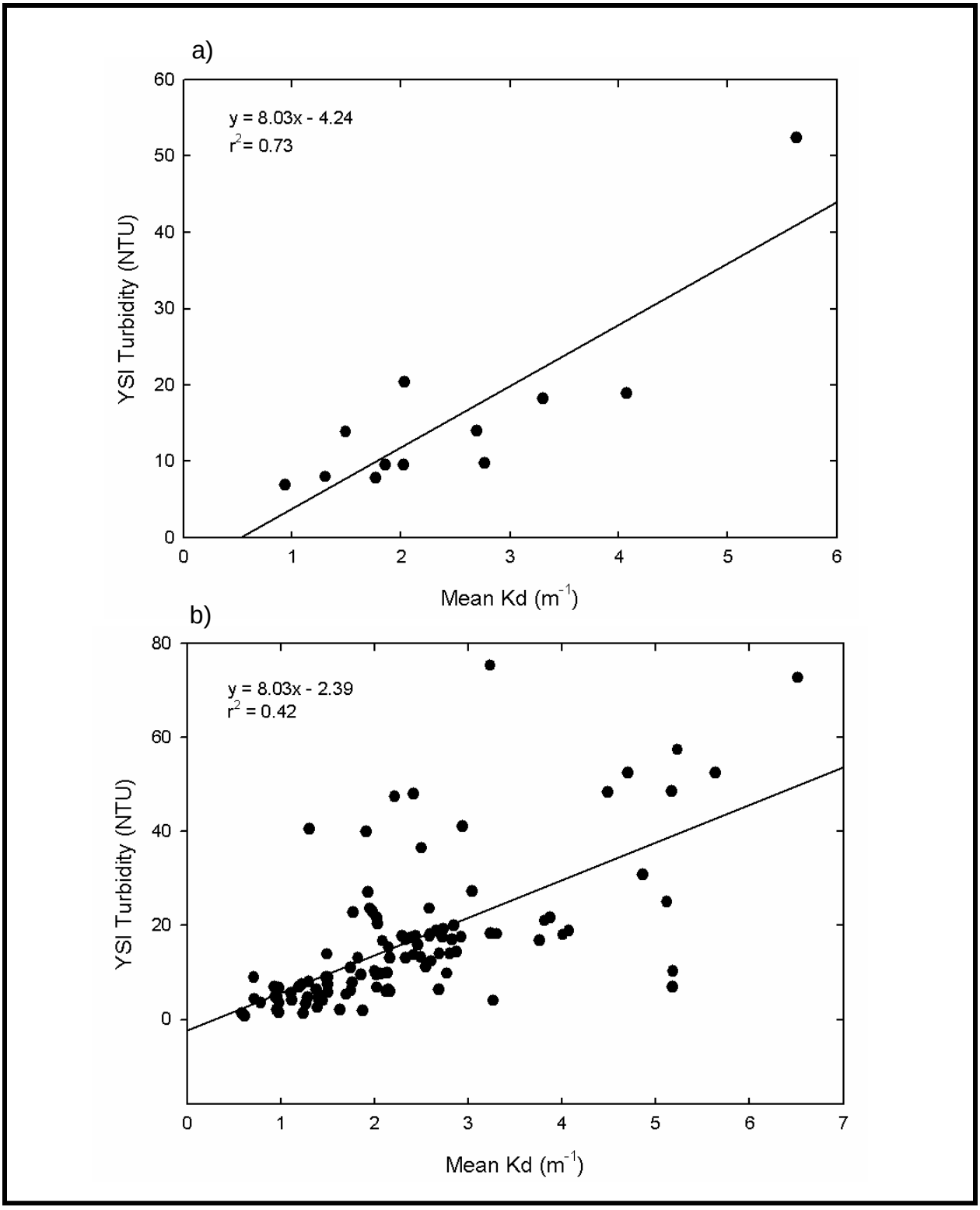

Figure 3-10. Linear regression of YSI turbidity (NTU) versus calculated water column light attenuation (Kd) for a) one cruise on June 23, 2003, and b) all Coastal Bays cruises in 2003.

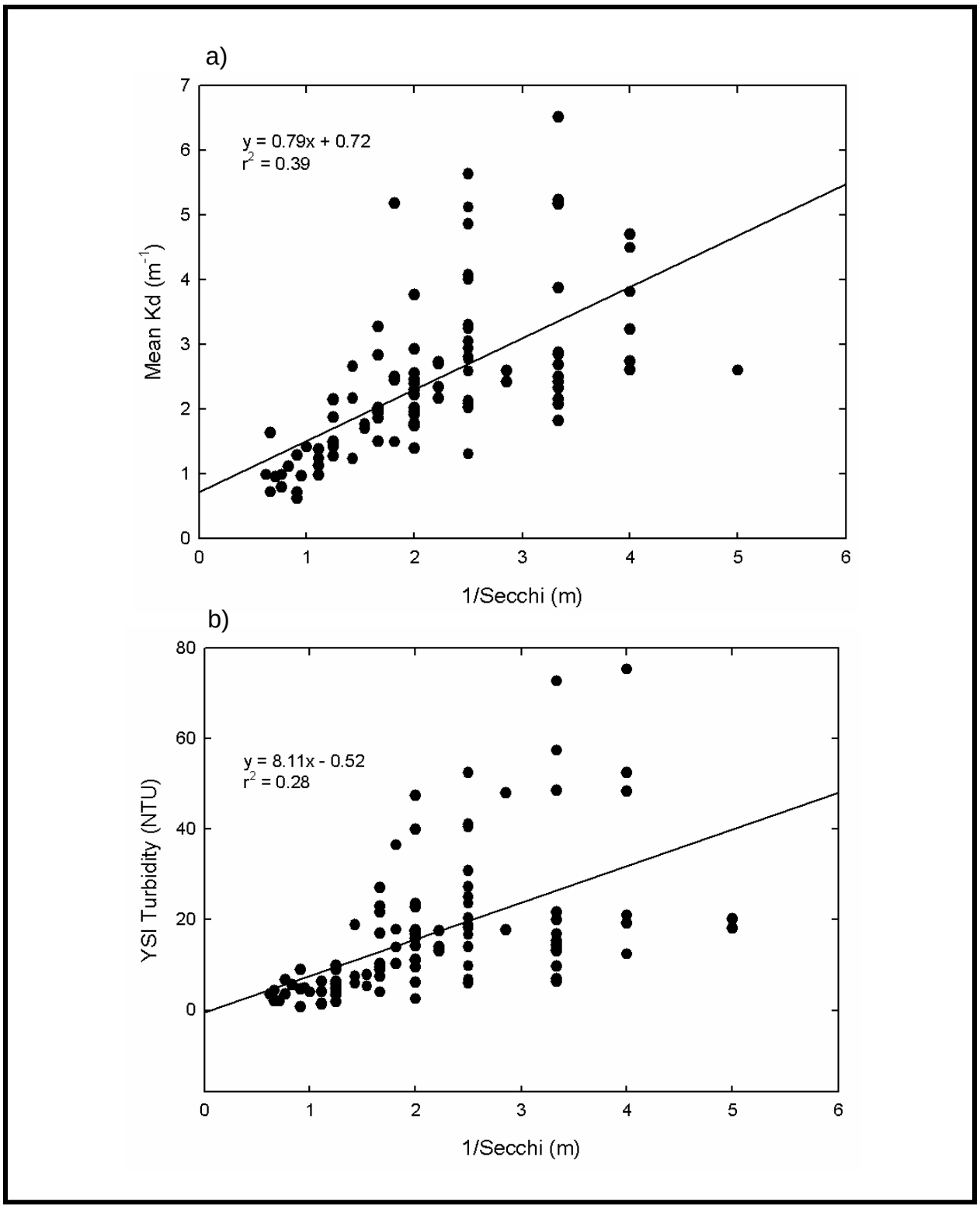

Figure 3-11 Linear regression of a) calculated light attenuation coefficient (kd) versus 1/Secchi, and b) YSI turbidity (NTU) versus 1/Secchi for all Coastal Bays cruises in 2003.

