Observations and Analyses of Upper Ocean Responses to Tropical Storms and Hurricanes in the Vicinity of Bermuda

Wil J. Black*, Tommy D. Dickey**

OPL/UCSB

*6487 Calle Real Suite A, Goleta, CA 93117. E-mail: will.black@opl.ucsb.edu, Telephone:805-681-8207, Fax: 805-967-5704. **6487 Calle Real Suite A, Goleta, CA 93117. E-mail: tommy.dickey@opl.ucsb.edu, Telephone:805-681-8207, Fax: 805-967-5704.

Abstract

The interaction between the atmosphere and ocean is of fundamental importance for understanding the dynamics and thermodynamics of the atmosphere and the ocean. Understanding of the upper ocean response to intense wind forcing has been limited by the paucity of direct observations. A circular region within a radius of 400 km of Bermuda has been struck by 188 tropical storms or hurricanes from 1851 through 2005 and by 20 since 1995. Here we describe new direct and remote sensing observations and analyses of recent events near the Bermuda Test Mooring including Hurricane Fabian (2003), Tropical Storm Harvey (2005) and Hurricane Nate (2005). Comparisons with Hurricane Felix of 1995 are also presented. Key features of the ocean response include rapid deepening of the mixed layer, rightward bias in SST cooling in relation to the hurricane or storm track, production of high velocity near-inertial currents, generation of near-inertial internal waves, and in some cases ocean color wakes produced by hurricane-forced upwelling and entrainment. The most impressive upper ocean response of the recent events was produced by Hurricane Fabian where SST cooling exceeded 4 °C, vertical mixing occurred to a depth of greater than 130 m and upper ocean currents reached 100 cm s^{-1}. Fabian triggered an ocean color event visible in SeaWiFS satellite images. The data sets and analyses presented here provide key information valuable for the development of advanced models designed to improve understanding and prediction of upper ocean responses and atmospheric feedbacks for hurricanes along with biological and biogeochemical effects.

Index Terms

4504 Air/sea interactions

4572 Upper ocean and mixed layer processes

Keywords

hurricane, cyclone, upper-ocean, heat flux

1. Introduction

Recent hurricane events such as those observed during the 2005 Atlantic hurricane season, and in particular Hurricane Katrina, have focused the attention of both the scientific community and society in general on the connection between hurricane activity and global warming. Several important studies (e.g., Webster et al., 2005; Emanuel, 2005; Hoyos et al., 2006) have focused on the link between heat content of the upper ocean and hurricane formation and intensity (dynamics), while other dispute such a trend is evident (Landsea, 2007). Furthermore, some climate models have predicted small increases in both hurricane activity and intensity over the next century under increased greenhouse gas conditions because of increased sea surface temperatures (SST) (Knutson and Tuleya, 2004). In order to fully investigate the connection between global warming and hurricane activity, it is important to understand processes that control hurricane activity such as vertical wind shear, specific humidity of the lower troposphere, and heat fluxes at the ocean-atmosphere interface (Shapiro and Goldenberg, 1998; Hoyos et al, 2006). Despite the technological advancements of the last two decades, we still lack sufficient data and information relevant to atmospheric and oceanic dynamics and thermodynamics, as well as to air-sea fluxes during tropical storms, hurricanes, and typhoons.

Because of the very nature of tropical cyclones it is difficult to obtain direct in situ measurements during such events. Remote sensing of the atmosphere and the ocean using satellite instruments to infer wind speed, sea surface temperature, sea surface and wave height, and ocean color is proving to be extremely valuable (e.g., Babin et al., 2004;

Scharoo, 2005; Son et al., 2006). However, a complete characterization of the physical and biogeochemical properties of the upper-ocean water column is not possible using remote sensing data exclusively. Measurements of currents, temperature and salinity distributions throughout the water column, as well as ocean-atmosphere interface fluxes and biogeochemical variables, can only be obtained from *in situ* instrumentation. Traditional measurements methods such as shipboard sampling are dangerous or even impossible. While the number of *in situ* sampling assets is growing, to date, there have been only a limited number of such direct measurements in the open ocean during hurricane conditions (e.g., Brink 1989; Church et al. 1989; Dickey et al, 1998b; Zedler et. al. 2002). The open ocean setting for such measurements is particularly interesting since no bottom or coastal boundary effects come into play. For this reason, such data may be more easily used for the development and testing of numerical models. Furthermore, open ocean measurements are extremely important for predictions of storm intensities and tracks, since they depend on air-sea interaction processes, which occur while the storms are at sea.

