Moorings and Drifters for Real-Time Interdisciplinary Oceanography

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ABSTRACT

A telemetering electronics/control unit (OASIS) has been developed for use on moorings and free-floating drifters. The OASIS controllers are part of a long-term ''coastal ocean observatory,'' consisting of an infrastructure of ships, submersibles, an array of remote sensing platforms (moorings, drifters), communication links between sensors and laboratory, and data management facilities. The OASIS controller coordinates retrieval of data from a varying array of up to 28 oceanographic sensors, which may output digital, analog, or frequency data. The controller provides scheduling, sensor control software, data logging, preliminary data processing, and two-way telemetry between remote platform and ship or shore station. Telemetry allows real-time access to data and permits users to alter control parameters as necessary.

Two OASIS moorings have been successfully deployed off the central California coast since 1992. Real-time access and two-way telemetry has allowed the moorings to become testbeds for the deployment of new sensors and widely used observational and planning tools. Over longer timescales the moorings will be an important tool for tracking environmental variability. OASIS drifters have been tested in 11 deployments off California and 3 deployments in the equatorial Pacific. This paper describes the OASIS controller, its deployment on moorings and drifters, and presents oceanographic data that demonstrate the types of information obtained both from central California and the equatorial Pacific.

1. Introduction

Physical oceanographers and meteorologists have long recognized the need for continuous observations in order to characterize and understand climate and ocean variability (Enfield and Allen 1980; Hayes et al. 1991). The need to measure biological processes in the ocean at the appropriate temporal scale was recognized several decades ago (e.g., Harris 1980), but until the last few years it had not been realized (e.g., Dickey 1991). Development of in situ fluorometers, spectroradiometers, and transmissometers led to their deployment on moored (Dickey et al. 1991; Smith et al. 1991) and drifting (Abbott et al. 1990) systems, and a new era of biological oceanography had emerged. Still, biological and chemical oceanographers continue to be limited by the lack of additional instrumentation. In particular, there is a need for instrumentation that can directly measure or sample the biological properties (i.e., chlorophyll vs fluorescence) and instrumentation that can measure chemical constituents that affect the biological productivity. This situation is improving—instrumentation designed to take continuous biological and chemical measurements is under constant development and increasingly available (Kolber and Falkowski 1992; Jannasch et al. 1994; DeGrandpre et al. 1995; Friederich et al. 1995). The emergence of new instrumentation has generated the need for platforms and systems that could easily assimilate hardware and data output as well as provide real-time, two-way communication between instrumentation and the user. Two-way communication has become increasingly important for testing and debugging as well as monitoring data integrity (Frye et al. 1991).

At the Monterey Bay Aquarium Research Institute (MBARI) there was a need for a long-term set of platforms and systems that could serve a dual purpose: 1) provide a platform for the deployment and testing of unattended sensors and 2) make continuous physical, chemical, and biological observations in an eastern boundary coastal upwelling environment so as to describe their time-varying and covarying aspects. A survey of data acquisition systems for moorings in 1990 showed that the available systems were highly specific [e.g., the TOGA-TAO array described in Milburn and McClain (1990) and the MVMS described in Dickey (1991)] and could not be easily expanded. In addition, if the systems were capable of remote communication capabilities, it was typically of one-way communication via ARGOS. The lack of a generic data control and telemetry system prompted development of an electronics/data controller called OASIS (Ocean Acquisition

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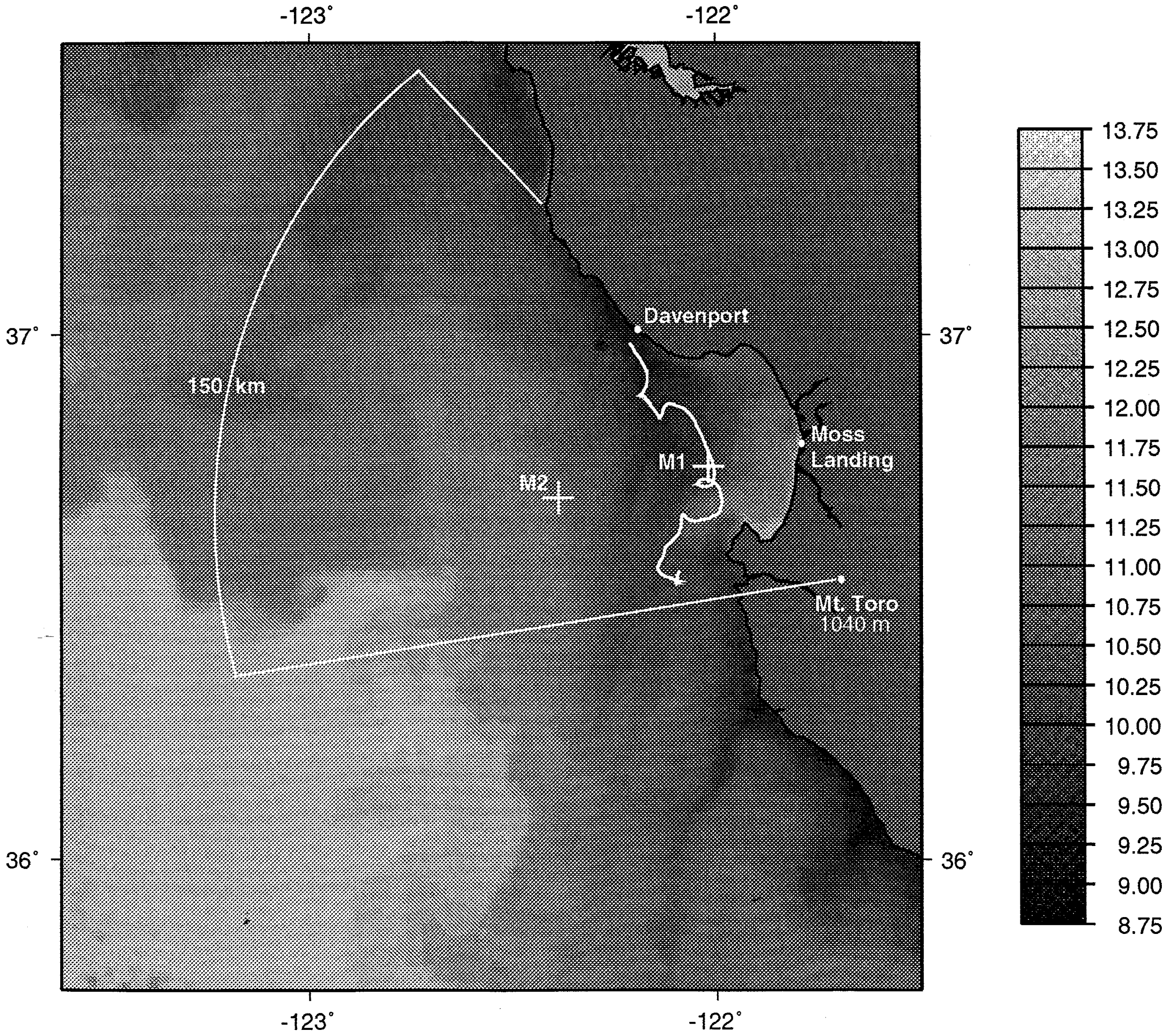

FIG. 1. An AVHRR image from 21 April 1995 with locations on Mt. Toro (packet radio repeater site), the M1 and M2 moorings, packet radio communications range, and an OASIS drifter track, as detailed in the text. MBARI's laboratories are located at Moss Landing. The AVHRR image shows a well-developed upwelling system, with an upwelling plume of cold water originating near Davenport and tending southward across the mouth of Monterey Bay. The drifter was deployed on 19 April at the beginning of the upwelling event and was advected downstream with the upwelling plume until recovery on 24 April after the drifter crossed or became entrained in a front between warm bay water and colder plume water.