3.3 DATAFLOW Data distributions

Because the DATAFLOW cruise tracks covered a substantial amount of the area in both the Northern and Southern Bays, a great deal of insight can be gathered from looking at the distribution of data collected throughout the entire season in the open water portions of these systems. With tributary data excluded, frequency histograms of YSI turbidity and YSI chlorophyll (translated to lab based total chlorophyll) are shown in Fig. 3-12. For both turbidity and translated chlorophyll-a, the distribution of data was significantly different between the two regions (Kolmogorov-Smirnoff test, $P<0.001$). Both median turbidity (13.6 NTU) and translated chlorophyll-a (20.8 $\mu g\ l^{-1}$) were higher in the Southern open bays, compared to the Northern open bays (8.25 NTU, and 8.72 $\mu g\ l^{-1}$).

Using the regression relationships between YSI turbidity and light attenuation coefficient (Kd) we estimated that a YSI turbidity reading of 10 NTU was approximately equal to the established SAV Light attenuation habitat criterion of 1.5 m^{-1} (Fig 3-10b). Using this value as a selection criterion, we calculated the percent of observations on each cruise that exceeded this criterion and plotted the percentage for each cruise. The resulting plot shows that for both the Northern and Southern bays, on most cruises, the entire area was either above or below the habitat criteria (Fig. 3-13a). Only two cruises in the Northern bays indicate any substantial (>20%) heterogeneity relative to habitat criteria. In a manner similar to the Chesapeake Bay Programs new criteria evaluation method we plotted the same data as a cumulative frequency distribution for each region (Fig. 3-13b). However, this diagram represents the actual percent of observations exceeding habitat criteria rather than an estimate of area based upon an interpolation of the data. These curves show that relative to habitat criteria, both the Northern and Southern bays were spatially homogenous with most of the area either passing or failing habitat criteria depending on the cruise date. This pattern was not evident for YSI chlorophyll data when translated to laboratory derived total chlorophyll-a. There was a substantial difference in the spatial heterogeneity between the Northern and Southern bays when the selection criteria was set to 15 $\mu g\ l^{-1}$. The Northern bays had fewer cruises with high percentages of the observations exceeding habitat criteria compared to the Southern bays (Fig. 3-14a). The cumulative frequency diagram also reflects the observed difference between the regions (Fig. 3-14b). These data provide that starting point, from which actual CFD will be calculated for the Coastal Bays.

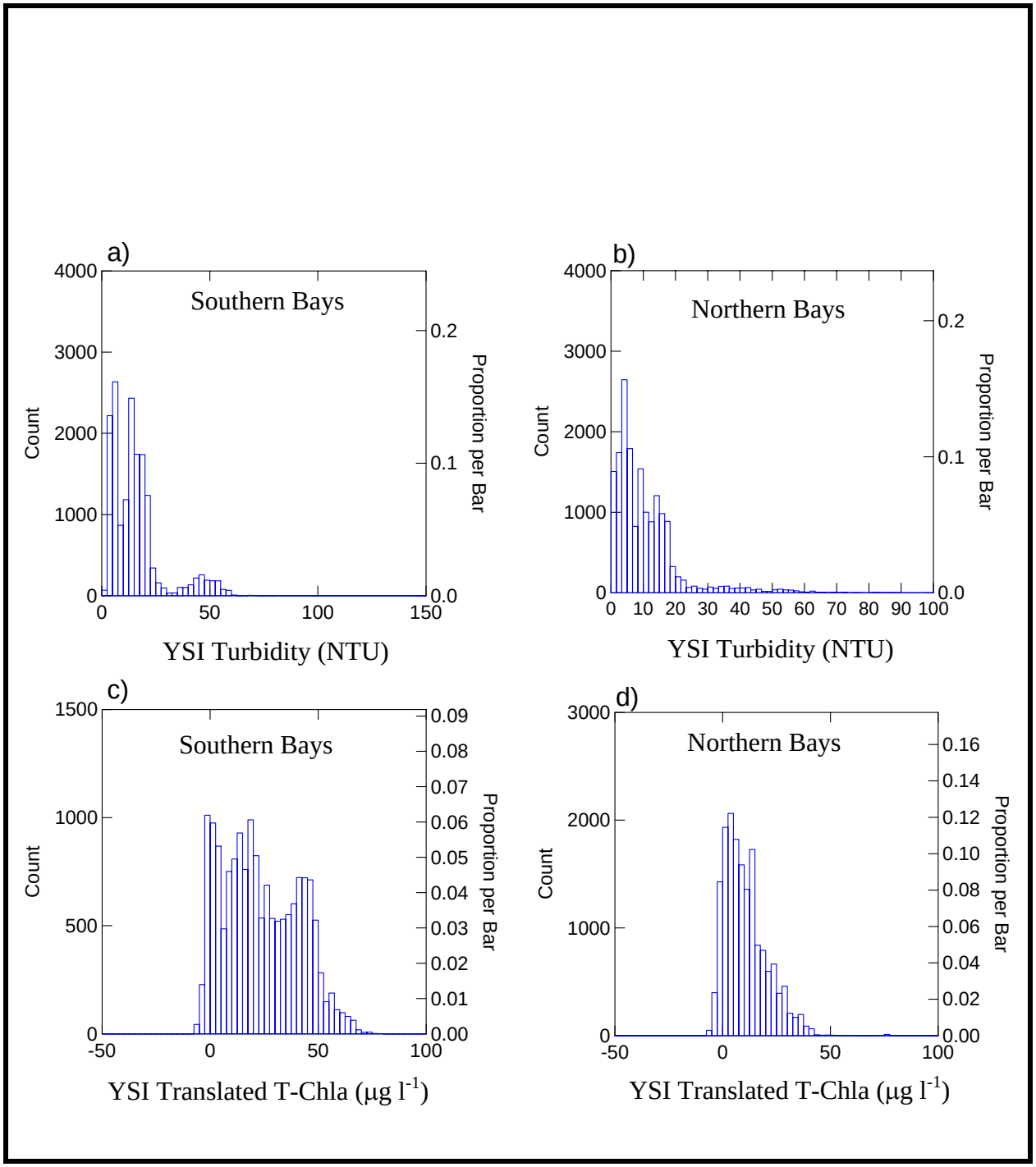

Figure 3-12. Distribution of DATAFLOW observations for open water portions of Northern and Southern bays 2003 for a-b) turbidity (NTU) and, c-d) DATAFLOW translated Total chlorophyll-a.

