The Oceanic Remote Chemical/Optical Analyzer (ORCA)—An Autonomous Moored Profiler

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ABSTRACT

An autonomous, moored profiler [the Oceanic Remote Chemical/Optical Analyzer (ORCA)] was developed to sense a variety of chemical and optical properties in the upper water column. It is presently used to monitor water quality parameters in South Puget Sound—a largely undeveloped area subject to extensive future urbanization. ORCA has three main components: 1) a three-point moored Autonomous Temperature Line Acquisition System (ATLAS) toroidal float; 2) a profiling assembly on the float with computer, winch, cellular system, meteorological sensors (wind, temperature, humidity, irradiance), solar panels, and batteries; and 3) an underwater sensor package consisting of a Seabird CTD profiler, YSI dissolved oxygen electrode, Wetlabs transmissometer, and Wetlabs chlorophyll fluorometer. At regular sampling intervals, ORCA profiles the water column using the winch and pressure information from the CTD. The data are recorded on the computer and transmitted to the lab automatically via cellular communications. Data are presented from a 1-day deployment in May 2000 and from a long-term, 7-month deployment. The dataset reveals the combination of intermittent stratification mixing and strong seasonal forcing in this estuarine system.

1. Introduction

a. Biogeochemical profiling

The concept of the ocean observing system has long interested oceanographers as a means of making detailed measurements in time and space. Historically, ships have provided the most common observing platform for oceanic research, affording flexibility in equipment and the human workforce required to accomplish a wide variety of tasks. Recently, autonomous systems have been developed that take advantage of existing sophisticated electronics, engineering concepts, sensors, and software. These systems can now perform some of the sampling previously possible only by ship at much more frequent intervals.

Moored and drifting floats have been the basis of most autonomous ocean observing systems thus far. The most extensive of these is the Thermal Array in the Ocean-Triton array of roughly 70 Autonomous Temperature Line Acquisition System (ATLAS) buoys in the equatorial Pacific, monitoring meteorological data and water temperature, salinity, and pressure using a string of sensors through the water column. These data are trans-

mitted back to a shore-based lab via radio frequency link (Dickey 1988), Argos satellite (McPhaden 1993), or cellular phone (Dickey et al. 1993). While moored observing systems have been generally confined to the measurement of physical parameters, progress has been made in adding optical (Abbott et al. 1990; Bricaud et al. 1995; Foley et al. 1997; Dickey et al. 1998; Chavez et al. 1999) and chemical (Johnson et al. 1989; Coale et al. 1991; McNeil et al. 1999; Hanson and Donaghay 1998) sensors. Optical and chemical sensors have been combined on moorings (Dickey et al. 1998; McNeil et al. 1999).

Characterization of light, nutrient, and density stratification in the ocean requires vertically resolved sampling or profiling. Although moored autonomous observing systems have been generally confined to measurements at a few discrete depths, progress has been made on increasing the vertical resolution by profiling the water column, much like a ship's CTD rosette or towed package. This is a mechanically challenging task attracting a variety of engineering solutions. Some profiling mechanisms presently available include a retrofitted, buoyancy controlled cyclosonde profiler (dubbed the multivariable moored profiler) equipped with a CTD, two current meters, fluorometer, and photosynthetically active radiation (PAR) sensor (Dickey 1988), a surface winch (buoy profiler 701—Idronaut S.r.l.; Automated Floating Data Collection Systems—Systems Management Inc.), a bottom winch (LEO-15; von Alt et al. 1997; Forrester et al. 1997), a wheel-driven design that climbs the mooring wire (Doherty et al. 1999), a near-

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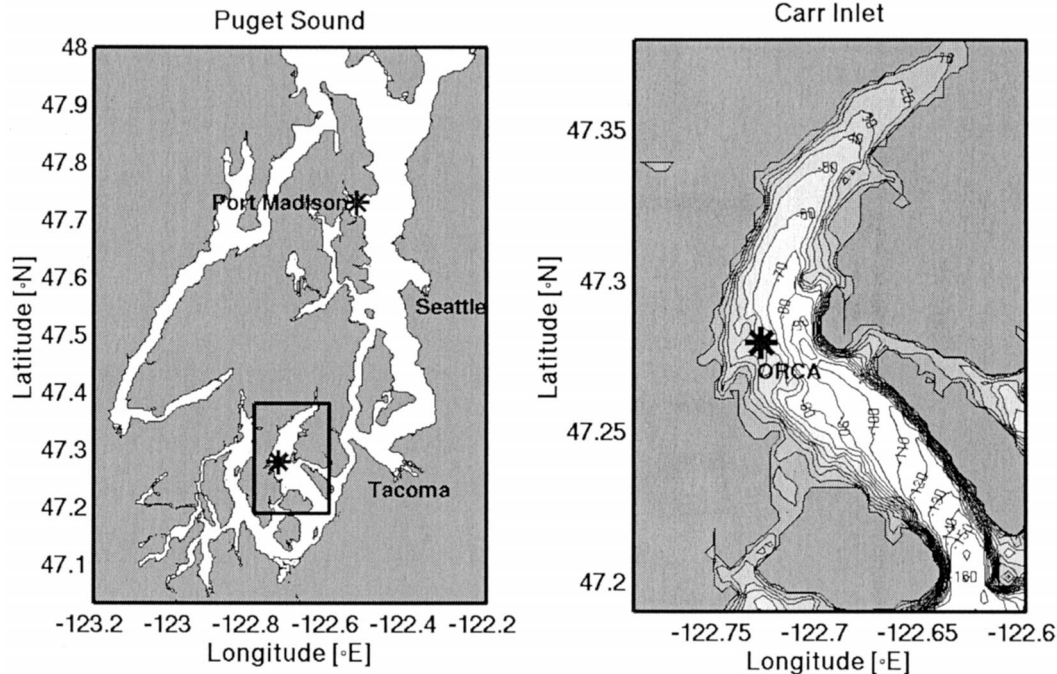E-mail: jdunne@princeton.edu

FIG. 1. Maps of study site. (left) Puget Sound with locations of ORCA testing and mooring deployments (stars). Carr Inlet is shown in the box. (right) Bathymetric contour map of Carr Inlet showing mooring location.

neutrally buoyant ratcheting wave drive (Seahorse; Hamilton et al. 1999), oil bladder buoyancy drive (Remote Underwater Sampling Station—Apprise Technologies; Provost and du Chaffaut 1996), and an ocean-current-propelled wing (Echert et al. 1989). All of these profilers have distinct advantages and disadvantages making them suited to a particular range of natural conditions.

Our interest in aquatic observing system is to monitor water quality in Puget Sound, Washington. Water quality is assessed in terms of the ability of our regional aquatic environments to support fisheries, commerce, and recreation in addition to industrial and private discharges of waste. Impacts to water quality include physical change (water diversion, habitat destruction, sediment suspension, etc.) or chemical change caused by human impact (eutrophication and subsequent ecosystem change, toxicity). The means of assessment of change is frequently through time series measurements of temperature, salinity, phytoplankton biomass, particle mass, nutrient, and oxygen data.

