Dear co-authors,

The present version was completed February 27, 2000. Xuri Yu and Sarah Zedler have done some more statistics and plots which I believe help address some of the reviewers' criticisms concerning in-depth analyses. These have also helped us to strengthen the interpretations I believe.

The present draft is still a bit rough, but improved quite a bit in my opinion. I have attempted to set objectives in the introduction more clearly. I think the paper now accomplishes these. I kept the more technical and methodological aspects in as I still feel they are valuable at this point in time. I moved these earlier in paper as I think this clears up confusion of organization and goals of paper. I have tried to work in references to some other papers in the volume (like Debbie Steinberg's and Dave Siegel's), but I may need to do some more on this and expect some of you can add some insights here.

Because of the extremely short period of time we were given to revise the paper, coupled with my exceptionally heavy teaching and travel commitment this month, I suggest that we do not make major revisions to the original manuscript. However, I do encourage you to add new ideas and interpretations which I can relatively easily incorporate in a short period of time (that is, please give me specific sentences etc. and tell me where they should be inserted).

I realize that all of you are very busy also, so I want to emphasize that I really appreciate your efforts thus far and will understand if you cannot devote much time to the revisions on such quick notice. Again my apologies for a situation which was not in my control.

I am still planning to resubmit the paper close to Dave's requested date, so I will need any input by March 9 at latest to allow me to incorporate it. Xuri Yu and Sarah are doing a great job helping me with this here and have done a nice job creating and revising figures.

I am confident the new version will be a valuable paper. Best, Tommy

REVISED VERSION: FEB. 27, 2000

{ } = REMOVED MATERIAL
BOLD TEXT = NEW OR REPLACING WRITTEN MATERIAL

High temporal resolution measurements from the Bermuda Testbed Mooring: June 1994 - March 1998

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Abstract

The Bermuda Testbed Mooring (BTM) program was initiated in 1994 in order to provide the oceanographic community with a deep-water platform for testing new instrumentation. The BTM is also being used for *in situ* comparisons with satellite ocean color imager (SeaWiFS) data as well as other data products based on remote sensing and models. Scientific studies are utilizing data collected from the BTM, particularly in conjunction with the U.S. JGOFS Bermuda Atlantic Time-series Study (BATS). The mooring is located at 31°43'N, 64°10'W or about 80 km southeast of Bermuda. The number of measurements made from the BTM has steadily increased during the program. Most recently, surface instruments have collected meteorological and spectral radiometric data from the buoy tower and measurements at depth have included: currents, temperature, and optical and chemical variables. The high temporal resolution, long-term data collected from the mooring capture a **broad {**full**}** dynamic range of oceanic variability and provide important information concerning periodic and episodic processes ranging in scale from minutes to years. Importantly, the BTM enables collection of virtually continuous data during periods of inclement weather when traditional sampling is not possible. **{**The purpose of this report is to provide general descriptions of physical data collected from June 1994 through March 1998. Recent interdisciplinary data collected from May 3, 1997 - March 31, 1998 are highlighted. The measurements described here are valuable in that they provide high frequency, long-term data, which can be used for 1) detailed studies of a variety of physical, chemical, optical, and ecological processes, 2) contextual information for many other observations made near the BTM/BATS sites, 3) evaluation of undersampling and aliasing effects, and 4) developing and testing models.**} The use of deep-sea moorings for high frequency, long-term, interdisciplinary observations is quite unique, and thus new techniques, methodologies, and analyses are still evolving. Some of these are described in the present paper. In addition, the utility of interdisciplinary mooring time series for studying a variety of processes such as storms, mesoscale features, seasonal cycles, and interannual variability is demonstrated using BTM data sets. For example, our results show that the timing of the onset of springtime stratification and the**

breakdown of summer and fall stratification can vary by weeks depending on weather patterns and mesoscale features. I'll ADD A BIT MORE HERE ON RESULTS: ODD WARM, PRODUCTIVE FEATURE; DE-CORRELATION TIME SCALES AND SAMPLING ISSUES. OTHER IDEAS FOR ABSTRACT HIGHLIGHTS??

1. Introduction

The Bermuda Testbed Mooring (BTM) is a deep-sea mooring (Figure 1), which is available for long-term testing of oceanographic sensors and systems. The mooring was first deployed in June 1994. **{**Table 1 provides time periods of the first 9 deployments.**}** A brief introduction to the BTM program is given here since a comprehensive overview of the program and preliminary data (April 7 -26, 1995) are presented in Dickey et al. (1998a). In addition, focused BTM papers have been written on the upper ocean response to Hurricane Felix (Dickey et al., 1998b) and the passage of a major mesoscale eddy (McGillicuddy et al., 1998; McNeil et al., 1999) in 1995. **{**These results are summarized in Figure 2 and illustrate the utility of high frequency sampling.**}** Other recent papers have been devoted to optical **measurements and** variability (Stramska and Dickey, 1998; Stramska and Frye, 1998). Further information about the BTM program, related activities, data sets, and reports may be found on the OPL web site: http://www.**opl**.ucsb.edu/opl/opl.html. Data **for BTM Deployments 1-9** are reported here and are also provided on an accompanying CD-ROM disk. **The emphasis for this paper is on Deployments 5-9 (March 26, 1996 - March 31, 1998); however figures for all deployments are available on the CD-ROM disk.**

The BTM program was stimulated by the need for autonomous, interdisciplinary measurements. This need is underscored by the initiation of several national and international oceanographic programs (e.g., Joint Global Ocean Flux Study, JGOFS; Global Ocean Observing System, GOOS; **see Dickey, 2000a**) and forward-looking reports (e.g., Doney, 1999; Hay and Jumars, 1999) over the past decade. These programs and activities are concerned with the environmental and ecological causes and effects of global changes. The BTM program is synergistic with the U.S. JGOFS Bermuda Atlantic Time-series Study (BATS; initiated in October 1988; Michaels and Knap, 1996; see Steinberg et al. and other papers in this volume) and the Bermuda BioOptics Program (BBOP; initiated in 1992; Siegel et al., 1995, 1996, 1999a) in that the BTM program collects high resolution (minute-hour scale), long-term, time-series data while the BATS and BBOP programs collect more comprehensive sets of ship-based (profile) measurements at monthly (twice monthly in springtime) intervals. **The complementary nature of the two programs is addressed in the Discussion section.**

Another objective of the BTM program is to provide nearly continuous optical time-series data for calibration, validation, and algorithm development for ocean color satellites including SeaWiFS (**Mueller and Austin, 1992;** Esaias et al., 1995; **Dickey, 2000b**). The BTM data have further value since satellite-derived ocean color data are limited to the uppermost ocean layer (roughly one optical depth) and the number of viewing days are limited by cloud obscuration (e.g., Smith et al., 1991). **{**Bio-optical measurements made from moorings can provide critical complementary and virtually continuous information at a variety of depths, and optimize the number of "match-up" data (e.g., water-leaving radiance) with satellite measurements (e.g., Mueller and Austin, 1992)**}**. Additionally, large dynamical ranges are observed because of variations in solar elevation, cloud type and amount, wave and surface conditions, and concentrations and types of pigmented biomass. Comparisons of mooring and other satellite-based data sets, such as incident shortwave radiation and other surface heat fluxes, are extremely valuable as well (e.g., Bishop et al., 1997; Doney et al., 1998).

The BTM program also provides time-series oceanic measurements for scientific studies, often in conjunction with the BATS program. The BTM mooring site is roughly co-located with the BATS and BBOP sampling sites (Figure 1 **{**; this volume**}**). Some of the mutual goals of the BTM and BATS programs are: 1) to observe and interpret seasonal, annual, and interannual variability in the physics, biology, and chemistry of the upper ocean at an oligotrophic site; 2) to understand interrelationships among the biological, chemical, and physical characteristics of the water column; and 3) to provide data which may be used for **developing {**development**}** and testing **{**of**}** meteorological, physical, and biogeochemical models. **{**The BTM and BBOP programs are complementary in regard to optical measurements.**}** **{**The BTM site is located at 31°43'N, 64°10'W, adjacent to the primary BATS site which is located at 31°50'N, 64°10'W (Figure 1).**}** **{**This**}** The **BATS** site was chosen for the BTM **program** because 1) it is within a representative oligotrophic gyre, 2) it is in deep waters (~4530 m), yet is easily accessible, 3) rich historical data sets are available, 4) the BATS and BBOP programs provide comparative data sets, and 5) remote sensing data are collected for the Bermuda area (e.g., Nelson et al., 1999; Siegel et al., 1999b).