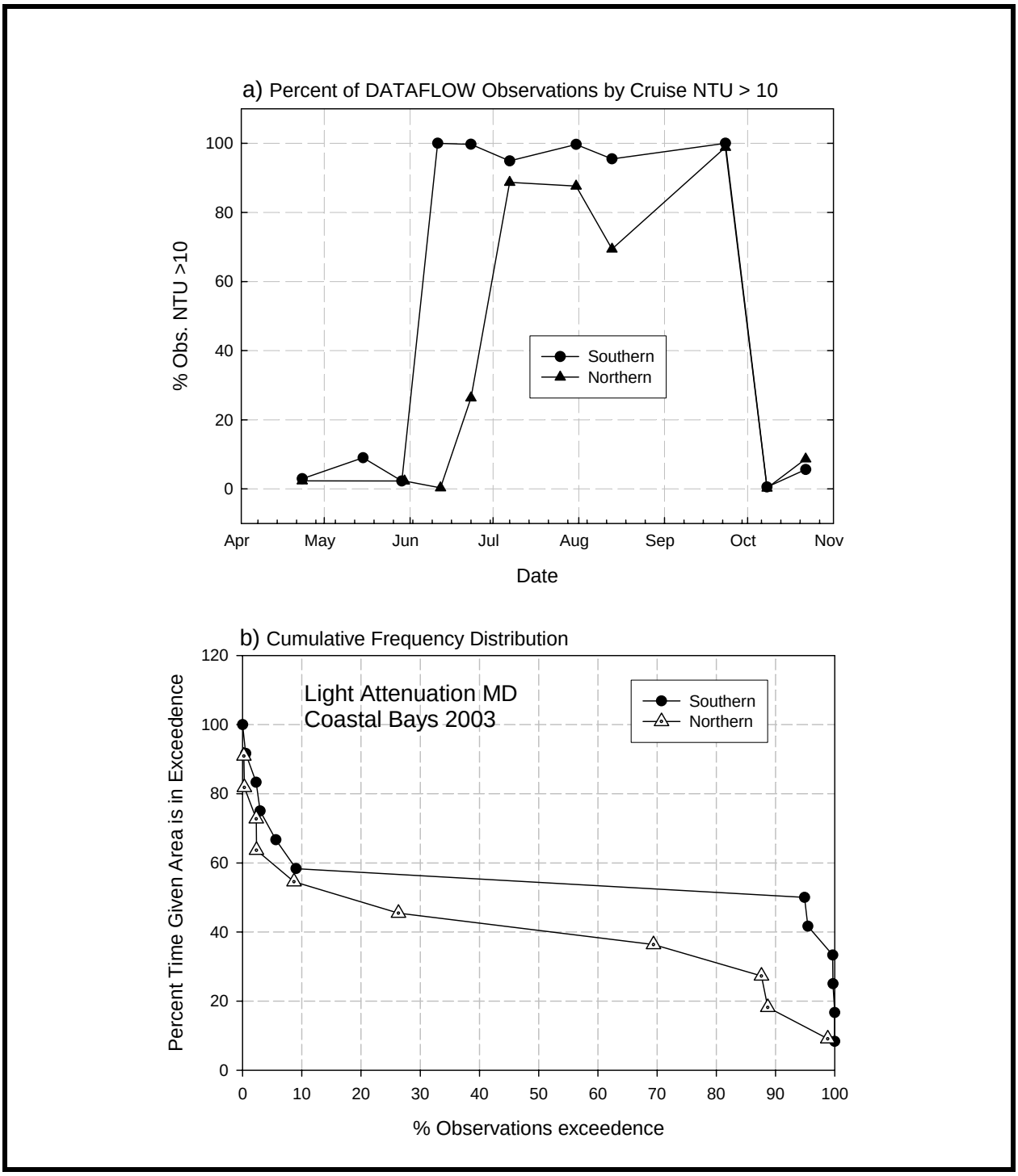

Figure 3-13. a) Percent of DATAFLOW observations by cruise above SAV habitat light criterion (estimated at 10 NTU) in open water, and b) cumulative frequency distribution of NTU observations above 10 NTU in open water.

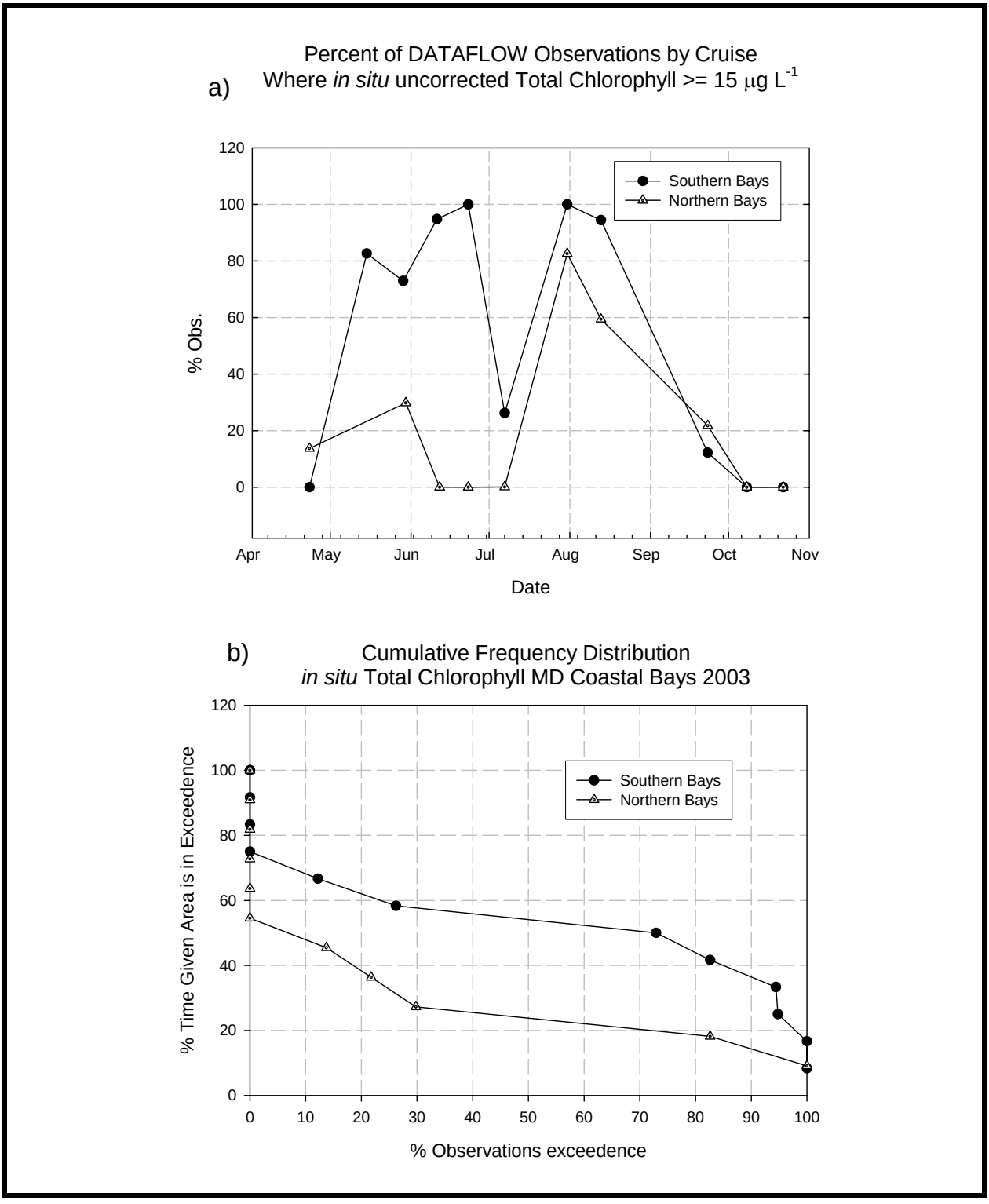

Figure 3-14. a) Percent of DATAFLOW observations by cruise above SAV habitat criterion of 15 mg l^{-1} (data converted to laboratory based total chlorophyll-*a* via regression analysis) in open water, and b) cumulative frequency distribution of total chlorophyll-*a* observations above 15 mg l^{-1} in open water.

3.4 Contour maps and spatial interpolation

The contour maps shown below provide a snapshot of surface water quality conditions during a typical summer and fall cruise for three subsystems of the Maryland Coastal Bays. These contour maps provide a visual representation of spatial heterogeneity in water quality within these regions. These maps also help to identify spatial structure that is lost when binning data into pass or fail categories as was done in Section 3-3. Three parameters are presented: YSI *in situ* chlorophyll concentration, turbidity, and dissolved oxygen concentration. While the chlorophyll maps were constructed with uncorrected YSI data, the resulting spatial patterns would be similar to those for corrected or translated chlorophyll-*a*. Because the slope of the relationship between YSI *in-situ* chlorophyll and lab derived values is not one-to-one (Fig. 3-9), the lowest category was binned from 0-10 $\mu g\ l^{-1}$ which roughly corresponds to a lab based 15 $\mu g\ l^{-1}$. For water column chlorophyll, Figures 3-15, 3-18, and 3-21 illustrate the relatively homogenous conditions in each of these water bodies during both a spring and fall cruise. The only significant spatial pattern or gradient in chlorophyll concentrations were found in the tributary systems. For example, chlorophyll concentrations in Bishopville Prong were of a very limited extent, but dramatically higher than at any other location (Fig 3-15b). Some spatial patchiness in chlorophyll was found in Newport Bay during the spring cruise, even though concentrations were higher than 10 $\mu g\ l^{-1}$ over the entire area (Fig. 3-21a). In contrast no spatial pattern was found during the October cruise at concentrations below 10 $\mu g\ l^{-1}$ (Fig. 3-21b).

