High-Frequency Marine Monitoring Pilot Project at the Seattle Aquarium

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1.0 INTRODUCTION

The King County Water and Land Resources Division's Marine and Sediment Assessment Group manages a comprehensive, long-term marine monitoring program designed to assess water quality in the Central Puget Sound Basin. The objectives of the marine monitoring program are to provide an understanding of water quality within King County and to assess the possible effects of discharges from County wastewater treatment plant and combined sewer overflow outfalls on water quality. Additionally, data collected have provided some insight into natural variability and long-term, climatically forced trends in water quality parameters within the Puget Sound system. Due to resource limitations, data is only collected monthly at marine stations, a sampling frequency which does not adequately capture the high variability in, and the relationships between, marine water quality parameters.

In November 2005, King County entered into a collaboration with the Seattle Aquarium and the private environmental monitoring company, YSI, in order to explore the feasibility of deploying a long-term high-frequency data collection system in Elliott Bay with the capability of reporting data via the internet in real-time. This moored instrumentation approach would allow collection of high-frequency water quality data over a 24 hour period, which has been a large data gap in the County's long-term dataset, and also allow focus on areas of highest concern.

Primary objectives of the pilot high-frequency marine monitoring project were the following:

1. Test and evaluate a telemetered water quality monitoring system.
2. Test and evaluate long-term deployment of specific water quality probes.
3. Collect high-frequency water quality data in Elliott Bay for the evaluation of natural variability on tidal, daily, and monthly time scales.

The Seattle Aquarium provided a secure location along the Seattle waterfront (Figure 1) from which to test the monitoring system. YSI provided solar panels, telemetry equipment, and access to the YSI Econet system in the form of a website for data reporting and system management, and technical assistance. King County supplied the sondes, sensors, laboratory analyses, and personnel required for the collection of water samples and sonde maintenance and calibration. The test system was installed and operational on November 23, 2005 and dismantled on December 11, 2006. This report summarizes results of the Seattle Aquarium pilot monitoring project. An overview of the sampling area, methodology employed, parameters measured, and data collected will be presented.

2.0 FIELD AND LABORATORY METHODOLOGY

2.1 Sampling Location

The sampling site was located along the Seattle waterfront in eastern Elliott Bay at Pier 59 within the fenced Seattle Aquarium property (Figures 1a and 1b). The sonde was suspended off of the pier at a depth of approximately 1 meter above the bottom in a location where the total water depth was approximately -20 feet MLLW (Figure 2). Figure 3 illustrates the relationship between sonde depth and tidal stage. The sonde was suspended from a fixed length of line and remained at a constant distance from the sea floor throughout the deployment. Tidal ebb and flow varied the water column depth above the sonde. For example, during low tide, sonde "depth" was shallower than during high tide even though the actual position of the sonde remained constant.

Figure 1a. Location of the high-frequency marine monitoring system at Seattle Aquarium (Pier 59) in Elliott Bay, Seattle, WA. Station was designated SEAQYSI by King County.

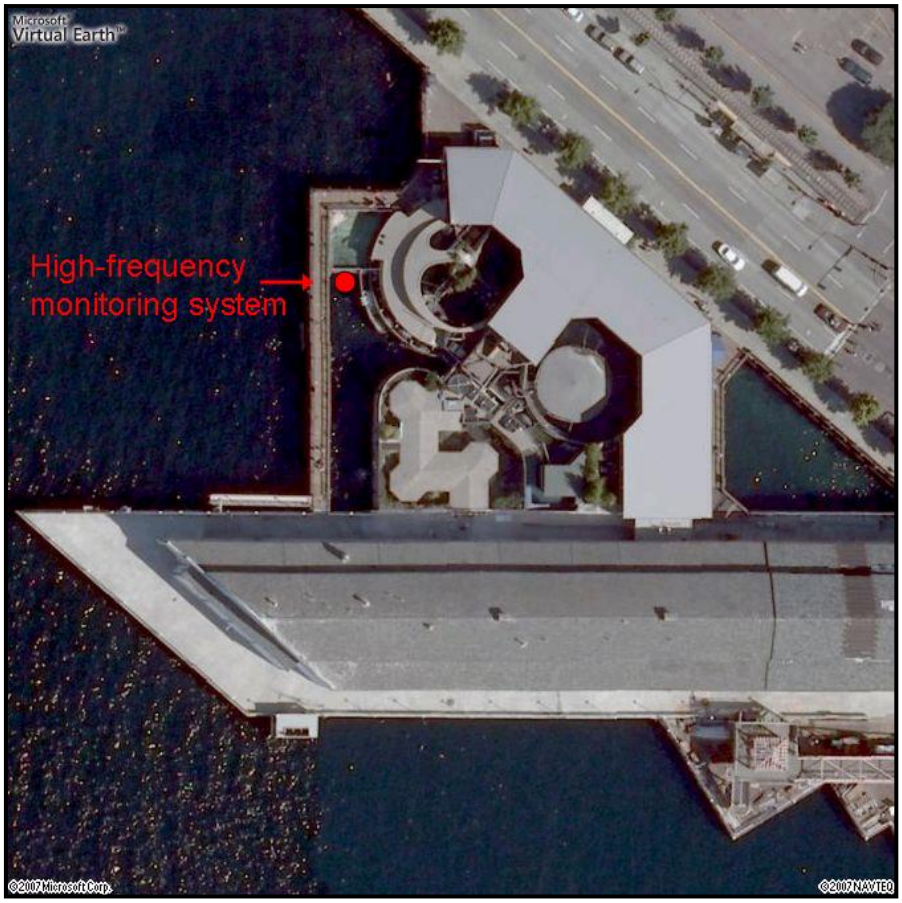

Figure 1b. Location of the high-frequency marine monitoring system within the Seattle Aquarium property.

Figure 2. Deployment of the sonde from Pier 59.

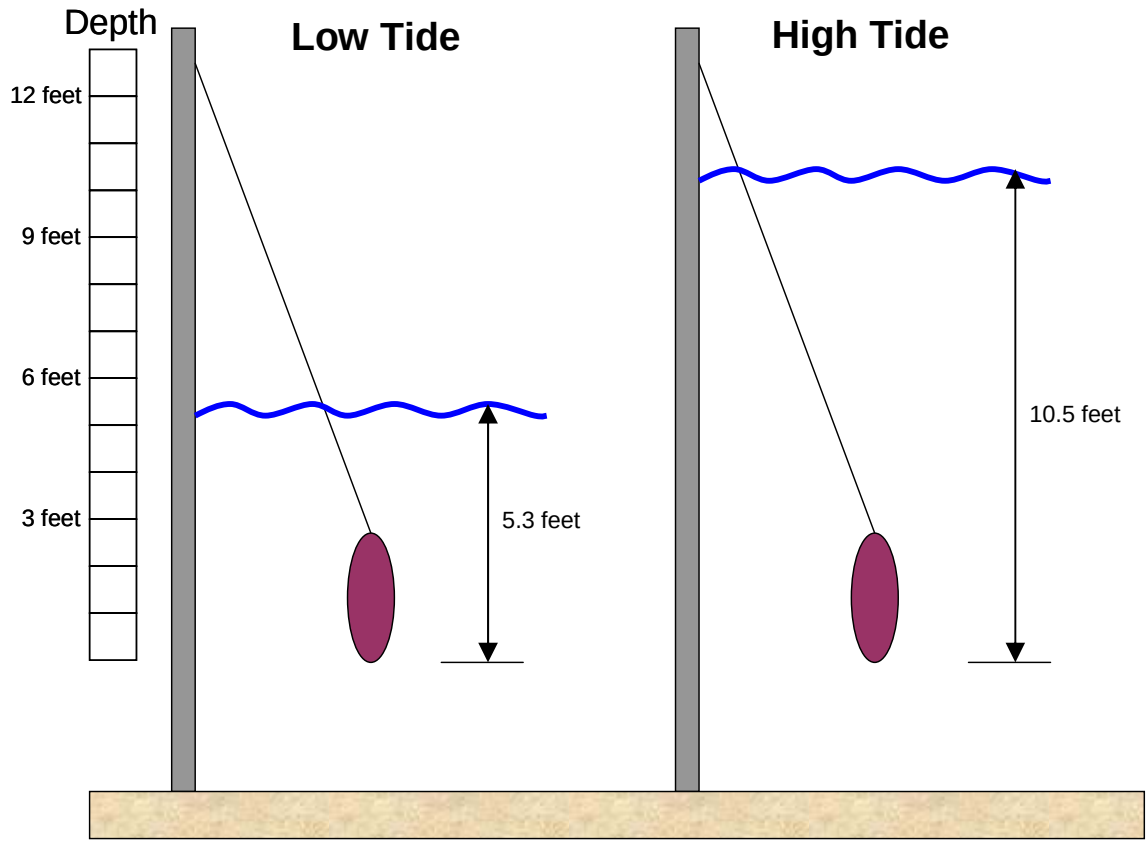

Figure 3. Diagram of sonde deployment and relationship of tidal phase to depth.

Flow along Seattle's waterfront where the sampling site was located is generally northward from Harbor Island and the East and West Waterways (Ebbesmeyer *et al.*, 1998). A major influence on the water quality at this location is freshwater input from the Duwamish River, which can be detected in Elliott Bay through temperature, salinity, density, and turbidity observations. Chlorophyll concentrations can also be affected by riverine input. Primary productivity is inhibited in Elliott Bay during periods of increased flow from the Duwamish River due to a combination of high turbidity levels, which reduces light available for photosynthesis within the water column, and low residence time of the outflow, which contributes to a lack of water column stability (Strickland, 1983).

