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Instruments and methods

Initial results from the Bermuda Testbed Mooring program

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Abstract

The Bermuda Testbed Mooring (BTM) has been deployed since June 1994 and provides the oceanographic community with a deep-water platform for testing and intercomparing new instruments. The mooring is located about 80 km southeast of Bermuda. Surface instruments collect meteorological and spectral radiometric measurements from a buoy tower. Measurements at depth include: currents, temperature, conductivity, optical properties, and nitrate and trace element concentrations. Data have been sent to shore and to a nearby ship using a new inductive-link telemetry system. The high temporal resolution, long-term data collected from the mooring provide important information concerning episodic and periodic processes ranging in scale from minutes to years. For example, short nitrate pulses and associated biological events have been observed in the mooring data sets, which were not seen in the periodic ship-collected time-series data. Evaluation of undersampling and aliasing effects characteristic of infrequent sampling are also enabled with these data sets. The primary purposes of this report are to describe new systems and to illustrate early data resulting from the BTM program. © 1998 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Several recent national and international interdisciplinary oceanographic programs (e.g., Joint Global Ocean Flux Study, JGOFS; Global Ocean Ecosystems Dynamics, GLOBEC) are devoted to improving our understanding of the environmental and ecological causes and effects of global change. The success of these and other interdisciplinary programs depends on the availability and application of emerging technologies that are crucial to improve observational databases (e.g., SCOR, 1993; Dickey, 1991. Dickey et al., 1996a; U.S. JGOFS Planning Report 18). In many cases, a particular technology can serve the needs of more than a single program (e.g., Dickey, 1988). Comprehensive programs such as the Global Ocean Observing System (Merlivat and Vezina, 1992; GCOS-14, 1995) will need to implement interdisciplinary sampling programs using several different platforms in order to observe processes on time and space scales ranging over ten orders of magnitude (e.g., Dickey, 1991; Dickey et al., 1996a). Development of relevant technologies is proceeding rapidly and is valued by observationalists and numerical modelers who wish to form collaborations (e.g., U.S. JGOFS Planning Report No. 14, 1992; SCOR, 1994, 1996).

Although considerable progress has been made, efforts are hampered by the lack of common testbeds for the testing of sensors and systems and the interpretation of their data. One of our key objectives is to establish a testbed mooring program that can serve the oceanographic community's needs in this area. Use of the Bermuda Testbed Mooring (BTM), which is serviced at roughly 4 month intervals, allows investigators to regularly exchange instruments in order to evaluate sensor and system performance. Time-series data collected from the mooring can be intercompared, intercalibrated, and interpreted using comprehensive shipboard data sets obtained during monthly or bi-weekly cruises as part of the Bermuda Atlantic Time-series Study (BATS) program, as well as other related mooring and remote sensing programs conducted out of the Bermuda Biological Station for Research (BBSR) (Michaels and Knap, 1996).

Satellite-derived color data are confined to the uppermost layers, and viewing days are limited by cloud obscuration (e.g., Smith et al., 1991). However, bio-optical measurements made from moorings can provide critical complementary and virtually continuous information at a variety of depths. In particular, moored optical systems can be used for groundtruthing and algorithm development for ocean color imaging satellites (e.g., Esaias et al., 1995).

Many of the sensors and systems developed and tested on the mooring are also suitable for deployment on other platforms, such as drifters, floats, autonomous underwater vehicles, and offshore structures, all of which will likely be used in future GOOS sampling (U.S. GOOS Report, 1992; GCOS-14, 1995). Finally, the collective data sets provided by the BTM, BATS, and related programs will be most useful for several numerical modelers who use the Bermuda area measurement programs to simulate physical and biogeochemical processes (e.g., primary production, carbon flux, etc.) (e.g., Fasham et al., 1990, 1993; Bissett et al., 1994; Doney, 1996; Doney et al., 1996).

Important variability associated with episodic events and mesoscale features on time scales of less than a few weeks cannot be resolved with monthly or bi-weekly shipboard sampling. It has been suggested that the determination of annual and interannual carbon fluxes are in considerable error because of undersampling (e.g., Platt and Harrison, 1985). Bio-optical time-series data have been used to estimate such errors (Wiggert et al., 1994).

Nitrate concentrations generally control both primary and new production, and thus carbon fluxes, especially in oligotrophic ocean waters. As has often been suggested, short-term and sporadic event-driven nutrient injections into the photic zone may be responsible for the enhanced primary production as observed from C-14 incubation experiments (e.g., Klein and Coste, 1984; Glover et al., 1988; Marra et al., 1990). Such injections, however, are difficult to observe with traditional shipboard methods. We have therefore been testing an in situ nutrient analyzer capable of near-real-time continuous data collection for dissolved nitrate. This instrument, the OsmoAnalyzer, is described below.

Understanding of the influence of metal variability on oceanic processes including biological production and for distinguishing anthropogenic anomalies versus natural variability has gained considerable attention within the past decade. For example: (1) Do natural pulses of iron fallout from the atmosphere affect biological growth rates? (2) Do anthropogenic metal emissions produce concentration anomalies that exceed natural background variability? Several studies that have used sampling at intervals of weeks to months have observed large changes in metals such as lead, aluminum, manganese, and iron (e.g., Boyle et al., 1986; Duce, 1986; Martin and Gordon, 1988; Savoie et al., 1989; Jickells et al., 1994). These collective observations have stimulated the development of the moored in situ trace element serial sampler system (MITESS), which is described later. Clearly, many important phenomena are highly episodic and transient. It is likely that nearly continuous records are critical for solving a host of other oceanic problems.

The BATS and other associated programs are particularly valuable for the BTM program (see review by Michaels and Knap, 1996 and other papers in Deep-Sea Research vol. 43, Nos. 2 and 3, 1996). The primary BATS site is located at 31°43.7′N, 64°10.1′W (Fig. 1). This site was chosen for the BTM because (1) it is within a representative oligotrophic gyre, (2) it is in deep waters ($\sim$4567 m), yet is easily accessible, (3) rich historical data sets are available, (4) the JGOFS BATS program presently provides relevant data sets, and (5) high-resolution remote sensing data are collected for the Bermuda area.

The BATS site has been sampled as part of the BATS program since October 1988. Research cruises are made monthly (bi-monthly cruises in springtime) to the BATS site. Core measurements include: (1) profiles of temperature, salinity, beam attenuation coefficient or c660, stimulated chlorophyll fluorescence, photosynthetically available radiation (PAR), dissolved oxygen, nutrients, particulate organic carbon and nitrogen, primary productivity, phytoplankton pigments, dissolved organic carbon, nitrogen, and phosphorus, (2) net tow and video sampling of zooplankton, (3) bacteria assays, and (4) trap determined sinking carbon flux. Bio-optical profile data are also being obtained during these cruises as part of the Bermuda BioOptics Project (BBOP, Siegel and Michaels, 1996; Siegel et al., 1995, 1996). The profile data provide excellent vertical resolution ($\sim$1 m from the surface to $\sim$200 m), but relatively poor