Water column turbidity appeared to show a bit more spatial structure in each of these systems compared to chlorophyll for Assawoman Bay. For example, on June 23, 2003 substantial spatial structure was found compared to the October cruise (Fig. 3-17). However, for Newport Bay, the entire area appears to be quite spatially homogenous (Fig 3-23).

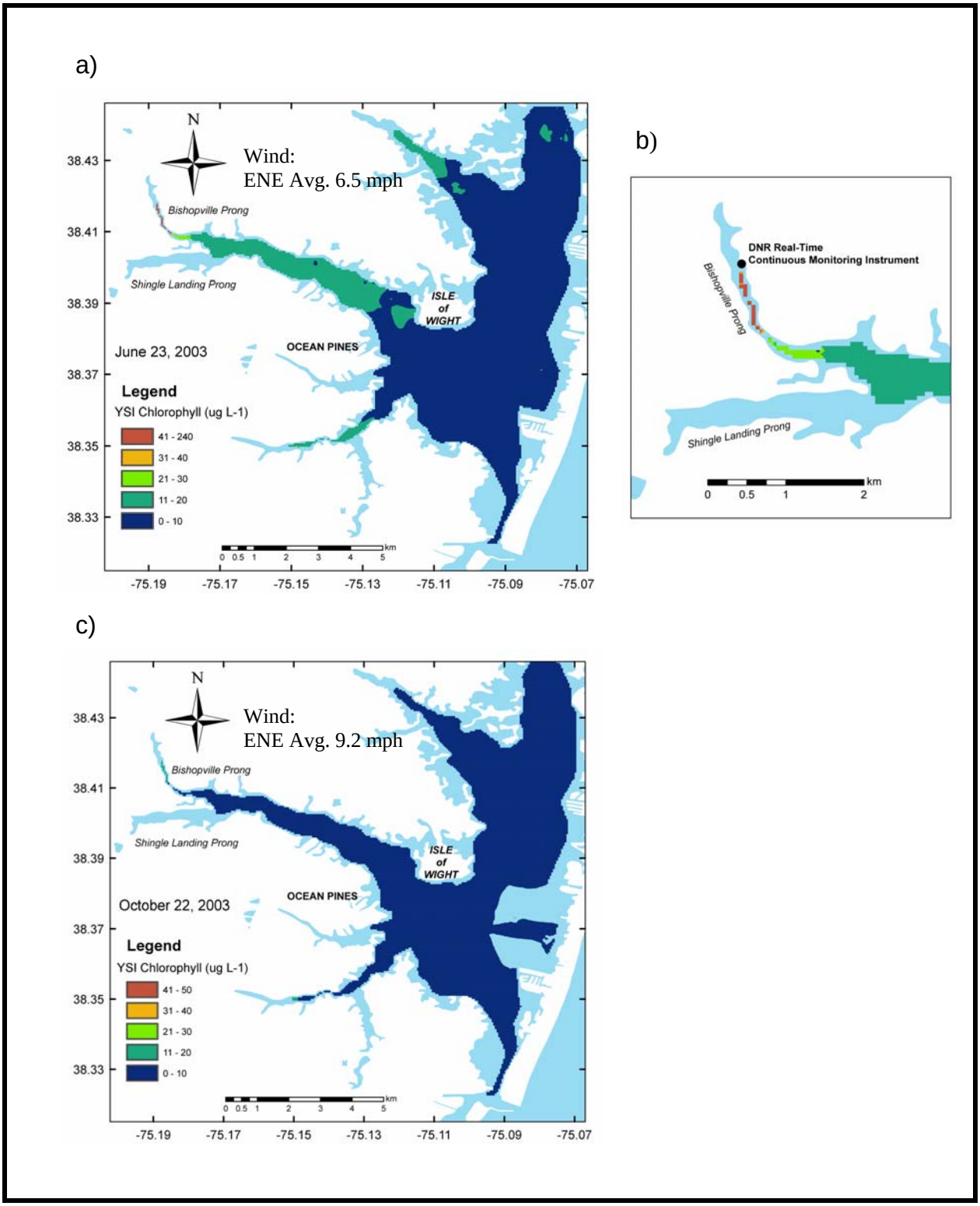

Figure 3-15. Contour maps for Isle of White Bay for uncorrected YSI chlorophyll concentrations on a) June 23, 2003, panel b) detail of chlorophyll gradient in Bishopville Prong from June, 2003, and c) October 22, 2003.

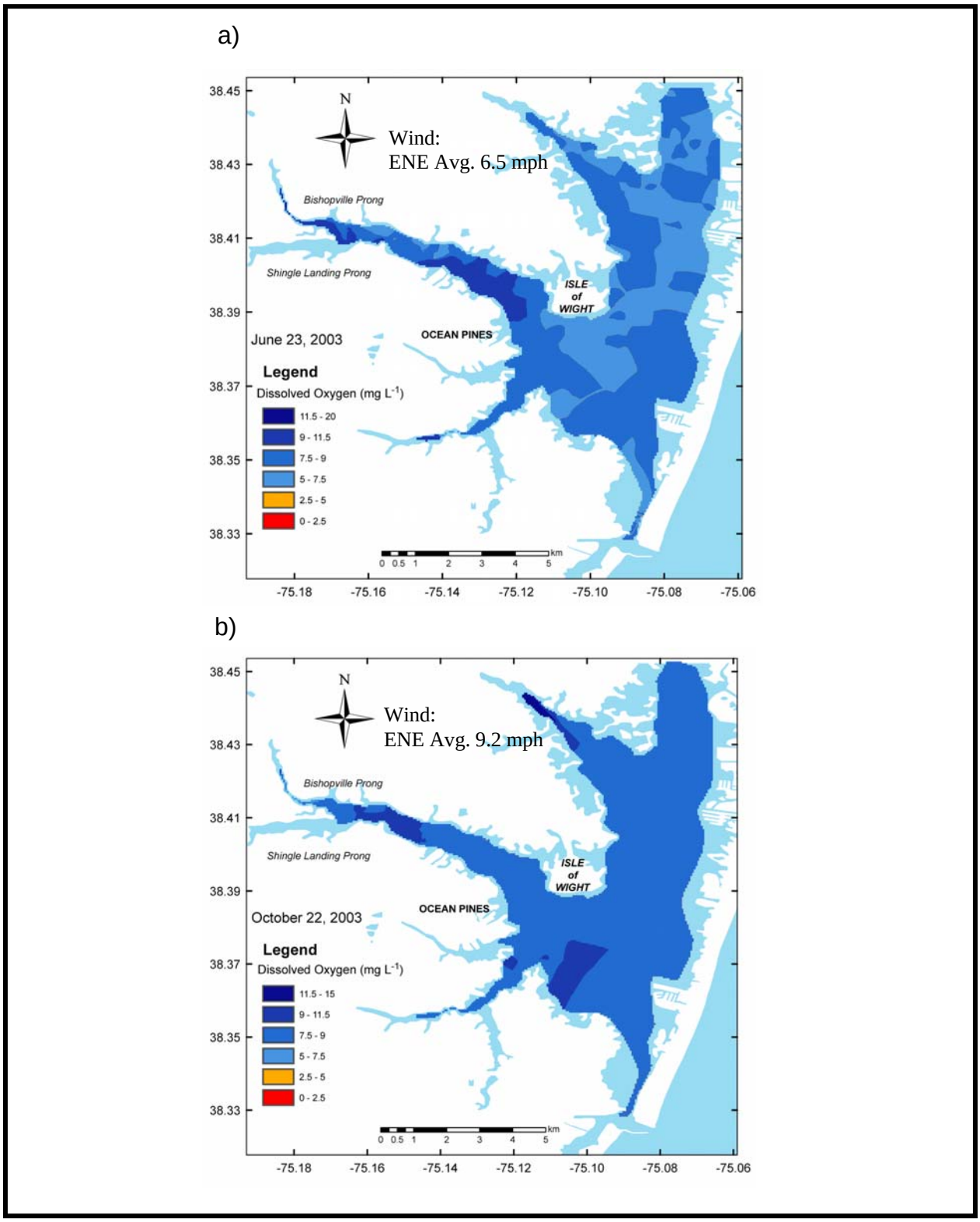

Figure 3-16. Contour maps of surface water dissolved oxygen concentrations on a) June 23, 2003, and b) October 22, 2003.