While local monitoring programs provide geographically extensive measurements of water quality parameters, the sampling rate is far too coarse to support a mechanistic analysis of variability forcing from tidal and other diurnal cycles as well as weather patterns. Here we describe the development of an autonomous observing system designed to sample the upper water column at high frequencies over long duration.

b. Study site

Puget Sound is a deep fjord system in the U.S. Pacific Northwest. The main basin of Puget Sound is turbulent and well mixed while reaches further inland, primarily in South Puget Sound, are subject to sluggish circulation and seasonal stratification in the spring and summer months. This presently leads to frequent, intense phytoplankton blooms in surface waters and decreased oxygen levels at depth. This sensitivity is illustrated schematically in Fig. 1a from a synthesis of local water quality monitoring data. While South Puget Sound is mostly undeveloped, the region is predicted to undergo extensive urbanization over the coming decades. This will increase discharge of industrial and private waste and, subsequently, the risk of water quality impacts such as harmful algal blooms and oxygen depletion through eutrophication. Such ecological damage could potentially affect resident populations of salmon, harbor seals, stellar sea lions, porpoise, and killer whales as well as local economies based on shellfish aquaculture, boating, and line fishing.

The Oceanic Remote Chemical/Optical Analyzer (ORCA; see Fig. 2) is moored in approximately 50 m of water in Carr Inlet, South Puget Sound at 47°15.8′N, 122°43.7′W approximately 1.5 km offshore (Fig. 1b). Average daily air temperatures vary between lows and highs of −0.2° and 6.9°C in January and 9.6° and 17.2°C in July. Insolation and rainfall are both highly seasonal and opposite in phase. Daily averages for insolation are

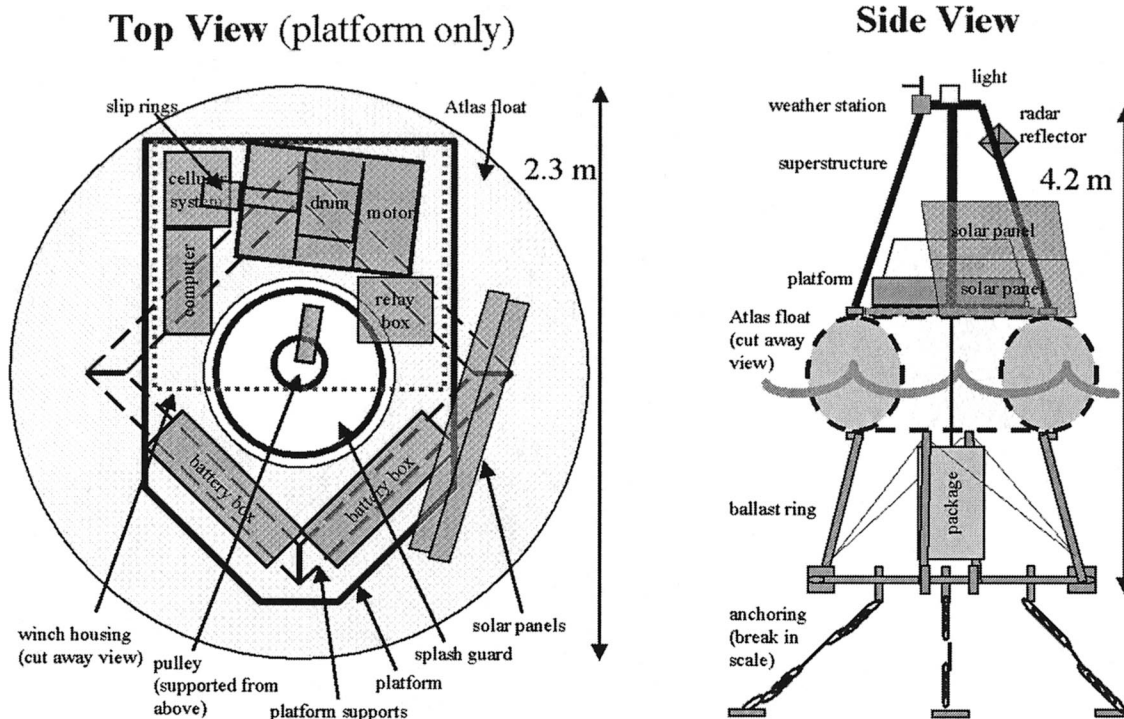## Top View (platform only)

Side View

FIG. 2. Schematic of the ORCA platform. (left) Top view with platform only (superstructure, ballast ring, and anchoring removed). (right) Side view with triple-point mooring assembly.

1.0 kW h m^{-2} day^{-1} in January and 5.9 kW h m^{-2} day^{-1} in July, while averages for rainfall are 1 cm day^{-1} in winter and 0.01 cm day^{-1} in summer. Winds during the entire year are generally weak (<8 m s^{-1}) except for occasional storms in winter that last a few days and can have winds in excess of 20 m s^{-1}. Carr Inlet itself is approximately 4 km wide and 20 km long and 100 m at its deepest for about half way along its axis. Its primarily north–south orientation presents the greatest fetch to storms with strong northerly or southerly winds. Wave action is generally weak with significant wave heights less than 0.6 m. However, storm-derived wave heights can be in excess of 1 m. The inlet is stratified in summer and well mixed in winter, with summer water temperatures varying between 14° and 18°C at the surface and 12° and 13°C at depth in summer and falling to an isothermal 8°C in February and March. Nutrients are generally limiting to primary production in summer surface waters but replete otherwise. Though no major rivers empty into Carr Inlet, salinity stratification occurs in summer, suggesting significant freshwater inputs. Tidally driven currents average 15 cm s^{-1} with tidal excursions of approximately 2 km and tidal height varying by about 3 m.

2. Methods

a. Mooring configuration

ORCA was designed and constructed at the University of Washington from a combination of commercially available components (Table 1) and custom ones developed at the University of Washington with assistance from UW Oceanography Technical Services. ORCA has three main components: a three-point moored float, a profiling assembly, and an underwater sensor package. The float itself is a 2.3-m-diameter fiberglass ATLAS toroid float with net buoyancy of 2400 kg for durability, visibility, accessibility from a small boat, and large enough working area for two people (Fig. 3). Mounted atop the float is a platform with winch housing, battery housings, superstructure, and solar panel attachments. Power is derived from four 12 V, 98 A h sealed gel-cell batteries that are recharged using two 75-W solar panels. The solar panels are mounted one atop the other facing south at a 20° angle from vertical. A 2 n mi amber flashing beacon and a radar reflector are mounted on the superstructure. The float has a 250-kg galvanized steel ring hung 1.3 m below the float for ballast. The ring serves as the connection point for the three anchor lines that provide additional ballast. The anchor lines begin with 12 m of ½-in.-thick long-link chain to absorb wave, wind, and storm stresses. This length of chain also serves the purpose of occupying the bulk of the euphotic zone to limit biofouling of the main cable. The main cable is 200 m of polyurethane-jacketed nilspin 3/19 wire rope (total thickness 13 mm) allowing us to obtain a scope of 4:1 for the mooring in 50 m of water. At the seabed, the anchor line ends with 7 m of 1-½-in.-thick anchor chain to absorb tidal and storm stresses terminated at two railroad wheels (620 kg).