There are several other prominent features that have been observed after the passage of cyclones from previous studies (e.g. Price, 1981; Price, 1983; Price et al., 1994; Gill, 1984; Zedler et al, 2002). Some of the more relevant aspects for this study are described next.

1) The upper-ocean current response in the wake of the cyclone is notably asymmetric with enhanced currents occurring on the right-hand side of the storm track. The asymmetric response results primarily from the translation motion of the hurricane. The

absolute magnitudes of the cyclone's wind speeds are greatest in the forward right quadrant of an advancing cyclone as both the cyclone's rotational and translational components are acting in concert. So, some of the asymmetry may be attributed to this effect. However, another effect is likely more important as elucidated by Price (1981, 1983), and Dickey and Simpson (1983). These investigators explain that the rightward bias is primarily produced because in the ocean frame of reference (i.e., at a mooring site in our case), the wind stress vector effectively turns clockwise in time on the right-hand side of the cyclone track and anti-clockwise on the left-hand side of the track. For most hurricanes, the scale of the storm and its translation speed are such that the turning rate of the wind stress vector on the right-hand side of hurricane are often near that of the turning rate of inertial motion. This results in approximate resonant coupling between the turning wind stress vector and the wind driven upper ocean currents. On the left-hand side of the translating hurricane, the opposite effect occurs as the wind stress vector rotation is in opposition to the wind-generated currents. The sensitivity of these couplings has been described in detail by Dickey and Simpson (1983). For the remainder of the paper we will refer to this phenomenon as the resonance effect.

2) Strong asymmetry in the SST response occurs in the wake of the storm. This results in a cool swath of SST usually centered 100-400 km on the right hand side of the storm track and up to 400 km in width. The change in SST can be as large as 6 °C (Price 1981), and several degrees larger than on left hand side of the track. The explanation for this rightward bias effect relies primarily on the discussion presented above concerning

currents. In particular, there is more shear-induced mixing on the right-hand side where mixed layer currents are enhanced via the resonance effect.

3) The dominant frequency present in current and temperature (in the thermocline) time series is generally about 5% higher than the local inertial frequency and is sometimes termed the blue shift (e.g., Price, 1983; Dickey and Simpson, 1983; Church, 1989; Shay et al. 1998) and is due to the coupling between the mixed layer currents and the pressure gradient.

4) Horizontal and vertical propagation of near-inertial internal waves transfer kinetic energy from the ML to the thermocline (e.g. Leaman and Sanford, 1975; Price 1983; Gill 1984; Zedler et al, 2002). The vertical transport of energy is marked by anticyclonically rotating currents with depth (up to a 180° phase shift with depth) as the near-inertial wave propagates downward. The vertical shear caused by the internal waves results in decreased Richardson numbers and induces entrainment at the base of the mixed layer.

5) Large ocean color signatures are sometimes left in the wake of hurricanes and typhoons lasting for up to three weeks (Hoge and Lyon, 2002; Walker and Leben, 2005; Babin et al., 2004; Son et al. 2006). These signatures are visible from ocean color satellites and are generally attributed to increased chl-a concentrations or increased concentrations of colored dissolved organic matter (CDOM) in the surface waters. It is an open question whether such increases are simply due to entrainment of the deep

chlorophyll maximum layer (DCML) into surface waters or to phytoplankton blooms triggered by nutrient upwelling and/or entrainment in the wakes of the storms.