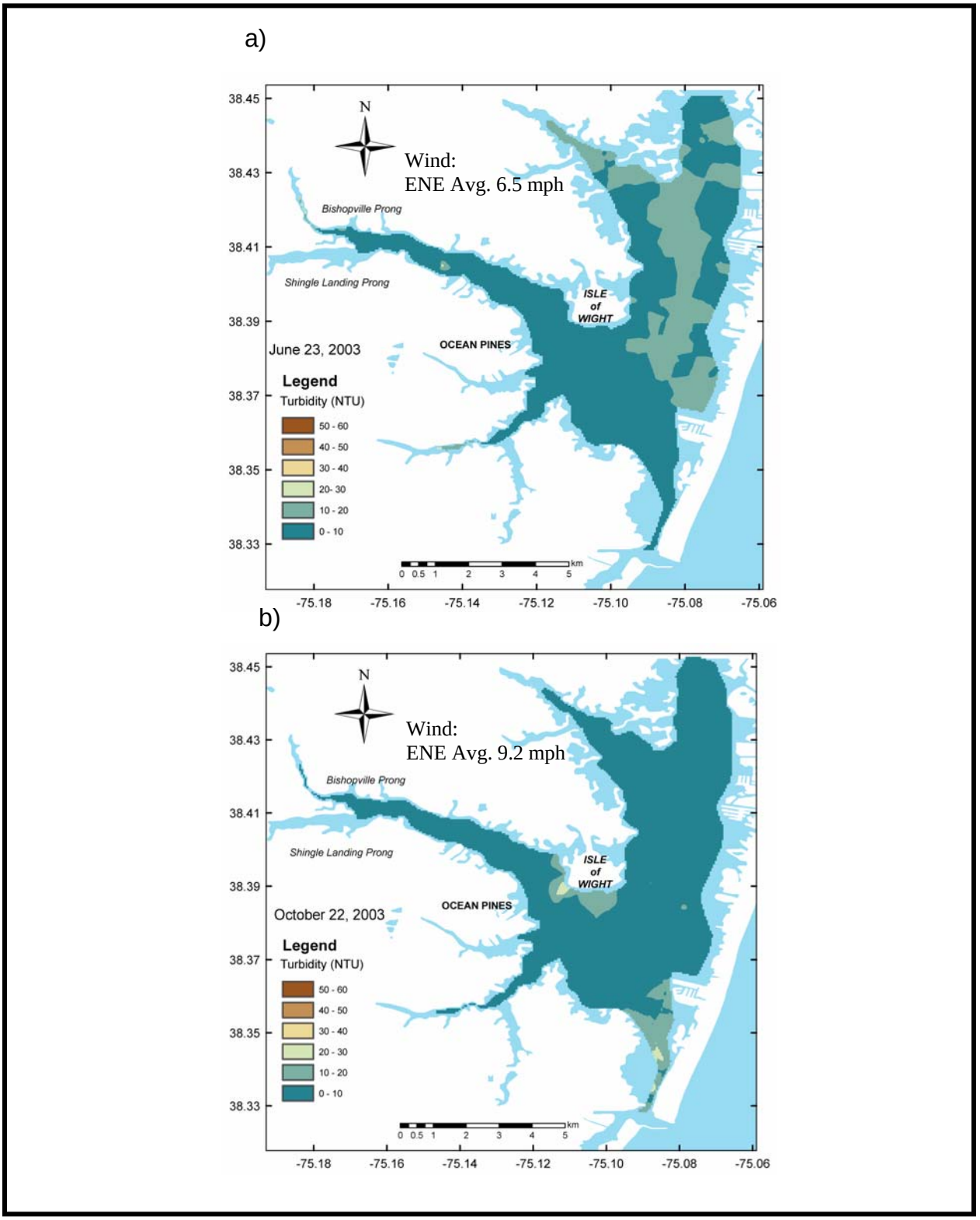

Figure 3-17. Contour maps of YSI water column turbidity for Isle of White Bay on a) June 23, 2003, and b) October 22, 2003..

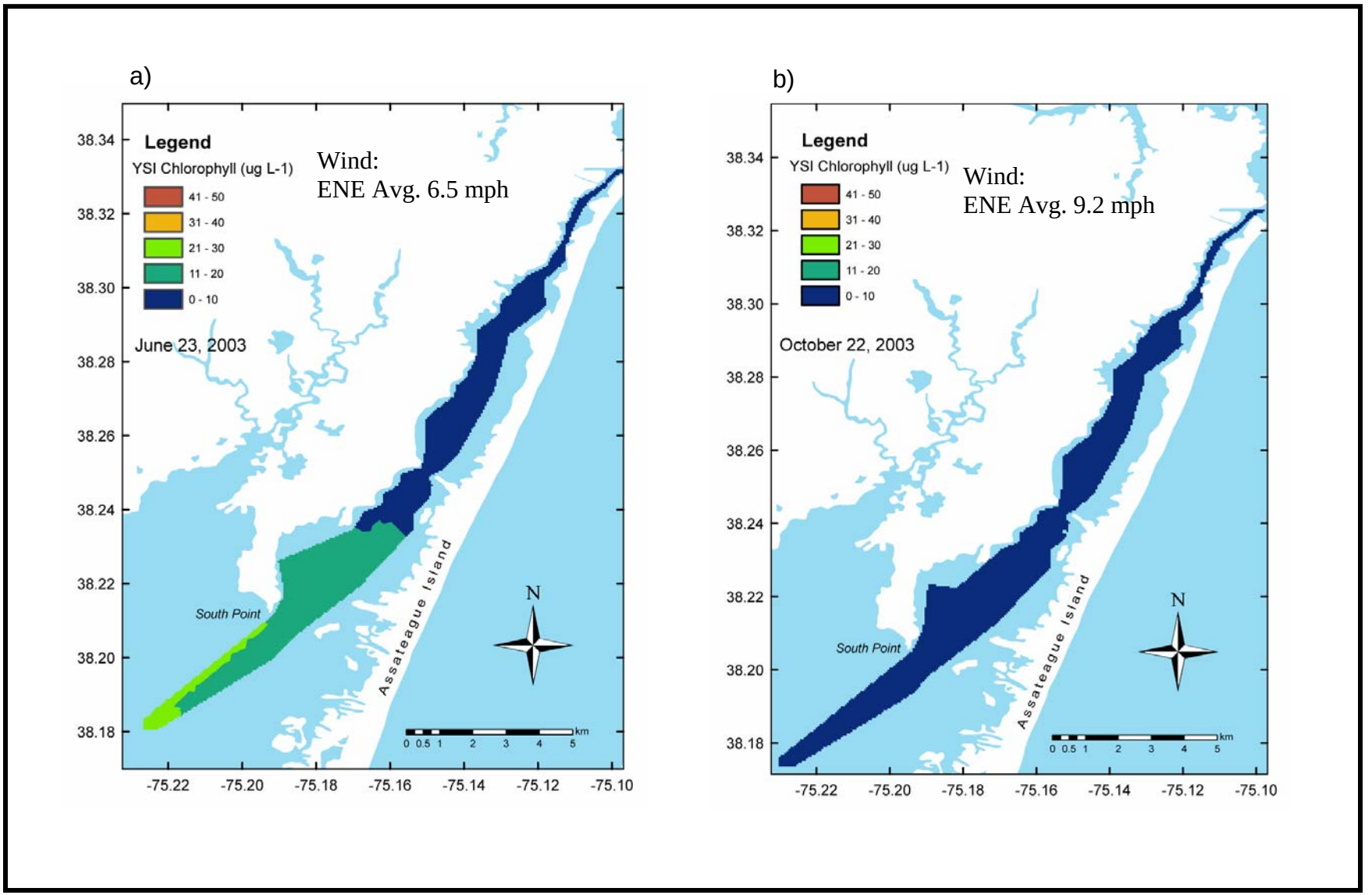

Figure 3-18. Contour maps of YSI water column chlorophyll for Sinepuxent Bay on a) June 23, 2003, and b) October 22, 2003.