Time-series collected from the BTM spanning the period from June 3, 1994 through March 31, 1998 are summarized by deployment period in Table 1 (Deployments 10-12 have been completed since submission of this manuscript). The time-series of the various measurements are not continuous for several reasons: 1) new instruments were added during the program, 2) data gaps exist during periods between mooring recoveries and redeployments, 3) weather and sea-state conditions and ship-related problems have caused delays in some redeployments, 4) biofouling of sensors, and 5) failure of a mooring strength member (late November 1995). It is worth noting that the mooring has withstood severe wind and wave conditions. Interestingly, the single mooring failure occurred following passage of three hurricanes in the region in 1995 and all instruments were recovered. Three other hurricanes (Edouard, Hortense, and Lili) passed through the region in 1996, although not as close to the mooring as Felix. Thus, we consider the engineering of the mooring to be quite sound and successful. The time-series of subsurface temperature (Figures 2 and 3) illustrate the periods when data were collected. It is evident from these figures that the months of approximately May through January were the most frequently sampled (at least 3 out of the 4 years), whereas the months of February through March were only sampled once. This paper focuses on data collected from the BTM's meteorological systems, temperature sensors, MVMSs, ADCP, MORSs, and nitrate analyzers. With these data, it is possible to describe seasonal, and to a limited degree interannual, variability for the late spring-early winter period. Relatively low frequency (periods greater than 1 day) phenomena are of primary interest for this paper; however, higher frequency variability has also been captured with these data sets (e.g., Dickey et al., 1998b; Stramska and Dickey, 1998; McNeil et al., 1999).

{Here we describe physical data sets obtained from June 1994 through March 1998. Recent interdisciplinary data, collected from May 1997 through March 1998, are also highlighted in this report. The present work is placed in context by using comparisons with concurrent and previous work in the Sargasso Sea.**}**

The primary objectives of the present paper are 1) to describe instrumentation and analytical methods for deep-sea interdisciplinary moorings, 2) to present BTM data sets so that other oceanographers can also utilize these observations, and 3) to use BTM time series data to identify, quantify, and interpret key processes contributing to variability of upper ocean physics and biology on time scales from hours to the interannual. Finally, we discuss the synergism between the BATS and BTM measurement programs.

{2. Materials and Methods}

2. Instrumentation and Analytical Methods

This section is subdivided into four parts. The first describes the BTM and its instrumentation. The second focuses on new intercomparisons of BTM and shipboard data sets. The third describes meteorological analyses using model products and intercomparisons with direct BTM measurements. And, the fourth part describes statistical methods used to quantify the variability of the BTM measurements.

<u>BTM and Instrumentation</u>

A brief discussion of instrumentation and methods used for the BTM is provided here **for completeness** (see Dickey et al., 1998a and OPL website for details). The surface expression of the mooring (Figure 1) is a 2.5-m diameter buoy, which houses recording systems, controllers, telemetry systems, and batteries. The buoy tower supports an Argos transmitter to provide buoy position and telemeter data, meteorological instruments, and an optical package. The present meteorological system includes sensors for measuring winds, air temperature, shortwave radiation, relative humidity, and barometric pressure. The anemometer and radiometer are located 4.4 m above the ocean surface. Estimates of wind speed at 10 m above the surface, U_{10}, are computed using a formula presented by Large et al. (1995). Sampling regimens are summarized in Table 2. For Deployments 1-4, meteorological variables (sensors for wind speed and direction) were sampled for 10-min once per hour. The peak wind gust (3-sec value) was also recorded during the 10-min sampling period. A new weather system (sensors for wind speed and direction, relative humidity, barometric pressure, and shortwave radiation) was used for Deployments 4-9. This system sampled every minute, recording 5-min averaged data along with the highest (gust) value every minute. Gust values are important in extremely high wind/wave conditions (e.g., gales and hurricanes) because of poor exposure of the anemometer when the buoy is in wave troughs (e.g., Dickey et al., 1998b) as 5- or 10-min average data typically give underestimates by several percent. The bulk formulae for the sensible and latent heat flux and net longwave radiation calculations follow those used by Doney (1996).

Surface optical measurements include spectral downwelling irradiance at λ=412, 443, 490, 510, 555, 665, and 683 nm (Satlantic OCI-200) and downwelling scalar irradiance or photosynthetically available radiation (PAR, Li-COR 192SA). Data are collected for 20 sec at 6 Hz and are recorded every 15 min (except during the night) on a 120 Mbyte hard drive.

The depths of the various subsurface sensors and systems have varied from deployment to deployment. Nominal instrument depths are indicated in this paper; specific depths and other detailed information are given in data reports referenced on the OPL web site. A composite mooring configuration is shown in Figure 1. Several different types of sensors are used to measure physical parameters from the BTM. For example, temperature is measured with self-recording temperature systems (TPODS, Brancker, Inc.) as well as thermistors on several of the systems (generally 3.75 min averages). The multi-variable moored system (MVMS; e.g., Dickey, 1991; Dickey et al., 1991, 1993) measures physical and optical parameters (3.75 min averages). Physical data collected with the MVMS include: horizontal components of vector averaged currents (based on EG&G VMCM; Weller and Davis, 1980), temperature, and conductivity (Sea-Bird SBE-4). An uplooking acoustic Doppler current profiler (ADCP located at ~210m; RDI 150 KHz) was added for Deployment 5 and measures horizontal currents (nominally from near the surface to ~200 m) using a sampling interval of 7.5 min at multiple vertical bin depths (bin size is 3 m).

The BTM is equipped with several types of subsurface optical sensors **for a variety of applications (e.g., Dickey, 2000b; Dickey and Falkowski, 2000).** The MVMS's optical sensors include a beam transmissometer (Sea Tech; Bartz et al., 1978) which is used to determine the beam attenuation coefficient (c660), a fluorometer (Sea Tech; Bartz et al., 1988) which measures stimulated chlorophyll-*a* fluorescence, an upwelling radiance sensor (683 nm; natural fluorescence; Biospherical MRP-200; Kiefer et al., 1989), and a scalar irradiance sensor for determining photosynthetically available radiation (PAR, Biospherical QSP-200; Booth, 1976).

The MORS radiometers (Satlantic OCI-200) are located at nominal depths of 15 and 35 m and measure downwelling spectral irradiance ($E_d(\lambda)$, Satlantic OCR-200) and nadir upwelling spectral radiance ($L_u(\lambda)$, Satlantic OCI-200) at wavelengths of λ=412, 443, 490, 510, 555, 665, and 683 nm. 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 systems. Light (spectral radiometers and scalar irradiance sensors) and tilt sensors are sampled and data are stored in the same manner as the surface spectral radiometer (Table 2). The system can be operated for about four months in this configuration. The primary limiting factor at this time is biofouling. Derived products include spectral radiance and irradiance ratios, spectral diffuse attenuation coefficients, $K_d(\lambda)$ and $K_L(\lambda)$ (from $E_d(\lambda)$ and $L_u(\lambda)$ data respectively), spectral water-leaving radiance, $L_w(\lambda)$, and chlorophyll-*a* concentrations.