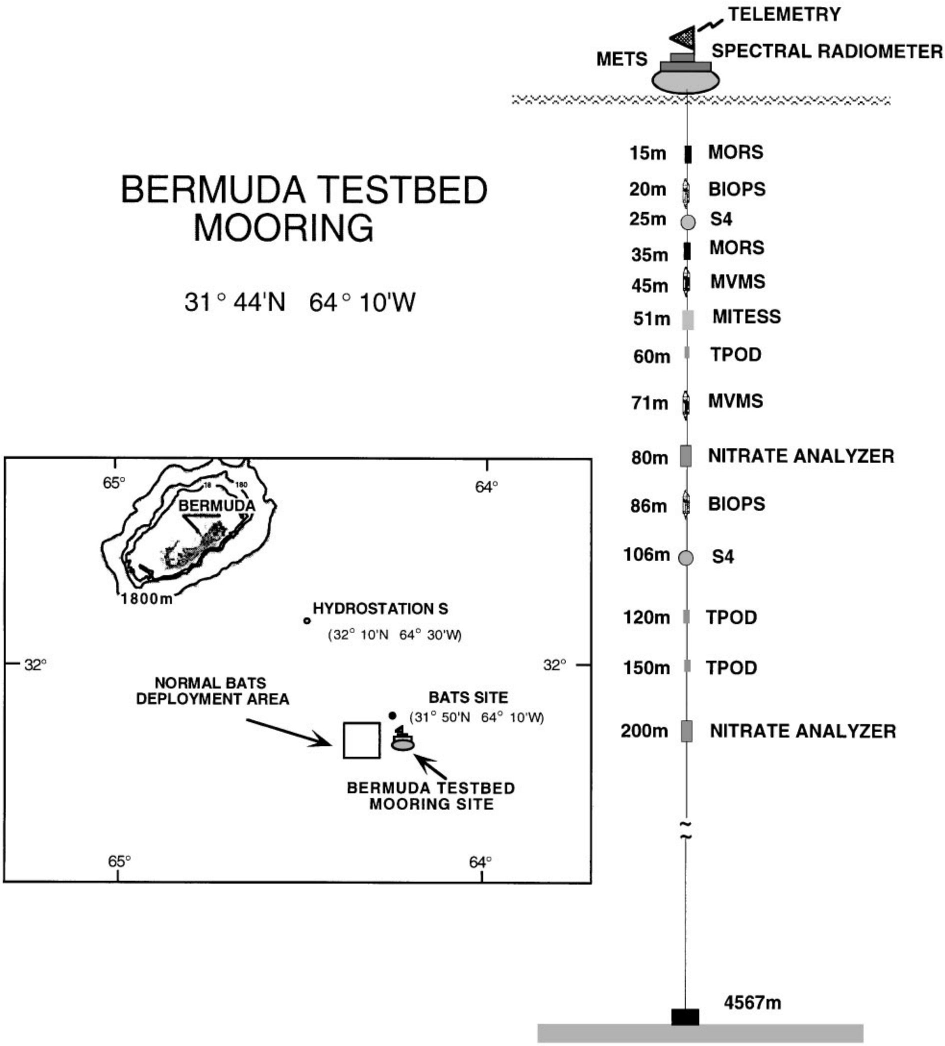

Fig.1. Bermuda Testbed Mooring configuration for the third deployment, 6 April–24 August 1995. Instrumentation systems are described in text. Geographic site of mooring is also shown.

temporal resolution, whereas the mooring data provide excellent temporal resolution (order of minutes to an hour), but relatively poor vertical resolution ($\sim$10 m or greater). The profiling system includes several bio-optical sensors that are compatible with the BTM sensors to be described later. Clearly, both sampling modes are necessary for detailed optical studies.

The BBSR is also equipped with an HRPT satellite receiver system (TeraScan: SeaSpace, Inc.) for acquiring and processing AVHRR image data. Typically, four satellite passes are captured per day. Using these images, basin scale and local mesoscale features can be resolved, thus providing spatial context for time-series observations. The sea surface temperature (SST) retrievals are validated with monthly or bi-weekly shipboard CTD casts at the BATS site and underway thermosalinograph data collected during R/V Weatherbird II cruises in the region. An interesting example of AVHRR imagery obtained during Hurricane Felix's passage in August 1995 near the mooring site is presented in Nelson (1996). TOPEX/Poseidon altimetry data are also being examined (personal communication, Erik Fields and David Siegel). These complementary remote sensing measurements are valuable for the BTM work and vice versa.

2. Materials and methods

The BTM site is located within a half-day's steam from Bermuda, so minimal time is spent in transit. Mooring redeployments take place approximately every four months. The mooring used for the BTM program is based on a mooring used previously as part of the Atlantic Long-Term Oceanographic Mooring (ALTOMOOR) engineering program near Bermuda (Bocconcelli et al., 1991; Frye et al., 1996).

The mooring array used for the third BTM deployment is illustrated in Fig. 1. Instrumentation ranging in developmental stages is used on the mooring (see Table 1

Table 1
Summary of instrumentation used on the Bermuda Testbed Mooring. Asterisks indicate systems placed on mooring after Deployment 3. Wavelength is symbolized as λ, and partial pressure of carbon dioxide is $p\mathrm{CO}_2$

System	Measurements
METS	Wind speed and direction, air temperature, barometric pressure, and humidity
MORS (surface)	Downwelling irradiance at 7 λ's, PAR, and tilt
TPODS	Temperature
S4	Currents, temperature
MVMS	Currents, temperature, conductivity, PAR, beam c(660 nm), stimulated fluorescence, and natural fluorescence (upwelling radiance at 683 nm)
BIOPS	Spectral absorption and attenuation at 9 λ's, PAR, and stimulated fluorescence
MORS (subsurface)	Downwelling irradiance at 7 λ's and upwelling radiance at 7 λ's, PAR, pressure, temperature, and tilt
Osmoanalyzers	Chemical nutrients (nitrate), conductivity, and temperature
MITESS	Trace metals i.e. Pb, Fe, Al
Telemetry system	Mooring design and telemetry
ADCP*	Current profile measurements
ACM*	Acoustic current measurement
CARIOCA*	$p\mathrm{CO}_2$, stimulated fluorescence, sea surface temperature, and wind speed and direction
ORBCOMM Telemetry*	Data throughput test of new low earth orbiting ORBCOMM satellite transmitting meteorological data

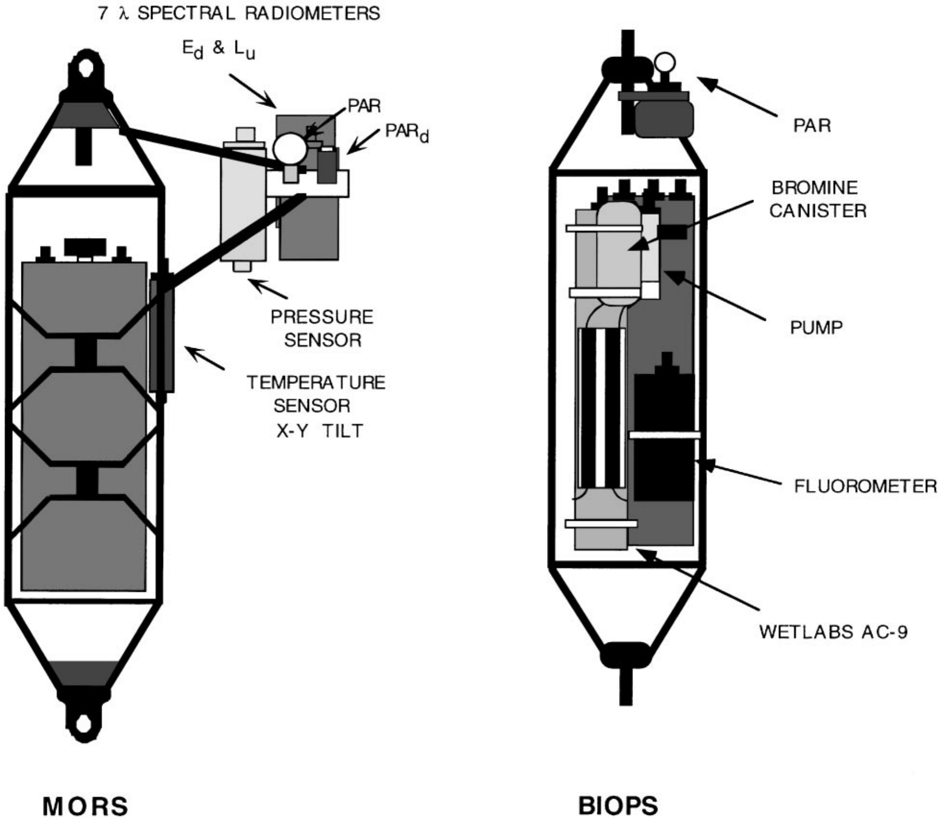

Fig. 2. Bio-optical instrumentation packages: MORS and BIOPS.

for summary). For example, S4 current meters (InterOcean Systems Inc.) and self-contained recording temperature sensors (TPODS; Richard Brancker Research Ltd.) are in common use; the multi-variable moored systems (MVMS; described below) have been developed over the past eight years (e.g., Dickey, 1991; Dickey et al., 1993a, b); and the bio-optical systems (MORS and BIOPS; Fig. 2), the nitrate analyzers (OsmoAnalyzer; Fig. 3), and the Moored In situ Trace Element Serial Sampler system (MITESS; Fig. 4) are in the early stages of field testing. The telemetry system (Fig. 5) is also newly developed. The number and types of sensors and systems deployed from the mooring have evolved with each succeeding deployment. For example, new systems (Table 1) presently being deployed include an acoustic current meter (ACM, Falmouth Scientific, Inc.; A. Fougere), CARIOCA (a tethered buoy with pCO_2, fluorescence, temperature, and wind sensors; L. Merlivat), a meteorological system, an ADCP (150 kHz; RDI Inc.), and a telemetry system (ORBCOMM).