In the present report, we first provide a brief historical summary of tropical storms and hurricanes, which have passed through the region of the western North Atlantic in the general region of the island of Bermuda. Next, we present recent data collected before, during and after the passages of Hurricane Fabian (2003), Tropical Storm Harvey (2005), and Hurricane Nate (2005). Primary data sets were obtained using the Bermuda Testbed Mooring (BTM) and various satellite sensors. These data are used to derive scaling parameters that are then compared with parameter estimates based on data obtained from direct measurements and model simulations of earlier intense regional atmospheric events including Hurricane Felix (1995). Our primary focus is upon the evolution of the thermal and velocity structure of the mixed layer and upper thermocline in response to strong atmospheric forcing. We conclude with a brief view toward future interdisciplinary research and modeling activities for the open ocean region off Bermuda, which we suggest is well placed for the development of a "tropical storm observatory/testbed" for future coupled atmosphere-ocean and interdisciplinary oceanic research and model development.

2. Background

The North Atlantic Ocean has experienced an average of 9.7 tropical storms and 5.4 hurricanes each year from 1851 to 2005 (data obtained from the NOAA Coastal Services Center http://maps.csc.noaa.gov/hurricanes/). There is considerable variability in the annual frequency of occurrence of these storms and hurricanes on the interannual to decadal timescales. While a complete study of these statistics is beyond the scope of this paper, it is important to provide a brief description of the hurricane activity near the BTM site. The BTM is a deep-sea mooring that lies 80 km southeast of the island of Bermuda and is often impacted by tropical storms and hurricanes. Figure 1 shows the storm tracks of tropical cyclones or hurricane passing with 400 km of the BTM site since 1851. An estimated 188 tropical storms or hurricanes have entered the 400-km circle from 1851 through 2005, averaging 1.2 events per year (Figure 1a). It is likely that this number is an underestimate since fewer observations were possible in the earlier portion of the historical record, especially until roughly 1944 when aircraft flights into hurricanes began. From 1995 through 2005, which spans most of the operational period of the BTM, this region has experienced 20 tropical storms or hurricanes, averaging 1.7 per year. The most active years were 1999, 2001, 2003, and 2005 with three storms each year. In 2001 all three storms were hurricanes, while two hurricanes occurred in each of the years of 1999 and 2003 and only one hurricane entered the region in 2005. Four of these storms passed close enough to the BTM (<150 km) to provide large responses in upper ocean temperature, currents, and bio-optical measurements. The storm tracks of Hurricane Felix (1995), Hurricane Fabian (2003), Hurricane Nate (2005) and tropical storm Harvey (2005) (all subjects of this study) are highlighted in Figure 1b. Recently, Hurricane Florence passed within 150 km of the BTM site in 2006, (Figure 1b, red track) however these data are in the process of being analyzed and are not discussed in this paper.

3. Measurement and Analytical Methods

The measurement and analytical methods used for this study are organized as follows. First, general background information concerning the BTM measurement program is presented. Some of the key details describing the instrumentation deployed from the BTM during the periods of interest are then given along with the parameterizations applied to obtain wind stress, and a brief description of the means used for removing mooring motion biases is provided. Next, analyses relevant to near-inertial currents are explained. Finally, complementary satellite observational methods used for this study are discussed.

BTM Measurement Program

The Bermuda Testbed Mooring (BTM) program was initiated in June 1994 in order to provide the oceanographic community with a deep-water (site depth is ~4530 m) platform to test new instrumentation, collect data for interdisciplinary scientific studies, and provide calibration and validation data sets for satellite ocean sensors (Dickey et al., 1998a, 2001). The BTM site, which is located about 80 km southeast of Bermuda at 31°43’N, 64°10’W (Figure 2), was selected in part because of the accessibility of deep waters within a few hours ship steam from Bermuda and in part because of the many complementary activities (mostly ship-based) that are regularly executed in the vicinity. These activities include Hydrostation S (since 1954; see Michaels and Knap, 1996), the Bermuda Atlantic Time Series (BATS since 1988; see Steinberg et al., 2001) program, the Ocean Flux Program (OFP, since 1978; see Conte et al., 2001), and the Bermuda BioOptics Program (BBOP; initiated in 1992; Siegel et al., 2001). Many specialized research programs are also conducted near the BTM/BATS/Hydrostation S/OFP/BBOP sites in order to capitalize on the long-term records and concurrent complementary data sets.