TABLE 1. Description of commercial components (along with number used), manufacturers, and specifications (along with product number) utilized in ORCA.

| Component (#)	Manufacturer	Specifications (product #)
Float (1)	Sunbacker Fiberglass — Woodinville, WA	4-legged Atlas fiberglass toroidal buoy; diameter 2.3 m; thickness 0.9 m; net buoyancy 2400 kg
Battery (4)	Solar Electric Spec. — Lacey, WA	Sealed, gell, deep cycle, solar cell; output 12 V/98; weight 32 kg (12SC92/12V)
Solar panel (2)	Siemens Solar Inc. — Camarillo, CA	Length 1.2 m; width 0.5 m; output 14 V; capacity 75 W; weight 10 kg (SP75)
Regulator (1)	Morningstar Corp. — Wash. Crossing, PA	Sunsaver solar voltage regulator, output 28 V (10LDVD2)
Beacon (1)	Carmanah Tech. — Victoria, BC	Solar-powered amber flashing beacon; range 2 nm; frequency 0.25 Hz (600-064)
Winch (1)	AGO Envir. Elect. — Victoria, BC	2–24V; 10-A winch with worm drive; drum width 15 cm; drum core thickness 17 cm; flange thickness 34 cm (CSW-1)
Slip ring (1)	Mercotac Inc. — Carlsbad, CA	Modular, 6-conductor slip ring with boot (SRU-6/630)
Hydrowire (1)	Falmat Inc. — San Marcos, CA	22-gauge, 5-conductor, Kevlar reinforced, polyurethane jacketed cable; thickness 7 mm (FM040-400-DF-8)
Pulley (1)	AGO Envir. Elect. — Victoria, BC	Smartblock composite block with line-out counter (PS06)
Computer (1)	Onset Computer Corp. — Bourne, MA	Tattletale-8 microprocessor with PR-8 electronics board (TT8)
Data storage (1)	Persistor Inst. Inc. — Bourne, MA	Persistor computer module with 48-Mbyte CompactFlash data card (CF1)
Cellular system (1)	Cavanah Comm. — Oxnard, CA	3-W, 9600-baud, analog cellular transceiver (CDS-8800)
CTD (1)	Seabird Elect. Inc. — Bellevue, WA	Conductivity, temperature, and pressure sensors, T–C duct, pump (SBE-5T), antibiofouling collars and guard cage; max. rate 2 Hz (SBE-19)
Fluorometer (1)	WET Labs. Inc. — Philomath, OR	Wetstar miniature fluorometer (WS-3-MF-P)
Transmissometer (1)	WET Labs. Inc. — Phiolmath, OR	C-star 660-nm transmissometer, pathlength 10 cm (CST-306PR)
Oxygen sensor (1)	Seabird Elect. Inc. — Bellevue, WA	YSI polarographic type dissolved oxygen sensor with plenum (SBE-23Y)
Transponder (1)	Benthos — North Falmouth, MA	Transmit 26 kHz; receive 32 kHz (UAT-376)
Weather station (1)	Davis Inst. Corp. — Hayward, CA	Energy EnviroMonitor weather station with wind speed, wind direction, temperature, humidity, and light sensors
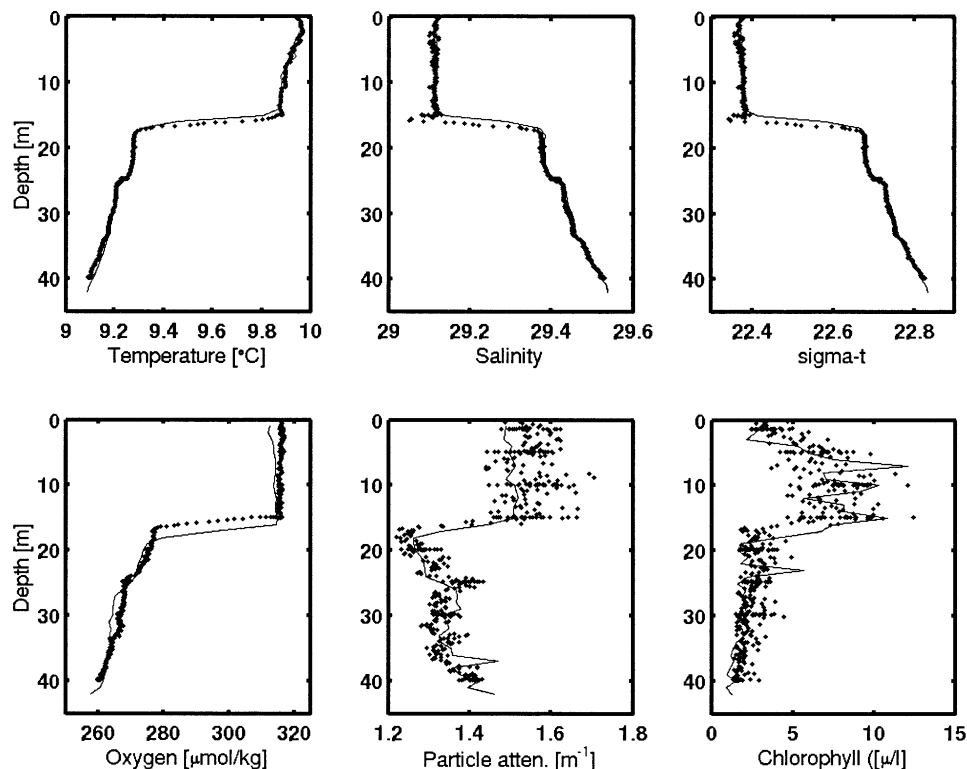
FIG. 3. Example comparison of conventional ship CTD (solid line) and ORCA profile (dots) from the Port Madison short-term deployment (11–12 May 2000).

Profiling is accomplished using a winch and hydrowire configuration. ORCA utilizes a 24-V, 1/3-hp marine winch that profiles the sensor package upward at approximately 13 m min^{-1}. The hydrowire passes from the winch through a 20-cm-diameter pulley with a fare lead of 55 cm down through the center of the toroid. A revolution counter on the pulley provides a lineout indicator. Preliminary tests were conducted using a version of this winch with a level-wind system. This system proved unreliable due to the short fare lead involved. The level wind was eventually abandoned, and replaced with a self-winding system consisting of a drum 15 cm wide with a 17-cm-diameter core and 34-cm-diameter flanges. This drum holds 100 m of hydrowire. The hydrowire has five, 22-gauge wires reinforced with Kevlar with 2-mm-thick polyurethane jacket for a total diameter of 7 mm. The cable is attached to the winch through a 6-conductor slip ring assembly. Power to the winch is regulated using a custom controller allowing both manual and computer control. Computer control is performed using a custom system based on the Tattletale 8 with a PR-8 electronics board developed by the UW Oceanography Engineering Services. Data storage is handled using a Persistor 48-Mbyte memory card and electronics board. Cellular communication is accomplished with a 3-W cellular system. The computer software was developed at the University of Washington (UW) with technical assistance provided by the UW Applied Physics Laboratory.