The mooring (Fig. 1) is supported by a 2.5 m diameter buoy fabricated of Surlyn foam. Surface recording systems, controllers, and batteries are housed inside the buoy.

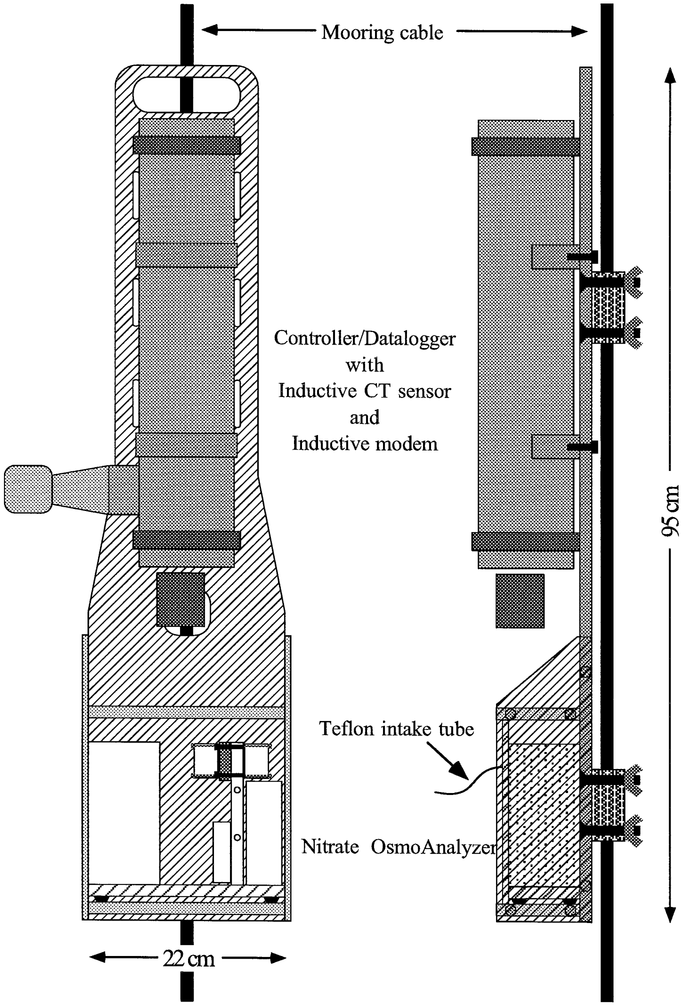

Fig. 3. Nitrate Osmoanalyzer system.

The buoy tower supports an Argos transmitter to provide position of the buoy and data transmission, an RF antenna for short-range data transmission, meteorological instruments, and a radiometer package. The meteorological package includes sensors for measuring wind speed, wind direction, and air temperature (Coastal Climate Weatherpak). These variables are sampled every hour, recording 10 min average data. The peak wind gust (highest 3 s value every 10 min) is also recorded during this 10 min sampling period. This measurement is important, particularly under high wind, high sea conditions, such as those experienced during the passage of Hurricane Felix in August 1995. The anemometer and radiometer are located 4.5 m above the ocean

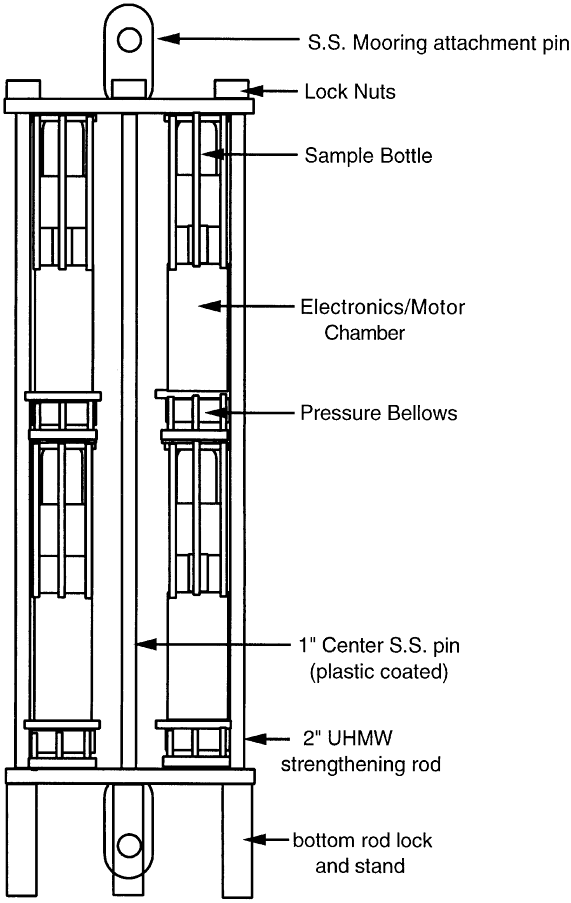

Fig. 4. Moored In situ Trace Element Serial Sampler system (MITESS).

surface. Commonly used estimates of wind speed at 10 m above the surface, U_{10}, are computed using a formula presented by Large et al. (1995). A pyranometer is used to measure short-wave radiation (Eppley PSP). Optical measurements include spectral downwelling irradiance at $\lambda = 412$, 443, 490, 510, 555, 665, and 683 nm (Satlantic OCI-200), and downwelling PAR (LI-COR 192SA). These sensors and a tilt sensor are sampled for 2 min at 6 Hz every hour (local time) between 6 a.m. and 10 a.m. for 5 min every hour between 11 a.m. and 1 p.m., for 2 min every hour from 2 p.m. to 7 p.m. and for 2 min at midnight and 1 a.m. Data are stored on a 120 Mbyte hard drive.