2.2 Equipment/Sensors

The primary instruments used for water quality analysis on this project were YSI 6600EDS Multiparameter sondes (Figure 4). A YSI 6600EDS (Extended Deployment System) sonde consists of a cylindrical pressure-resistant body with a cable connection on one end and temperature, conductivity (salinity), pressure (depth), dissolved oxygen, turbidity, pH, and fluorescence (chlorophyll) probes on the opposite end. Sensor specifications are listed in Table 1. An anti-fouling wiping system was used to prolong

the calibration life and a "Rapid Pulse [tm]" dissolved oxygen sensor removed the need for a stirring mechanism.

Figure 4. A YSI 6600EDS Multiparameter sonde.

Table 1. Sensor Specifications

	Range	Resolution	Accuracy
Temperature (^oC)	- 5 to 50	0.01	+/- 0.15
Conductivity (mS/cm)	0 - 100	0.001 - 0.1	+/- 0.5% of reading + 0.001
Salinity (ppt)	0 - 70	0.01	0.1
Depth (m)	0 - 61	0.001	+/- 0.12
Dissolved Oxygen (mg/L)	0 - 50	0.01	+/- 0.1
Turbidity (NTU)	0 - 1000	0.1	0.3
pH	0 - 14	0.01	+/- 0.2
Chlorophyll (µg/L)	0 - 400	0.1	Detection Limit: 0.1

The 6600 EDS sonde was cabled to a YSI 6200 Remote Data Acquisition System (DAS). The DAS is a shore-based data logger and telemetry unit that managed sensor sampling, data buffering, and cellular telemetry to a base station. The 6200 DAS consisted of a power control module, a Campbell Scientific data logger, three 12-volt batteries, a cellular telemetry unit, a single solar panel and a marine data cable (Figure 5). Data were collected every 15 minutes and the 6200 DAS transferred the data hourly to the YSI Econet web interface which allowed real-time sampling adjustments, sensor failure detection, calibration evaluation, data acquisition, storage, review, and download *via* the internet.

Figure 5. The solar panel (left) and box containing the telemetry and data logger equipment (right) are shown as installed at the Seattle Aquarium.

2.3 Web Interface

The primary reason King County was interested in testing the YSI system was the need for a reliable, high-frequency real-time data acquisition and storage solution. The YSI Econet is a turn-key (i.e., allows access remotely from any location), web-based data storage system that is fully customizable and readily accessible using any web interface. The data are transmitted to a secure server and posted directly to a customizable web site (Figure 6). The data can be kept secure or released to the public in near-real time. Data download options include automatic or customizable graphs, HTML or CSV formats. The near-real time remote data acquisition system also allowed for the determination of sensor failure or calibration issues. Alarms in the form of e-mail alerts were also available. If field personnel were unable to quickly service the sonde, parameters could be turned off *via* the web interface. Additionally, changes to the sampling regime (e.g., a change in measurements from once every 15 minutes to once every four hours) could be performed through Econet.

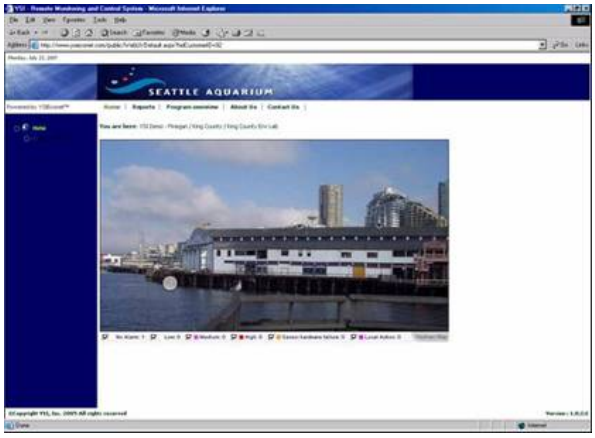

Figure 6. The customizable website used for the pilot project.

2.4 Laboratory Methods/Data Quality Assurance Results

Quality control (QC) samples were collected monthly using a modified Van Doren-type bottle lowered manually to the same approximate depth as the sonde. These samples were transported to the King County Environmental Laboratory and analyzed within their respective holding times for pH, salinity, dissolved oxygen, and chlorophyll-*a*. Temperature and turbidity were analyzed on site using a VWR digital field thermometer and a Hach portable turbidity meter, respectively. Laboratory QC employed for chlorophyll-*a* included analysis of a batch lab duplicate and method blank. Check standards or laboratory control samples were used for pH and salinity. No QC samples were analyzed for dissolved oxygen. All QC data were uploaded into a shared database, Laboratory Information Management System (LIMS). Methods used to analyze control samples are summarized in Table 2.

Table 2. QC Control Sample Analysis Methodology

Parameter	Laboratory Method	Field Method	MDL
Chlorophyll-*a*	EPA 445.0 (Fluorescence)	-	0.05 μg/L
Dissolved oxygen	SM4500-O-C (Winkler Titration)	-	0.5 mg/L
pH	SM4500-H-B (Metrohm 736 GP Titrino pH Meter)	-	-
Temperature	-	VWR Field Thermometer	-
Turbidity	-	Hach Portable Turbidity Meter	0.5 NTU
Salinity	SM2520-B (Guildline 8410A Portable Salinometer)	-	2 PSS

Sondes were generally calibrated monthly for conductivity (salinity), pH, dissolved and oxygen, and zeroed for fluorescence (chlorophyll) based on need and workload availability. Conductivity (salinity) and pH were also verified with check standards. During some periods, calibration was purposely extended to further evaluate calibration longevity and/or anti-fouling capability. For example, during June, July, August and most of September sondes were not serviced monthly in order to evaluate the anti-fouling system (see Section 2.5 for more detail). Post-deployment calibration end checks were completed for conductivity (salinity), pH, dissolved oxygen, and fluorescence

(chlorophyll) and evaluated against the initial calibrations. Data were qualified based on the results of the post-calibration check or observed data anomalies. Some data comparisons were skewed due to difficulty in determining the depth of the sonde based on tidal fluctuations, water clarity and pier height.

Quality control windows used to qualify the data are defined below:

	Temp* **(^oC)**	**Cond (mS/cm)**	**Salinity (PSS)**	**pH**	**Dissolved Oxygen (mg/L)**	**Turbidity* (NTU)**	**Chlorophyll (μg/L)**
Lab Check Sample	+/- 0.5	n/a	+/- 0.3	+/- 0.2	+/- 20% rpd	+/- 20% rpd	+/- 20% rpd
End Check	n/a	+/- 10%	+/- 0.3	+/- 0.2	+/- 4% sat	+/- 20% rpd	+/- 20% rpd

rpd - relative percent difference
* - Duplicates analyzed in field.

2.5 Reliability/Performance of Equipment

Overall, the YSI 6600 EDS sondes were extremely durable and maintained excellent calibration stability for most parameters. Temperature, depth and conductivity (salinity) data obtained were of excellent quality. Even after months of deployment without servicing, conductivity check standards were within 3% of the true value. Out of a total of more than 25,000 readings, less than 1% of the salinity values were questionable, those being the result of an extended period (12 weeks) between calibrations.

pH readings were fairly stable throughout the study. A slight drift was evident during the first two months of 2006, but after maintenance and proper calibration, pH values were all within quality control limits. Dissolved oxygen sensors provided mostly excellent data but failed quality control standards more than the other parameters. The chlorophyll fluorometer and the turbidity probe data provided general trend information, but did not compare very well to data obtained from discrete samples analyzed in the laboratory.

From June 1 to September 21, 2006, the sonde was left deployed to test the anti-fouling capabilities during the most productive months. After 12 weeks, salinity values were well within control windows compared to samples analyzed in the lab, pH was within 0.01 units, and turbidity was within 0.5 NTU. Dissolved oxygen remained within calibration limits for approximately 4 weeks. All parameters except depth and temperature failed to provide reportable data after 15 weeks. Considering the extensive biofouling on the sonde, the results were impressive (Figure 7).

The only sonde problems experienced were minor anti-fouling wiper issues which caused occasional data breaks. These were due to a software glitch that was later fixed by the instrument manufacturer. The dissolved oxygen sensor required a moderate amount of

effort to maintain calibration. The turbidity and fluorescence (chlorophyll) probes both failed and had to be replaced more than once.

Figure 7. Biofouling is evident on the sonde following an extended deployment during the productive summer months.

The 6200 DAS and Econet systems worked nearly flawlessly. The system was installed in approximately two hours and was online immediately. The unit was installed in November and experienced slight battery voltage issues due to the initial direction in which the solar panel faced (east). Following an adjustment in which the solar panel was reinstalled facing south, power was never an issue. Data storage issues were nonexistent and the web site was up 99.9% of the time. Some parameters were excluded on a few of the sonde deployments due to incorrect instrument setup but this was the result of human error and was not an instrument issue.

3.0 DATA SUMMARY

The data were spot-checked daily through the Econet web interface, reviewed thoroughly on a weekly basis, and downloaded monthly.

3.1 Depth

Monitoring depth ranged from 3.9 to 21.4 feet over the course of the year-long deployment and averaged 14.4 feet. The depth of the sonde varied with the tides and the tidal pattern of Elliott Bay is discernable when examining the monthly depth data (Figure 8).