ORCA uses the standard sensors designed for shipboard CTD profiling mounted within a stainless steel cage (30 cm wide, 1 m high) from Seabird Electronics (product number 801269). The hydrowire is terminated at the sensor cage with a combination of polypropylene cable grip and thimble. Power and communications from the surface terminate at a module that provides power for the sensors during sampling and trickle-charged through the hydrowire at all times. It consists of a 12 V, 5 A h battery and voltage regulator. At the center of the cage is a Seacat CTD profiler from Seabird Electronics (SBE-19) supplying power and communications to the auxiliary instruments. Communications to the SBE-19 are routed through the power regulation module. Water is pumped through a tributyl tin collar at the inlet and outlet of the water flow path, past the conductivity cell, the Seabird-YSI oxygen electrode, to a Wetlabs Wetstar chlorophyll fluorometer, and then to a Wetlabs C-star 660-nm, 10-cm pathlength transmissometer. For added security, a fully autonomous underwater acoustic transponder is mounted on the cage to facilitate recovery of the package if the hydrowire breaks.

b. Current sampling configuration

In its present configuration, ORCA profiles every slack tide using a time interval of 371 min. Between samplings, the sensor package hangs at 40 m beneath the euphotic zone to limit biofouling. The surface computer controls the sequence and timing of sampling operations. It first turns on the CTD and reads pressure data and then supplies power to the winch to move the sensor package to a programmed depth. The winch lowers the sensor package from its parking depth of 40 m to the profile's deepest depth of 45 m, waits 2 min to warm up the oxygen sensor before returning the sensor package to the surface. On the way to the surface the sensor package stops every 5 m for 20 s to ensure sensor equilibration and synchrony along the inline flow path while taking discrete samples. The package then performs a continuous downcast for an uninterrupted CTD profile before returning to its parking depth. After stopping the CTD sampling, all data are uploaded from the CTD. These data are also transmitted to the shore-based lab via cell phone for processing.

At the University of Washington, a Linux personal computer with modem (Starr Comm 34K external modem; 3342E-003-2) serves as host computer. ORCA calls in as a user, transfers files in 4–8-Kbyte blocks, and hangs up. As complete file transfer is never guaranteed over the cellular line, so ORCA may have to call multiple times. A Matlab program runs continuously and periodically checks for new files. If it finds them, it concatenates the transferred files back into the original data files and calls a DOS emulator to execute a Seabird Seasoft data conversion program. It then extracts the data, plots each profile (Figs. 4 and 8) and saves it to an Internet-accessible folder. The program performs calibration corrections to the data and runs an objective analysis mapping routine on each profile to develop contour plots of the entire time series (Figs. 6 and 7) that is also saved to the Internet-accessible folder.

ORCA underwent an intensive, overnight field test with sensor calibration in Port Madison, Puget Sound (11–12 May 2000) and was moored in Carr Inlet, Puget Sound, on 26 May 2000 in approximately 50 m of water, 2 km from shore at 47°16.771′N, 122°43.686′W. Sensor calibration samples are taken every 2–4 weeks through a combination of Washington State Department of Ecology's monthly sampling program (available online at http://www.ecy.wa.gov/programs/eap/mar_wat/mwm_intr.html) and cruises of opportunity. Calibrations of the oxygen sensor were performed using Winkler titrations during periodic maintenance cruises. Over the first 3 months no drift in the chlorophyll fluorometer was observed. Drift in the transmissometer, however, has been dramatic due to sedimentation in the flow cell degrading both the baseline and sensitivity steadily over time. As a result, we do not present transmissometer results from the long-term deployment.

3. Discussion of ORCA results

a. Short-term deployment

The overnight field test in Port Madison (11–12 May 2000) provided two functions. The engineering objec-
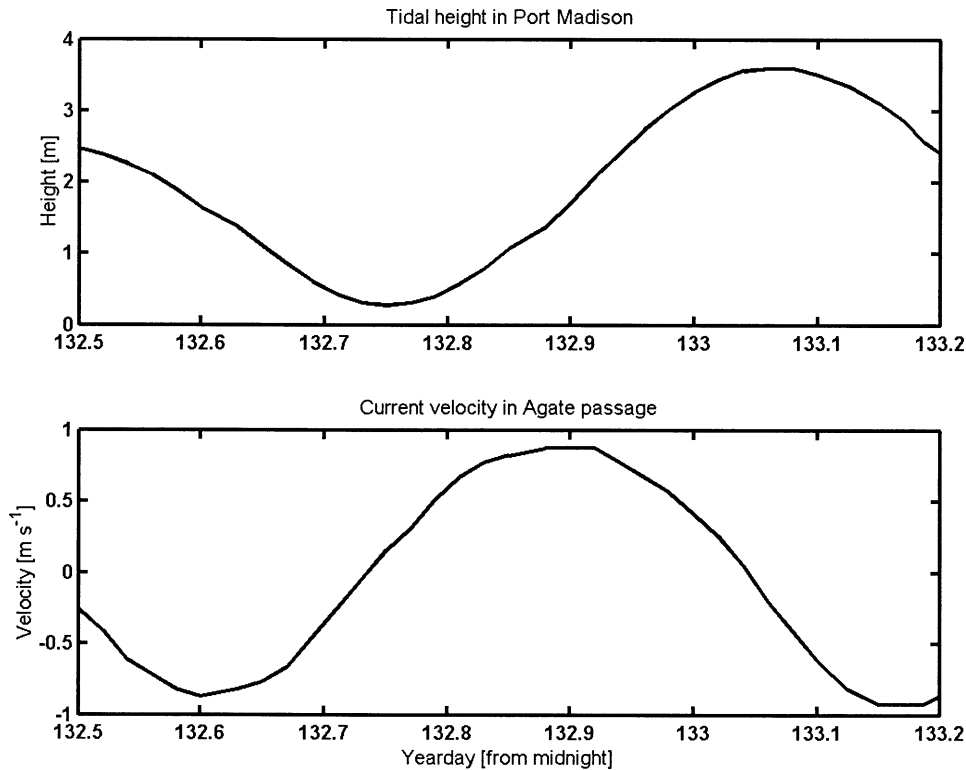
FIG. 4. Conditions during the Port Madison short-term deployment (11–12 May 2000) vs time (year day from midnight). (top) Tidal height in Port Madison (m). (bottom) Current velocity at the north end of Agate Passage (m s^{-1}).

tive was to prove the durability of ORCA for extended profiling in saltwater. The scientific objective was to gain rough insight into the strength of small timescale (tidal, diurnal) variability in Puget Sound in order to assess the minimum profiling interval necessary to describe the natural variability. A rapid sampling interval of 30 min was used to profile the upper 40 m. ORCA profiled 32 times between 1225 to 0454 LT. before encountering a failsafe in the software forbidding movement of the package in the wrong direction. This movement, due to incomplete self-level-winding of the cable onto the drum during the upcast, resulted in an occasional jerky motion as the cable slips from the side of the drum to the center and the package falls a few centimeters. The software has since undergone extensive revision to ignore this intermittent winch action.