Chlorophyll-*a* concentrations were estimated in two ways. The first used the BTM time-series fluorometer data sets and concurrent bottle sample data obtained during BATS sampling. Separate linear fits were applied to BATS Turner chlorophyll-*a* data and BTM fluorescence for the **shallow** (defined to be < 80 m) and deeper (80 to 200 m) regions where data were obtained. **Coefficients of correlation between BATS Turner chlorophyll and BTM chlorophyll fluorescence were calculated for the shallow and deep samples, respectively. These** coefficients of correlation, r^2, varied between 0.61

and 0.76 **{**(see Figures 11a,b,c???)**}**. These values are comparable to the r^2 values obtained for regressions between BBOP fluorescence and BATS Turner chlorophyll-*a* values. The mean distance between sampling sites (i.e., mooring-BBOP or mooring-BATS stations) for Deployments 7, 8, and 9 was 6.8 km, ranging between 3.2 and 15.8 km. It was not possible to calibrate the 51 m fluorometer for Deployment 9 because of an inadequate number of ship-based data. The second method for estimating chlorophyll-*a* used the subsurface spectral radiometer data sets and an ocean color SeaWiFS algorithm (O'Reilly et al., 1998). The algorithm selected for the present analysis is **{**a**} O'Reilly et al.'s** modified version of OC2 (updated coefficients given on SeaWiFS website), which uses an empirical relation between the ratio of remote sensing reflectance, $L_u(\lambda)/E_d(\lambda)$, at 490nm to that at 555 nm, Rrs490/Rrs555, and *in situ* chlorophyll-*a* data (from SeaWiFS SeaBAM database). **{**The OC2 coefficients presented in O'Reilly et al. (1998) were modified to improve estimates of low and high chlorophyll-*a* .**}**

Time-series of nitrate concentrations were obtained using chemical analyzers (OsmoAnalyzers). The analyzers utilize osmotic pumps, which propel both sample and reagent fluids through a miniature flow-injection style manifold as described by Jannasch and Johnson (1992) and Jannasch et al. (1994). The mooring has been configured with three analyzers, one at 200 m to monitor the top of the nutricline and two at 80 m to sample for nutrient fluxes into the euphotic layer. Nitrate concentrations are sampled every 10 or 15 min (Table 2). Other BTM experimental chemical, optical, and telemetry systems have been described in Dickey et al. (1998a) and more recent BTM instrumentation is described on the OPL website.

Intercomparisons of BTM and Shipboard Data Sets

There have been relatively few intercomparisons among measurements made from different platforms (e.g., ships, moorings, drifters, satellites, and AUVs). In addition, comparisons between directly sampled data sets and model simulations are gaining attention as attempts are made to improve predictive capabilities and to extrapolate local measurements to broader regions. Comparisons among various BTM sensors are ongoing (e.g., Dickey et al., 1998a; Gilboy et al., 1999). A few new examples of intercomparisons using the present data sets are provided here.

Ship-based temperature profile measurements, which were made using a CTD as part of the BATS program, are compared with those obtained from the BTM (the latter shown as x's in Figure 4). Clearly the CTD data have superior vertical resolution whereas the mooring provides excellent temporal resolution. The comparisons are quite good for most cases although there are some interesting exceptions in the upper 50-100 m (e.g., July 16, 1997 and February 12, 1998). Explanations for the discrepancies include the fact that the shipboard measurements are not co-located with the mooring (nominal 20 km radius for BATS sampling), and thus horizontal spatial gradients lead to differences.

Profile measurements of several bio-optical properties and spectral optical variables have been conducted as part of the ship-based BBOP activity described earlier (e.g., Siegel et al., 1996). The radiometric measurements (MORS) made from the BTM have been compared with those obtained by the BBOP program. A few of these results are presented here. BBOP sampling was executed during 9 days of the roughly 3 month Deployment 7. Spectral downwelling irradiance data from the 35-m BTM MORS package are plotted as continuous records for these days in Figure

5. The nearly concurrent BBOP data are shown in the figure as x's. The three BTM MORS data curves indicate the maximum, minimum, and mean values obtained during each 20-sec sampling interval. The variability results from a number of high frequency effects (e.g., changing wave and cloud conditions). Again, considering the fact that the profile measurements were not perfectly coincident with the mooring measurements (generally within 10 kilometers), the agreement is quite good (r^2 values greater than 0.8 in Figure 5). It is worth noting that BTM radiometers are now providing hourly values of quality water-leaving radiance. BTM data collected beginning with Deployment 11 (beginning in April 1999) have been used by the NASA SIMBIOS Project to groundtruth the SeaWiFS ocean color satellite. This aspect will be described in detail in a future paper.

Meterological Model and BTM Data Intercomparisons

Wind stress, incident shortwave radiation, and net heat flux loss were modeled by Doney et al. (1998) for the years 1985 - 1997 using the 6-hourly National Center for Environmental Protection (NCEP) operational analysis and daily cloud fraction and surface insolation estimates from the International Satellite Cloud Climatology Project (ISCCP). It should be noted that the ISCCP derived estimates use averages over a square of side 280 km. Bermuda meteorological data were not included in the World Weather Watch/Global Telecommunication System (GTS) data set, which was used to drive the NCEP/NCAR climate system model. Monthly values of shortwave radiation obtained from the BTM pyranometer for March 1998, May 1997, and June 1997 compare well with those based on the aforementioned analyses by Doney et al. (1998). The BTM average insolation for these months (234 ± 71 W/m^2), the Doney et al. value (239 ± 41 W/m^2), and the average insolation measured on the island of Bermuda (231 ± 79 W/m^2 for March - June 1991) are in good agreement with the Bishop et al. (1997) insolation climatology (248 ± 69 W/m^2).

Time-series for the individual heat loss terms and total net heat loss obtained from the BTM meteorological sensors are shown along with the Doney et al. (1998) model estimates in **Figure 6a** (data were not available to model the 1998 portion). Sensible and latent heat flux values based on the BTM data were generally somewhat lower than those of the model; however, the two estimates track the variability reasonably well. The BTM data are greater in the case of the net longwave contribution, although the variability again tracks fairly well. One possible reason for the disparities in longwave estimates is the difference in the calculation of the cloud fraction. The ISCCP cloud fraction data for 1997 were unavailable for use as input for the NCAR model, so climatological values were used in their place. By contrast, the BTM derived cloud fraction estimate was calculated using a formula presented by Bishop and Rossow (1991) (based on Reed, 1977) for shortwave insolation. The total net heat flux loss (bottom panel Figure 6a) shows fair agreement between the observations and the model, although the model values are generally somewhat greater than the BTM observations (maximum differences are roughly 50 W m^{-2}). The total heat flux (incident radiation - net outgoing) time-series (monthly average) using the BTM and Doney et al. (1998) model are shown in the bottom panel of Figure 6b. The maximum differences are roughly 50 W m^{-2} in mid-July and 100 W m^{-2} in November and December. The observed and modeled wind stress time-series are shown in Figure 6b. Variability is tracked well and magnitudes are generally in good agreement. As Doney (1996) has indicated, the model analysis tends to damp effects of extreme weather events. Considering, the differences in spatial and temporal scales sampled and the necessary averaging, these results are quite encouraging. Details concerning intercomparisons of model results with other shipboard observations in the region (e.g., Isemer and Hasse, 1985a,b) are given in Doney (1996).

Statistical Methods

Horizontal eddy kinetic energy (EKE) time-series were computed by determining the long-term mean (average over 8 deployments) component velocities, subtracting the long-term means from the 2-day running mean velocities, summing the velocity component squares of the deviations, and dividing by 2. This method, which follows that of Dickson (1983), depicts motions about the mean with periods greater than 2 days and shorter than general circulation time scales. The term "eddy" is not intended to suggest closed circulation cells, though such cells do sometimes pass the site.

Broadband data have been used to compute several spectra. Spectra were computed for current speed, temperature, and chlorophyll-*a* using 512-point fast Fourier transforms (FFTs) and half-hour averaged data. The mean was removed and each data segment was tapered using a Blackman window prior to computing the FFTs.

Statistical analyses of variability in the form of auto-correlations were also performed in order to estimate the characteristic decorrelation time scales of temperature, currents, and chlorophyll. These analyses are useful for interpretation as well as evaluation of sampling schemes (e.g., How often should samples be taken?). To calculate auto-correlations, high-resolution time series of temperature, component currents, and chlorophyll were daily averaged and then a high-pass filter (60 days) was applied to remove low-frequency variability, mainly seasonal variations. The time lags for zero-crossing correlation from these time series indicate the de-correlation time scales. Cross-correlation between temperature and chlorophyll were also calculated. The high-resolution time series were daily averaged and then low-frequency variability was removed.