System for Interdisciplinary Science). OASIS controllers have been deployed since 1992 on two moorings in and offshore of Monterey Bay, California (Fig. 1; M1 and M2 moorings), where they coordinate data flow from a variable and expandable array of sensors and provide two-way telemetry, via packet radio, between controller and ship or shore station. A parallel short-term experiment in two-way communication, using cellular phone technology, occurred at the same time as our initial deployment (Dickey et al. 1993). A novel aspect of the OASIS controllers is the two-way telemetry that allows users to communicate directly with their instrument or the controller itself to debug or change sampling parameters. The software architecture allows for new code to be uploaded from the base station.

The OASIS controllers are part of a "coastal ocean observatory," which consists of an infrastructure of ships, submersibles, an array of remote sensing platforms (moorings, drifters), communication links between sensors and laboratory, and data management facilities. In this paper the OASIS controller and its capabilities are described. We describe its deployment on moorings and drifters and present examples of oceanographic data that we have obtained with the controllers in central California during spring 1995, and the equatorial Pacific during an iron-fertilization experiment.

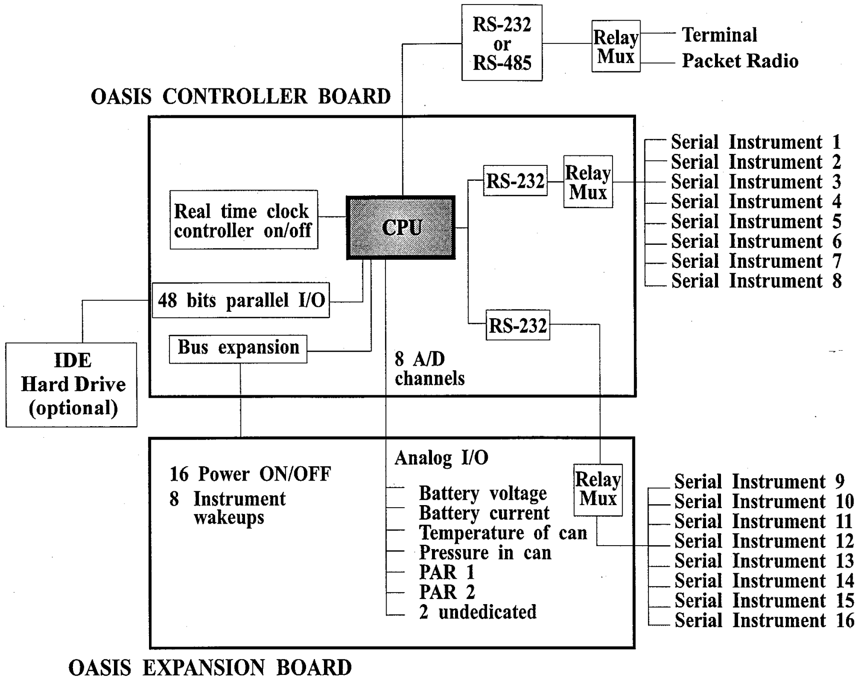

FIG. 2. Schematic of the layout of the OASIS "mother" and "daughter" expansion boards, along with sensors served by RS232 or A/D channels on the M1 mooring.

2. Materials and methods

a. The OASIS controller

OASIS controllers coordinate data flow and were designed for flexibility, reliability, and low power use. They acquire data from a maximum of 28 sensors, store it temporarily, then upload it via packet radio to a ship or shore station. Controller hardware is on a "motherboard" and a "daughter" expansion board (Fig. 2), and is centered on the Intel 87C196 chip (CPU operating range: 3.5–16 MHz). Three UARTs (universal asynchronous receiver–transmitters) pass serial input–output—two UARTs external to the CPU with 16 dual-pole relays serve up to 16 sensors, and a UART on the CPU serves either a terminal or the packet radio. On the daughterboard analog-to-digital ports receive voltage input from another 8 sensors, and 48 bits of parallel I/O logic provides on–off switching and sensor wakeups. Analog conditioning and power switching (eight 5-A power field-effect transistors controlled by logic bits) are provided on the daughterboard. Four frequency counters, four frequency generators, three pulse-width modulators, and buss expansion are present but not currently used on the motherboard. Controller memory consists of 1) permanent program code in a socketed 32-kbyte EPROM, 2) user-modifiable program elements in 24-kbyte CMOS RAM, and 3) temporary data storage in 1-Mbyte RAM. Twenty-four bits of the parallel I/O have been used to implement a general-purpose ATA-type interface to a hard disk drive for long-term data archival. The first drive used was a 40-Mbyte Kittyhawk II—a very small, low power, shock resistant drive made by Hewlett Packard—but this could easily be replaced, and has been, by IDE-type disk drives, allowing storage of multiple gigabytes.[1]

Controller software is written in C and occupies 25 kbyte of memory; it provides instructions for the sampling cycle. For each sampling cycle, a multitasking scheduler activates the controller and starts a series of drivers that interrogate individual sensors. Because communication protocols and output of the sensors vary, a different driver is used for each sensor (see section 2b). Controller software also allows remote users to reset or change sensor sampling parameters, either directly at the instrument level or in the controller, when necessary, via packet radio (see below). A final driver instructs the controller's packet radio to listen on schedule for a remote connection as part of the data upload process. Once sampling or upload is completed, the scheduler shuts the controller down until the next scheduled task. Software architecture allows for upload of patches or new code via the packet radio. The duplex capability has been extensively used.

Data upload is initiated from ship or shore station. For operations in and offshore of Monterey Bay, a request for upload is sent via packet radio from MBARI's laboratory to a repeater on Mount Toro (Fig. 1) and then

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[1] Schematics of the hardware are available at http://www.mbari.org/~markp/oasis.htm

to a third radio in an OASIS controller. The radios are 1200-baud AX.25 terminal node controllers (TNCs; PacComm) with R-net, 2-W telemetry modules (Motorola), operating at 460 MHz with an overall effective baud rate of 400. Effective range for communications is about 150 km (Fig. 1); shadowing by mountains restricts communications to the south. When a connection is established, all data since the previous request (e.g., remaining in the controller RAM) is encoded and sent to shore. Throughput has not been limiting; during drifter deployments as many as six OASIS controllers have operated simultaneously on one frequency, with the controllers on staggered hourly upload schedules. The most heavily sensored platform, the M1 mooring, currently uploads approximately 500 kbyte day^{-1} (Table 1). Ashore, the data are received by an HP700 workstation where they are decoded and broken into daily data files for each sensor with calibrations applied. All of this occurs automatically. Users may then view up-to-the-hour working plots of data from each sensor, either at MBARI or through the Internet.[2] Shipboard users also have access to uploads via packet radio, microwave link, or cellular telephone, depending on shipboard facilities.

In the equatorial Pacific, data uploads were transmitted directly from drifters to a shipboard workstation, with an effective range of 40 km. Workstation software applied calibrations, broke the data into sensor-specific data files, and produced plots of sensor output. Mooring deployments occurred in 1996 in the equatorial Pacific. As ARGOS satellite uplinks can throughput only 92 bytes daily, OASIS telemeters discrete noontime measurements (coinciding with SeaWiFS satellite passovers) and daily average values, as is done with the physical data on the TOGA-TAO array (Hayes et al. 1991). The remainder of the high-frequency (10 min) OASIS data is logged on hard disks aboard the moorings. In central California a classified satellite uplink with much greater rates of throughput is being tested.

OASIS controllers distribute power to sensors and are themselves powered by 12-V batteries. On moorings, a 90 A h lead-acid battery charged by 10-W solar panels provides power (eight panels on M1; three on M2), which has not been limiting. On drifters, D-cells (less than or equal to 20 cells) have proven sufficient to power sensors and radio, although frequency of data collection and upload have been reduced to extend battery life. The longest drifter deployment to date has been 23 days in the equatorial Pacific.