Over the 18 h of its operation, three ship CTD rosette casts were made for calibrations of CTD, oxygen, fluorometry, and transmissometry data. Oxygen and fluorometry data are calibrated to Winkler oxygen and chlorophyll from bottle samples. ORCA transmissometry is normalized to ship's transmissometry. An example comparison of downcasts from ORCA and the ship's CTD rosette are shown in Fig. 4. The two profiles agree quite well in the placement and magnitude of the thermocline as well as the magnitude of its impact on variability in oxygen, fluorometry, and transmissometry.

ORCA was able to capture the strong tidal forcing of physical and biological variability at this site. The time series started at the beginning of an ebb tide and continued through the following flood tide and into the next ebb tide. Tidal height in Port Madison and currents through Agate Passage are shown in Fig. 5. The entire ORCA time series are shown for physical and biological parameters in Fig. 6. We observed a 17-m excursion of the pycnocline between ebb tide and flood tide as the relatively warm, fresh waters from Agate Passage replaced the cold, saline waters of Puget Sound (Figs. 5 and 6). The situation was reversed during the flood tide. The total effect was to maximize stratification at low slack water and minimize it during ebb and flood. In general, the biological parameters follow the physical ones (Fig. 6b). Chlorophyll and oxygen exhibit addition variability in the form of afternoon surface maxima in concert with the diurnal cycle. Transmissometry exhibits two forms of additional variability: increased absorbance near the bottom, presumably due to sediment resuspension, and infrequent episodes of midwater maxima, presumably due to passage of algal flocs through the sensor path.

b. Long-term deployment

The dataset from Carr Inlet already consists of over 600 profiles, with high temporal resolution (first every
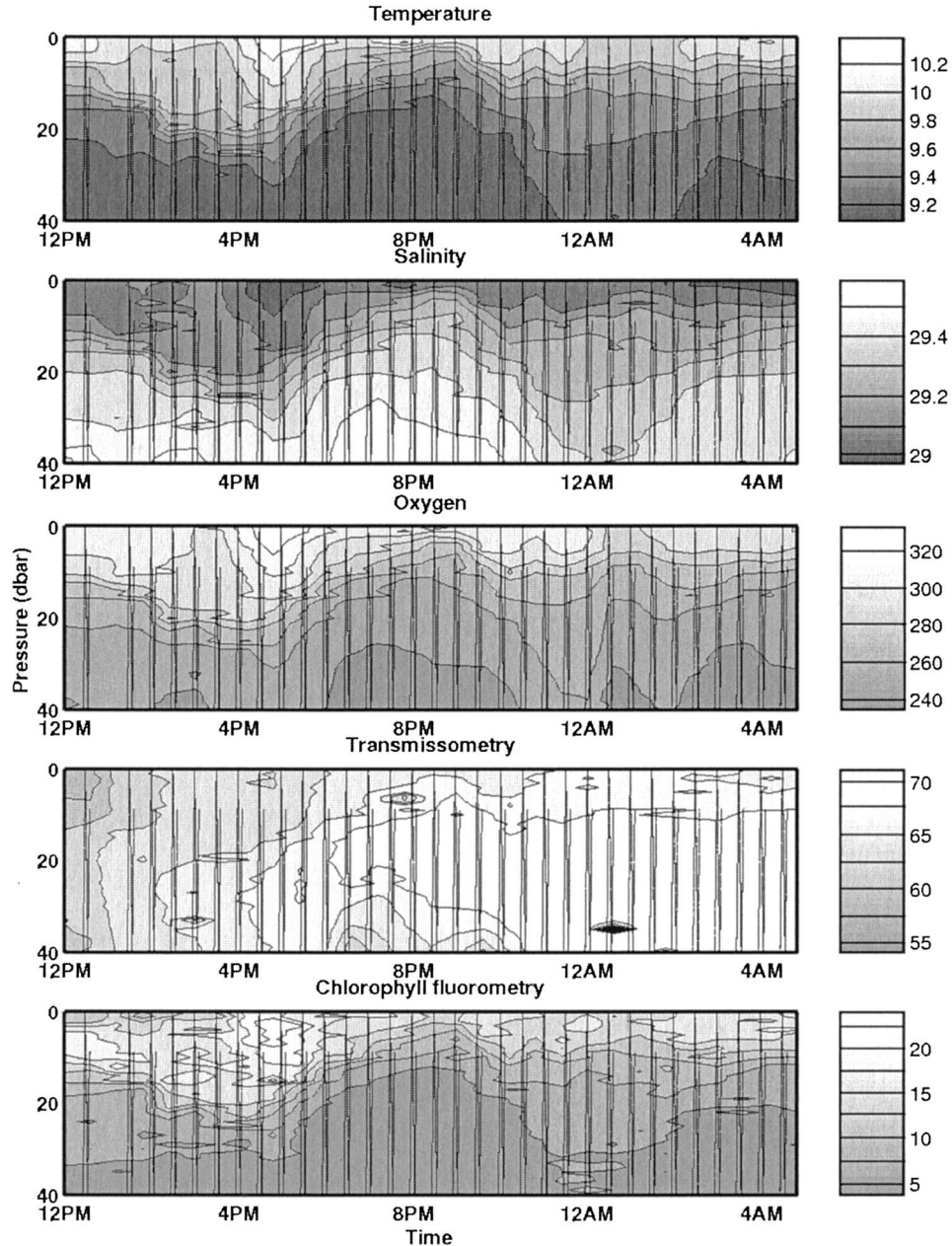
FIG. 5. Maps of parameters measured during the Port Madison short-term deployment (11–12 May 2000) vs pressure (db) and time unclosing physical parameters of temperature (°C), salinity and density (σ_t), and biological parameters of oxygen (μmol), transmissometry (m^{-1}), and chlorophyll fluorometry (μg L).

185 min, then every 371 min) and long duration (7 months described in this report). The entire ORCA time series of physical and biological parameters is shown in Fig. 7. These data are discontinuous due to software and hardware failures that were corrected as they came about (see ''disadvantages'' in Table 3). Nonetheless, ORCA has been operational more than 70% of the time thus far and has provided a valuable, high-resolution record of water column variability in Carr Inlet. Covariation in all parameters indicates a tight coupling