3. Results

Omit next paragrah ____

{Time-series collected from the BTM spanning the period from June 3, 1994 through March 31, 1998 are summarized by deployment period in Table 1. The time-series of the various measurements are not continuous for several reasons: 1) new instruments were added during the program, 2) data gaps exist during periods between mooring recoveries and redeployments, 3) weather and sea-state conditions have caused delays in redeployments, 4) biofouling of sensors, and 5) failure of a mooring strength member (late November 1995). It is worth noting that the mooring has withstood severe wind and wave conditions (Figure 7). Interestingly, the single mooring failure occurred following passage of three hurricanes in the region in 1995 and that all instruments were recovered. Three other hurricanes (Edouard, Hortense, and Lili) passed through the region in 1996, though not as close to the mooring as Felix. Thus, we consider the engineering of the mooring to be quite sound and successful. The time-series of subsurface temperature (Figure 2) illustrate the periods when data were collected. It is evident from these Figures 2 and 3 that the months from approximately May through January were the most frequently sampled (at least 3 out of the 4 years), whereas months from February through

March were only sampled once. This report focuses on data collected from the BTM's meteorological systems, temperature sensors, MVMSs, ADCP, MORSs, and nitrate analyzers. With these data, it is possible to describe seasonal, and to a limited degree interannual, variability for the late spring-early winter period. Relatively low frequency (periods greater than 1 day) phenomena are of primary interest for this paper; however, higher frequency variability has also been captured with these data sets (e.g., see Figure 2).**}**

Seasonal Description of Physical Data for Years 1994 - 1998

The following general descriptions of the BTM data sets utilize a seasonal chronology in order to compare and contrast the physical seasonal cycles when sufficient data were available. For convenience, we have computed statistics on a monthly basis **{**(included on CD-ROM)**}** and used the following seasonal convention: spring (April - June), summer (July - September), autumn (October - December), and winter (January - March). **Many of the figures show only the more recent data (Deployments 7 - 9); however, figures and data for the first nine deployments are included on the accompanying CD-ROM disk.**

Spring (April-June):

Wind speed time-series are shown in Figure **7**. Monthly mean winds speeds were ~5-6 m s^{-1}. Throughout the entire record, it is apparent that synoptic scale weather systems typically passed through the site every few days. Winds in excess of 14 m s^{-1} occurred a few times during the spring of each year. Incident PAR time-series (1-h averages) are shown in Figure **8**. There was considerable variability because of varying cloud conditions (e.g., up to a factor of about 4 during mid-day).

The seasonal cycle of the upper ocean is most evident in the temperature time-series shown in Figures **2 and 3**. The Figure 2 time-series must be carefully examined as depths of temperature sensors changed between deployments. A color-coded bar is included to facilitate intercomparisons of the various depths. Deeper temperature features are more apparent in Figure 3. Besides the seasonal cycle, it is evident from the complete record that considerable variability occurred **even on time scales shorter than** a day (see Figures **2, 6, 7 and 8**; e.g., diurnal cycle in shallowest temperature records, storm events including hurricanes; Dickey et al., 1998b) and for as long as a month or more (mesoscale features including eddies; McGillicuddy et al., 1998; McNeil et al., 1999). We report two mixed layer depths (Figure **9**) using: 1) a criterion of 0.3 °C ($MLD_{0.3}$), which is comparable to the method used in BATS reports and papers, and 2) a 1.0 °C criterion ($MLD_{1.0}$). The latter provides a deeper estimate of the mixed layer depth. Larger differences between the two indicate greater stratification. The 0.3 °C criterion is typically more useful for examining conditions necessary for spring blooms (e.g., Stramska and Dickey, 1993; Dickey et al., 1994), whereas the 1.0 °C criterion enables identification of deep winter mixing with modest upper layer stratification. The mixed layer depth temperatures (T_{MLD}) were obtained by using the temperatures of the shallowest thermistors (~10-14 m for Deployments 1-4 and ~2-4 m for Deployments 5-9). The minimum recorded T_{MLD} values in 1995 and 1996 were ~19 °C in the early springtime (April) and the maximum values were ~29 °C in late summer (August), respectively. The maximum daily average $MLD_{0.3}$s ($MLD_{1.0}$s) were >250 m (>250 m) [note: the deepest thermistor used in calculation is at

250 m] in March 1998 and the minimum values were ~5-10 m (~8-13 m) in the late summers. It should be noted that interpolations were used for deep mixed layers where the resolution was coarse.

The primary phenomenon of relevance to the springtime period is the initiation of seasonal stratification and warming of the near-surface layer. As evidenced by the **{**1995 and 1996**}** time-series of temperature (Figures **2 and 3**) and mixed layer depth (Figure **9**), the evolution of stratification was not a steady progression. This is apparent in the April-May temperature time-series, which show dramatic decreases in near-surface temperatures and reduced stratification before seasonal stratification resumes. Two processes which **{**can**}** contribute to these observations are intense wind mixing (often accompanied by cool, relatively dry air and possibly convection) and cold mesoscale features. **Relatively cold and warm** mesoscale features **{**and **possibly** warm outbreak waters**}** (earlier described for the general region by Cornillon et al., 1986, and Dickey et al., 1991, 1993) are apparent in our time-series. These are most evident by noting the periods when the subsurface temperatures decline to values of around 19 °C **{**(e.g., mid-July 1995)**}**, indicative of subtropical mode-water or 18 °C water masses (Worthington, 1976) and by persistent subsurface temperature elevations of a few degrees **{**(e.g., late October 1995)**}**, respectively. **The latter case can lead to earlier onset of stratification.** The mode-water is created in the winter by deep convective mixing (e.g., Talley, 1982). In addition, current time-series (1-day averages; Figure **10**) indicate considerable variability associated with **both relatively cool and relatively warm** mesoscale features **{**in the spring of 1995 and to a lesser extent in 1996**}**.

{Horizontal eddy kinetic energy (EKE) time-series were computed by determining the long-term mean (average over last 8 deployments) component velocities, subtracting the long-term means from the 2-day running mean velocities, summing the velocity component squares of the deviations, and dividing by 2. This method, which follows that of Dickson (1983), depicts motions about the mean with periods greater than 2 days and shorter than general circulation time scales. The term "eddy" is not intended to suggest closed circulation cells, though such cells do sometimes pass the site.**}** The results of {these} **horizontal eddy kinetic energy** computations are shown in time-series (Figure **11**) and tabular forms by deployment (Table 3) and by season (Table 4) for the nominal depths of 45 and 71 m. The mean climatology for eddy kinetic energy was computed by ensemble averaging the 2-day running mean eddy kinetic energy for the entire time-series record (see Figure **11 for last two years**). The mean currents for the entire time-series are quite low (less than 3.5 cm s^{-1} at 45 m and less than 0.6 cm s^{-1} at 71 m). The mean currents evaluated for each deployment and by season are not unexpectedly somewhat greater because of the **selected** averaging periods. **For the springtime,** about 75% of the TKE resided in EKE at 45 m and ~82% at 71 m (Table 4).