Current speed and direction and temperature are measured at two depths (25 and 106 m) using S4 (InterOcean) electromagnetic current meters. These are sampled at 2 Hz, and 1 min averages are stored every 30 min. Temperature is also measured with

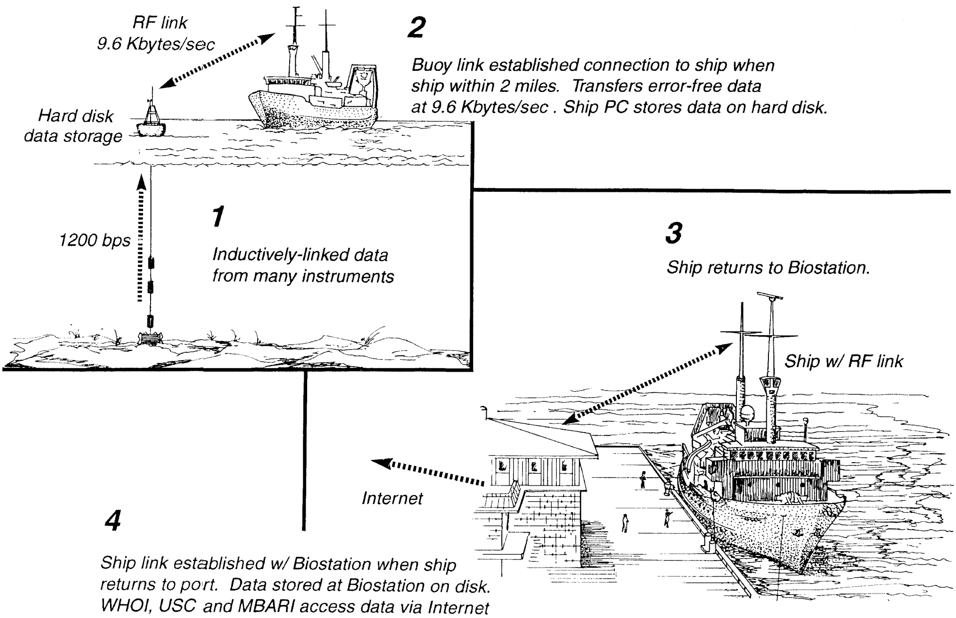

Fig. 5. High-speed RF link from mooring buoy to ship to shore.

self-recording temperature systems (TPODS, Brancker) every 15 min at depths of 60, 120, and 150 m. The multi-variable moored system (MVMS; e.g., Dickey et al., 1991, 1993a, b) records 3.75 min averages of physical and optical data at 45 and 71 m. Physical data collected with the MVMS include vector-averaged currents (based on EG&G VMCM; Weller and Davis, 1980), temperature, and conductivity (Sea-Bird SBE-4).

The MVMSs also include optical sensors. A beam transmissometer (Sea Tech; Bartz et al., 1978) is used to determine the beam attenuation coefficient ($c(660)$). In addition, stimulated chlorophyll fluorescence intensity is measured with a fluorometer (Sea Tech; Bartz et al., 1988). Other measurements include photosynthetically available radiation (PAR, Biospherical QSP-200; Booth, 1976) and upwelling radiance at 683 nm (natural fluorescence; Biospherical MRP-200; Kiefer et al., 1989).

New bio-optical systems (BIOPS, Fig. 2) include sensors to measure chlorophyll fluorescence and PAR as described above and a spectral absorption–attenuation meter (WET Labs AC-9; Moore and Bruce, 1996) at 20 and 86 m. The BIOPS packages are sampled for 30 s at 30 min intervals and recorded on a 120 Mbyte hard drive. Data can be collected for four months using this sampling scheme. The AC-9 concurrently measures spectral attenuation coefficients, $c(\lambda)$, and spectral absorption coefficients, $a(\lambda)$, at nine wavelengths ($\lambda = 412$, 440, 488, 520, 560, 630, 650, 676, and 715 nm) using dual path (25 cm pathlength) measurements. Slowly dissolving bromine tablets were used as an experiment to combat biofouling during the third deployment.

The absorption a meter principle (e.g., Yentsch, 1962; Moore et al., 1992) entails use of a tube with a shiny reflective interior enabling measurement of both scattered and directly transmitted light. The interior of the attenuation c tube is black. The scattering coefficient may be computed from the relation $b(\lambda) = c(\lambda) - a(\lambda)$. There are obvious fundamental applications for the AC-9, such as determining spectral absorption of biogenic and non-biogenic particles, chlorophyll and phaeophytin concentrations (using differential absorption measurements), and particle concentrations. Determination of phytoplankton biomass can be obtained using the AC-9. Further, it is likely that computations of combinations of differences and ratios of combinations of $a(\lambda)$, $b(\lambda)$, and $c(\lambda)$ will provide identification information as well. Although the AC-9 is a relatively new instrument, it has undergone intensive laboratory testing for characterization and has been used in profiling mode (e.g., Zaneveld et al., 1994; Brody et al., 1997; Moore and Bruce, 1996; Petrenko et al., 1997).

Another moored optical system (MORS; Fig. 2) was developed to provide necessary in situ verification and interpretation (e.g., groundtruthing and algorithm development) of remotely sensed ocean color data (e.g., for SeaWiFS and other satellite color sensors). Satellite and mooring data may both be used to estimate biomass and primary productivity globally (e.g., see U.S. JGOFS Planning Report Number 18, 1993; Smith et al., 1991; Dickey, 1991; Dickey et al., 1991; Marra et al., 1992; Waters et al., 1994). Satellite-based measurements have the advantage of providing broad spatial coverage of the very near-surface ocean, whereas moored instruments provide excellent temporal resolution as well as data at depth. The MORS systems are placed at nominal depths of 15 and 35 m. The MORS radiometers measure downwelling spectral irradiance (Satlantic OCI-200) and nadir upwelling spectral radiance (Satlantic OCR-200) at wavelengths of 412, 443, 490, 510, 555, and 665 nm, which are compatible with those of the SeaWiFS color imager, plus 683 nm for natural fluorescence. In addition, scalar irradiance sensors with both spherical (PAR; LI-COR LI-193SA) and cosine collectors (PAR_d; LI-COR LI-192SA), tilt sensors, temperature sensors, and pressure sensors are included on the MORS system. Light (radiometers and PAR) and tilt sensors are sampled in the same manner as described earlier for the surface radiometer. Data are stored on a 120 Mbyte hard drive. The system can be operated for about four months in this configuration.

Analyses of nitrate concentrations are accomplished using osmotically pumped chemical analyzers (Osmoanalyzers). The analyzers (Fig. 3) utilize osmotic pumps, which propel both sample and reagents through a miniature flow injection style manifold as described by Jannasch et al. (1992, 1994). This technology is used to eliminate almost all moving components and major power requirements. It has proven successful when deployed in coastal environments such as the waters of Monterey Bay (Jannasch et al., 1994). Osmotic pumps are driven by molecular diffusion across a rigid, permeable membrane, separating a saturated salt solution from fresh water. The Osmoanalyzers have flow rates of approximately 20 $\mu l\, h^{-1}$ (160 $ml\, y^{-1}$), a 90% response time of < 30 min, and a detection limit of 0.1 $\mu M\ NO_3$. Self-contained low-power dataloggers control the Osmoanalyzers and an inductive conductivity sensor (Falmouth Scientific). Data are recorded internally and telemetered hourly via an inductive modem. The Osmoanalyzer weighs less than 5 kg in water and is clamped directly to the mooring cable. It operates for about 3.5 months per deployment, taking readings at 5–10 min intervals. Every four days, each analyzer is calibrated in situ with a mechanically injected set of standard solutions (50 μl solenoid pump, Lee Corp.). Standardization consists of injecting a 10 μM NO_3 solution and a blank solution out through the intake tube 3 h apart. The solutions remaining within the intake tube are then analyzed exactly the same way as the samples. The analysis of sequential standard and blank takes about 8 h and can be seen as hiatuses in the data. The mooring was configured with three analyzers, one at 200 m to monitor the top of the nutricline and two at 80 m to sample for nutrient injections into the mixed layer.