between physical and biological processes. Through the summer and early fall, variability in wind, rainfall, and sunlight forced temperature and salinity producing intermittent periods of strong stratification and deep mixing. The seasonal cycle in temperature and salinity was also intense, with the intermittently high surface temperatures disappearing entirely in the fall and salinity increasing steadily throughout the summer and fall. Oxygen and chlorophyll covaried in the summer through a combination of physical response to the intermittent
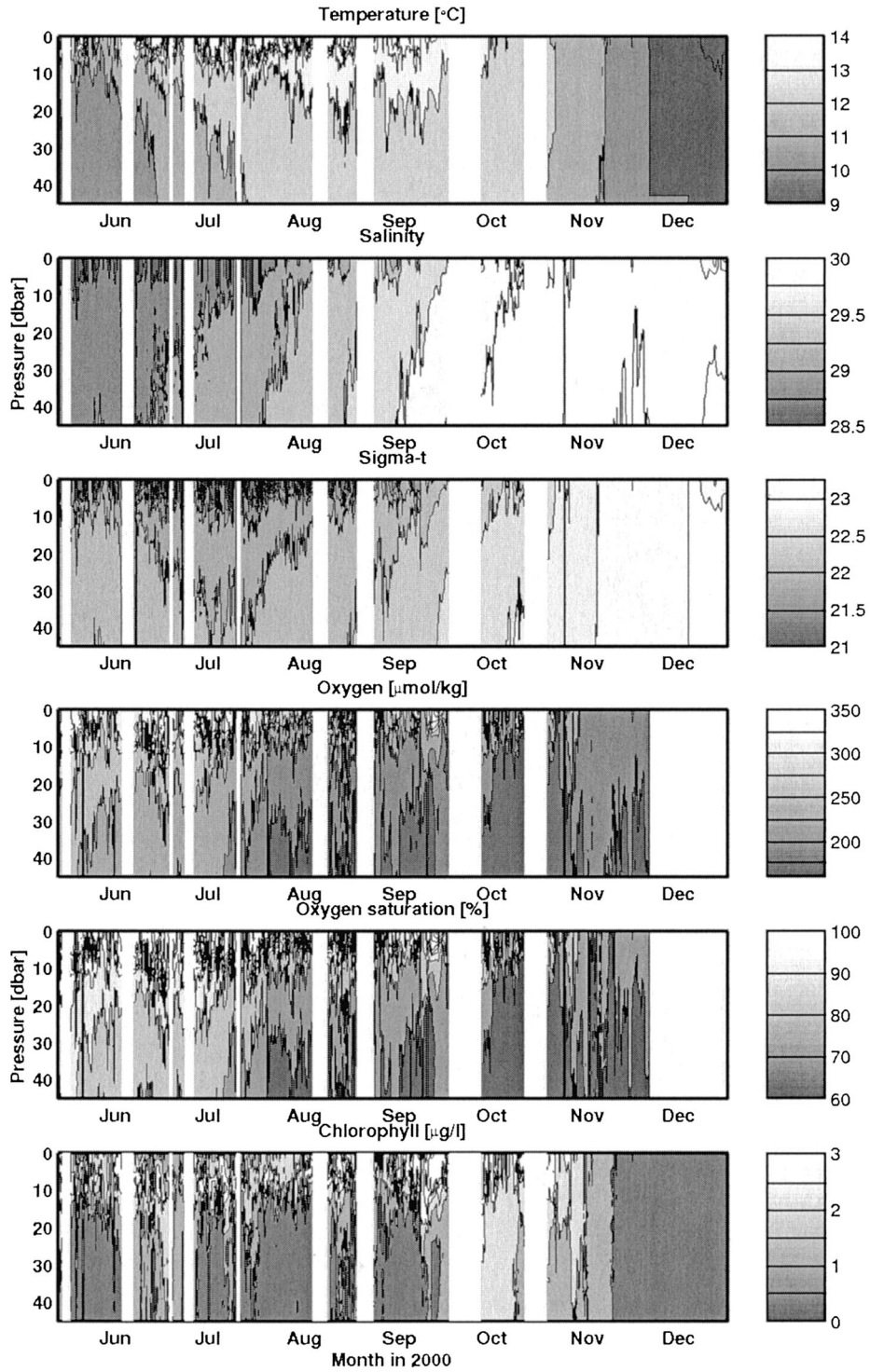
FIG. 6. Maps of temperature (°C), salinity, density (σ_t), oxygen (μmol), oxygen saturation (%), and chlorophyll fluorometry (μg L)—vs pressure (db) and time (year day) from Carr Inlet (26 May–5 Dec 2000).

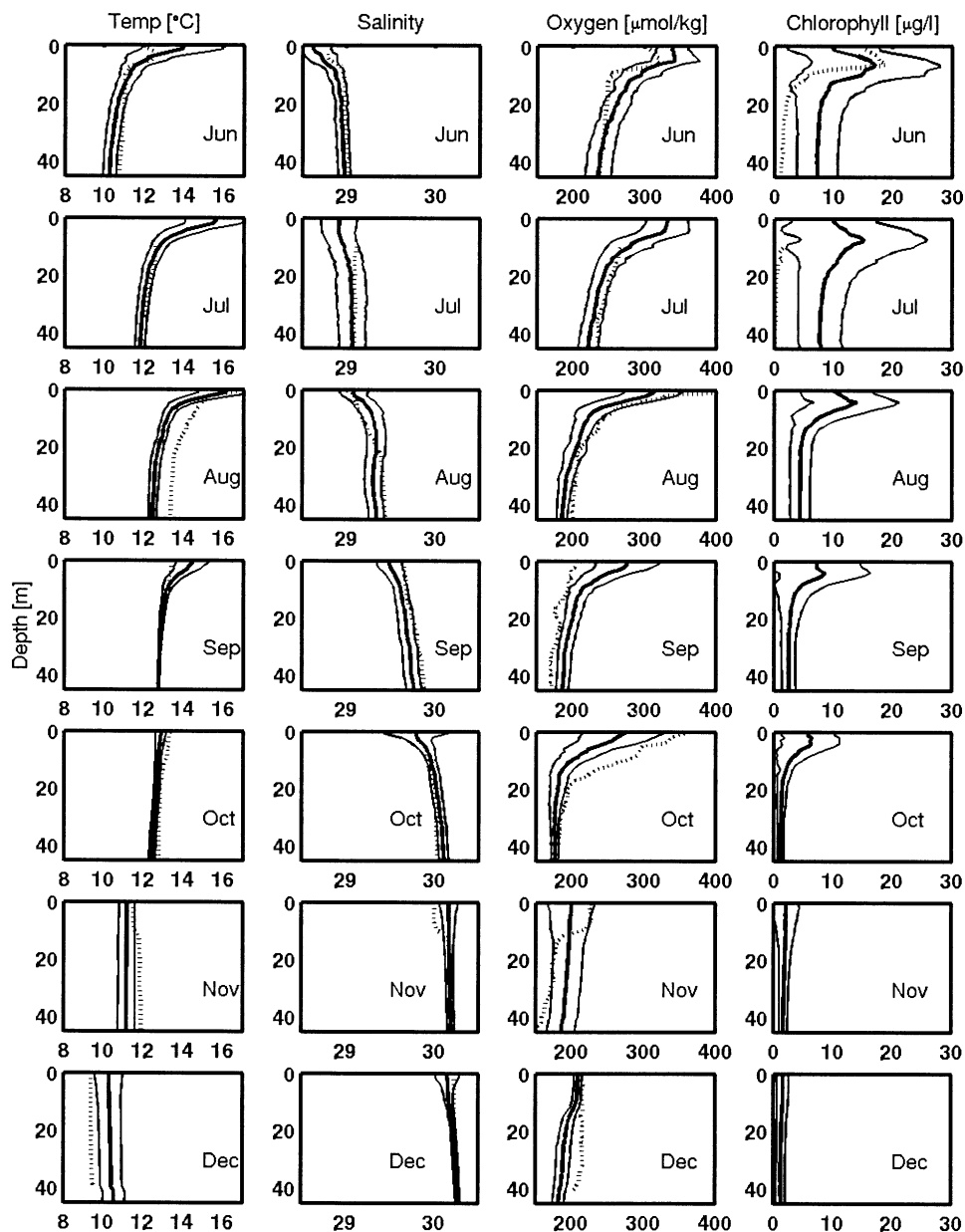FIG. 7. Monthly averages and std devs in Jun–Dec 2000 temperature (°C), salinity, density (σ_t), oxygen (μmol), and chlorophyll fluorometry (μg L)—vs depth (m) from Carr Inlet.