For the May 1995 period, it is likely that both intense wind mixing and mesoscale features contributed to interruptions in the onset of springtime stratification as indicated by the high winds and the turning and strength of the velocity vectors. A general inference is that the timing of the onset of springtime stratification and spring blooms at our site is highly dependent on both the specific year's meteorological conditions and the presence or absence of significant **warm or cool** mesoscale features (note differences between timing of onset and persistence of stratification in springs of 1995 and 1996). **The use of continuous sampling from moorings is essential to capture this important, but ephemeral transition which likely varies up to about a month.**

Summer (July-September):

Data were collected from the BTM during all the summers of 1994 -1997. The build up of seasonal stratification is clearly evident (Figures 2 and 3); however, major interruptions in the trends were caused by passages of synoptic scale weather systems and mesoscale features. Particularly dramatic examples occurred during the summer of 1995 as a major mesoscale feature passed the mooring (centered on July 15), followed only a month later by Hurricane Felix (beginning on August 15). Both events have been documented and will not be detailed here (for Hurricane Felix: see Dickey et al., 1998b, Nelson, 1998, and Zedler, 1999; for the eddy, see McGillicuddy et al., 1998; McNeil et al., 1999). The mean wind speeds (see Figure 7) during the summer months (~4-6 m s^{-1}) were somewhat lower than those of the springtime. However, the greatest wind event (U_{10} winds in excess of 38 m s^{-1}) occurred with the very near passage of Hurricane Felix on August of 1995. Bermuda was near the tracks of other hurricanes in 1995 (e.g., Hurricanes Luis and Marilyn are evident in September wind time-series), although no others came as close to the BTM site as Felix. Other notable high wind events are evident in September and October 1996 (three occasions of instantaneous winds greater than 30 m s^{-1}). Incident PAR time-series (Figure 8) again indicate large variations caused by changing cloud conditions.

Seasonal heating, synoptic-scale wind-forced events, and mesoscale features contributed to the temperature variability evident during the summers (Figures 2 and 3). Near-surface temperatures, T_{MLD}, generally increased by about 7 °C from early spring to late summer. Data from the present time-series and BATS reports indicate that the $MLD_{0.3}$ shoaled from depths of roughly 150-250 m to 10-15 m (Figure 9). Occasional warm and cold mesoscale features (e.g., see deeper temperature, current, and EKE records; Figures 2, 3, 10, and 11) are evident. As noted for the springtime period, stratification built and waned on several occasions over quite short time periods, which underscores the need for nearly continuous observations to avoid undersampling (e.g., aliasing) and to capture and interpret important event scales of variability which can affect the seasonal cycle (e.g., Dickey, 1991; Wiggert et al., 1994). For the summer season, the fraction of EKE to TKE was about 57% at 45 m and over 84% at 71 m. The difference between the fractions for the two depths may be related to the intensity of surface forcing by major wind events including hurricanes or low frequency variations during this season. It is noteworthy that considerable variability was evident in the summertime in near-surface temperature records due to diurnal heating (see shallowest temperature data in summers; Figure 2). Inertial oscillations are also evident in most of our current records; however, those associated with Hurricane Felix were most remarkable, reaching speeds of over 100 cm s^{-1} (Dickey et al., 1998b). In addition, hurricane-forced large amplitude (~15 m) isotherm displacements associated with near-inertial internal gravity waves (process called "inertial pumping"; e.g., Price, 1983) were recorded in the thermocline in the wake of Hurricane Felix (see Dickey et al., 1998b and Zedler, 1999).

Autumn (October - December):

Winds were somewhat greater during the autumn (mean monthly values of ~7 m s^{-1}) than during the spring or summer periods and heat loss terms in the heat budget increased in importance while solar insolation declined. The breakdown of seasonal stratification began in September for each of the years except for 1995 when Hurricane Felix lead to an early breakdown (Figure 2). Interestingly, the peaks in upper ocean temperature occurred toward the end of August to early September in 1994, 1996, and 1997. However, the passage of Hurricane Felix in August 1995 clearly influenced the temperature evolution at the site in 1995. The peak annual surface temperature occurred just prior to the passage of Felix. Moderate seasonal stratification then resumed and continued until mid-October, but near-surface temperatures did not return to values as high as they were before the hurricane; secondary annual peak occurred in mid-September (Figure 2). It does not appear that the wind events occurring in the summer and early autumn of 1996 had major effects on the temperature structure, perhaps because of their relatively short duration and the presence of strong near-surface stratification.

Near-surface temperatures generally decreased by about 7 °C from their seasonal peak values in late summer, falling to those observed in early December (Figure 2). $MLD_{0.3}$ increased from ~15-20 m in early September 1998 to ~100 m in December while $MLD_{1.0}$ increased from ~20 m to ~125 m (Figure 9). Some of the largest currents observed at the site occurred during late October - early November 1995. These were apparently associated with a major mesoscale feature, which is also evident in the subsurface temperature time-series as a very warm water mass (Figures 2 and 3). The fraction of EKE to TKE was about 59% at 45 m and over 74% at 71 m for this period (Table 4). As was the case for the build up of seasonal stratification, the deepening of the mixed layer and the breakdown of stratification often occurred in a sporadic manner because of the episodic nature of both the atmospheric forcing and the passages of mesoscale features.

Interestingly, the subsurface physical and biological time series reveal complex features as evidenced in data collected from October 26, 1996 through January 4, 1997 (Figure 12). During this period, near surface temperature decreased monotonically while temperatures at 71, 104, and 154 m displayed large variations (up to ~4 °C). The current data at 81 and 153 m show that strong mesoscale features passed during the period, first with cyclonic and then anti-cyclonic rotation. Curiously chlorophyll fluorescence at 71 m more than doubled as the warm subsurface feature passed. This is counter to the more typical elevation of chlorophyll associated with cooler waters. The explanation for these observations is not evident, but likely advection of an unusual water mass is a root cause.

Winter (January - March):

Our time-series are most limited during the winter period. Thus, it is not possible to intercompare interannual results for this period. However, data were collected in January during three of the years of the study. The winds were somewhat greater (~7-9 m s^{-1}) during the winter of 1998 than any of the other seasons. The seasonal increase in solar insolation following the winter solstice is evident, and considerable variability was caused by clouds associated with frontal passages and storms. Upper layer temperatures generally decreased rather slowly as the MLD continued to deepen (see 1998 record); however, considerable variability is evident in the MLD time-series, which is again related to meteorological and mesoscale events (Figures 2, 3, 7, and 9). Less than half of the TKE resided in EKE for the winter (Table 4). This is a considerably smaller fraction than for the other seasons; however, general inferences should be guarded because of the record lengths.

Summary of Seasonal Variability

The seasonal cycle was clearly the largest signal in temperature above the permanent thermocline. In the summer and early fall, the diurnal temperature cycle was often evident within the upper layer and inertial oscillations are sometimes observed in the thermocline. Intense wind forcing caused strong mixing of the upper layer and inertial current oscillations; mesoscale features also contributed strongly to the observed variance in the upper layer. Longer records are required to determine if there are appreciable seasonal, interannual, and interdecadal signals in eddy kinetic energy at the study site. However, mesoscale features were ubiquitous and annually contributed over 63% of the kinetic energy at 45 m and over 78% at 71 m (Table 3). The difference between these was likely caused primarily by the greater contribution of wind forcing to the TKE at 45 than at 71m. Differences in EKE values at 45 and 71 m were generally less during the winter and early spring when the mixed layer was deep and greater during the remainder of the year when the mixed layer was shallower. Effects of intense mixing events and passages of mesoscale features on the biological and optical seasonal cycle can be dramatic.

Description of Interdisciplinary Data Collected: May 1997 - March 1998

The most recent observations (Deployments 7-9) are highlighted below as they were the most comprehensive (greatest number of interdisciplinary measurements, spanning 11 months). In addition, the largest number of developmental sensors and systems were deployed on the BTM during this period. Deployment 7 spanned the late-spring through mid-summer period; Deployment 8, the mid-summer through autumn period; Deployment 9, the winter period. The summer period was characterized by the lowest winds (mean monthly averages of 4-5 m s^{-1}) and the winter had the greatest winds (mean monthly averages of 7-9 m s^{-1}) (wind stress shown in Figure 6b). The air temperature time-series shows a regular seasonal cycle, peaking in July-August at ~27 °C with minimum temperatures in winter of 15 °C. The air temperature cycle lagged the solar insolation cycle by about 2 months. Diurnal variability was evident in both the air temperature and T_{MLD} records during the summer, and synoptic scale variability was pronounced during the winter. The relative humidity was especially variable (50-100%) except during the summer, typically tracking synoptic-scale weather patterns.