A new Moored In situ Trace Element Serial Sampler (MITESS) was deployed at 51 m. The purpose of the MITESS is to examine the temporal variability of trace metals in the upper ocean. Details concerning the design and development of the MITESS will be presented elsewhere; however, a brief description of the MITESS is given here. The mechanical and electronic design focused on the following goals and criteria: (1) sampler materials must be fundamentally trace-metal clean and easy to reclean after deployment, (2) sample bottles should be flushed well before sealing, (3) mechanical operations must be simple, (4) the system must withstand stresses of extended deployments (6–12 months) at any depth, (5) the system must be inexpensive and straightforward to construct, and (6) the system must be deployable from standard moorings and never jeopardize mooring integrity. The MITESS system consists of a colony of 12 independent sampling modules mounted on a durable mooring unit (Fig. 4). For trace metal cleanliness, the entire exterior of the unit is constructed of ultra-high molecular weight polyethylene (UHMW). Six sample modules snap together horizontally into a hexagon surrounding the center strength member. Two of these hexagonal composites are stacked vertically within the complete mooring unit. Both levels surround a central plastic-encased stainless-steel load-bearing rod. Each sample module functions independently during deployment, so failure of any individual module does not affect the others. Each module has a sealed pressure-compensated chamber filled with Fluorinert™, an inert non-conducting fluid. The interior of this chamber houses a motor, controlling electronics, and batteries. The system's electronics and controllers are described in the appendix. 500 ml polyethylene sample bottles are filled with dilute (1 N) high-purity hydrochloric acid. The timer-controlled DC motor opens the screw-cap bottles by rotary motion, allowing the low-density dilute acid to be replaced by dense seawater via passive density-driven flow (laboratory tests show that replacement occurs within a few minutes; in the field, the bottles are left open for 15 min and the salinities of the resulting samples indicate complete replacement). Samples are preserved by diffusion of dilute acid retained in a diffusion chamber placed inside each bottle. The diffusion chamber is constructed of high-purity Teflon™ PFA, which is hot-acid leached before use.

Satellite telemetry via the Argos data collection system (DCS) is used for summary data collection. However, a major engineering development aspect of the mooring project involved inductive telemetry of data from a number of subsurface sensors to the surface and then on to land-based stations via the R/V Weatherbird II (Fig. 5). Details are given in Frye et al. (1996), and a brief summary follows. The method entails use of inductive coupling via toroidal pickups on the mooring line. Inductive modems are interfaced to subsurface instruments and transfer data to the surface buoy. Data from each instrument are transferred via the insulated mooring line with a seawater return. No direct electrical connection or special termination is required. The data are stored and a subset of data are transmitted via Argos. The stored data can also be off-loaded by wireless ethernet telemetry when the R/V Weatherbird II is within range (about 2 km). The RF data are full-bandwidth, whereas the Argos data are limited to hourly averaged samples. The RF link transmits 10 kbytes/s during file transfer, while the Argos link transfers about 1 kbyte/day Full-bandwidth data are also stored internally on all systems and downloaded after each deployment. The telemetered data are useful for the purposes of 1) tracking of the buoy in the event of mooring failure, 2) verifying operation of the system, 3) preliminary data analysis and quality control, 4) determining the need for more rapid mooring sampling or quick response/special shipboard sampling at the BATS site when events (e.g., hurricanes, mesoscale features, blooms, etc.) are underway, and 5) providing first-look data for satellite color sensor validation/algorithm development. The system's two-way communication capability further allows changing of instrument parameters from shore (e.g., gain adjustments) and for carrying out event specific experiments. The development of the telemetry aspect of this work is important in the long-term scheme of utilizing moored and drifter instrumentation arrays for remote sites as part of global ocean/climate observing networks (e.g., Frye and Owens, 1991; Fougere et al., 1991; Frye and Berteaux, 1992; Dickey et al., 1993a; Von der Heydt et al., 1994).

3. Results

The first deployment of the Bermuda Testbed Mooring was on 3 June 1994, with a limited number of systems. More recent deployments have included more sensors and systems. The first portion (6–25 April) of the third deployment period (6 April 1995–23 August 1995) is used here to illustrate the types of data collected with the various systems described above. The intent of this paper is to illustrate the types of data collected by the BTM rather than to present a detailed analysis. However, it should be noted that the third deployment was especially interesting, as a subsurface eddy, with the highest chlorophyll levels in several years (centered on 15, July 1995) and Hurricane Felix (passing on 15 August 1995; Dickey et al., 1998b; Nelson, 1996, 1998) were observed. These events and other specialized results will be described in other papers.

The region of the BATS site is dominated by the seasonal cycle (e.g., Michaels and Knap, 1996). The mixed layer depth and phytoplankton concentrations vary seasonally, but the respective timing and intensities vary interannually. Mesoscale eddies are common and contribute to the spatial and temporal variability of the physical and biogeochemical properties.

During the period 6–26 April (year days 96–116), the winds (gusts reported here) were variable and typically less than 20 m s^{-1} except for the first few days (Fig. 6). The period was relatively cloud free, as indicated in the surface PAR data. However, there

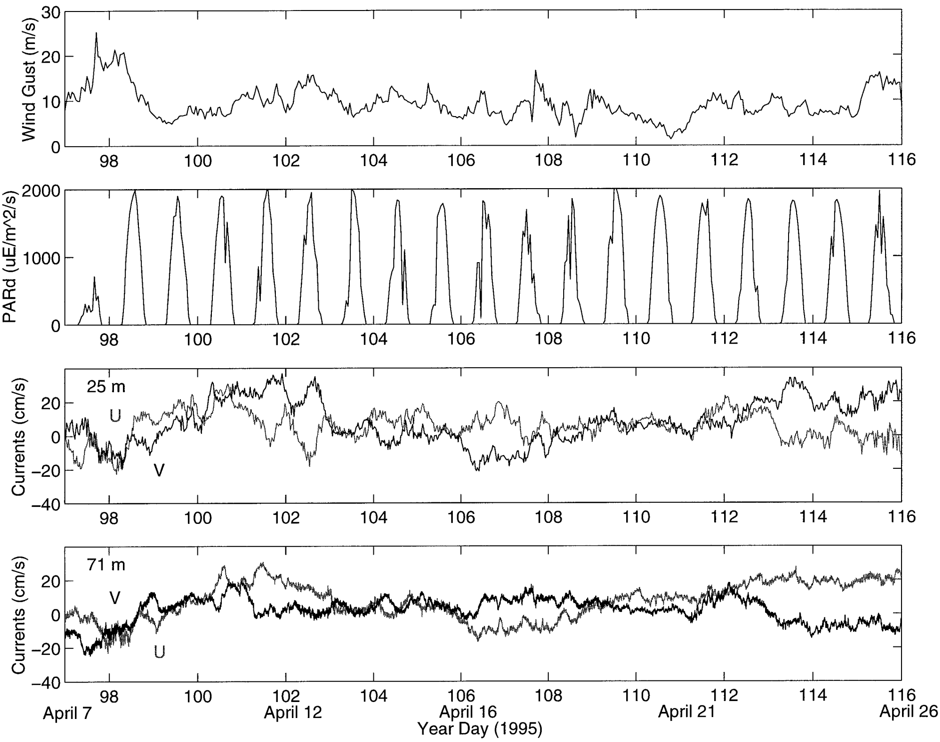

Fig. 6. Time series of (a) wind gust, (b) surface PAR_d, (c) 25 m zonal and meridional currents (U, V), and (d) 71 m zonal and meridional currents (U, V).

were occasional periods of broken cloud conditions, and 7 April (year day 97) was overcast. The currents were quite low, with amplitudes of horizontal components typically less than 25 cm s^{-1}, only modest vertical shear, and minimal inertial motion (Fig. 6).

Temperatures at selected depths (25, 71, and 150 m) are shown in Fig. 7. The deployment began just after the deepest wintertime mixing, when the mixed layer depth was in excess of 200 m. On 6 April, the temperature difference from 45 to 150 m (not shown here) was less than 0.5°C, with these depths lying slightly above the 18°C mode water of the Sargasso Sea. Seasonal stratification had just begun, as the temperature difference between 25 and 150 m was less than 1°C at the beginning, but greater than 2°C only two weeks later. During the period 11–16 April (year day 101–106), the currents changed direction, and advection of a warmer water mass past the mooring is evident in the temperature time series (Fig. 7).