Controller, packet radio, and GPS receivers are housed in an 8.5″ × 24″ closed-end PVC tube, with an aluminum face plate machined to hold three connectors (six 4-pin pie connectors each; SeaCon/Brantner), Dorn bushings for antenna coax, and a check valve for tube pressurization.

b. Sensors and their interfaces

The sensors supported by OASIS controllers are diverse and include meteorological and physical, chemical, and biological oceanographic measurements (Table 1). Most sensors are commercially manufactured with the exception of CO_2 (Friederich et al. 1995) and nitrate (Jannasch et al. 1994) analyzers, which were developed at MBARI. Most sensors output serial data but some produce only analog voltages. Because each instrument has its own control and output requirements, each interface is different. Several instruments depend on OASIS for on–off switching, data logging, and some processing. Each instrument has its own set of characteristics and a detailed description of each is beyond the scope of this article. Detailed descriptions are available directly from the manufacturers.

- Ocean temperature, meteorological, and compass data are frequency measurements made by ATLAS (Milburn and McClain 1986), but similar capability exists on OASIS. ATLAS collects and stores each 10 min. For the TOGA-TAO array the 10-min data is averaged to daily values and only the daily values are kept. We have modified ATLAS software to allow access to the high-frequency data.
- Ocean current (ADCP) measurements are taken every 15 min. Once acquisition and processing are completed, the ADCP broadcasts data over its serial line, and OASIS captures the data.
- The nitrate analyzer (Jannasch et al. 1994) takes and stores a measurement every 5 min. OASIS wakes it up and retrieves fresh data every 30 min.
- Position data are obtained each 30 min; the GPS receiver is turned on and 3 min of data are collected and averaged by OASIS.
- The CTD takes and sends a measurement each 10 min upon OASIS command. CTD data include temperature and salinity and output from a fluorometer and transmissometer.
- OASIS turns on power to the spectroradiometers (PRRs) and listens—three PRRs are daisy-chained on one serial line with the transmit and receive cables shorted so all instruments can hear each other. The instruments transmit data sequentially and a number of scans are averaged by OASIS so that a synchronous measurement of radiance and irradiance is obtained. The spectroradiometers measure radiance and irradiance at wavelengths used by ocean color satellites (412, 443, 490, 510, 555, 665, 683).
- OASIS turns on the CO_2 analyzer hourly, then waits 3 min for an embedded thermoelectric cooler to reach equilibrium before requesting a sample. The CO_2 analyzer measures air- and ocean-equilibrated samples simultaneously and reports the difference between the

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[2] Internet address for data plots is http://www.mbari.org.

TABLE 1. Devices that have been deployed on moorings and drifters in Monterey Bay, California, together with some basic statistics.

Device	Manufacturer	Properties measured	Output type	Sample interval (min)	Max current (mA)	Consump day (mA h@12 V)	Output (byte day^{-1})	Platforms deployed on	Sensor locations
Current profiler (150-kHZ ADCP)	RDI	Acoustic backscatter	RS232	15	235	689	81 648	M1	Near surface (0–300, 8-m bins)
CTD w/ Fluorometer Transmissometer	Seabird, SeaTech, SeaTech	Salinity, temperature, chlorophyll fluorescence, optical clarity	RS232	10		186	3024	M1, M2, Drifters	Near surface
ATLAS	PMEL	Temperature (10 depths + air), relative air humidity, wind speed, and direction	RS232	10	25	103	6624	M1, M2	Air, 10 thermistor depths
GPS	Magellan	Latitude, longitude	RS232	30	330	792	1248	M1, M2, Drifters	Air
CO_2 analyzer (LI 6252)	LICOR/ MBARI	Carbon dioxide	RS232	60	1040	1200	720	M1, M2	Air, near surface
Spectroradiometers (OCR-100, PRR)	Biospherical Satlantic	Downwelling irradiance Upwelling radiance	RS232	10	165	160	48 096	M1, M2	Air, near surface
	Biospherical	Downwelling irradiance, upwelling radiance	RS232	10	50	50	21 600	M1	10 m, 20 m
Nitrate Osmo Analyzer	MBARI	Nitrate, temperature, salinity	RS232	5	50	56	9216	M1, M2, Drifters	Near surface, 20 m
PAR sensors (LI 192SA)	LICOR	Irradiance	Analog	10	0	0	2016	M1, M2	Air
Battery, temperature, pressure	MBARI	Voltage, temperature, pressure	Analog	30	0	0	864	M1, M2, Drifters	Inside OASIS can
OASIS	MBARI	Data acquisition, telemetry	RS232	n/a	25	75	—	M1, M2, Drifters	—
Packet radio	PacComm, Motorola	Telemetry	RS232	60	900	100 mbyte^{-1} of data	—	M1, M2, Drifters	—
Oxygen sensor	YSI	Oxygen, conductivity, temperature	RS232	15	35	56	32	Drifters	Near surface
Light-scattering sensor	SeaTech	Optical backscatter	Analog	15	15	4	1152	Drifters	Near surface
Fluorometer	WetLabs	Chlorophyll fluorescence	Analog	15	40	11	1152	Drifters	Near surface

two. Once every 4 h OASIS instructs the CO_2 sensor to open both cells to the atmosphere to monitor any drift (see Friederich et al. 1995 for more details).
- The irradiance sensors (PAR) produce current, so at 10-min intervals OASIS converts their current output to voltage and digitizes the voltage.
- Analog data from a light-scattering sensor (LSS) and fluorometer were digitized directly by OASIS during some drifter deployments.

c. *Mooring and drifter hardware*

The M1 mooring is most heavily instrumented as it is closest to shore and serves as the primary test site for new sensors; with some exceptions (Table 1) the M2 mooring and drifters are equipped with a subset of the M1 sensor suite. The M1 mooring (Fig. 3) is a PROTEUS design (NOAA/PMEL; McPhaden et al. 1991) modified to accommodate OASIS, solar panels, an elevator assembly for mounting near-surface sensors, and cages for additional sensors at 10- and 20-m depth. The M2 mooring (not shown in figure) is an ATLAS design (also NOAA/PMEL; Milburn and McClain 1986) similarly modified except that it has a lighter elevator, which is not designed to support an ADCP. The elevators allow about monthly service of near-surface sensors, which are subject to substantial biofouling. Optical windows are particularly affected by fouling, especially by barnacles of the genus *Lepas.* Antifouling guards with either copper or tin compounds are used on the bio-optical instrumentation, as well as the conductivity cell; however, in this very productive environment, the most effective fouling control has proven to be frequent (i.e., monthly) swapouts. Stainless steel cages are deployed at 10 and 20 m beneath each mooring for additional sensors (Table 1). The M1 and M2 moorings are anchored in 1000 and 1800 m of water, respectively. Both moorings are on ‘‘slack’’ tethers (M1, approximately 40% excess; M2, approximately 20% excess) as follows: mooring, chain, cable, sinking line, floating line, acoustic release, and railroad wheel anchor assembly.

OASIS drifters use a WOCE-type Holey-sock drogue (Niiler et al. 1995) designed to move with near-surface ocean currents. The water-following characteristics of these drogues have been previously described (Niiler et al. 1995). They consist of 1) a surface float with an OASIS controller, antennas, a radio beacon, and strobe light; 2) a near-surface mount for sensors and 3) a drogue designed to minimize the direct effect of wind on drifter movement (Fig. 4). Sensors for a recent set of drifter deployments measured water temperature, salinity, nitrate (all as part of the nitrate analyzer), fluorescence, and light scattering (Table 1). All OASIS controllers are equipped with GPS receivers, which in drifter applications are used to fix drifter position.

3. Results

a. *Coastal California*

Infrastructure developed as part of MBARI’s coastal ocean observatory was exploited in spring 1995 as part of a multidisciplinary experiment to measure transfer of properties across the air–sea interface in a coastal upwelling environment (CoOP ’95). The MBARI contribution focused on the role of biology in CO_2 fluxes to and from the surface ocean. Time series of winds and temperature structure from the MBARI moorings show conditions during the experiment, which was conducted from 18 April until 8 May (Fig. 5). Strong and persistent northwest winds (greater than 20 kt) blew with only minor interruptions beginning 14 April. By 19 April the 10°C isotherm had risen approximately 40 m to the surface, indicating a strong upwelling event had begun. This event ended 27 April when winds became southerly and surface temperatures rose.