The net heat flux loss was estimated using our data by applying standard bulk empirical formulae as described earlier (e.g., Doney, 1996). The variability in the latent and net heat fluxes was well correlated with relative humidity, tracking synoptic weather systems. The non-solar net heat flux loss (Figure 6) was greatest during the autumn through winter period (monthly means ranging from about -190 to -280 W m^{-2}) and smallest during the spring and summer (about -100 W m^{-2}).

Horizontal current time-series, which were derived from a subset of the ADCP data, are shown for Deployments 7-9 in Figure 10. There was considerable variability in the horizontal current speeds. The months of lowest average current speeds at 45-m depth were July and August (17 cm s^{-1}) and greatest monthly current speeds occurred from September through December and in May (23-29 cm s^{-1}). The greatest shear generally occurred in the transition region between the MLD and the thermocline. The direction of the currents was fairly uniform with respect to depth below the MLD. Mesoscale features were evident during all three deployments. However, the fractions of EKE to TKE were lower for both the 45- and 71-m depths for Deployment 8 than for any other deployment (30%; Table 3). The difference between EKE at 45- and 71-m was the greatest for Deployment 8. This is likely the result of shallow stratification, which effectively separated the upper layer from the influence of the deeper mesoscale features.

Chlorophyll-*a* time-series for various depths are shown in Figure 13. The 15-m and 35-m chlorophyll-*a* time-series are based on the BTM spectral radiometer data and the SeaWiFS algorithm described earlier. These particular estimates appear to be too great by a factor of 2 or more in some cases based on historical data and our other measurements. The problem is likely related to the SeaWiFS algorithm, which is designed to encompass chlorophyll-*a* values from roughly 0.02 μg/l to 32.79 μg/l and is known to provide poorer estimates in the extremes. The other chlorophyll-*a* time-series are based on stimulated fluorometer data. There is considerable uncertainty in the absolute levels of chlorophyll-*a* concentrations because of the methodologies; however, it is likely that the variability is reasonably well represented. One of the strengths of the mooring measurements is their ability to record short time-scale, transient episodic events as well as diel cycles, which are clearly evident in Figure 13. In particular, diel variability was generally evident at depths from 15 to 51 m and at times even 80 m (inertial oscillations sometimes confound this interpretation for deeper depths; see McNeil et al., 1999). It appears that a subsurface chlorophyll-*a* maximum developed in the springtime, which is consistent with historical and concurrent BATS and BBOP data sets.

Relatively large values of chlorophyll-*a* were evident in late May down to 45 m. Pulse-like chlorophyll-*a* bursts (often lasting for a few days) were also apparent during all deployments (Figure 13). These are likely related to passages of cold mesoscale features, but also possibly on occasion from warm mesoscale features as indicated above. This is supported by our earlier analyses (e.g., Dickey et al., 1998a; McGillicuddy et al., 1998; McNeil et al., 1999), which suggest that at ~80 m there is often a strong correlation between increases in nitrate concentration, decreases in temperature, and increases in chlorophyll-*a*. This situation is also indicated in Figure 13a by inspecting the nitrate, temperature and chlorophyll-*a* time-series.

The 1% light level depth (Figure 9) was nearly constant (~100 m) over Deployments 7-9, which is consistent with previous results (e.g., BATS data sets). From June through November, the 1% light level depth was 50 m or more deeper than the mixed layer depth. Nutrient limitation was more important than light limitation for primary productivity during these seasons. In the winter, the mixed layer was often considerably deeper than the 1% light level depth, although there were some exceptions. Time-series based on the 35-m spectral downwelling irradiance and upwelling radiance data are shown in Figure 14 for Deployment 7 (only 490 nm data are displayed). The diffuse attenuation coefficient for 490 nm shows variability consistent with chlorophyll-*a* in the upper layer.

4. Discussion

It is interesting to note that the long-term mean flow at the site is very low (less than 4 cm s^{-1} at 45 m and less than 1 cm s^{-1} at 71 m; see Table 3). These values are generally consistent with other relatively long-term observations in the region obtained by Owens et al. (1982) who reported mean values of about 4 ± 4 cm s^{-1} at 250m over 445 days at the Polymode site (31°00'N, 69°30'W). The present and future results should be useful for interpretation of sediment trap data sets, which are collected near the BTM and BATS sites (e.g., Conte et al., this volume). In

particular, models of sinking particle trajectories (Siegel and Deuser, 1997) clearly need data such as those collected with the BTM for input and verification.

The maximum monthly mean surface temperatures, SSTs, during the BTM observations 1994-1998 were 27 - 28 °C. The range of maximum SST values reported for the complete 10-year BATS data sets is about 26 - 29°C. The minimum SST value obtained during our only winter observations (1997-1998) was about 20 °C which is very near the typical minimum BATS SST value. The minimum monthly MLDs obtained from the BTM data were $MLD_{0.3}$~12 m and $MLD_{1.0}$~14 m, occurring in the summer period. These are quite consistent with the BATS values. The deepest MLDs using both criteria occurred during the winter of 1998 and are well within the range of deepest MLDs (250 - 300 m) recorded by BATS investigators. Although our chlorophyll-*a* time-series are not continuous over the four years, it is interesting to note that the BTM and BATS chlorophyll-*a* values estimated during the passage of the July 1995 eddy are apparently the second greatest of the entire BATS program (over a decade).

The BTM nitrate data have shown variability as high as that of the concurrently measured physical parameters, and apparently even higher than chlorophyll-*a* (Figure 13a). Nitrate concentrations at 80m peaked to over 2 μM for up to several days in May and June 1997. Nitrate was measurable (>0.1 μM) during times when the temperature dropped below 19.2° C. The nutrient supply to the mixed layer appears to be primarily controlled by physical processes. The biological response within the mixed layer, as indirectly measured by chlorophyll-*a* fluorescence, appears to have a slower response (likely because of the time-scale of phytoplankton growth). Unlike the more clearly defined nutrient signal observed during the passage of the July 1995 eddy (McNeil et al., 1999), the May-June 1997 signal may be more representative of the outlying edge of an eddy or the deeper intrusion of mode water.

Mesoscale features have been previously suggested as playing an important role for new production and phytoplankton dynamics near Bermuda (e.g., Jenkins, 1988). More recently, the influence of mesoscale features was estimated by McGillicuddy et al. (1998) using 1) the present BTM data set (July 15 eddy event; McNeil et al, 1999), 2) shipboard observations, 3) TOPEX/Poseidon altimetry data (using correlations with isopycnal displacements at 300 m; Siegel et al., 1999a; McGillicuddy et al., 1999), and 4) a regional eddy-resolving model (McGillicuddy and Robinson, 1997). The conclusion of McGillicuddy et al. (1998) is that the flux of nutrients induced by mesoscale eddies may be sufficient to balance the nutrient budget of the Sargasso Sea. Long-term direct measurements, such as those described here, along with other methods as described in McGillicuddy et al. (1998), will need to be used to verify this important assertion. The curious occurrence of high chlorophyll concentrations with warm water features (as described earlier) warrants more investigation as well. It should also be noted that we can close chemical and physical budgets only with multiple platforms.

The present data sets contain several synoptic scale wind events, which likely result in pulse-like nutrient fluxes into the euphotic layer and thus phytoplankton blooms. Previous work during the spring 1985 Biowatt study (few degrees north and west of Bermuda) also illustrated such effects (Marra et al., 1990). Diel variability in temperature, chlorophyll-*a*, and beam attenuation coefficient are also evident in several of the BTM records, particularly after the setup of stratification. Earlier work (during ODEX in the North Pacific, Siegel et al., 1989; during Biowatt, Hamilton et al, 1990; and MLML, south of

Iceland, Stramska and Dickey, 1992) has focused on this time scale, showing similar results.