Time series of nitrate concentration, chlorophyll fluorescence, and attenuation coefficient (c(660)) are also shown in Fig. 7. The chlorophyll and attenuation coefficient time series are remarkably coherent throughout the period, which indicates that

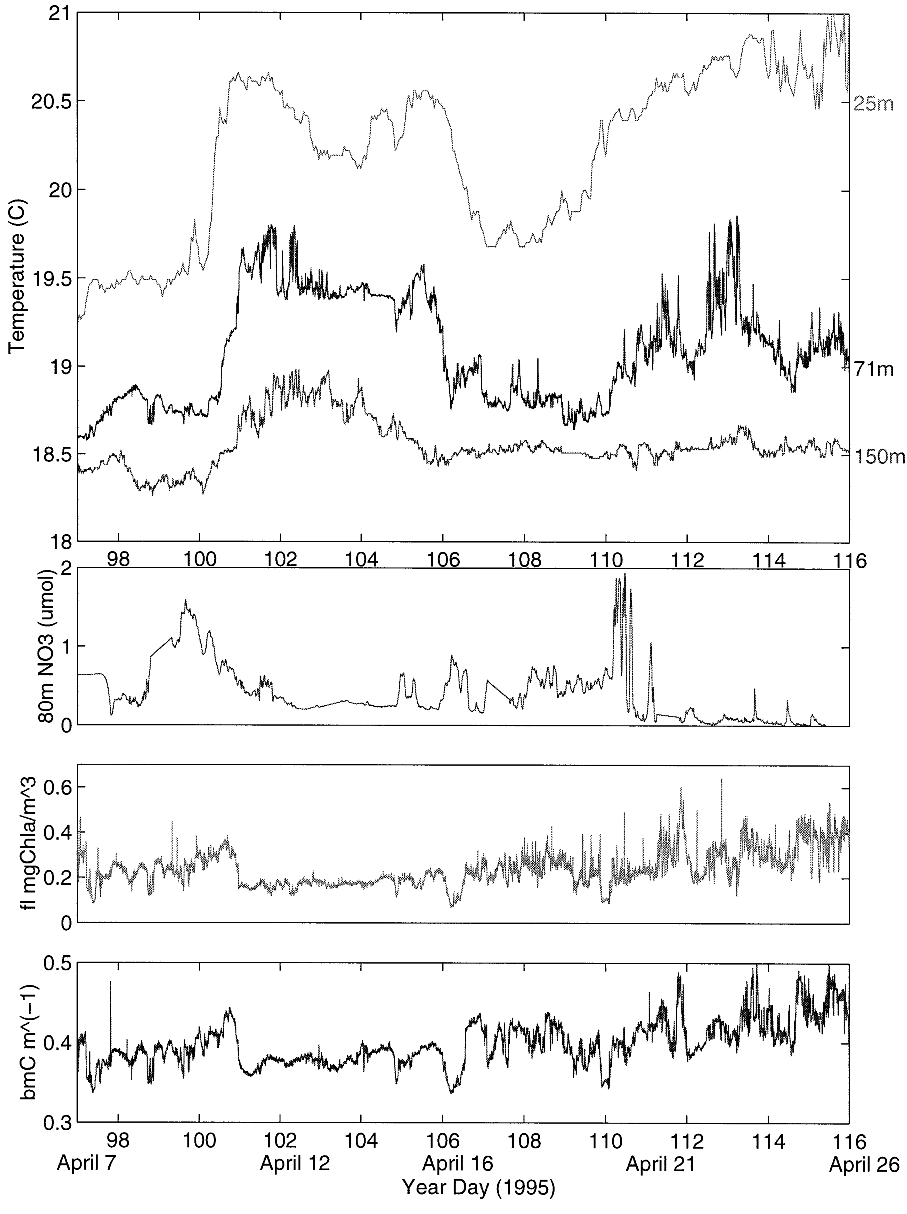

Fig. 7. Time series of (a) temperature at 25, 71, and 150 m, (b) nitrate concentration at 80 m, (c) chlorophyll fluorescence at 71 m, and (d) attenuation coefficient at 660 nm ($c(660)$) at 71 m.

the particulate matter measured by the beam transmissometer was likely phytoplankton. Diel variability in these records is not apparent. There are slight increasing trends in both chlorophyll fluorescence and $c660$, indicative of the onset of the spring bloom. During the period of 8–10 April (year day 98–100), an increase in nitrate concentration (to ~ 1.5 μmol) at 80 m appears to correlate with a decrease in temperature at depths greater than 45 m. This is suggestive of nutrient injections associated with deeper nutrient-rich 18°C mode waters. There appears to be a correlation between this feature and increases in chlorophyll fluorescence and $c(660)$ at 71 m about a day later (Fig. 7). A week later, a second cooling period is observed from 16–20 April (year day 106–110). Although we also observe elevated nitrate during this time, the nitrate, fluorescence, and $c(660)$ signals are more variable. From this point onwards (after 20 April, year day 110), the temperature continues to increase as nitrate decreases. Although many of the nitrate maxima are associated with temperature minima, it is also clear that the two properties do not covary consistently. During the same period, the simultaneous increase of chlorophyll fluorescence (and $c(660)$) is not clear. More detailed analyses of these and other BTM data sets will evidently be required to explain these complex observations.

The surface and 15 m downwelling spectral (seven wavelengths) irradiances obtained with the MORS are shown in Figs. 8 and 9. The effects of clouds are evident in these time series, particularly on 7 April. Computations of several derived quantities, such as the spectral diffuse attenuation coefficient, $K_d(\lambda)$ and various spectral radiance and irradiance ratios, have been made but will be presented elsewhere. However, it is worth noting that time series of $K_d(\lambda)$ evaluated for 7.5 m and $a(\lambda)$ from the 20 m BIOPS show similar variability. The radiometric data will be useful for several remote sensing applications (e.g., estimation of water-leaving radiance or evaluation of solar elevation effects).

The AC-9 system used with the moored BIOPS package was developed only recently and has been used primarily in profile mode from ships. Time series of a subset of measured absorption and attenuation coefficients ($c(488)$, $c(560)$, and $c(676)$ nm) from the 86 m BIOPS along with $c660$ from the 71 m MVMS are shown in Fig. 10. The time series shown in Fig. 10 indicate strong variability, comparable to that observed with the MVMS's beam transmissometer, $c(660)$. There is strong coherence in all wavelengths of $a(\lambda)$ and $c(\lambda)$ during the entire record. Signal-to-noise ratios are relatively small for measurements of inherent optical properties in very clear oligotrophic waters, such as those off Bermuda. An additional difficulty presented for moored AC-9 measurements is biofouling. For this particular deployment, bromine solution was introduced as an anti-fouling agent into the sampling tubes between measurement periods and flushed out before sampling. After analyzing the AC-9 data, we concluded that the bromine solution likely partially degraded the optical windows. Because of the apparent bromine contamination, it was necessary to offset the measured values obtained from the AC-9 for $c(676)$ to match those of the 71 m MVMS's $c(660)$ record. The other absorption and attenuation coefficients were adjusted to be consistent with concurrent AC-9 profile data taken near the mooring from the R/V Weatherbird II (personal communication: Eric Brody and David Siegel). The AC-9 results are encouraging. This aspect of the BTM