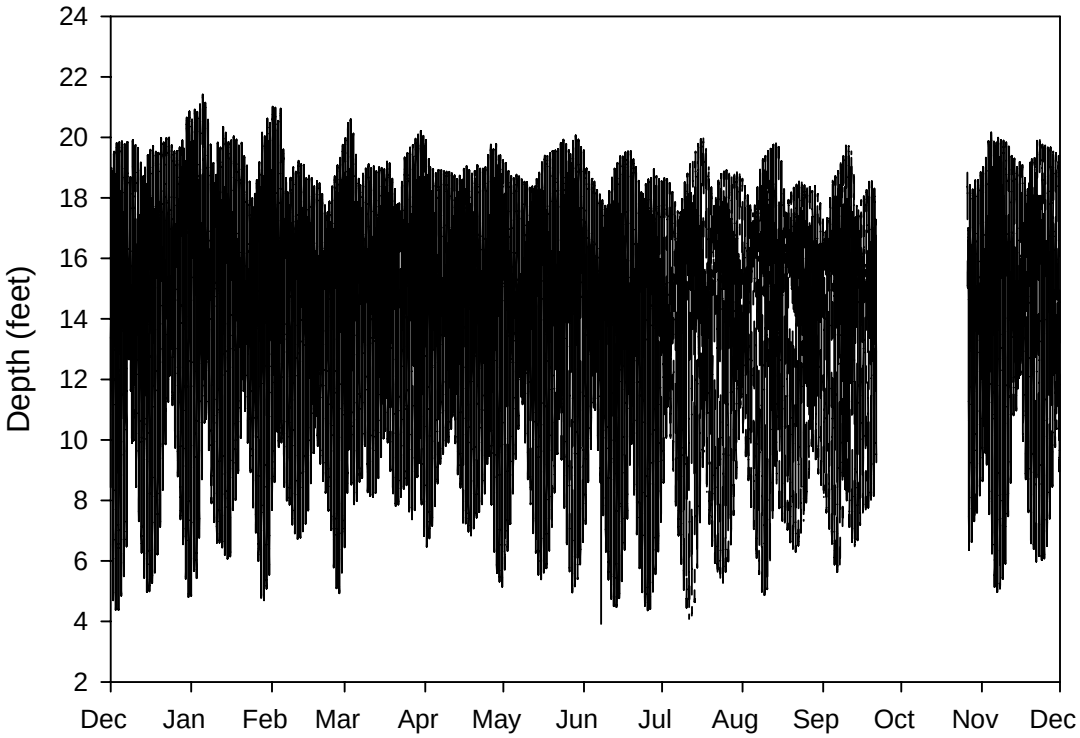

Figure 8. Sonde depth (feet) throughout year of deployment.

Depth is not reported between September 21 and October 26 due to a sonde having incorrect parameter units. The depth was reported in meters instead of feet which caused the data to not be reported. The data was visible on the website, but was not accessible for downloading. This incident underscored the importance of setting all of the sonde parameters correctly.

3.2 Temperature

An important physical characteristic of seawater is its temperature. Water temperature influences biological and chemical activity as well as dissolved gas content. Water temperature is dependent upon many factors including depth, air temperature, season, tidal mixing, weather events, amount of freshwater input, and mixing within the water column.

Temperature data quality throughout the deployment was extremely good. Temperatures ranged from 7.35 to 15.60 ^{o}C, with an average recorded temperature of 10.78 ^{o}C. Seasonal temperature patterns are seen in Figure 9, with lowest temperatures observed in winter and early spring, and highest temperatures seen in the summer and early autumn.

This pattern matches that of Seattle air temperature (Figure 10) (National Weather Service Seattle-Tacoma International Airport Station), suggesting that the primary control of water temperature at the monitoring site is air temperature.

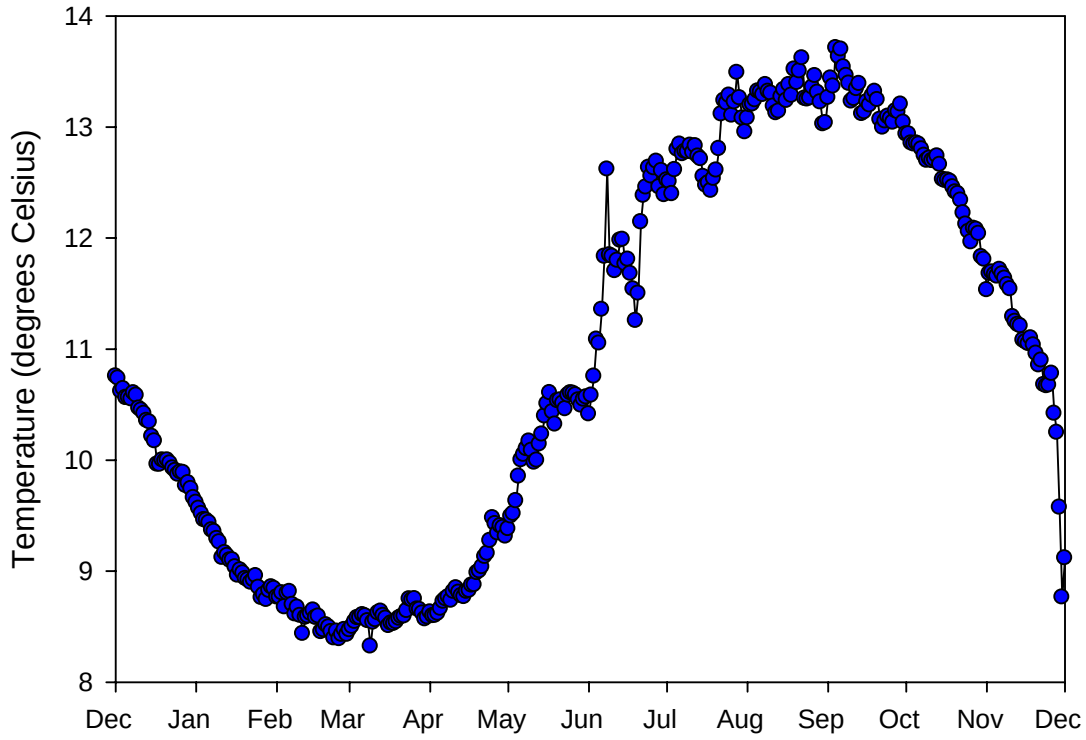

Figure 9. Daily mean water temperatures throughout year of deployment.

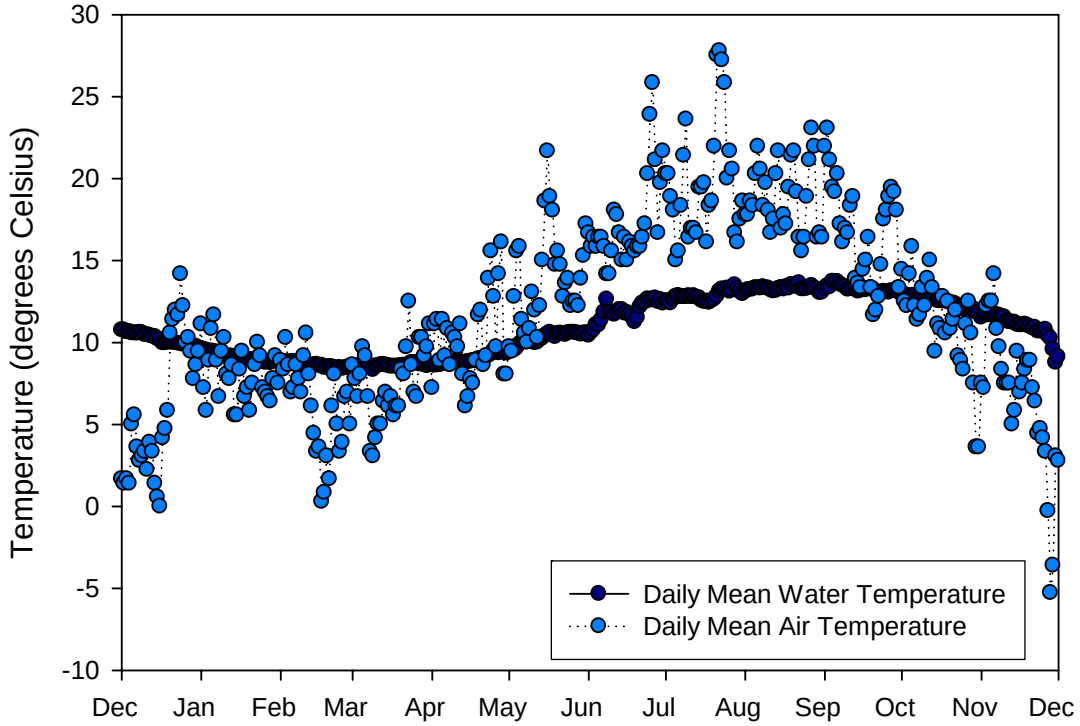

Figure 10. Comparison of Daily Mean Water and Air Temperatures.

When temperature is examined over a 24 hour period with water-column depth above the sonde as the other variable, a strong relationship between the two variables is observed (Figure 11). In both winter (March) and summer (August) months, maximum temperatures are observed when the sonde is near the surface while lower temperatures are observed as water-column depth above the sonde increases. This is likely the result of the diminishing effect of solar radiation on temperature as depth increases throughout the water column. The range of temperatures measured during the 24 hour period on August 7 was also significantly greater than that measured on March 6 reflecting the greater range in air temperature during summer months in Seattle.