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{A detailed examination of the higher frequency variability (e.g., internal gravity waves) and co-variability of our data is beyond the scope of the present report. However, we have used the broadband data to compute several spectra. Spectra are shown for current speed, temperature, and chlorophyll-*a* using 512-point fast Fourier transforms (FFTs) and half-hour averaged data (Figures 15-17). The mean was removed and each data segment was tapered using a Blackman window prior to computing the FFTs. However some spectra are described here. The speed spectra are shown in Figure 15 for depths of 27, 45, and 150 m for Deployments 7-9 to allow comparison with respect to both depth and season. It should be noted that at frequencies greater than about 0.25 cph, the ADCP speed spectra level off. This is not the case for comparable spectra computed using the MVMS (VMCM) and ACM data (Gilboy et al., 1999). It is likely that the leveling off is caused by instrumental noise of the ADCP (Irish et al., 1995), thus spectral values in this range should be ignored. Temperature spectra are presented in a similar fashion in Figure 16. All spectra are useful for examining variability at time scales longer than a few hours. The diurnal and inertial periods (period of 22.8h or frequency of 0.0438 cph) are near each other, and are thus complicating factors for interpreting our spectra. Biological signals in the upper ocean are typically linked to the diurnal light cycle.

Current speed spectra (Figure 15) for 27 and 45 m depths show pronounced peaks in the vicinity of the inertial frequency. Not unexpectedly, this peak is much weaker at 150 m as the source of inertial forcing is at the surface (mesoscale features are relatively more important at depth). Broadening (half-width) and shifting of the inertial energy peaks depends on the degree of mesoscale activity encountered at the mooring site during the particular deployment (e.g., Granata et al., 1995; McNeil et al., 1999). The energy in the sub-inertial range is likely dominated by mesoscale features. Energy in the near-inertial and sub-inertial frequency ranges generally decreases with depth, especially below the mixed layer. Near-inertial energy at the 27-m depth is quite similar for Deployments 7-9, however energy in the subinertial range is about a factor of 2 lower at 150 m than at 27 m except for Deployment 9. This is likely because the mixed layer is very deep (100-150 m) during this period. The semi-diurnal tidal flows are typically an order of magnitude smaller than the inertial currents.

The temperature autospectra are shown in Figure 16. The shapes of the spectra are similar to the speed autospectra in the subinertial range. There are peaks near 24 h in the 15-m autospectra during Deployments 7 and 8, which is consistent with the aforementioned diurnal temperature signal in the near-surface time-series. Although these peaks do not contain as high of a fraction of the variance as for the currents, they are still significant relative to higher frequencies. The diurnal signature is not evident during Deployment 9 because the mixed layer is deep. Finally, the chlorophyll-*a* autospectra for the 45-m depth are shown in Figure 17. The diurnal peak is evident for Deployments 8 and 9, though not for Deployment 7. Processes contributing to the bio-optical diurnal signals include cell division cycle, cell size and refractive index modification, photosynthetic parameters, carbon incorporation rates, cellular pigment concentration, and chlorophyll-*a* fluorescence (e.g., Siegel et al., 1989; Ackleson et al., 1990; Hamilton et al., 1990; Stramska and Dickey, 1992).

Intercomparisons

There have been relatively few intercomparisons among measurements made from different platforms (e.g., ships, moorings, drifters, satellites, and AUVs). In addition, comparisons between directly sampled data sets and model simulations are gaining attention as attempts are made to improve predictive capabilities. Comparisons among various BTM sensors are ongoing (e.g., Dickey et al., 1998a; Gilboy et al., 1999). A few examples of intercomparisons using the present data sets are provided here.

Wind stress, incident shortwave radiation, and net heat flux loss were modeled by Doney et al. (1998) for the years 1985 - 1997 using the 6-hourly National Center for Environmental Protection (NCEP) operational analysis and daily cloud fraction and surface insolation estimates from the International Satellite Cloud Climatology Project (ISCCP). It should be noted that the ISCCP derived estimates use averages over a square of side 280 km. Bermuda meteorological data were not included in the World Weather Watch/Global Telecommunication System (GTS) data set, which was used to drive the NCEP/NCAR climate system model. Monthly values of shortwave radiation obtained from the BTM pyranometer for March 1998, May 1997, and June 1997 compare well with those based on the aforementioned analyses by Doney et al. (1998). The BTM average insolation for these months (234 ± 71 W/m^2), the Doney et al. value (239 ± 41 W/m^2), and the average insolation measured on the island of Bermuda (231 ± 79 W/m^2 for March - June 1991) are in good agreement with the Bishop et al. (1997) insolation climatology (248 ± 69 W/m^2).

Time-series for the heat loss terms and total net heat loss obtained from the BTM meteorological sensors are shown along with the Doney et al. (1998) model estimates in Figure 17a (data were not available to model the 1998 portion). Sensible and latent heat flux values based on the BTM data were generally somewhat lower than those of the model; however, the two estimates track the variability reasonably well. The BTM data are greater in the case of the net longwave contribution, although the variability again tracks fairly well. One possible reason for the disparities in longwave estimates is the difference in the calculation of the cloud fraction. The ISCCP cloud fraction data for 1997 were unavailable for use as input for the NCAR model, so climatological values were used in their place. By contrast, the BTM derived cloud fraction estimate was calculated using a formula presented by Bishop and Rossow (1991) (based on Reed, 1977) for shortwave insolation. The total net heat flux loss (bottom panel Figure 17a) shows fair agreement between the observations and the model, although the model values are generally somewhat greater than the BTM observations (maximum differences are roughly 50 W m^{-2}). The total heat flux (incident radiation - net outgoing) time-series (monthly average) using the BTM and Doney et al. (1998) model are shown in the bottom panel of Figure 17b. The maximum differences are roughly 50 W m^{-2} in mid-July and 100 W m^{-2} in November and December. The observed and modeled wind stress time-series are shown in Figure 17b. Variability is tracked well and magnitudes are generally in good agreement. As Doney (1996) has indicated, the model analysis tends to damp effects of extreme weather events. Considering, the differences in spatial and temporal scales sampled and the necessary averaging, these results are quite encouraging. Details concerning intercomparisons of model results with other shipboard observations in the region (e.g., Isemer and Hasse, 1985a,b) are given in Doney (1996).

Ship-based temperature profile measurements, which were made using a CTD as part of the BATS program, are compared with those obtained from the BTM (the latter shown as x's in Figure 18). Clearly the CTD data have superior vertical resolution whereas the mooring provide excellent temporal resolution. The comparisons are quite good for most cases although there are some interesting exceptions in the upper 50-100 m (e.g., July 16, 1997 and February 12, 1998). Explanations for the discrepancies include the fact that the shipboard measurements are not co-located with the mooring (nominal 20 km radius for BATS sampling), and thus horizontal spatial gradients lead to differences.

Profile measurements of several bio-optical properties and spectral optical variables have been conducted as part of the ship-based BBOP activity described earlier (Siegel et al., 1996). The radiometric measurements (MORS) made from the BTM have been compared with those obtained by the BBOP program. A few of these results are presented here. BBOP sampling was executed during 9 days of the roughly 3 month Deployment 7. Spectral downwelling irradiance data from the 35-m BTM MORS package are plotted as continuous records for these days in Figure 19. The nearly concurrent BBOP data are shown in the figure as x's. The three BTM MORS data curves indicate the maximum, minimum, and mean values obtained during each 20-sec sampling interval. The variability results from a number of high frequency effects (e.g., changing cloud conditions). Again, considering the fact that the profile measurements were not perfectly coincident with the mooring measurements (generally within 10 kilometers), the agreement is quite good (r^2 values greater than 0.8 in Figure 19). Degradation of moored radiometric sensors and relatively infrequent calibration remain areas of concern. However, temporal aliasing of ship-based measurements is also problematic. Thus, nearly continuous time-series such as those obtained with the BTM, complemented with ship-based and other measurements, are critical**.}**

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A detailed examination of the higher frequency variability (e.g., internal gravity waves) is beyond the scope of the present report. However, we have used the broadband data to compute several spectra (Figures 15-17) to summarize the scales of natural variability. The current speed spectra are shown in Figure 15 for depths of 27, 45, and 150 m for Deployments 7, 8, and 9 to allow comparison with respect to both depth and season. It should be noted that at frequencies greater than about 0.25 cph, the ADCP speed spectra level off. This is not the case for comparable spectra computed using the MVMS (VMCM) and ACM data (Gilboy et al., 2000). It is likely that the leveling off is caused by instrumental noise of the ADCP (Irish et al., 1995), thus spectral values in this range should be ignored. Temperature spectra are presented in a similar fashion in Figure 16. All spectra are useful for examining variability at time scales longer than a few hours. The diurnal and inertial periods (period of 22.8h or frequency of 0.0438 cph) are near each other, and are thus complicating factors for interpreting our spectra. Biological signals in the upper ocean are typically linked to the diurnal light cycle, but deeper signals may be at the inertial period (see McNeil et al., 1999).