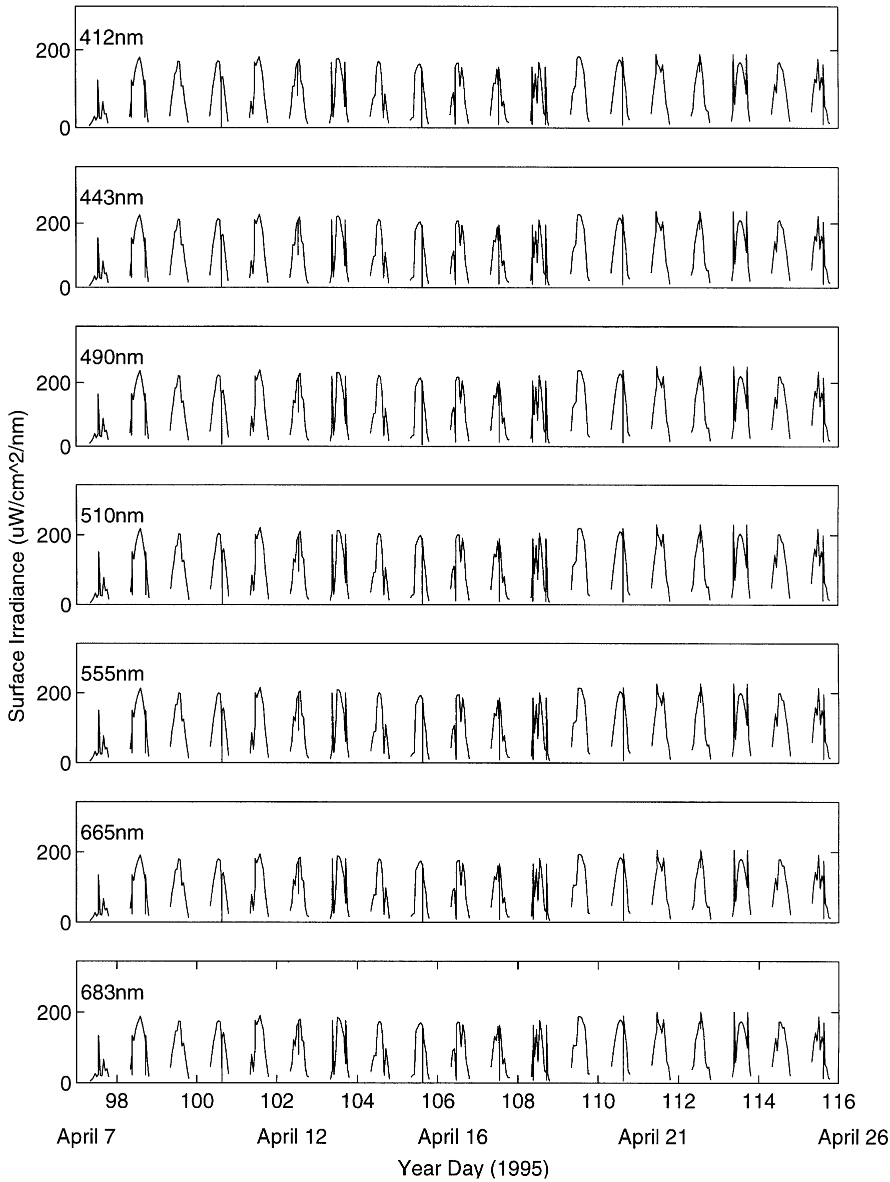

Fig. 8. Time series of surface downwelling spectral irradiance for wavelengths of (a) 412 nm, (b) 443 nm, (c) 490 nm, (d) 510 nm, (e) 555 nm, (f) 665 nm, and (g) 683 nm.

program underscores the importance of complementary shipboard sampling for emerging technologies.

Finally, preliminary results were obtained using the Moored In situ Trace Element Serial Sampler system (MITESS). The time series of lead concentration at 51 m for the

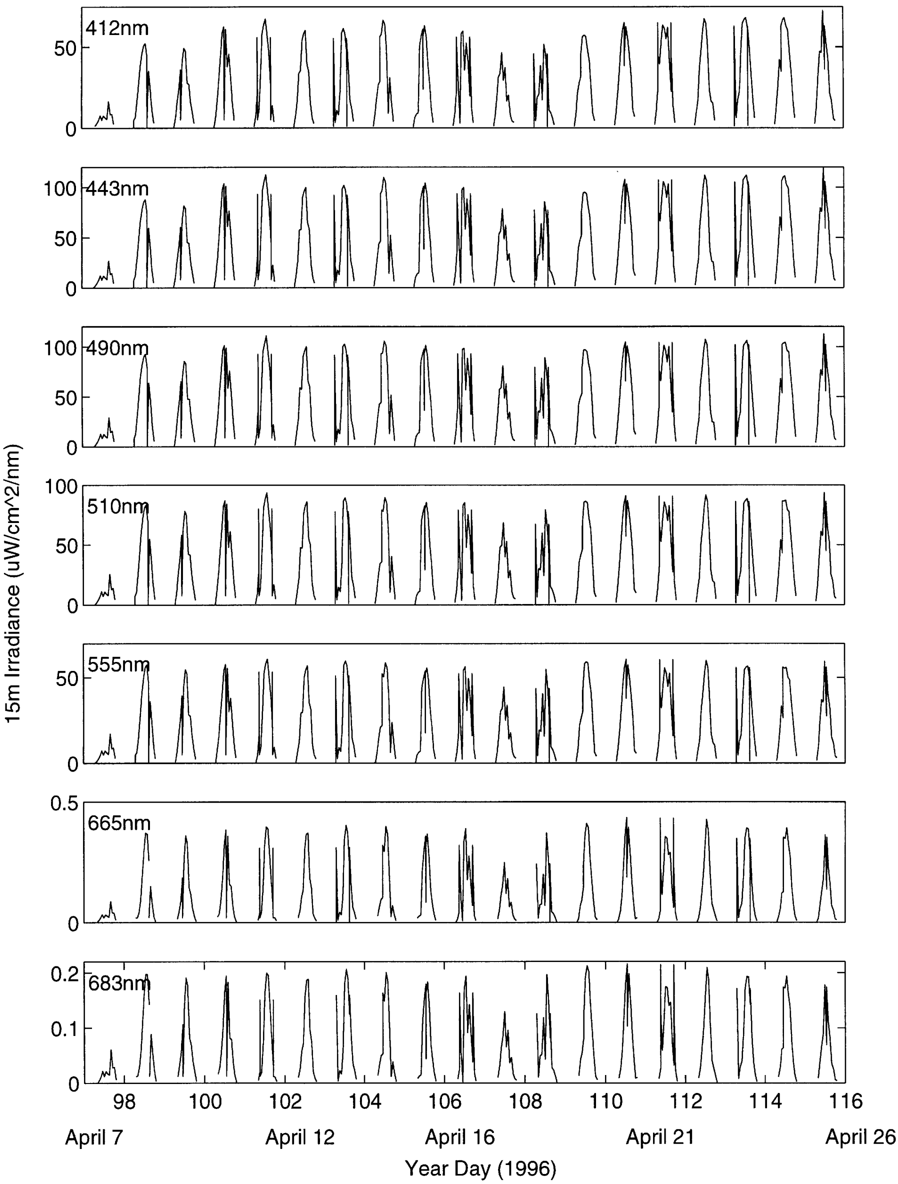

Fig. 9. Time series of downwelling spectral irradiance at 15 m for wavelengths of (a) 412 nm, (b) 443 nm, (c) 490 nm, (d) 510 nm, (e) 555 nm, (f) 665 nm, and (g) 683 nm.

third deployment is shown (at right) in Fig. 11 (after Wu and Boyle, 1996) along with data collected from ship sampling near the mooring site over the past 16 years. The time series indicates that upper ocean lead concentrations near Bermuda declined, likely because of phasing out of leaded gasoline through 1990. Mean annual levels