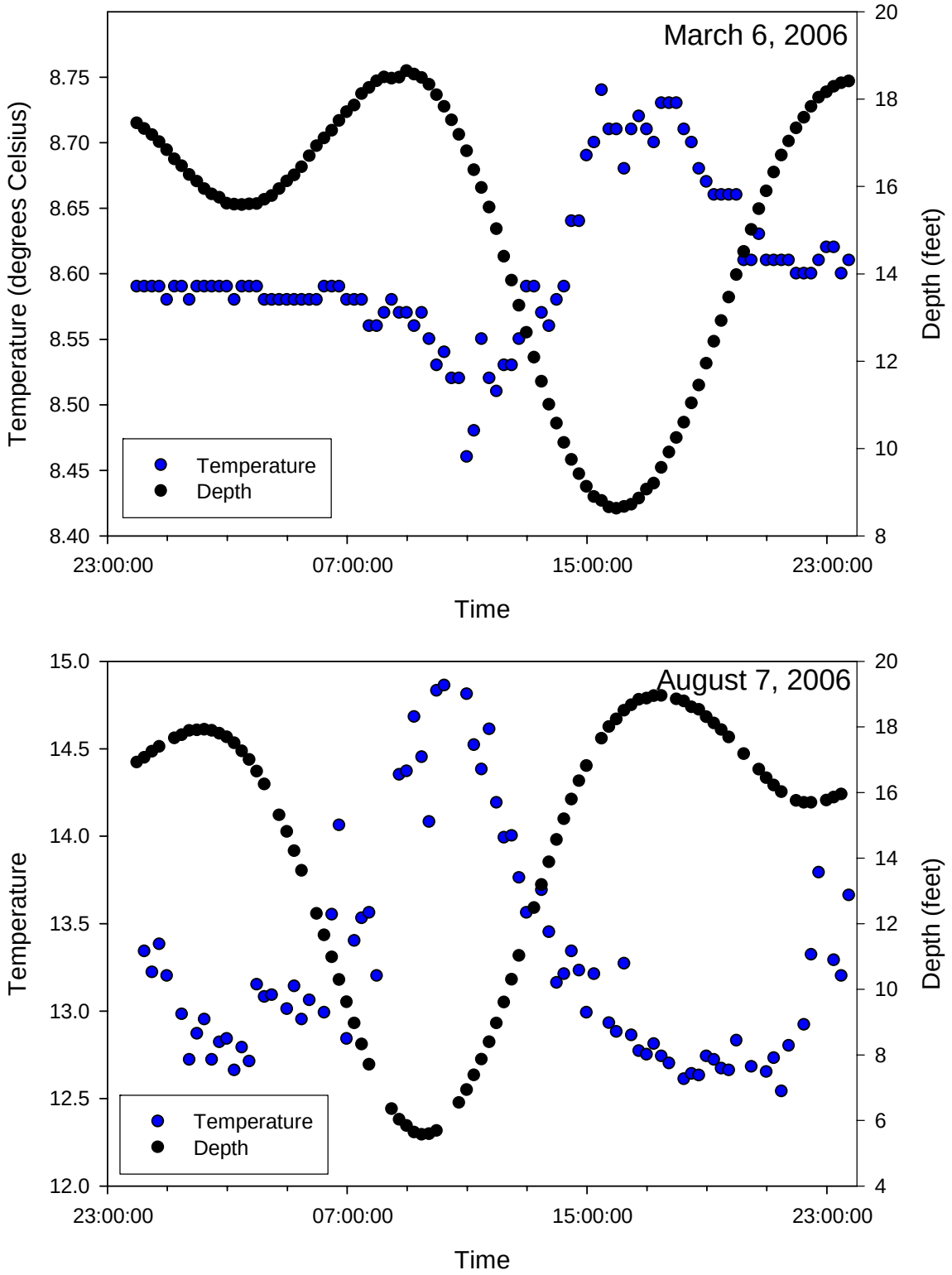

Figure 11. Relationship between temperature and depth in March and August over a 24 hour period.

3.3 Salinity

Salinity within an estuary is mainly controlled by the amount of freshwater input and can also vary due to tides, oceanic water input, precipitation events, and mixing within the water column. Salinity generally increases with depth.

Salinity data obtained were of good quality throughout the deployment. Daily mean salinities ranged from 15.84 to 30.72 PSU, with an average salinity of 28.77 PSU. Salinity measurements obtained from August 24 through September 21 were flagged as "Rejected" due to extensive biofouling. Salinity data was not collected from September 22 through October 26 due to instrument configuration errors that prevented data download. Periods of low salinity corresponded with periods of higher precipitation (Figure 12) and higher outflow from the Duwamish River (Figure 13).

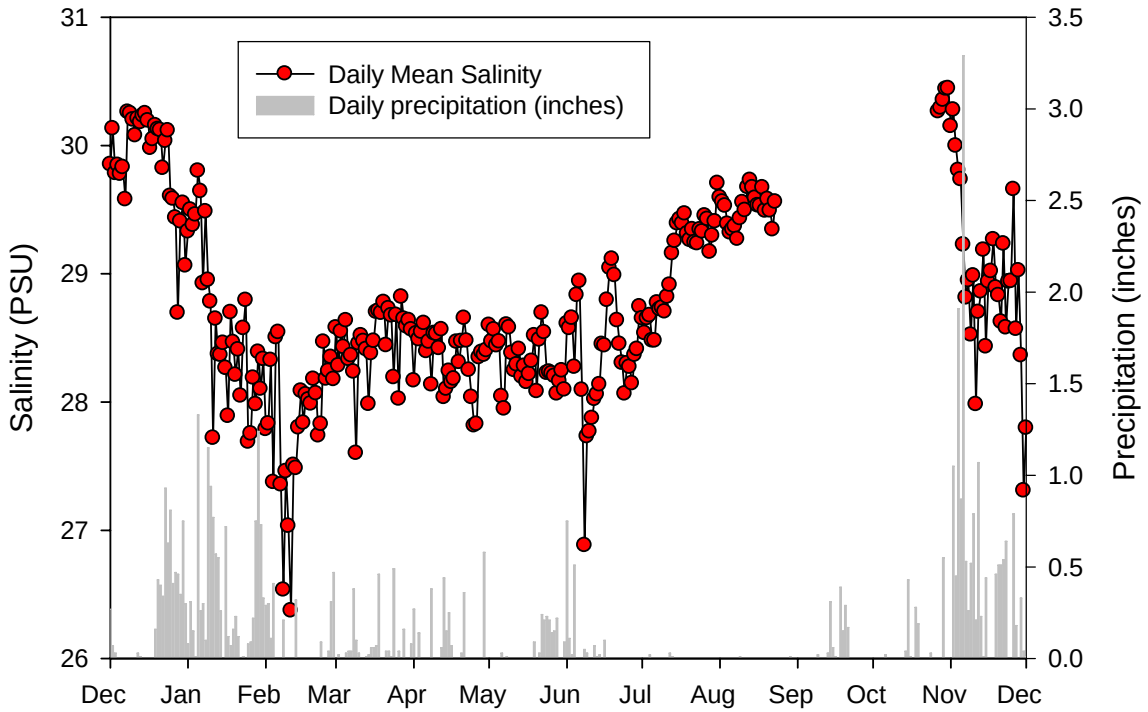

Figure 12. Daily mean salinities and daily precipitation throughout year of deployment.

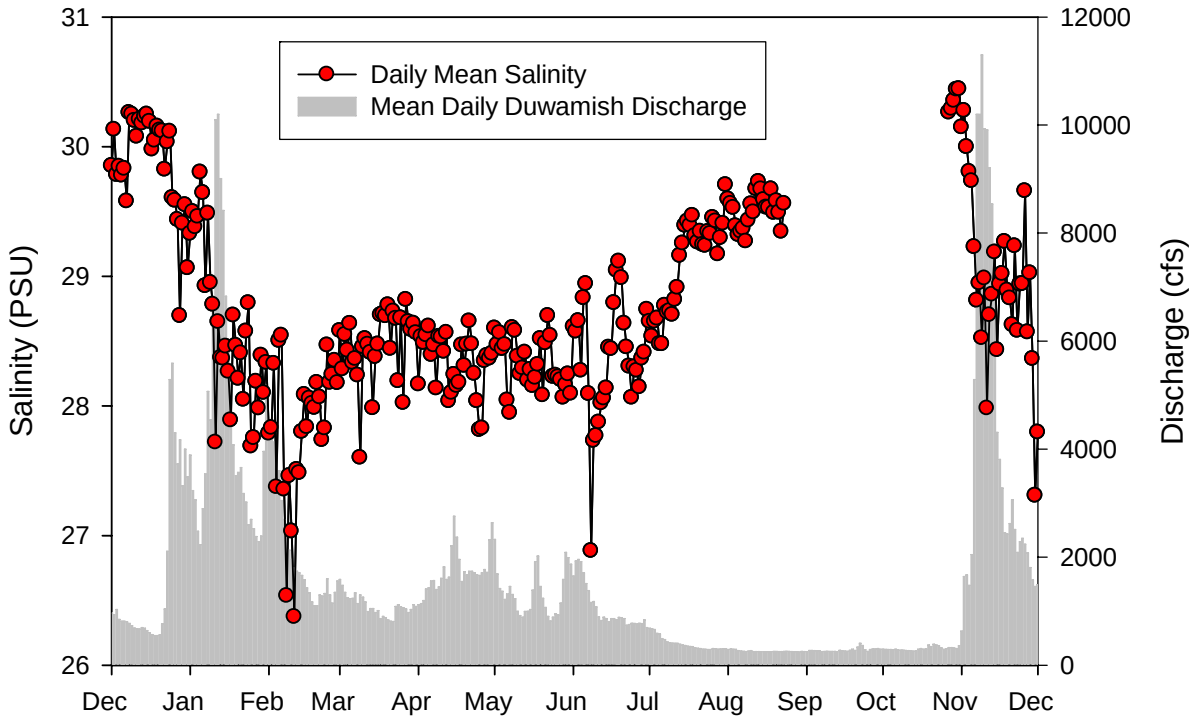

Figure 13. Daily mean salinities and Duwamish River mean daily flow throughout year of deployment.