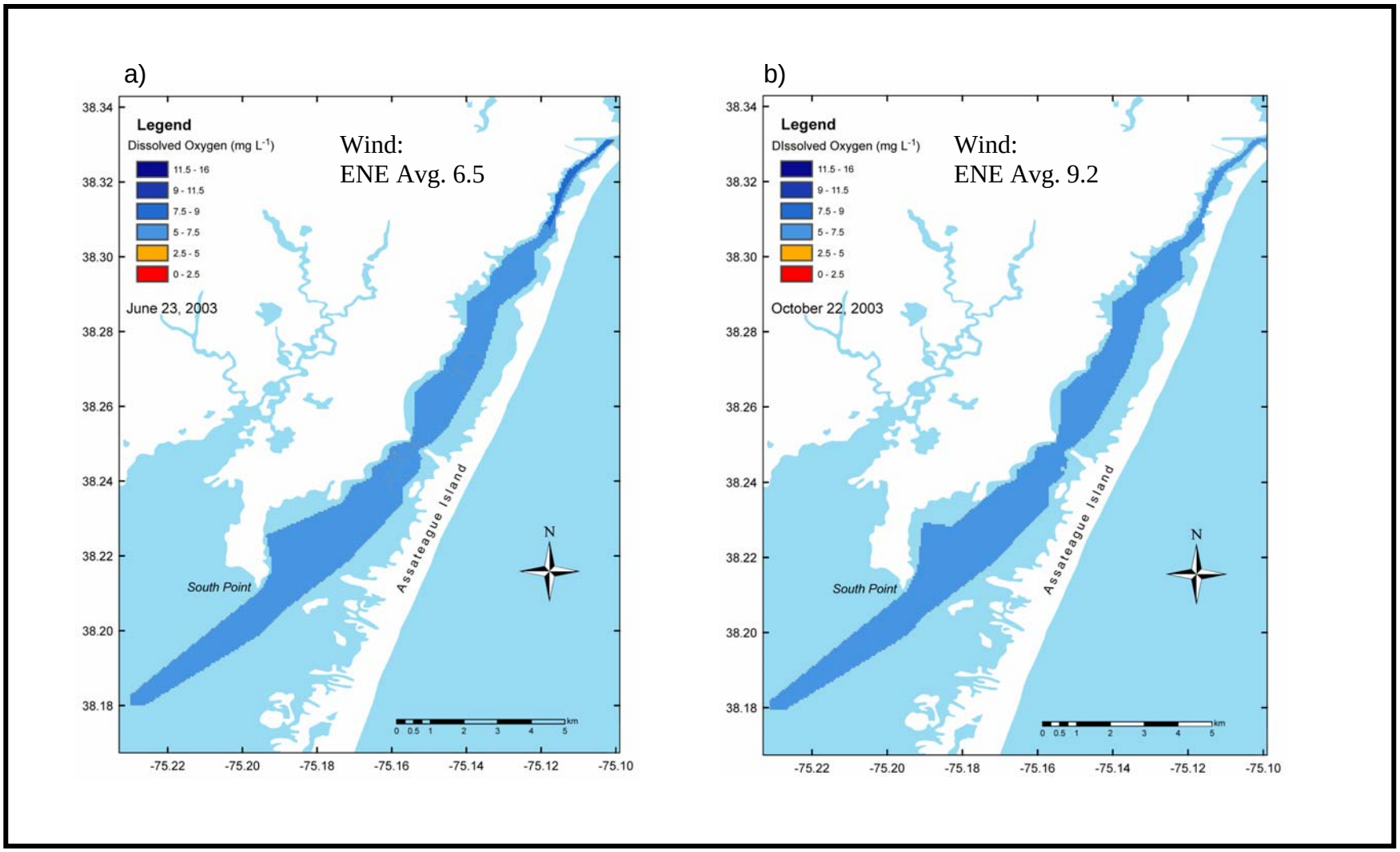

Figure 3-19. Contour maps of YSI surface water dissolved oxygen concentrations for Sinepuxent Bay on a) June 23, 2003, and b) October 22, 2003.

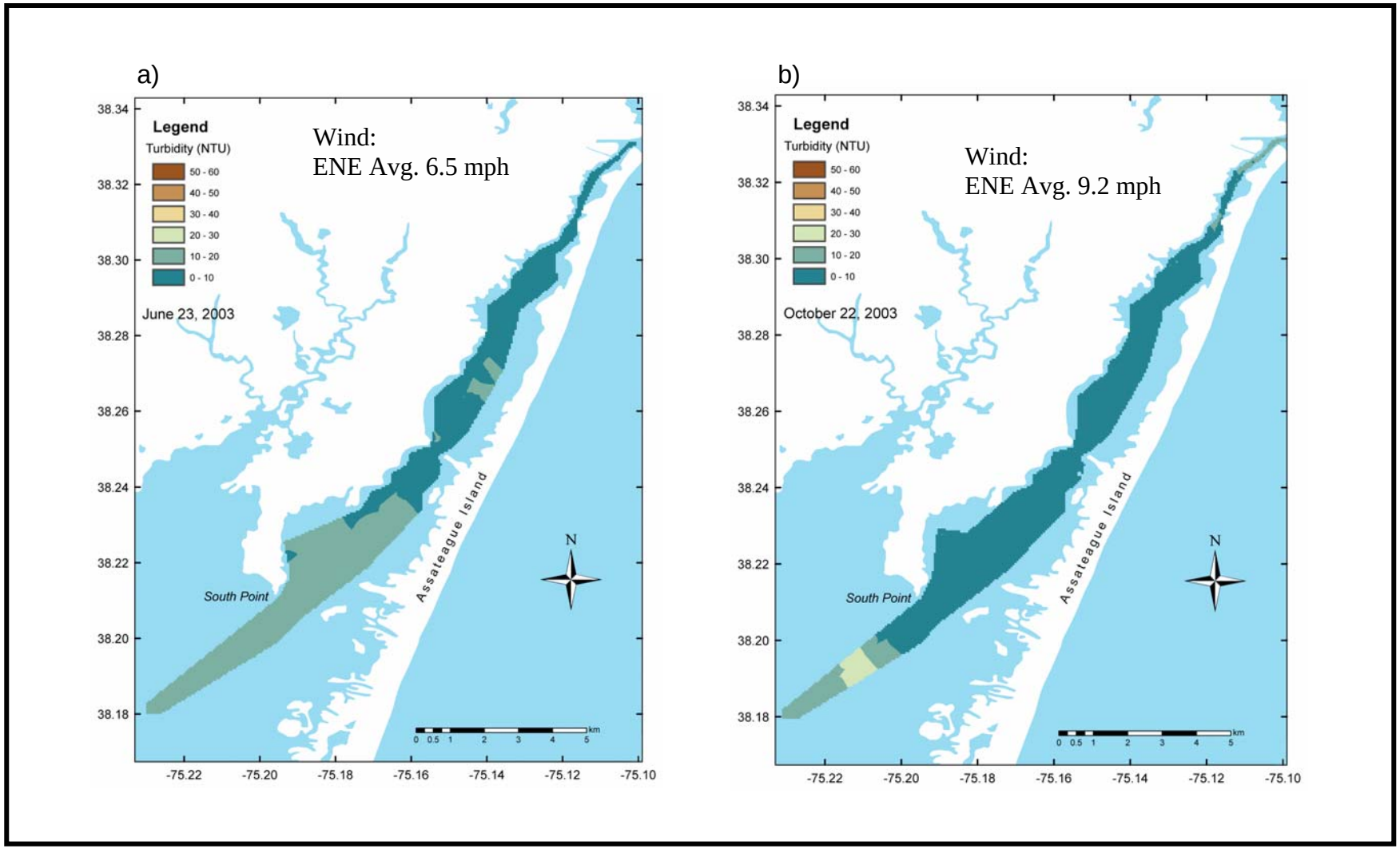

Figure 3-20. Contour maps of YSI turbidity (NTU) for Sinepuxent Bay on a) June 23, 2003, and b) October 22, 2003.