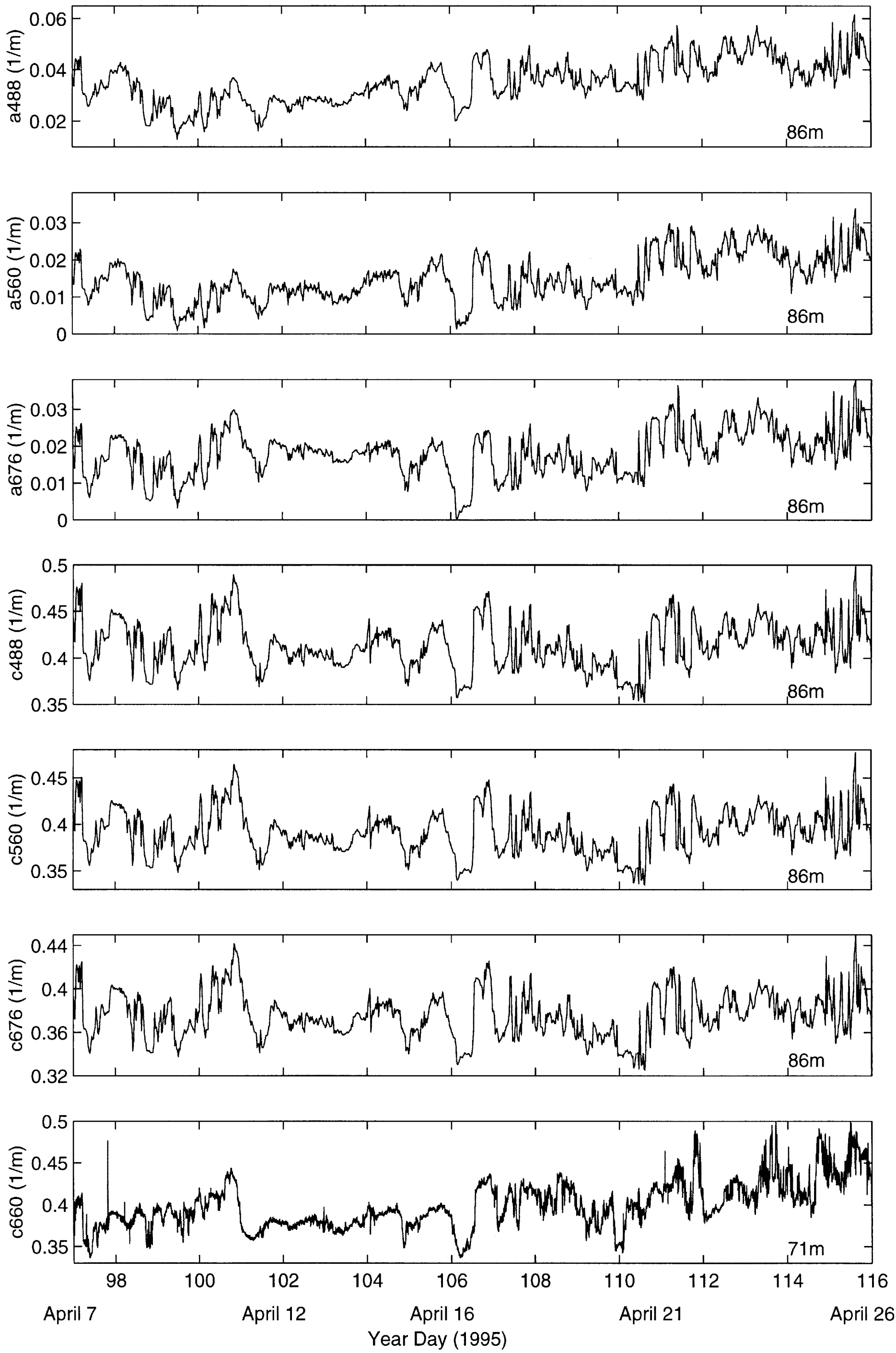

Fig. 10. Time series of absorption and attenuation coefficients at 86 m for selected wavelengths (488, 560, and 676 nm) and $c(660)$ at 71 m.

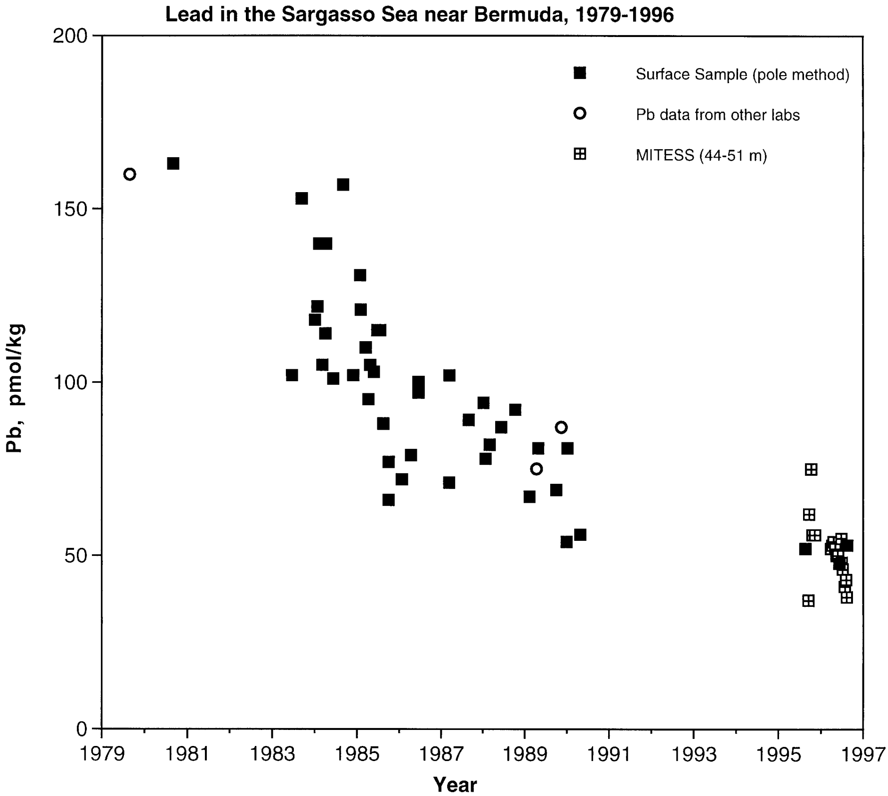

Fig. 11. Time series of lead concentrations in the upper ocean near Bermuda as obtained from shipboard and moored samplers, 1979–1990. 1979 and two 1989 samples ("other laboratories") were collected and analyzed by Caltech laboratory (Schaule and Patterson, 1983; Veron et al., 1993). Year is marked on January 1. 1983–1984 samples reported by Boyle et al. (1986); 1984–1987 samples reported by Boyle et al. (1994), and 1987–1996 samples reported by Wu and Boyle (1997). MITESS samples collected in 1995–1996.

have declined only slightly since that year (Wu and Boyle, 1997). The high degree of variability within a year (some on time scales as short as a week; Fig. 11), however, necessitates relatively frequent sampling, such as that enabled by MITESS, in order to understand the origin of the short-term variability. For example, in the samples from 1995–1996, lead varies by more than a factor of two (38–86 pmol kg^{-1}). Similar variability was observed in 1983–1984 by Boyle et al. (1986).

4. Summary

The present report describes the preliminary phase of the recently instituted Bermuda Testbed Mooring (BTM) program. Creative ideas and emerging instrumentation will continue to be tested using the BTM. The program has already demonstrated its utility for developing, testing, calibrating, and intercomparing interdisciplinary instruments. The importance of complementary shipboard sampling for emerging mooring-based technologies has also been shown. Data have been telemetered to shore and to a nearby ship using a new inductive-link telemetry system. Interestingly, the data collected from the mooring are already providing important information concerning episodic and periodic processes and have included major events such as hurricanes and a highly productive subsurface eddy. The present observations are being used for biogeochemical models and will also be used for algorithm development for groundtruthing of satellite color sensors.

Finally, the BTM data are available to the oceanographic community. A summary of the various deployments, a guide to data reports (with calibration information) and papers, recent data highlights, and information for potential BTM users may be found on the worldwide web (http://www.icess.ucsb.edu/opl/opl.html).

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Appendix. Description of MITESS electronics and controllers

The electronics are stable at high pressures, so a pressure-resistant housing is not required. The electronics consist of a single 6 cm diameter circuit board containing a Motorola PIC16LC84 microcontroller, real-time clock chip, and 25 other components. The sampling time for each sealed unit is programmed prior to deployment using wireless communication from a portable computer using infrared transmission through the polyethylene housing. Inter-unit communication and external event-driven triggering is also possible using these IR ports. Power requirements are low: six C-cell batteries, in principle, should function for more than a year (batteries retrieved after 4-month field deployments have proven to have significant reserves in laboratory tests). The system could be altered to fulfill somewhat different uses, and the electronics are reprogrammable (EEPROM). Opening and closing is monitored and controlled by a Hall effect sensor counting rotations of the internal motor. Non-volatile memory records opening and closing times in the field.