Current speed spectra (Figure 15) for 27 and 45 m depths show pronounced peaks in the vicinity of the inertial frequency. Not unexpectedly, this peak is much weaker at 150 m as the source of inertial forcing is at the surface (mesoscale features are

typically more important at depth). Broadening (half-width) and shifting of the inertial energy peaks depends on the degree of mesoscale activity encountered at the mooring site during the particular deployment (e.g., Granata et al., 1995; McNeil et al., 1999). The energy in the sub-inertial range is likely dominated by mesoscale features. Energy in the near-inertial and sub-inertial frequency ranges generally decreases with depth, especially below the mixed layer. Near-inertial energy at the 27-m depth is quite similar for Deployments 7-9, however energy in the subinertial range is about a factor of 2 lower at 150 m than at 27 m except for Deployment 9. This is likely because the mixed layer is very deep (100-150 m) during this period. The semi-diurnal tidal flows are typically an order of magnitude smaller than the inertial currents.

The temperature autospectra (Figure 16) show shapes similar to the speed autospectra in the subinertial range. There are peaks near 24 h in the 15-m autospectra during Deployments 7 and 8, which is consistent with the aforementioned diurnal temperature signal in the near-surface time-series. Although these peaks do not contain as high of a fraction of the variance as for the currents, they are still significant relative to higher frequencies. The diurnal signature is not evident during Deployment 9 because the mixed layer is deep. Finally, the chlorophyll-*a* autospectra for the 45-m depth are shown in Figure 17. The diurnal peak is evident for Deployments 8 and 9, but not for Deployment 7. Processes contributing to the bio-optical diurnal signals include cell division cycle, cell size and refractive index modification, photosynthetic parameters, carbon incorporation rates, cellular pigment concentration, and chlorophyll-*a* fluorescence (e.g., Siegel et al., 1989; Ackleson et al., 1990; Hamilton et al., 1990; Stramska and Dickey, 1992).

Another related and useful statistical analysis involves computation of auto-correlations (procedur described earlier). The first zero crossing of these functions is generally interpreted as a characteristic de-correlation time scale. The data collected during Deployments 7-9 were used to produce the auto-correlation functions illustrated in Figure 18a and b. The horizontal current de-correlation scales vary slightly with depth. The de-correlation scales lie in the range of 10 to 15 days. The temperature auto-correlation functions are shown in Figures 18c and display a similar range of de-correlation scales. It is interesting that the 180 m zonal velocity component and 157 m temperature de-correlation scales are the shortest (~8-10 days). It is not obvious why this is the case. The auto-correlation functions for the 80 and 200 m chlorophyll time series are shown in Figure 18d. Again, the deeper record (200m) has a shorter de-correlation scale than the shallower (80 m) record; around 5 compared to 10 days.

A final statistical analysis using the Deployment 7-9 data sets involves the computation of the cross-correlation of temperature and chlorophyll (method described above). The time series of temperature and chlorophyll (with removal of low frequency variability including seasonal cycle) are shown in Figure 19. An inverse relation between temperature and chlorophyll is generally evident as expected (low temperature, high nutrient concentration, high chlorophyll). The characteristic time lag between temperature and chlorophyll is about 1 day as indicated in the right panel of Figure 19.

These analyses highlight two important points: 1) there is considerable variability associated with physical and biological processes at time scales less than two weeks

and 2) there is need for relatively high frequency sampling to address biogeochemical processes.

5. Summary

The present results characterize the seasonal cycle and high frequency variability at the BTM site near Bermuda. There is evidence of interannual variability in the seasonal cycle based on our present results. There is clearly a need for very long (decades) time-series to study important phenomena such as the North Atlantic Oscillation (e.g., Wunsch, 1999). The use of high frequency sampling reveals that the timing and character of the onset and cessation of seasonal stratification is affected not only by the solar insolation cycle, but also the passages of synoptic-scale weather patterns of varying intensity (including hurricanes) and mesoscale features including both cold and warm mesoscale features. The importance of such relatively high frequency processes has been previously noted by several investigators (e.g., Dickey et al., 1993; Doney, 1996; Doney et al., 1996; McGillicuddy et al., 1998; Doney, 1999) **and is quantified by our present de-correlation calculations**. **It is interesting that other papers in this volume (e.g., Steinberg et al., Siegel et al., Nelson et al.) point to likely uncertainties arising from temporal undersampling and assumptions of steady-state conditions applied to quasi-random, non-linear, and episodic processes which are often out of equilibrium.**

There are several advantages and disadvantages associated with shipboard versus mooring sampling for long-term time series. There have been few opportunities for comparing and contrasting the respective derived data and methodologies. Thus, it is worthwhile to discuss this aspect based BATS and BTM results. Some of the key advantages of the shipboard method include: 1) ability to do a large number of measurements which are technically feasible only from shipboard at present, 2) capability of observing slowly varying patterns of change, and 3) excellent vertical resolution. Disadvantages include: 1) relatively poor temporal resolution (aliasing and undersampling), 2) demanding of man-power and shiptime, and thus expensive. Advantages of the mooring approach include: 1) excellent temporal resolution with the potential for very long-term records (important for models used to attempt to understand variability on scales from hours to several years), 2) relatively few personnel and limited shiptime needed, and 3) capability of telemetering data in near real-time. Disadvantages include: 1) the number of variables is limited (but increasing) and 2) relatively poor vertical resolution (unless autonomous profilers used). Mooring and shipboard sampling are synergistic, and both will be necessary to provide data with sufficient variety and resolution to study problems such as biogeochemical cycling and episodic and long-term physical variability. Neither methodology captures horizontal variability synoptically.

The present data, which are available on an accompanying CD-ROM, should be useful for a variety of future analytical and modeling activities. It is anticipated that the addition and expansion of physical, biogeochemical, and bio-optical sensors on moorings like the BTM along with increasingly powerful remote sensing and AUV capabilities used in conjunction with numerical models (e.g., Doney, 1999) can be utilized to further advance our knowledge of physical and biogeochemical processes and their coupling in the open ocean.

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2	Sept. 16, 1994 - Jan. 28, 1995
3	Apr. 5 - Aug. 23, 1995
4	Aug. 29 - Nov. 22, 1995
5	Mar. 26 -Aug. 15, 1996
6	Aug. 21, 1996 - Jan. 22, 1997
7	May 3 - July 30, 1997
8	Aug. 8 -Nov. 20, 1997
9	Nov. 26, 1997 - Mar. 31, 1998

Table 1. BTM deployment periods.

Instrument Package	Instruments	Sampling
METS	Campbell Scientific: rel. hum., temp., bar. press. Li-COR: SW rad. RM Young: winds	10 min ave. for Deploy. 1-4; 5 min ave. for Deploy. 5-9
MORS	Satlantic: radiometers Accustar: inclinometer Li-COR: PAR sensor Sea-Bird: press., temp.	6 Hz sampling for 20 sec every 15 min (daytime only)
MVMS	EG&G: horiz. currents Sea Tech.: transmissometer, fluorometer Biospherical: PAR, 683 nm sensor Sea-Bird: temp., cond.	3.75 min ave.
TPOD	Brankner: temp.	3.75 min ave.
ADCP	RDI: horiz. currents	7.5 min ave./ 3 m vert. bins
Osmoanalyzer	MBARI: nitrate conc.	5 min ave. every 10 or 15 min

Table 2. Instrument sampling regimens.