stratification and mixing and biological response to primary production and respiration. At depth, we observed the generation and strengthening of undersaturated oxygen conditions throughout the summer and early fall. While the onset of intense mixing in the fall destroyed stratification, low oxygen conditions persisted throughout November and December.

A data synthesis expressing the scope of physical and biological variability as monthly averages and depth-specific standard deviations is shown in Fig. 8. Temperature increased to a surface high in July and a maximum heat inventory over the water column in August.

Temperature stratification decreased through September, becoming well mixed in October and cooled through November and December. Salinity monotonically increased with depth and time from June through December. The highest values of oxygen were in surface waters in June and decreased over the water column until becoming well mixed in November. Chlorophyll fluorescence also exhibited its highest values in June, but differed from oxygen in episodic subsurface maxima, presumably a consequence of nutrient or light limitation of photosynthesis at the surface and light limitation at depth.
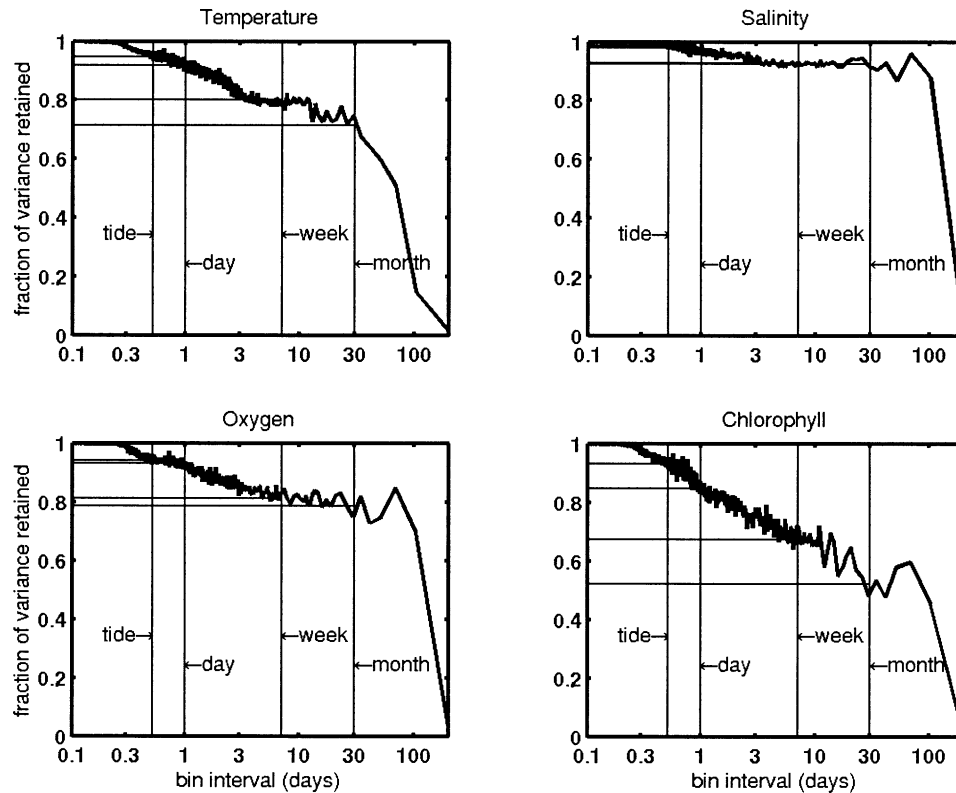
FIG. 8. Fractional variance of bin-averaged temperature, salinity, oxygen, and chlorophyll fluorometry data in the upper 10 m vs the bin size. Timescales of the semidiurnal tide, a day, a week, and a month are shown for reference and the corresponding variance (%) listed in Table 2.

To examine the timescales of physical and biological variability in Carr Inlet surface waters (upper 10 m), we analyzed the variance of binned data relative to the variance of the unbinned data over a spectrum of binning time intervals. We first averaged data in the upper 10 m and determined the overall variance, treating each profile as its own bin (i.e., bin interval ≤ profiling interval). We then increased the bin interval to include the average of multiple profiling intervals and recalculated the variance. The result of performing this operation hundreds of times for different bin intervals is shown in Fig. 8 in terms of the ratio of the variance after binning to the total variance versus the bin interval. In this way, the variance in the data was determined as a function of timescale, or bin interval. Timescales of

the semidiurnal tide, a day, a week, and a month are shown for reference in Fig. 8 and Table 2. In all four parameters, over half of the variability occurs on timescales greater than a month. This indicates that seasonal forcing is the primary reason for variability in Carr inlet. The tidal component does not appear to be strong in any of the parameters; chlorophyll shows the greatest variance with 7%. Temperature has significant variance on the day-to-week timescale (12%), presumably due to heating during episodes of clear weather. Though salinity is almost completely forced by the seasonal component (92%), it also has significant variance on the day-to-week timescale (5%), due to episodes of freshwater input during rain. The variability in oxygen concentration on the day-to-week scale may be due to gas exchange induced by changes in saturation, wind events, and biological production. Variance in chlorophyll is distributed among timescales, presumably due to a combination of variability in light limitation, nutrient limitation, ecosystem structure, and physical patchiness.

TABLE 2. Component of variance (%) in tidal, day, week, and month timescales for temperature, salinity, oxygen and chlorophyll fluorometry from the ORCA dataset in the 0–10-m depth interval corresponding to Fig. 9.

Timescale	$T(\%)$	$S(\%)$	$O_2(\%)$	Chl (%)
<Tide	5	1	6	7
Tide–day	3	1	1	8
Day–week	12	5	12	18
Week–month	9	1	3	15
>Month	71	92	79	52

4. Discussion of ORCA development

In the development of ORCA, we have faced many design decisions, the most important of which are presented in Table 3. There were compromises between

TABLE 3. Major design decisions in the development of ORCA (including other options considered), their advantages, and disadvantages.