When salinity is examined with depth over a 24 hour period, a relationship between the two variables is observed (Figure 14). In both winter (January) and summer (August) months, lower salinities are observed when the sonde is near the surface. This is likely the result of the shallow layering of fresh water over the more dense salt water at deeper depths. The range of salinity values measured on January 11 was significantly greater than that measured on August 15 due to the greater influence of freshwater during the winter season.

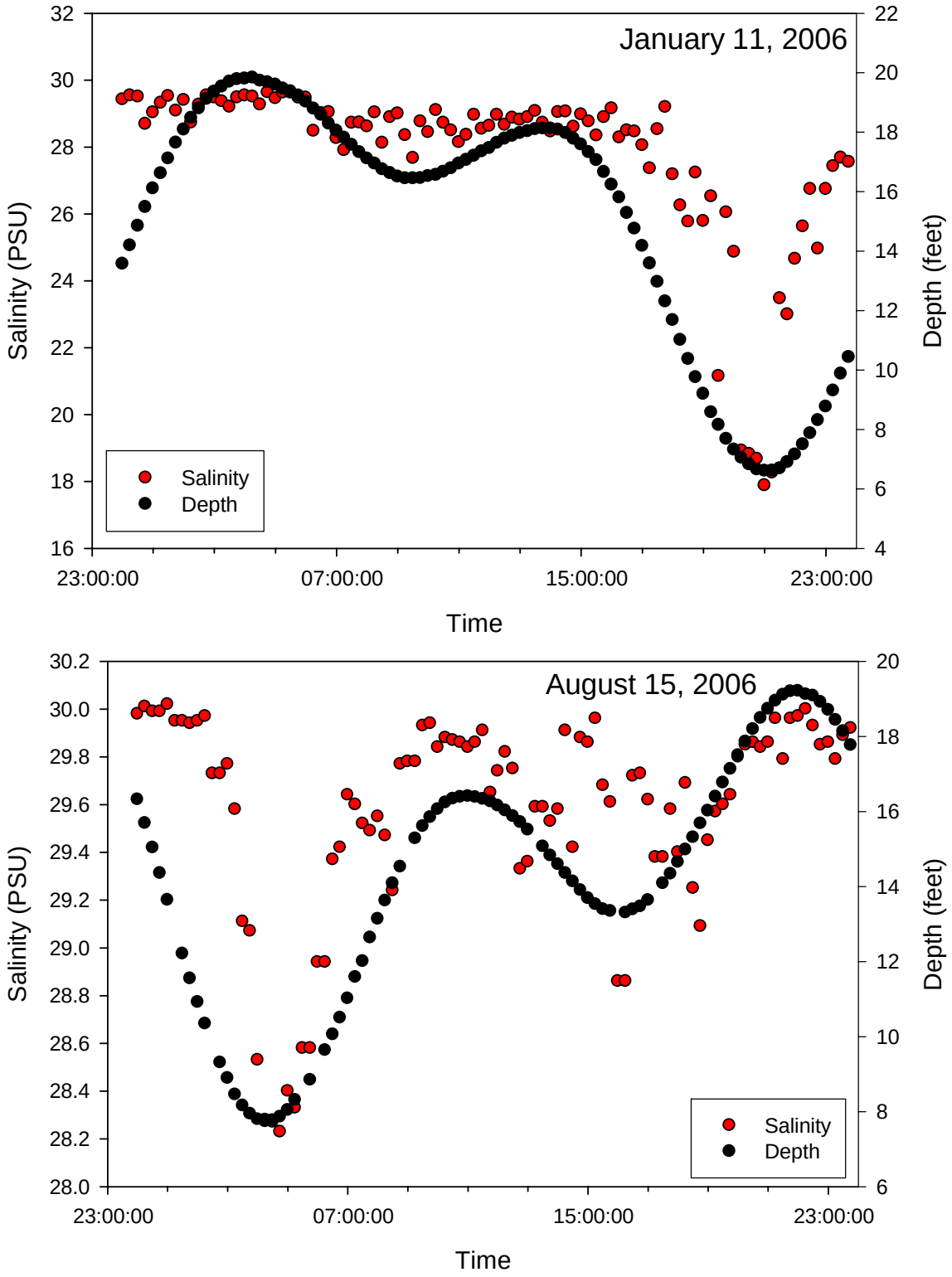

Figure 14. Relationship between salinity and depth in January and August over a 24 hour period.

3.4 Dissolved Oxygen

Dissolved oxygen is an important factor controlling the presence or absence of marine species. Aquatic plants and animals require a certain amount of dissolved oxygen for respiration and basic metabolic processes. Waters with high concentrations of dissolved oxygen are generally considered healthy ecosystems. Dissolved oxygen levels vary with changes in water temperature, with the capacity of water to hold dissolved oxygen decreasing as temperature increases. Stratification of the water column can impede vertical mixing of highly oxygenated surface waters with water depleted in oxygen beneath the stratified layer. Anthropogenic input and bacterial remineralization of organic matter can also decrease oxygen levels.

Dissolved oxygen data did not meet quality control criteria more often than other parameters. Data of good quality ranged from 5.07 to 12.08 mg/L, with an average dissolved oxygen concentration of 7.73 mg/L. Daily mean dissolved oxygen concentrations calculated from data of good quality are shown in Figure 14.

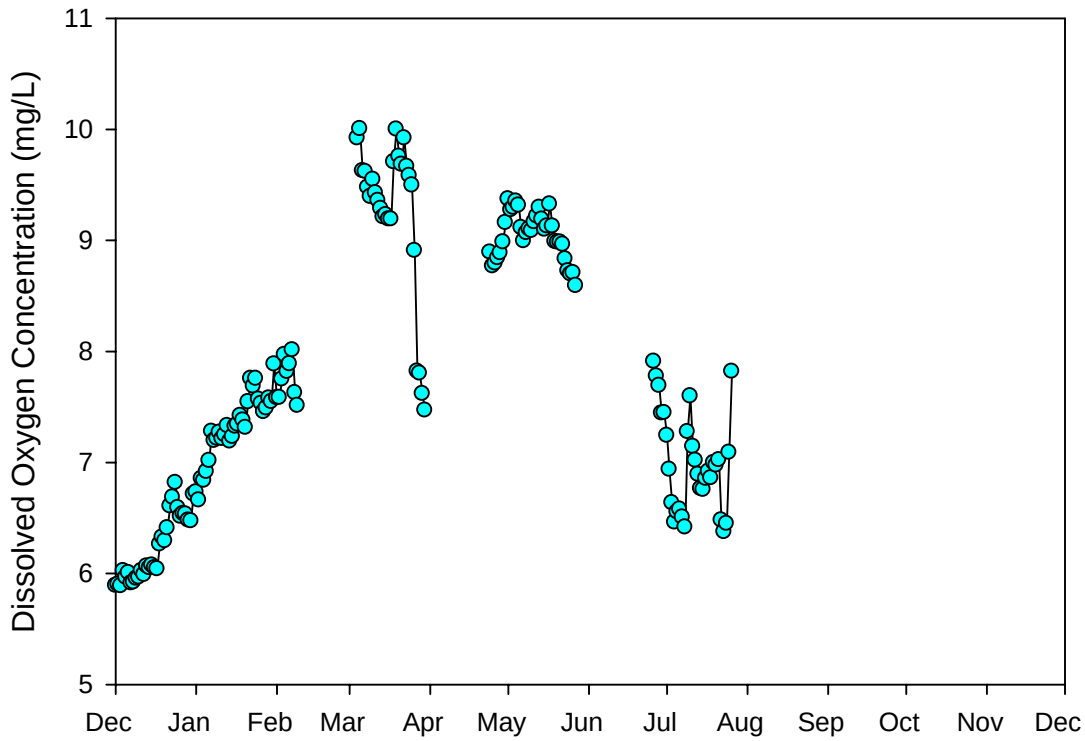

Figure 15. Daily mean dissolved oxygen concentrations throughout the year of deployment.

When dissolved oxygen is examined with depth over a 24 hour period, a relationship between the two variables is observed (Figure 16). In both winter (January) and summer (July) months, maximum oxygen levels are observed when the sonde is near the surface and lower levels are observed as water column depth above the sonde increases. This is likely due to greater air-sea flux near the surface resulting in higher oxygen levels.