Also on 19 April an OASIS drifter was deployed near Davenport, California, at the source of a persistent upwelling plume that typically flows into and offshore of Monterey Bay (Fig. 1; Rosenfeld et al. 1994). The goal of the drifter deployment was to track movement of freshly upwelled water in the plume and to document changes in properties as the upwelled water aged and moved. During its 5-day deployment the drifter moved southeasterly across the mouth of Monterey Bay, passing very close to the M1 mooring before turning southwesterly to move offshore of the Monterey Peninsula (Fig. 1). The mean rate of drifter movement was 20 cm s^{-1}, or about 17 km day^{-1}, with a maximum velocity of 63 cm s^{-1}. A series of drifter deployments (Fig. 6) have shown that during upwelling-favorable (northwesterly) winds, drifters move south or southeasterly past the M1 mooring in 1–3 days; under variable or southwesterly winds, drifters move onshore and northward. The drifter track in Fig. 1 is overlaid on an AVHRR SST image from 21 April. Although the AVHRR image is static, it reveals a fully developed upwelling system, with the coldest water north of Monterey Bay near Davenport, and a gradually warming plume almost due south. The drifter track follows this plume, excepting a deviation into warmer water just offshore of the Monterey Peninsula, suggesting that the drifter was advected with water upwelled near Davenport southward during this upwelling event. The sensors on the drifter support these observations (Fig. 7). Salinity and nitrate concentration were high, and fluorescence, an indicator of phytoplankton concentration, was low during the first few days of the deployment. During initial deployment of the drifter at the source of the upwelling plume we noticed that the water was chalky in color. The light-scattering sensor reflected these high particle concentrations in the first few days, and the water cleared as it advected away from the upwelling center. On 22 April the sensors tracked a large decrease in salinity and nitrate and an increase in particles and fluorescence as the drifter ap-

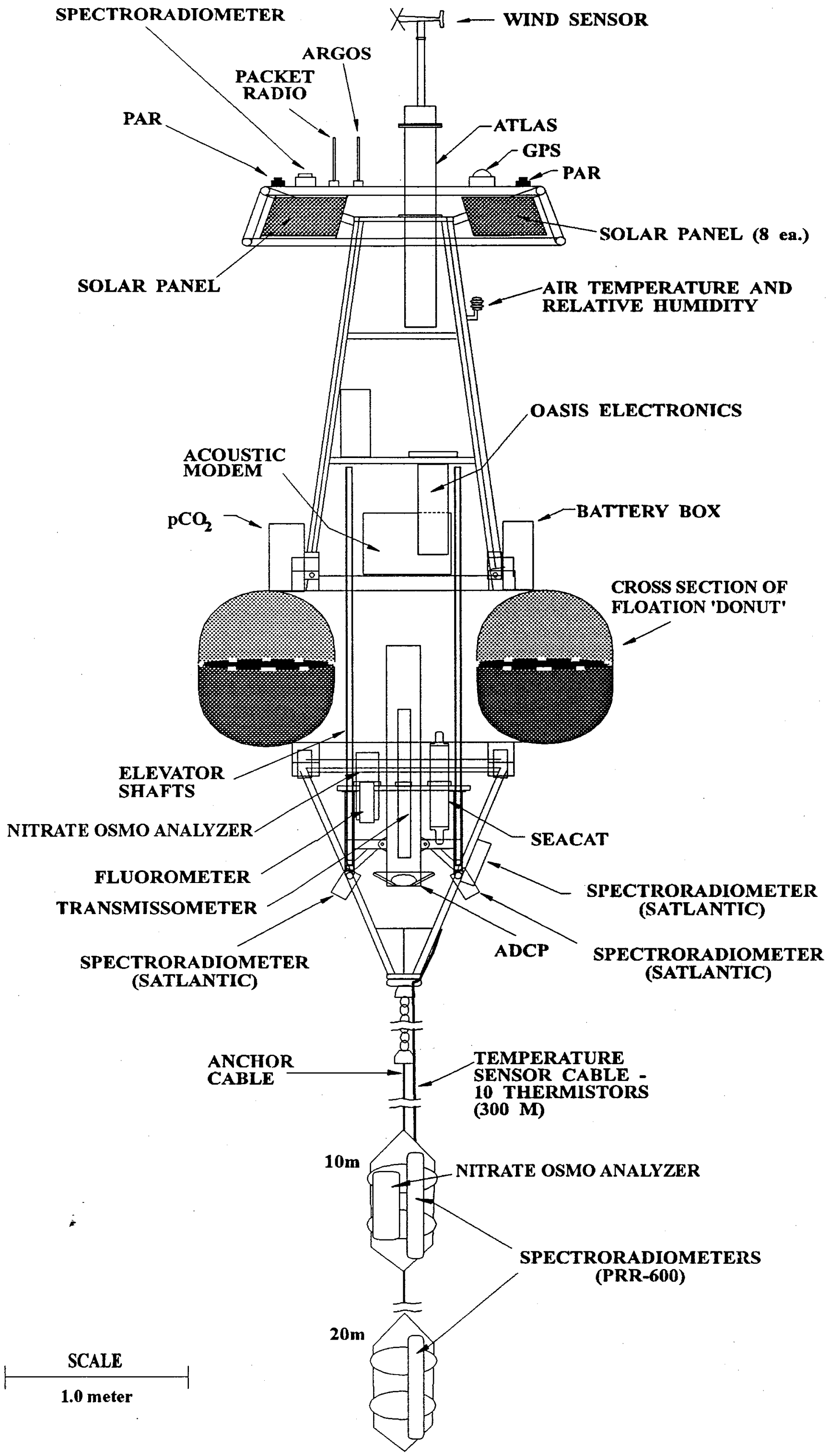

FIG. 3. Schematic of the M1 mooring, including basic sensor suite. An elevator assembly supports near-surface sensors at 1 m including ADCP and CTD; the elevator is raised approximately monthly through the "doughnut" hole in the float for instrument change-out and servicing. Two sensor-support cages are suspended at 10 and 20 m beneath the mooring; a thermistor chain to 300 m is not shown.