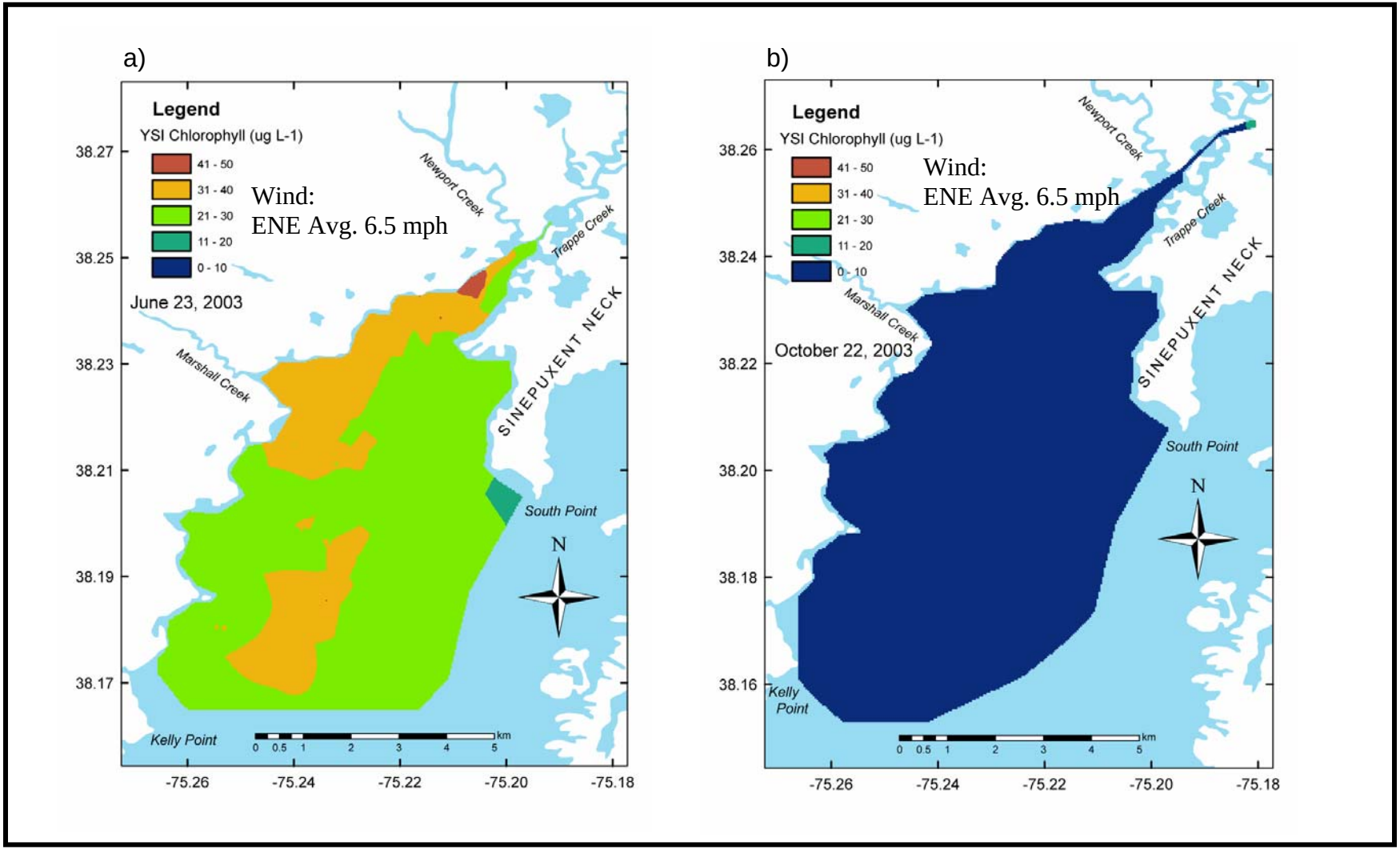

Figure 3-21. Contour maps of YSI uncorrected chlorophyll for Newport Bay on a) June 23, 2003, and b) October 22, 2003

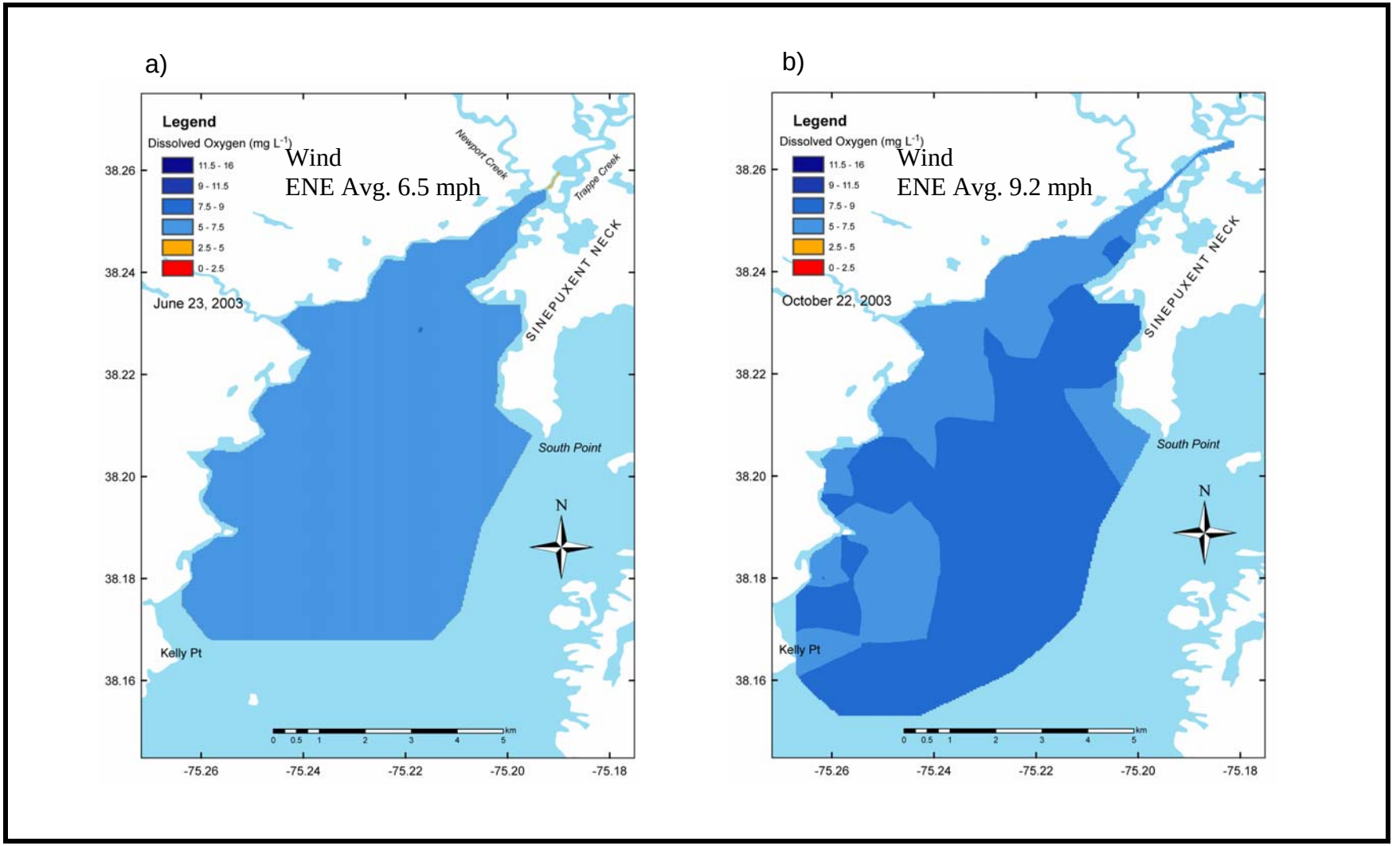

Figure 3-22. Contour maps of YSI surface water dissolved oxygen concentrations for Newport Bay on a) June 23, 2003, and b) October 22, 2003.