Design decision (other options)	Advantages	Disadvantages
Winch profiling (variable buoyancy, wind-driven, wave-driven, ROV)	Flexibility in size and weight of sensor package; ability to profile at fixed speed and accurately maintain a discrete depth; technologically simple	Extremly large power consumption, limiting the maximum depth of profiling
Surface buoy (bottom-mounted system)	Easily accessible; reduces pressurization and power restrictions	Prone to wind and wave strain, animal inhabitation, collision, fishing nets and lines, and vandalism
Atlas toroidal float (solid float)	Large surface expression for visibility and stable working area; allows profiling through center for security; proven robust to ocean conditions	Size and weight make it extremely difficult for a small boat to deploy; fiberglass can crack upon collison
Self-level-winding (electrical and mechanical level wind)	Technologically simple and robust	Limits the width of the drum to 1/6th of the fare lead. As our drum width (15 cm) is large for our face lead (60 cm), we experience nonlevel winding
Short fare lead (long, exposed fare lead, direct — no pulley)	Allows winch and cable to be enclosed in a small housing — protected from weather, vandals and curious people, while allowing access to package through toroid	Limits the width of drum for self-level-winding
Hydrowire (acoustic modem)	Allows fast communication with surface and power supply to sensors	Requires slip rings and large diameter cable; limited lifetime of 1 yr
Solar panel recharge (wind power, large battery reservoir)	Affords predictable power to the system indefinitely as long as demands remain within the recharge capability	Severely limits power in winter; forces ORCA to be oriented with solar panels southward; provides extra windage
Three-point mooring (one- and two-point mooring)	Allows us to fix ORCA's position and orientation to the sun; adds stability to toroid; prevents the anchor lines from interfering with the hydrowire	Extremely difficult to deploy
TT8-based custom controller (commercial system)	Provides extremely flexible hardware and software control for multiple serial communications; low power consumption	Custom hardware is expensive. Without the benefit of documentation or base code to emulate, programming is time-consuming
Persistor memory (TT8 memory)	Affords large, permanent data storage capacity with easy user interface	
Cellular communications (radio)	Allows us to retrieve data, change sampling configurations and computer software remotely with power consumption tranmitting over long distances	Unreliable connection forces multiple uplinks to ensure data transfer; potentially expensive
UNIX base-station (Windows PC base-station)	Allows autonomous retrieval of data (both out-calling and in-calling), data reduction and Internet posting	Further investment of time and resources in system configuration

adapting commercially available components and contracting ocean engineers to design and manufacture our own. Where possible, we attempted to utilize the experience of other oceanographers rather than create new components by subcontracting engineers. In most cases, we chose the option providing the greatest flexibility. The primary challenge was in choosing a method of profiling. The surface design based on the ATLAS toroidal float allowed relatively easy automatic communications and maintenance. The surface winch and hydrowire design was capable of profiling a wide range of sensor configurations with different weight, size, and power and communications requirements. The self-level wind system provided robust winding with minimal engineering and mechanical problems. The combination of narrow drum and short-fare lead afforded us the security of keeping the system in a single housing above water while still providing direct access to the sensor package through the toroid. The TT8-based processor with a Persistor memory card allowed us to provide communications and power control to multiple serial and analog instruments. The cellular modem connection to the Unix host computer afforded us moderate speed (9600 baud) communications and autonomous data download.

Development of ORCA continued well after its deployment on 26 May 2000. This process was feasible because of the close proximity of ORCA to the University of Washington, and accessibility by a day-trip in a small boat. The system experienced problems related to software crashes, battery drain, corrosion, and mechanical failure that were diagnosed and corrected during these calibration day-trips. ORCA software changes were facilitated by the ability to transfer new programs autonomously using the cellular system. The first ORCA failure was tripping its winch-direction error

routines. Under even light seas, we observed occasional slipping during the ORCA upcast as the hydrowire failed to level-wind properly near the edges of the drum and would abruptly snap back toward the center, allowing the sensor package to fall slightly. On a single occasion (20 December), we observed a failure in the winch system as the hydrowire fouled on the winch drum. The other most troublesome hardware failure relates to power consumption. Over the first 2 months, we observed a power drain in the system as the solar panels, which faced the sun at angles, did not deliver power to the batteries. We discovered that the solar panels (each supplying 16 V when charging) required a similar angle to the sun to achieve the necessary voltage (>28 V) to charge the batteries. The solar panels were moved from their original positions at angles to each other into a stacked configuration at the same angle, due south $20°$ from vertical, to maximize energy collection efficiency.

ORCA has experienced three problems relating to data quality. A frequent observation at the beginning of the record was a disparity in the profiles obtained during the upcast and downcast. As the inlet for the sensors is at the bottom of the sensor package, we suspected that mixing of waters by the sensor package during the upcast caused smearing and delaying of the signal. This was addressed by changing the direction of the discrete stops from the downcast to the upcast and lengthening the period of the stops from 10 to 20 s. Another data quality issue arose in the occasional observation of intense spikiness in salinity as the sensor package passed through zones of high temperature stratification. This condition was relieved by addition of a Seabird temperature–conductivity duct (TC duct) to the Seacat-19 to route the temperature and conductivity probes into a single flow path. A final issue relating to data quality was a steadily diminishing transmissometer signal over time due to sedimentation on one of the lenses. This was rectified by reorientation of the transmissometer to have the lenses in a vertical (rather than horizontal) position with the inlet at the top and the outlet at the bottom. In general, biofouling of sensors was not observed over the deployment. This is a direct consequence of the situation of the sensor package beneath the euphotic zone and the use of a tributyl tin collar at the inlet and outlet of the water flow path to the instruments.

Currently, we are working to add intelligence on the sensor package to drive additional sensors such as an autonomous nitrate analyzer, a Wetlabs AC-9 spectral optics sensor, Pro-Oceanus total gas and nitrogen gas tension devices, and a photosynthetically active radiation sensor. We are also adding a meteorological station to the surface electronics to monitor wind, temperature, humidity, and solar radiation. When completed, ORCA will provide the conventional suite of ocean observations necessary for biogeochemical synthesis and modeling allowing us to monitor changes to water quality in South Puget Sound.

We still face challenges and future decisions. While the large surface expression of ORCA has many advantages, it results in a system extremely exposed to weather and vandalism. Though ORCA is currently limited to sampling the upper 60 m of the water column, it could be modified to extend the range to 120 m or more using larger flanges on the winch drum, a larger housing to accommodate this larger drum, and a longer cable. However, our choice of a winch-driven profiler has stringent power limitations as the power drain is directly proportional to the depth and frequency of profiling. A buoyancy-driven or other weightless profiler would alleviate the power expenditure associated with moving significant masses through the water column (currently 20 kg). While we experienced no failure in the winch during the two years of testing and deployment, cable lifetimes have been limited to about 6 months to a year. Finally, ORCA's three-point mooring configuration, while suitable for near-shore work, would be exceedingly difficult to deploy in the deep ocean.

This research has demonstrated the utility of the Oceanic Remote Chemical/Optical Analyzer as a high-resolution profiler for water quality and biogeochemical monitoring. ORCA has the capacity to autonomously profile the upper 60 m at 0.2-m resolution every 6 h. We have found these initial results extremely encouraging. As the dataset develops, we will continue our analysis with the goal of assessing the competition between incoming circulation, solar radiation, ecosystem dynamics, and possibly human influence in impacting Puget Sound biogeochemistry.

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