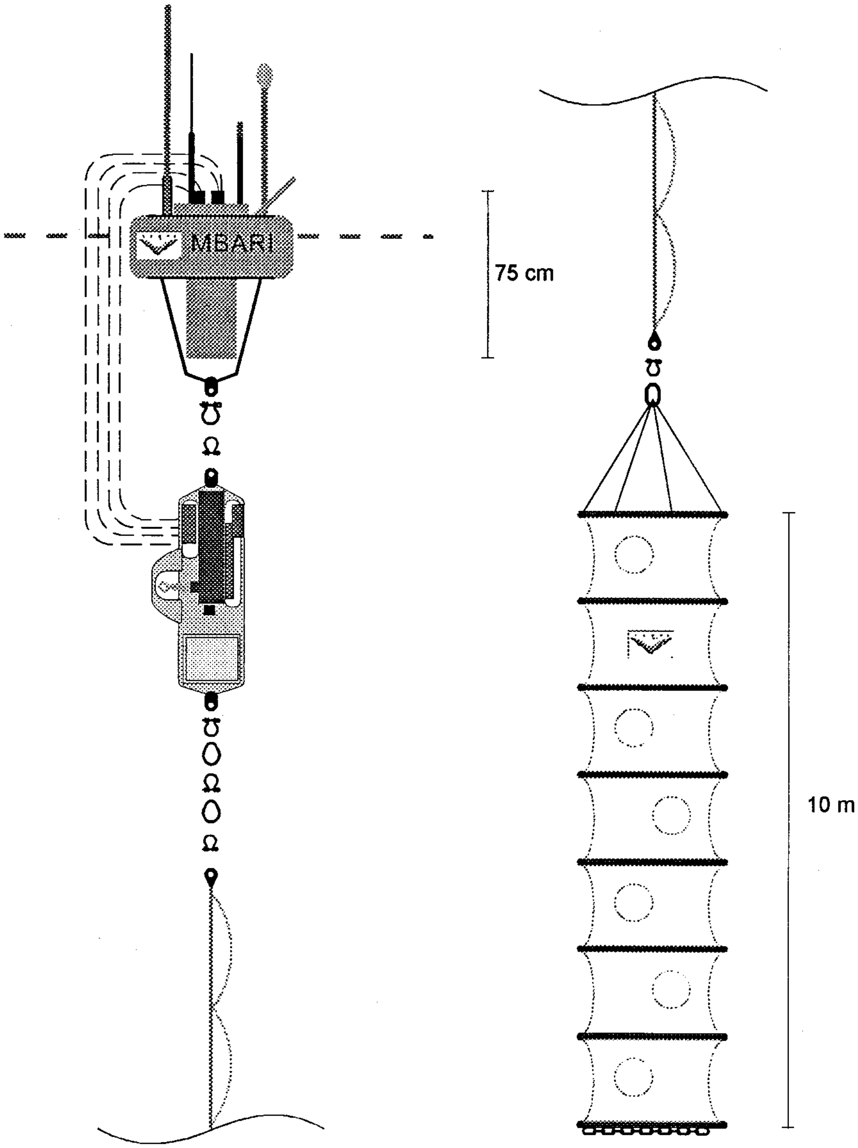

FIG. 4. Schematic of an OASIS drifter. The OASIS controller is supported in a doughnut-shaped flotation collar. GPS and packet radio antennas, a radio-pinger, strobe light, and lifting-eye are the above-surface components; a sensor rack at 1.5 m supported a nitrate sensor, LSS, and fluorometer during the deployment detailed in the text. Beneath the sensor rack a 5-m bungie and slack safety cord connect the drifter to a 10-m-long ''Holey sock'' or drogue, which reduces windage.

parently crossed or became entrained in a front in the warmer water just offshore of the Monterey Peninsula.

Time series of surface properties from the M1 mooring show conditions at this location before, during, and after the drifter deployment (Fig. 8). Gradual cooling from warmer winter conditions became dramatic at the M1 site on 18–19 April. Salinity also rose as the result of the upwelling of saltier waters from below and shows a sharp rise beginning on 18 April. During the preceding periods of weak upwelling, phytoplankton populations, as tracked by fluorescence (Fig. 8), were abundant. The strong upwelling that began on 18 April injected high levels of nitrate into the photic zone; the upwelling acted to dilute the phytoplankton populations and their concentration declined. Winds weakened slightly on 22 April (Fig. 5) allowing phytoplankton once again to increase at the M1 site (Fig. 8). This plant growth resulted in a steady decrease of recently upwelled nitrate and $p\mathrm{CO}_2$ at the M1 mooring from 24 to 28 April (Fig. 8). A strong wind reversal terminated the upwelling event on 27 April (Fig. 5). One effect of these wind reversals is onshore advection (Rosenfeld et al. 1994) of warmer, fresher, and lower nutrient and phytoplankton waters. These waters reached the M1 mooring on 29 April (Fig. 8).

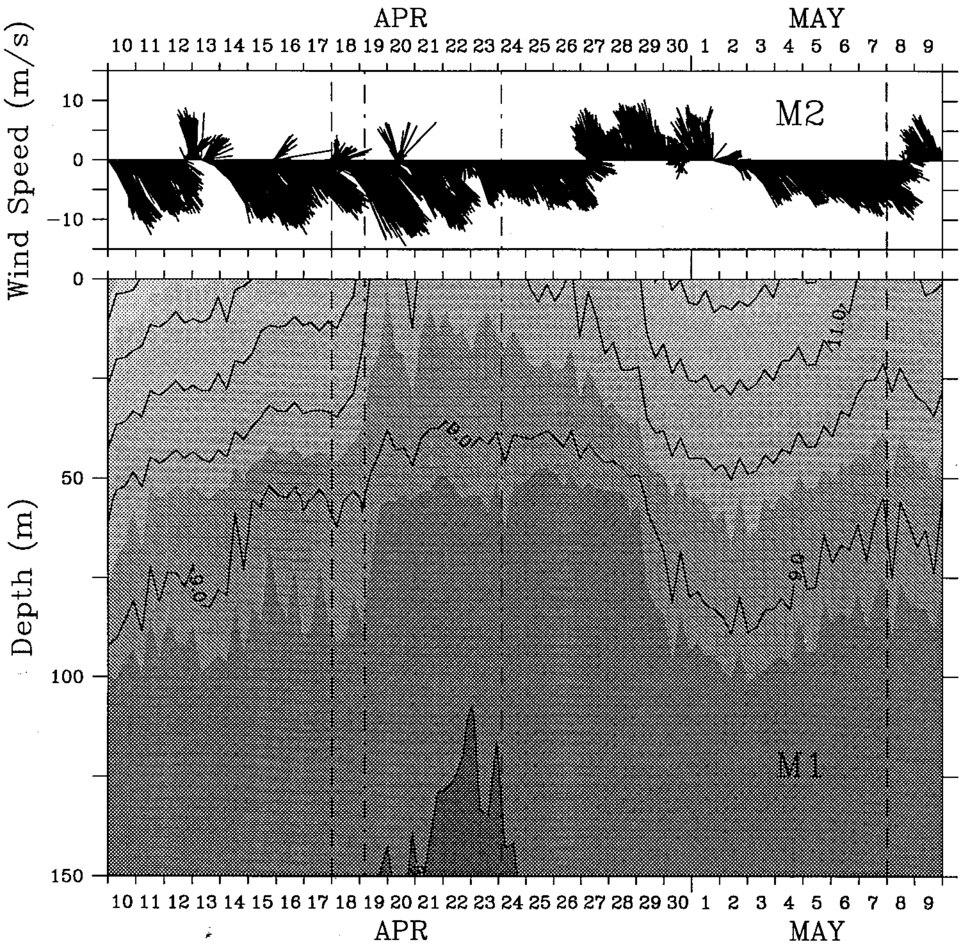

FIG. 5. A stick plot of winds at the M2 mooring and contoured temperature structure (thermistor chain data) from the M1 mooring, for 10 April through 10 May 1995. The M2 winds are plotted because they are less affected by nearshore diel wind fluctuations, and M1 temperature data were used because M1 was in the upwelling plume. The CoOP '95 cruise took place from 18 April to 8 May (dashed lines), and the OASIS drifter deployment detailed in the text took place from 19 to 24 April (dot–dash lines). Winds were upwelling favorable over most of the period, with strong northwest winds beginning 18 April initiating a strong upwelling event with 9°–10°C temperatures at the surface on 19 April. Surface temperatures at M1 lag those near Davenport by 1–3 days. The upwelling event concluded on 27 April when winds became southerly and surface temperatures rose.