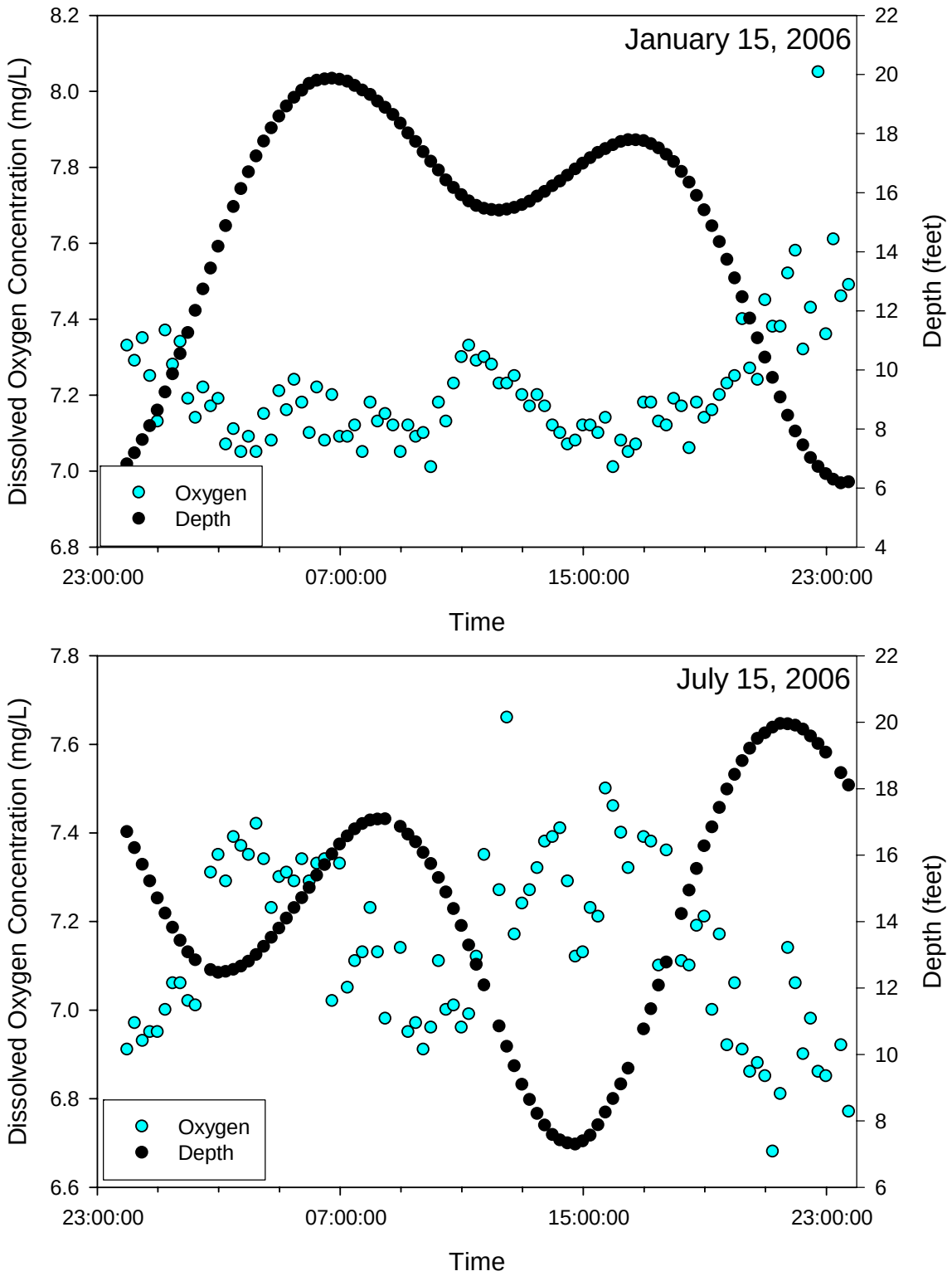

Figure 16. Relationship between dissolved oxygen levels and depth in January and July over a 24 hour period.

3.5 Chlorophyll

Chlorophyll-*a* is a green pigment used by algae and other green plants during the process of photosynthesis to convert energy from the sun, carbon dioxide, and water into sugar. Chlorophyll-*a* concentration is used as an indicator of phytoplankton biomass but is not an exact measurement of phytoplankton abundance. Chlorophyll-*a* levels are influenced by phytoplankton abundance which, in turn, is affected by solar radiation, water temperature, nutrient availability, water column stratification, and grazing community.

The chlorophyll fluorometer provided general trend information but, in general, data collected *in situ* did not compare well with laboratory analytical results. Chlorophyll-*a* levels ranged from 0 to 132.7 μg/L, with an average of 1.82 μg/L. Daily mean concentrations are shown in Figure 17.

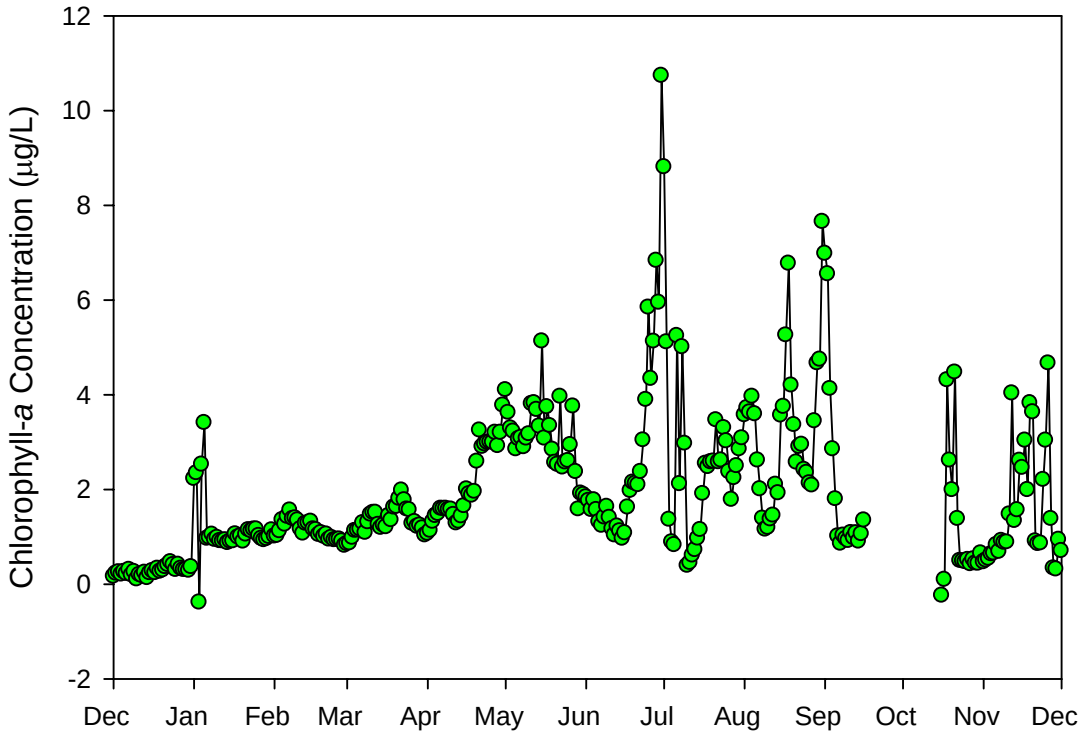

Figure 17. Daily mean chlorophyll-*a* concentrations throughout the year of deployment.

When chlorophyll-*a* concentrations are examined over a 24 hour period with water-column depth above the sonde as the other variable, a weak relationship between the two variables is observed during a bloom (June) (Figure 18). During non-bloom periods (e.g., February), however, levels of chlorophyll-*a* do not appear to vary with depth. During the bloom observed on June 29, peak chlorophyll levels were observed at approximately 15 to 18 feet.