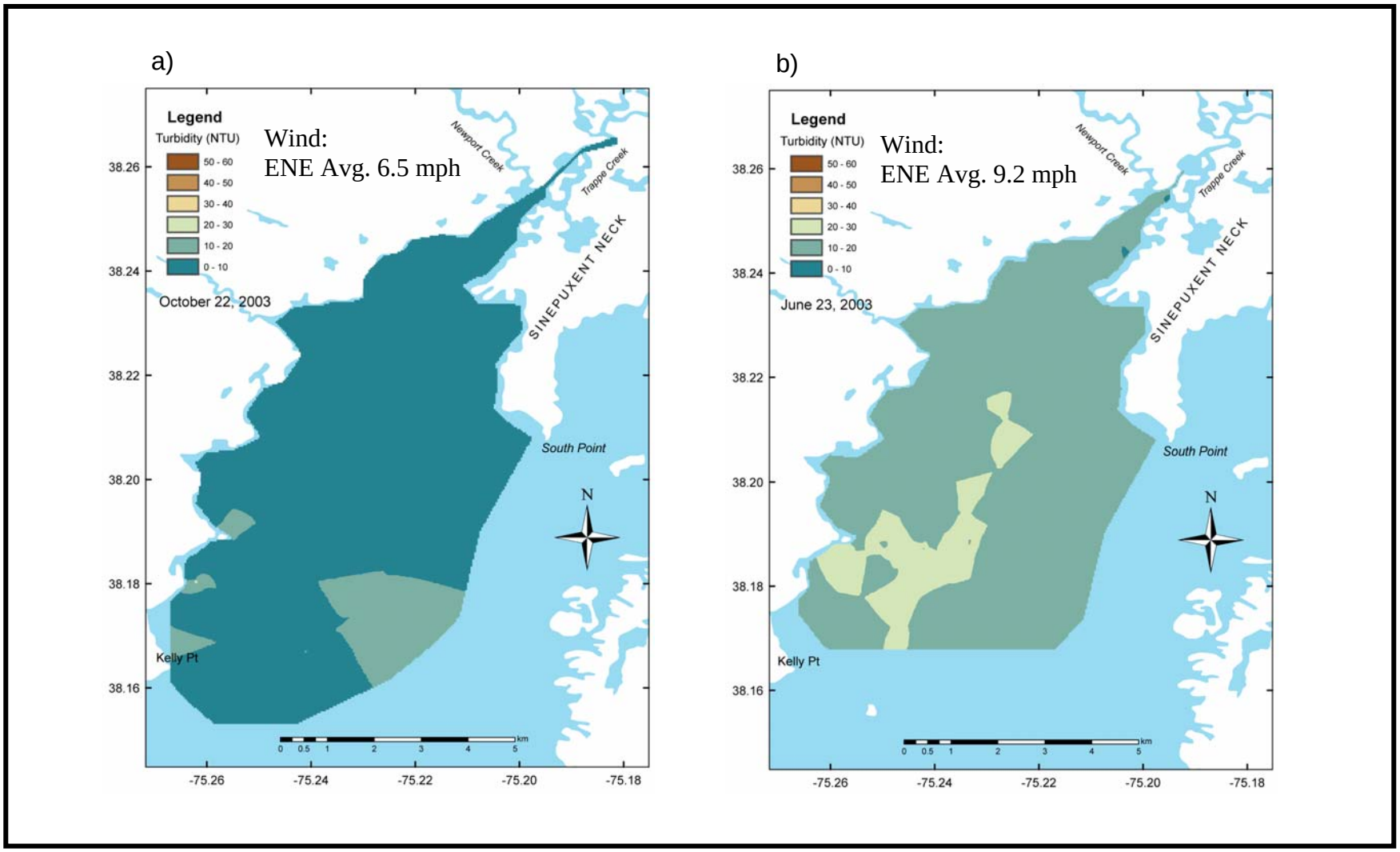

Figure 3-23. Contour maps of YSI turbidity (NTU) for Newport Bay on a) June 23, 2003, and b) October 22, 2003.

4.0 Discussion

Several temporal and spatial water quality patterns were found in the Coastal Bays in 2003. First, nutrient concentrations, and a variety of other water quality parameters, were significantly higher in the tributaries of Assawoman and Newport Bays than in the open water regions. For some tributary stations, such as CBDF05 in the upper portion of St. Martin River, concentrations of DIN, DIP and chlorophyll, as well as others were substantially higher than in the open water portions of the Bays. This distribution of water quality variables clearly indicates that pollution sources are associated with the tributaries and probably small creek systems. Despite the small size of these creek systems, continual monitoring in these areas is warranted both for detection of deteriorating or improving conditions.

Within the open water portions of Assawoman, Sinepuxent, and Newport Bays, spatial variations in most water quality variables was much less dramatic and concentrations were lower than in the creeks. Within individual cruise dates, interpolated maps of water column chlorophyll and turbidity revealed relatively homogenous conditions across the majority of both the upper and lower Coastal Bays (Figs. 3-15 to 3-23). However, on several occasions, water quality conditions in the open bays changed by a considerable degree compared to earlier conditions. The aspect of general spatial homogeneity was maintained, but concentrations were either higher or lower. This pattern, similar to a change of state, suggests a single factor acting in all areas is responsible. The most likely candidate is wind coupled with wave action acting on the small water column of the coastal bays.

When DATAFLOW observations were categorized as passing or exceeding specific habitat requirements (10 NTU for water clarity, and 15 $\mu g\ l^{-1}$ for chlorophyll) most of the open water areas in each region either passed or failed habitat criteria indicating relatively homogenous conditions in these areas (Figs. 3-13a, 3-1). Data binned in this way also reveals strong temporal variation in water clarity throughout the SAV growing season with adequate water quality found both early and late in the season and poorer conditions being characteristic of the summer. Such a strong seasonal pattern was found for water column chlorophyll in Newport, but not Assawoman Bay (Figs. 3-13a, 3-14a).

Finally, the range of data recorded at the fixed stations was very nearly the same as the range encountered throughout the entire DATAFLOW dataset for every parameter. This indicates that the choice and distribution of the fixed stations adequately represented a much of the spatial structure in water quality conditions found in Maryland's Coastal Bays. Much of the variation was found within the small tributary systems that could be adequately monitored with relatively few fixed stations. Within the open water portions of these bays, water quality appears relatively homogenous and is subject to change on a bi-weekly or shorter time scale. Information gathered by the additional DATAFLOW data did little to enhance our understanding of spatial patterns in these systems because of the lack of substantial fine-scale variability. However, DATAFLOW monitoring indicates that synoptic spatial variability is small in the open bays and easily characterized in the important creeks. Thus, future monitoring might best be achieved by emphasizing temporally rather than spatially intensive efforts.

5.0 References

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