The drifter, mooring, and satellite data suggest that the freshly upwelled water across the mouth of Monterey Bay (Fig. 1) is sandwiched between warmer and fresher water both inshore and offshore. The two water masses that bound the freshly upwelled water are distinct, however, in terms of their phytoplankton and nutrient characteristics. The inshore Bay water tends to have a higher phytoplankton biomass and nitrate can be completely consumed (Fig. 7). The waters offshore are more typical of California current waters. Blooms form at the front between the California current waters and those that have been freshly upwelled, but further offshore phytoplankton populations are low and there is often residual nitrate. On 19–20 April the ship crossed the upwelling plume and a set of underway surface measurements serves to illustrate the spatial distribution of properties (Fig. 9). Waters farther from shore had lower salinity, low fluorescence, and concentrations of nitrate of around 5 μmol L^{-1}. A relatively smooth gradient of decreasing temperature and increasing salinity and nitrate separated the offshore waters from those that had been freshly upwelled. An area of relatively high phytoplankton straddled the beginning of the smooth gradient but concentrations were low in the cooler and saltier waters. Gradients on the nearshore side of the upwelled water were much sharper. Phytoplankton populations increased rapidly and are much higher inshore. Nitrate begins to drop rapidly but, unfortunately, the section terminated several miles offshore of the Monterey Peninsula and did not completely penetrate into the bay waters. Had this been the case, bay waters of very low nitrate, such as those sampled by the drifter, should have

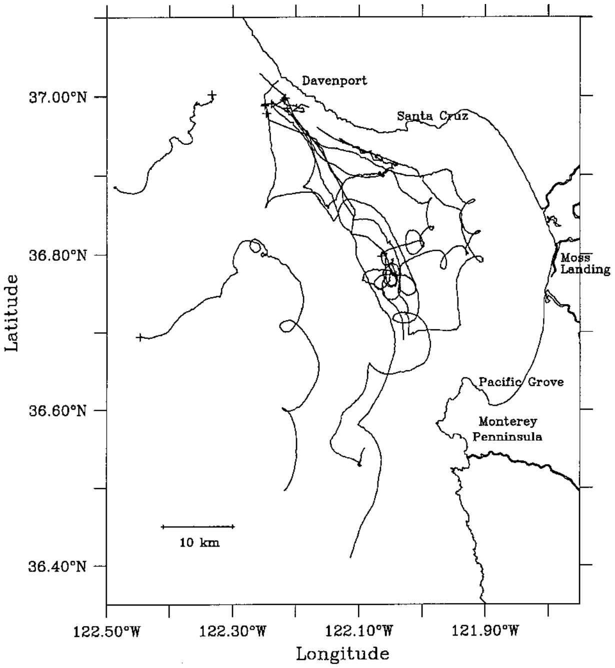

FIG. 6. Eleven OASIS drifter tracks in the Monterey Bay region, central California. Drifter deployment sites are marked with a "+". Most drifters were released near Davenport, the site of a persistent upwelling center (see Fig. 1). With upwelling-favorable (northwest) winds, drifters move south or southeasterly; under variable or southwesterly winds, drifters move onshore and northward.

been encountered. During this time of year Monterey Bay often contains upwelled water that has been retained in the bay for some days; relative to plume water it is warmer, can have somewhat reduced salinity, supports high chlorophyll concentrations, and is much lower in nutrients. Much of the historical richness of Monterey Bay as fishery grounds can probably be explained by plant production due to interaction between recently upwelled plume water and bloom water retained in the bay.

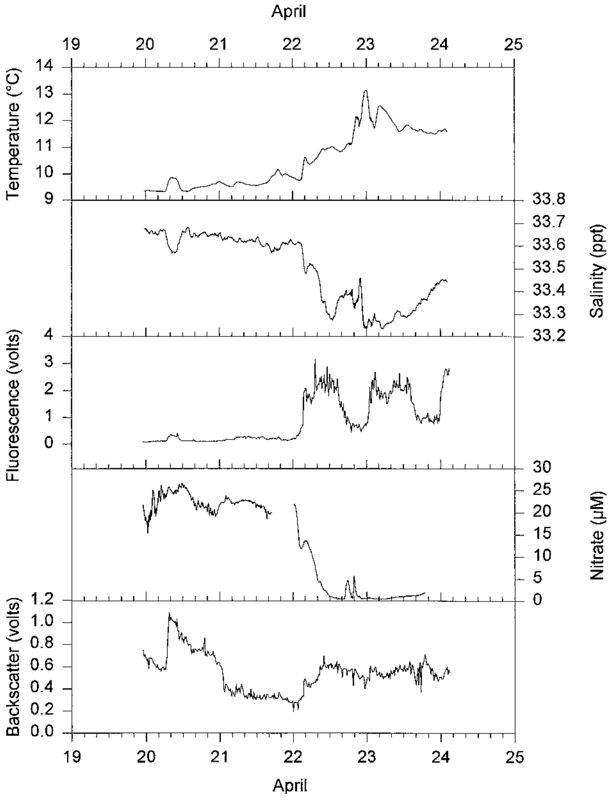

FIG. 7. Time series of sensor data from the drifter deployment detailed in the text. The drifter was deployed 19 April near Davenport at the source of the upwelling plume (see Fig. 1) and was recovered 5 days later (24 April) offshore of the Monterey Peninsula. Salinity was high for the first approximately 3 days of the deployment, as the drifter moved southward in the upwelling plume; after this salinity dropped as the drifter crossed or became entrained in a front between Monterey Bay water and the plume. Fluorescence (a measure of chlorophyll concentration) was uniformly low in plume water, but higher and with a typical diel cycle in the Monterey Bay water. Nitrate was high in plume water, but much lower in Monterey Bay water. Water clarity as measured by the light-scattering sensor was initially low in the upwelling source water (presumably due to a chalky material we have several times observed in this water) but increased down the length of the upwelling plume as the particles apparently settled out. Scattering was moderate in the Monterey Bay water due to the reflectance by phytoplankton cells.

b. *Equatorial Pacific*

In spring 1995, three drifters were deployed as part of IRONEX II—an experiment to determine if iron limits phytoplankton growth in the high nutrient–low chlorophyll waters of the equatorial divergence (Coale et al. 1996; Kudela and Chavez 1996). For 23 days and 800 km an OASIS drifter marked the center of an 8 km × 10 km patch of water fertilized with $FeSO_4$ in an attempt to stimulate phytoplankton growth (Fig. 10). The drifter's instrumentation (nitrate analyzer, fluorometer, and oxygen and light-scattering sensors) measured some changes that occurred after fertilization (Figs. 11, 12). After 6 days a substantial bloom of phytoplankton developed (Fig. 11). Comparison of fluorescence levels between the patch drifter and another drifter deployed outside the patch shows that only populations within the iron-fertilized patch responded (Fig. 12).

All drifters are subject to some "slippage" caused by wind on the surface drifter components and, to this extent, are affected by wind rather than current. Chlorophyll growth in the iron-fertilized patch provided an independent measure of patch position relative to the drifter and permitted evaluation of wind-induced slippage of the drifter from patch center. Chlorophyll fluorescence was mapped on day 6 of the experiment (Fig. 11), and comparison of the patch center position as estimated by fluorescence and the drifter indicates that slippage was less than 1% of the horizontal distance traveled to this point (e.g., Fig. 10). By day 6 the drifter

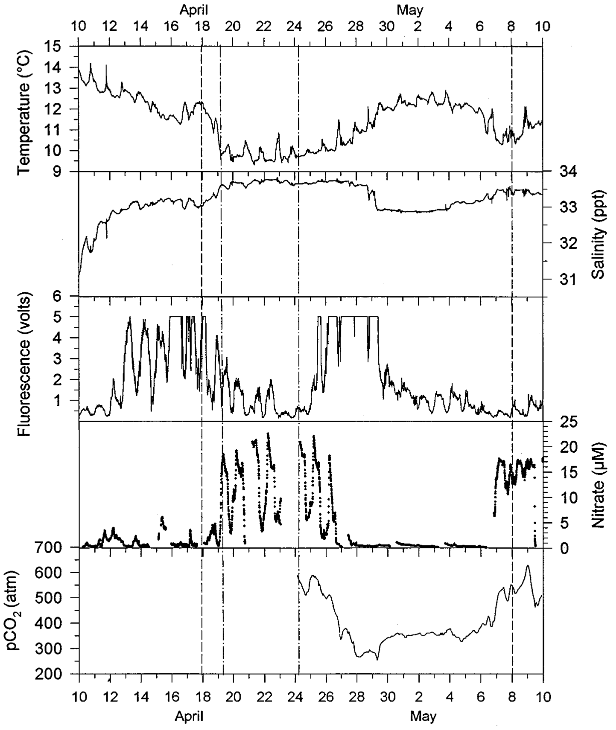

FIG. 8. Time series of near-surface sensor data from the M1 mooring for the cruise (dashed lines) and drifter deployment (dot–dashed lines) periods. CTD temperature and salinity show the expected inverse relationship, with the strong upwelling event commencing on 19 April and ending on 27 April. The drop in salinity at M1 lags the change in wind (Fig. 5) by approximately 2 days. Fluorescence (a measure of chlorophyll concentration) was moderate during the weak upwelling prior to 19 April, low at the beginning of the strong upwelling event, and high during the final several days of the strong event. We interpret this fluorescence peak as a phytoplankton bloom stimulated by nutrients provided by the strong upwelling event. This interpretation is corroborated by the nitrate and pCO$_2$ record, which shows high concentrations during the strong upwelling period but rapid drawdown in the high fluorescence water. We believe that the rapid nitrate drawdowns during the upwelling event are artifacts due to thermal cycling of the osmotic pumps. At temperature changes of greater than approximately 1°C h^{-1}, sample and reagents no longer mix in appropriate proportions, thus resulting in incomplete color formation within the analyzer.