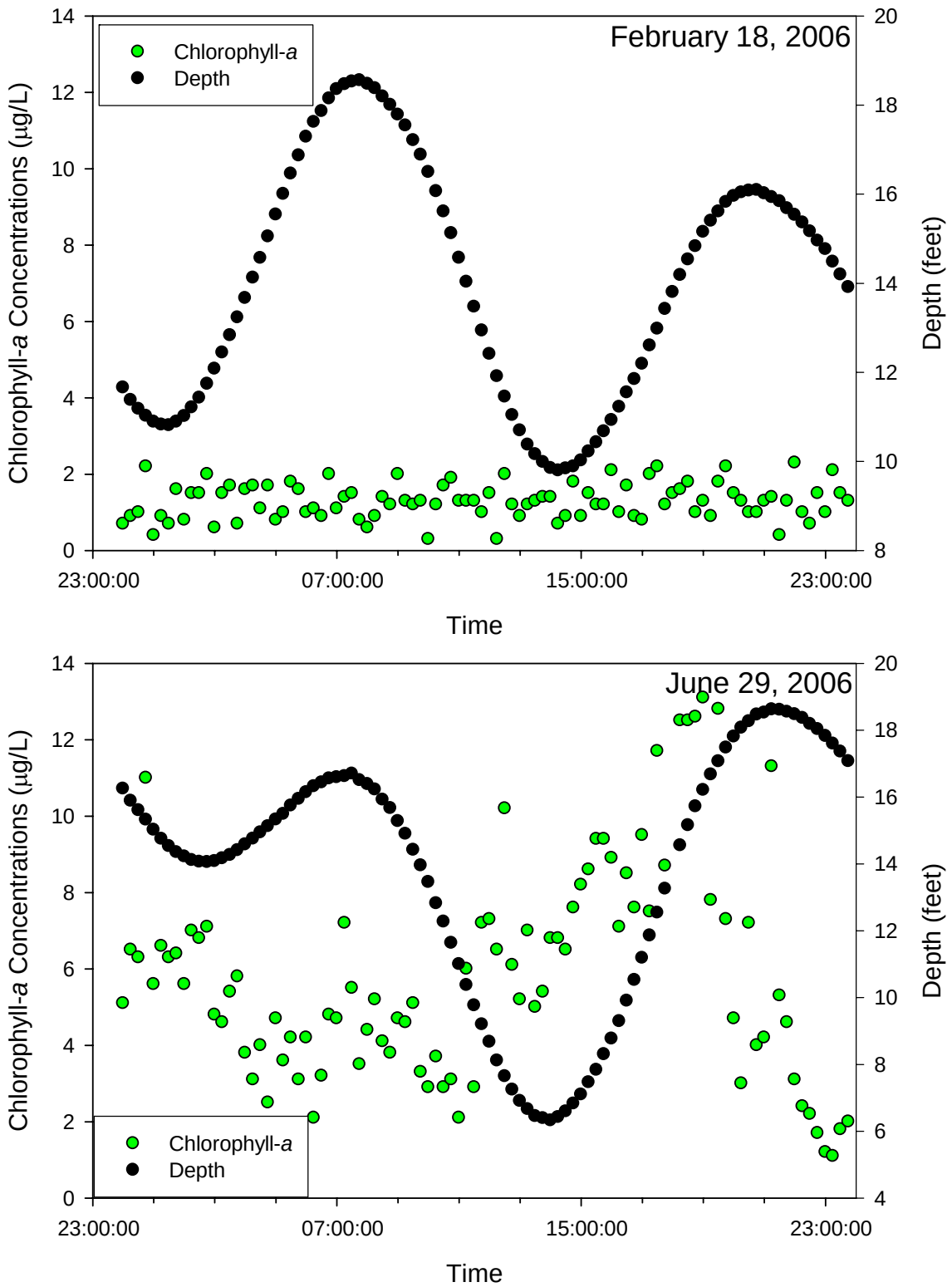

Figure 18. Relationship between chlorophyll-*a* levels and depth in February and June over a 24 hour period.

3.6 pH

Seawater pH levels have been generally thought of as stable with respect to long time scales and influenced on short time scales by processes such as productivity, respiration, and fresh water input. However, decreasing seawater pH levels over long periods of time due to the uptake of anthropogenic carbon dioxide from the atmosphere have recently been discovered throughout the world's oceans. This is referred to as ocean acidification (Feely *et al.*, 2004).

pH data showed a slight drift during the first two months of 2006 but, after maintenance and proper calibration, were stable and within quality control limits. pH ranged from 7.15 to 8.24, with an average pH of 7.79. Daily mean pH values are shown in Figure 19.

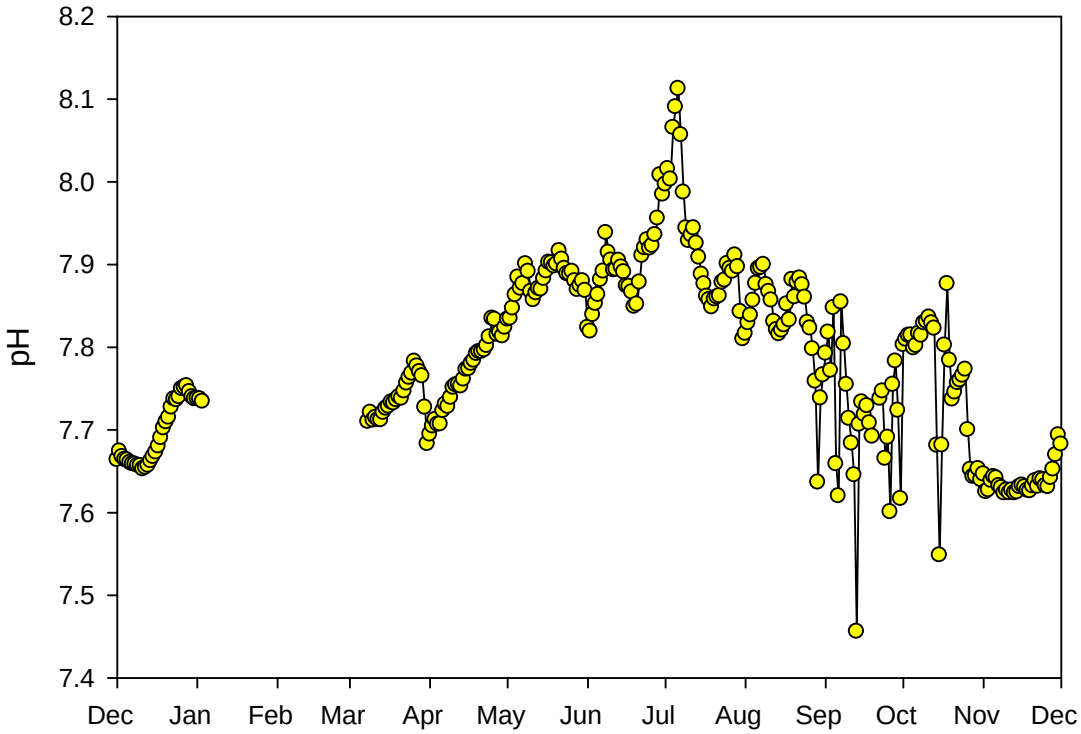

Figure 19. Daily mean pH levels throughout the year of deployment.

When pH is examined over a 24 hour period with water-column depth above the sonde as the other variable, a relationship between the two variables is observed, particularly at times of high productivity (Figure 20). However, it is difficult to attribute variations in pH to depth alone on June 29 since the period of the day that the monitoring equipment reached shallow depths less than 10 feet coincided with the period of the day with greatest solar radiation (11 a.m. to 5 p.m.). The pH of the euphotic zone generally increases during the day and decreases at night. Because photosynthesis requires sunlight, net uptake of carbon dioxide occurs during the day and results in higher pH values. A net release of carbon dioxide occurs at night due to dark respiration resulting in lower pH values.

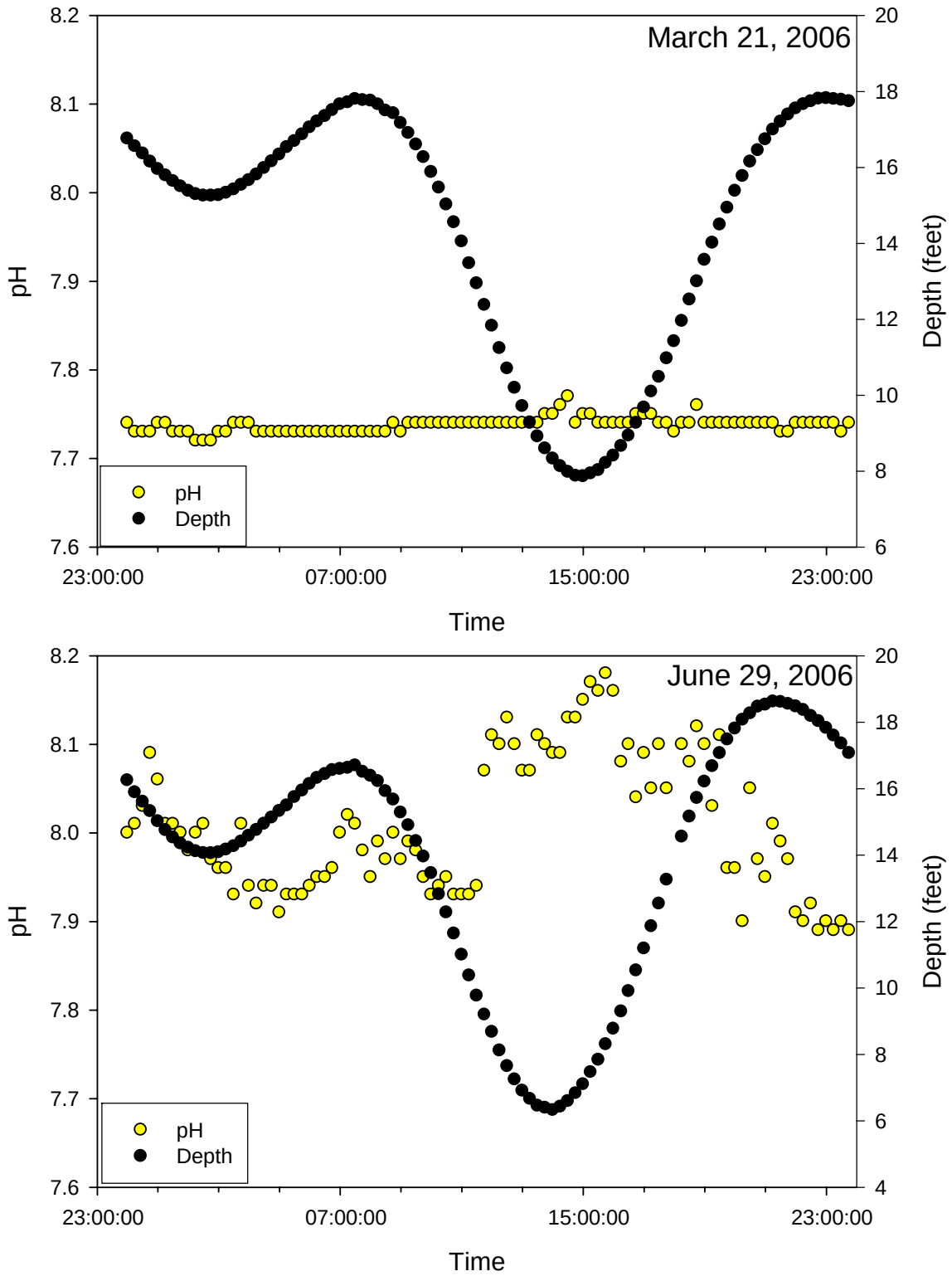

Figure 20. Relationship between pH levels and depth in March and June over a 24 hour period.