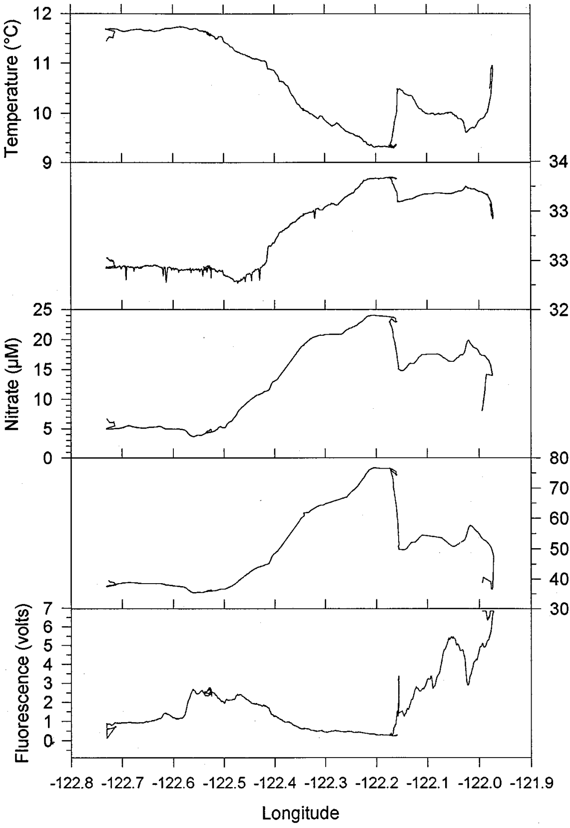

FIG. 9. Underway surface measurements across the upwelling plume. A smooth gradient was observed from the offshore warm, fresh, and relatively nitrate poor California Current waters to the cool, salty, and high nitrate freshly upwelled waters. Sharp gradients in most properties were found on the inshore side of the plume, as the ship passed into Monterey Bay water. Associated with this sharp gradient high concentrations of phytoplankton are observed.

had traveled over 300 km and was on the order of 2.5 km from the patch center.

Future work in the equatorial Pacific includes deployment of OASIS controllers on moorings of the TOGA-TAO array (McPhaden 1993) in fall 1997. The objectives are to 1) determine the relationships among physical forcing, primary production, nitrate supply, and the exchange of carbon dioxide between ocean and atmosphere; 2) determine, quantitatively, the biological and chemical responses to climatic and ocean variability; 3) determine the spatial, seasonal, and interannual variability in near-surface plant pigments, primary production, carbon dioxide, and nutrient distributions; and 4) obtain near real-time bio-optical measurements to groundtruth satellite measurements of ocean color. Preparation for these deployments has highlighted the need for higher bandwidth transmission of data from remote moored platforms.

4. Summary

Considerable effort at MBARI has been directed toward development of a coastal ocean observatory in the Monterey Bay region, which consists of an infrastructure of ships, submersibles, remote sensing platforms (moorings, drifters), communications between sensors and laboratory, and data management facilities. This observatory allows us to meld observations from different platforms on varying time and space scales relevant to our focus on phytoplankton production.

The OASIS controllers described in this paper are an important component of observatory infrastructure. They control and manage data flow from variable arrays of up to 28 sensors on remote platforms and provide two-way communications to and from the ship or shore stations. The telemetering capability allows automatic data upload in near-real time and modification of sensor control parameters as necessary. These interactive fea-

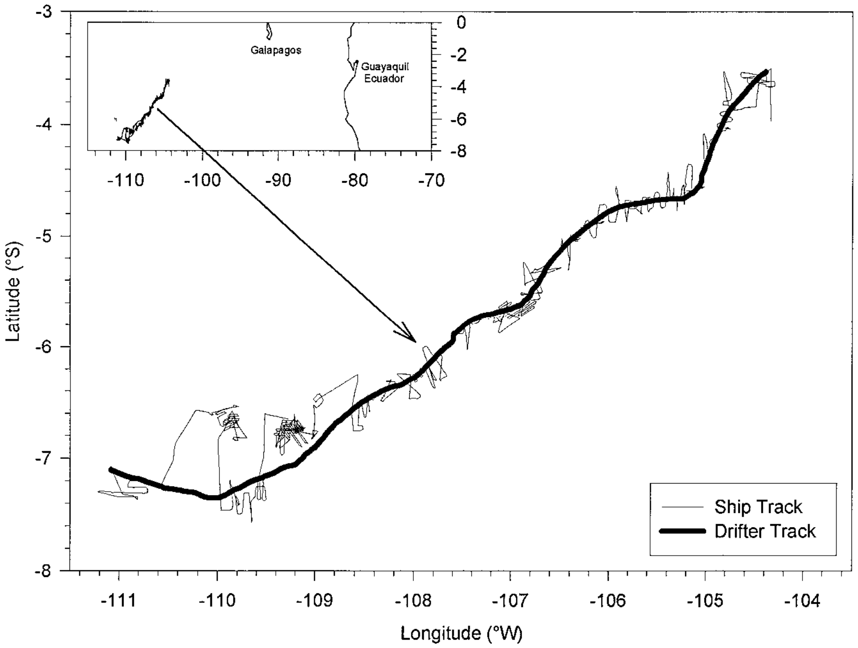

FIG. 10. Eulerian plot of the 23-day OASIS drifter track obtained during IRONEX II in the equatorial Pacific (inset); the drifter and patch moved southwesterly over the course of the experiment. The drifter marked the center of a patch of iron-enriched water, which was intensively sampled for evidence of phytoplankton release from iron limitation. The overlain ship track represents Lagrangian grid surveys of the patch performed around the drifter.

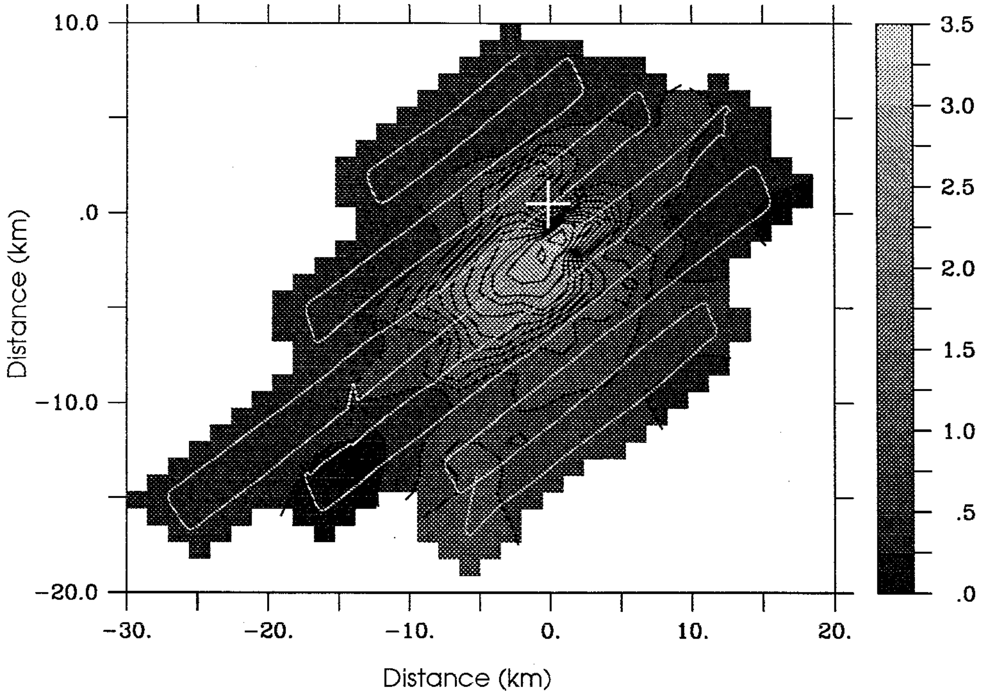

FIG. 11. Lagrangian plot of the iron-enriched patch of water in the equatorial Pacific during IRONEX II, at 5.6°S, 107°W (Fig. 10) 6 days after fertilization with iron. The OASIS drifter (+) marked the center of the patch, the white lines represent a ship track survey of the patch, and the contouring is chlorophyll.

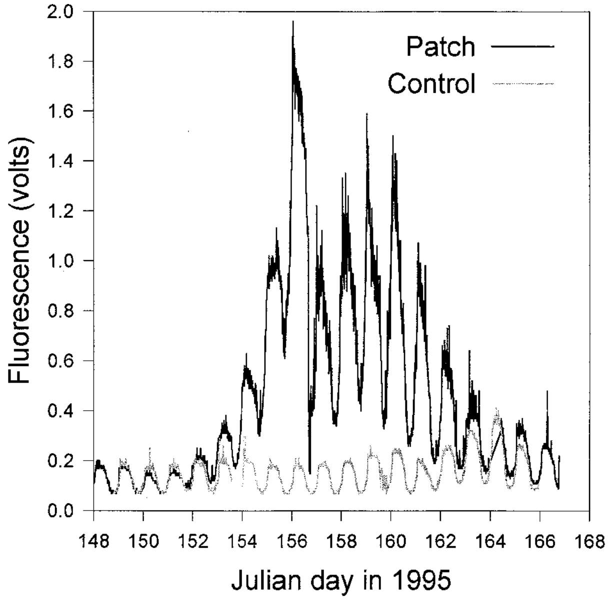

FIG. 12. Time series of fluorescence data from IRONEX II OASIS drifter deployments. A sensor on a drifter deployed outside the iron-enriched patch produced the ''control'' data (faint line), while a sensor on the drifter marking the center of the patch produced the ''patch'' data (dark line). This plot provides one of many lines of evidence that phytoplankton populations in the equatorial Pacific can be iron limited [see Kudela and Chavez (1996) for a complete description of the dataset]. The diurnal fluctuations in fluorescence are related to a relaxation of nonphotochemical quenching at night. An r^2 of 0.82 ($n = 84$) was found for fluorescence and extracted chlorophyll measurements.

tures have allowed moorings, in particular, to serve as testbeds for the deployment of new sensors. Real-time access has also allowed the remote platforms to become widely used observational and planning tools.

Two OASIS moorings have been deployed in and offshore of Monterey Bay since 1992. The nearshore M1 mooring lies in the path of a persistent upwelling plume and is sensitive to changes in the upwelling regime. The offshore M2 mooring lies at the eastern margin of the California Current and is much less affected by coastal upwelling. The relatively high frequency of data collection (10 min for most sensors) permits characterization of temporal variability on hourly to interannual scales (Chavez 1996). Should the moorings remain deployed for tens of years they will be valuable for tracking large-scale, long-time variability.

OASIS controllers have also proven useful on drifters and, in the Monterey Bay region, we have used drifters in concert with ship surveys to link the time-varying mooring data with spatial pattern. OASIS drifters have also been used in the equatorial Pacific to track a patch of iron-enriched ocean waters.

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REFERENCES

Abbott, R. M., K. H. Brink, C. R. Booth, D. Blasco, L. A. Codispoti, P. P. Niiler, and S. R. Ramp, 1990: Observations of phytoplankton and nutrients from a Lagrangian drifter off northern California. *J. Geophys. Res.,* **95,** 9393–9409.

Chavez, F. P., 1996: Forcing and biological impact of onset of the 1992 El Niño in central California. *Geophys. Res. Lett.,* **23,** 265–268.

Coale, K. H., and Coauthors, 1996: The IronEx-II mesoscale experiment produces massive phytoplankton bloom in the equatorial Pacific. *Nature,* **383,** 495–501.

DeGrandpre, M. D., T. R. Hammar, S. P. Smith, and F. L. Sayles, 1995: In situ measurements of seawater $p\mathrm{CO}_2$. *Limnol. Oceanogr.,* **40** (5), 969–975.

Dickey, T. D., 1991: The emergence of concurrent high-resolution physical and bio-optical measurements in the upper ocean and their applications. *Rev. Geophys.,* **29,** 383–413.

——, R. H. Douglass, D. Manov, D. Bogucki, P. C. Walker, and P. Petrelis, 1993: An experiment in two-way communication with a multivariable moored system in coastal waters. *J. Atmos. Oceanic Technol.,* **10,** 637–644.

Enfield, D. B., and J. S. Allen, 1980: On the structure and dynamics of monthly mean sea level anomalies along the Pacific coast of North and South America. *J. Phys. Oceanogr.,* **10,** 557–578.

Friederich, G. E., P. G. Brewer, R. Herlien, and F. P. Chavez, 1995: Measurement of sea surface partial pressure of CO_2 from a moored buoy. *Deep-Sea Res.,* **42,** 1175–1186.

Frye, D. E., W. B. Owens, and J. R. Valdes, 1991: Ocean data telemetry: New methods for real-time ocean observation. *Oceanus,* **34**, 46-52.

Harris, G. P., 1980: The relationship between chlorophyll *a* fluorescence, diffuse attenuation changes and photosynthesis in natural phytoplankton populations. *J. Plankton Res.,* **2,** 109–128.

Hayes, S. P., L. J. Mangum, J. Picaut, A. Sumi, and K. Takeuchi, 1991: TOGA-TAO: A moored array for real-time measurements in the tropical Pacific Ocean. *Bull. Amer. Meteor. Soc.,* **72,** 339–347

Jannasch, H. W., K. S. Johnson, and C. Sakamoto, 1994: Submersible, osmotically pumped analyzers for continuous determination of nitrate in situ. *Anal. Chem.,* **66,** 3352–3361.

Kolber, Z., and P. G. Falkowski, 1992: Fast repetition rate (FRR) fluorometer for making *in situ* measurements of primary productivity. *Proc. Ocean 92 Conf.,* New York, NY, IEEE, 637–641.

Kudela, R. M., and F. P. Chavez, 1996: Bio-optical properties in relation to an algal bloom caused by iron enrichment in the equatorial Pacific. *Geophys. Res. Lett.,* **23,** 3751–3754.

McPhaden, M. J., 1993: TOGA-TAO and the 1991–93 El Niño–Southern Oscillation event. *Oceanography,* **6,** 36–44,

——, H. B. Milburn, A. I. Nakamura, and A. J. Sheperd, 1991: PROTEUS—Profile telemetry of upper ocean currents. *Sea Technol.,* **32,** 10–19.

Milburn, H. B., and P. D. McClain, 1986: A low cost satellite data telemetry mooring developed for NOAA's climate research mission. *Proc. MCS '86 Marine Data Systems Int. Symp.,* New Orleans, LA, MCS, 393–396.

Niiler, P. P., A. S. Sybrandy, K. Bi, P.-M. Poulain, and D. Bitterman, 1995: Measurements of the water-following capability of Holeysock and TRISTAR drifters. *Deep-Sea Res.,* **42** 1951–1964.

Rosenfeld, L. K., F. B. Schwing, N. Garfield, and D. E. Tracy, 1994: Bifurcated flow from an upwelling center: A cold water source for Monterey Bay. *Cont. Shelf Res.,* **14,** 931–964.