3.7 Turbidity

Turbidity is a measure of water clarity and is an expression of the amount of light scattered or reflected by dissolved and suspended solids in the water column. As turbidity decreases, transparency increases. Input from rivers and streams can supply solids to a water body and increase turbidity. Wind and waves can indirectly increase turbidity by stirring up particulates in the water, particularly from the sea floor.

Data collected *in situ* by the turbidity probe provided analytical trend information but, in general, did not compare well with laboratory results. Turbidity values ranged from 0 to 1151.2 NTU, although anything over 100 NTU is most likely an anomaly. An average of 0.37 NTU in turbidity was obtained throughout the deployment. Daily mean turbidity levels are shown in Figure 21. Turbidity values greater than 20 NTU were measured only two times and were the result of the Seattle Aquarium releasing water near the monitoring equipment (Shawn Larson: personal communication).

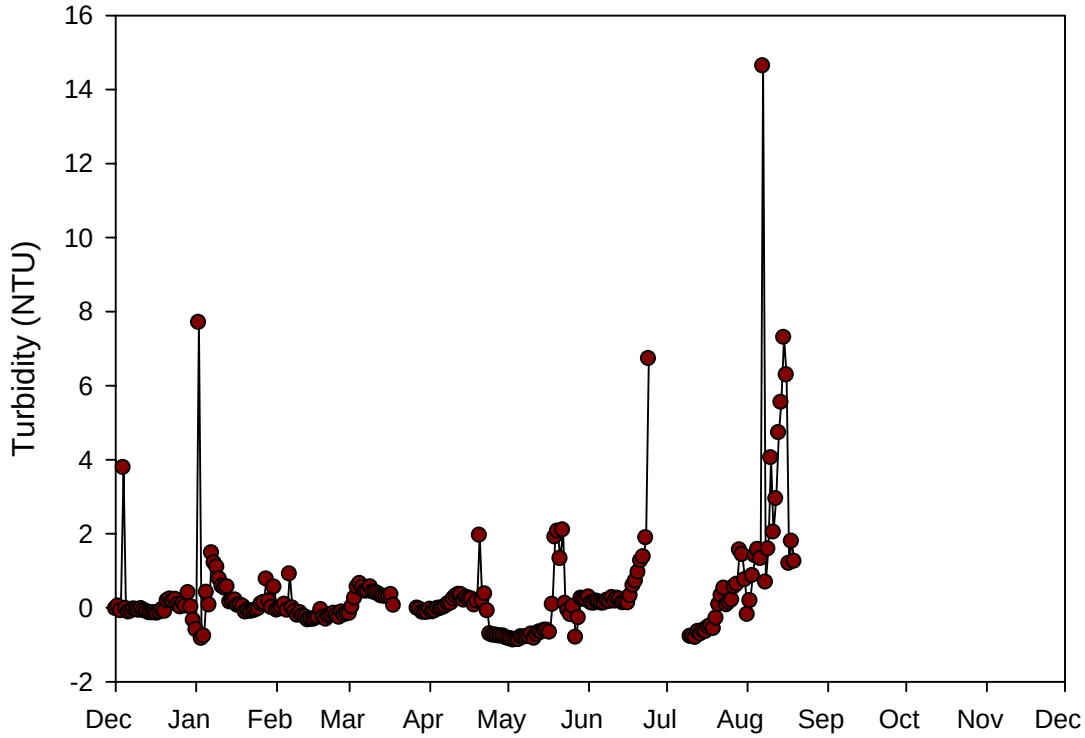

Figure 21. Daily mean turbidity levels throughout the year of deployment.

When turbidity is examined over a 24 hour period with water-column depth above the sonde as the other variable, a relationship between the two variables is observed (Figure 22). Turbidity values tended to be higher near the surface.

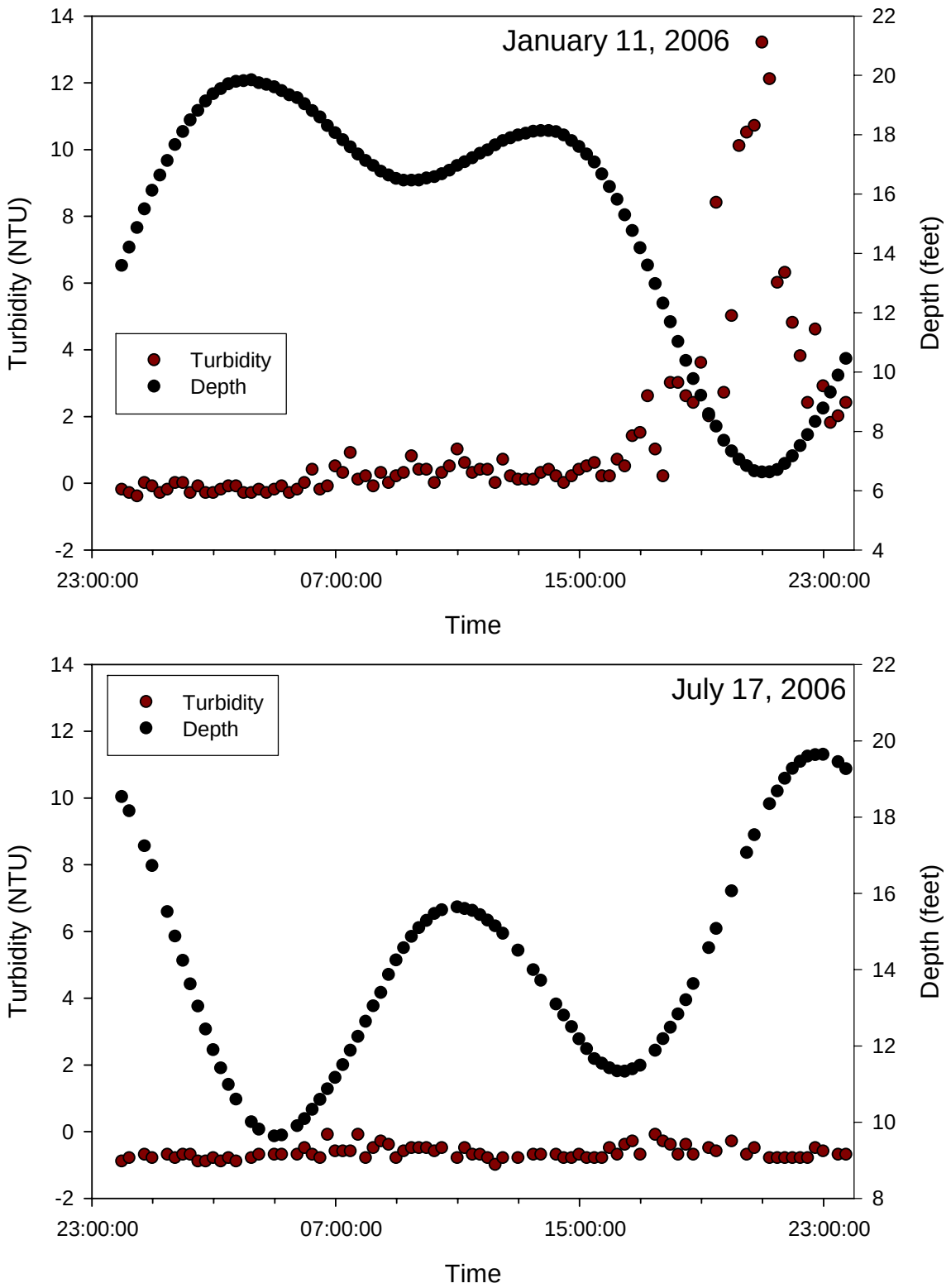

Figure 22. Relationship between turbidity and depth in January and July over a 24 hour period.

4.0 CONCLUSIONS

The major objectives of this pilot projects were to test the hardware and software of the system by evaluating the following:

- Ease of setup,
- Robustness of the physical hardware (data logger, solar panels, cabling, sonde, and sensors) in a marine environment,
- Power management,
- Calibration frequency requirements,
- Data management quality (telemetry system, web interface, database reliability)

Aside from the major testing goals, the data collected allowed for the evaluation of seasonal water quality trends in Elliott Bay and also provided useful data for the Seattle Aquarium's water quality monitoring program.

The following are findings resulting at the conclusion of the pilot monitoring project:

1. The 6200 Data Acquisition System and Econet^{tm} systems worked nearly flawlessly throughout the entire year of deployment.
2. No data storage issues were experienced and the web site was up 99.9% of the time.
3. The sonde could be deployed in Elliott Bay for approximately 4-6 weeks without maintenance. Although other sensors remained calibrated for longer than 4 weeks, the dissolved oxygen sensor required calibration every 4 weeks.
4. High quality high-frequency data was successfully collected for use in further analysis of Elliott Bay water quality conditions.
5. Installation of a permanent high-frequency water quality marine monitoring system is recommended at the Seattle Aquarium location in Elliott Bay.
6. The turbidity and fluorescence sensors only provide general trend data and do not provide the accuracy required to conduct statistical trend analysis.

5.0 REFERENCES

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