Due to the length of the BTM time series, and the high temporal resolution of the data, the oceanic processes that can be investigated using BTM measurements cover a wide range of temporal scales. In particular, BTM data provide important information concerning periodic and episodic processes ranging in scale from minutes to years. Moreover, the BTM enables collection of virtually continuous data during periods of inclement weather and high sea states when shipboard sampling is not possible. Earlier studies have focused on hurricanes (e.g., Dickey et al., 1998a,b; Zedler et al., 2003; Jiang et al., 2007), mesoscale eddies (e.g., McGillicuddy et al., 1998; McNeil et al., 1999; Dickey et al., 2001; Conte et al., 2003; Jiang et al., 2007), optical variability on many scales (e.g., Dickey et al., 1998a, 2001; Stramska and Dickey, 1998; Zheng et al., 2002, and Kuwahara et al., 2004), dust events (Sholkovitz and Sedwick, 2006), and seasonal cycles (Dickey et al., 1998a, 2001; Jiang et al., 2007).

Descriptions of Key Measurements, Parameterizations, and Corrections

The BTM configuration used during Deployment 18, which recorded Hurricane Fabian, is shown in Figure 2 along with the geographic location of the mooring. A similar configuration was used for Deployment 22, during which Tropical Storm Harvey and Hurricane Nate passed near the BTM. Specific relevant atmospheric measurements during these deployments included: barometric pressure, wind speed (including gusts) and direction, solar radiation, air temperature, and humidity. The BTM's anemometer and radiometer were located 4.4 m above the ocean surface. Estimates of wind speed at 10 m above the surface, U_{10}, were computed using a formula presented by Large et al. (1995) and the method outlined in Zedler (1999). Here we do not attempt a wave height correction. The meteorological system sampled every minute, recording 5-min averaged data along with the highest (gust) value in that time interval. Gust values are important in extremely high wind/wave conditions (e.g., gales, tropical storms, and hurricanes) because of poor exposure of the anemometer when the buoy is in wave troughs (e.g., Dickey et al., 1998b). This sampling problem causes the averaged data to typically give underestimates by several percent.

During Deployment 18, when Fabian passed near the BTM, water column measurements included: temperature (at depths of 2, 8, 19, 35, 47, 57, 72, 101, 151, 201 m; 30-minute averages), conductivity (for salinity), and currents. Conductivity sensors were placed at 34, 71, 150, 201, and 500 m. Unfortunately the 34 and 71 m sensors failed to start on deployment. Horizontal current measurements were obtained using an upward-looking RDI 150 KHz Acoustic Doppler Current Profiler (ADCP) located at approximately 201 m; these data were averaged every 15 min and binned within 3-m vertical intervals with the deepest bin at 192 m and the shallowest bin at 21 m. Data within the upper 45 m were not used for a 2-day period during Hurricane Fabian's closest approach because of bubble contamination (see Jiang et al., 2007).

For Deployment 22, when Tropical Storm Harvey and Hurricane Nate passed the BTM, temperature sensors were placed at 2, 3, 11, 19, 34, 45, 71, 100, 150, 200, 250, 750, 1250 and 1500 m. The ADCP data for this deployment were processed similarly to those for Deployment 18; however, the depth range was from 15 to 189 m.

Surface wind stress was computed for each of the deployments using the BTM wind speed data and scatterometer satellite data (see below for description of satellite data) in a manner consistent with Zedler et al. (2002) (see also Babin et al., 2004).
The wind stress, τ, was computed as

$$\tau = \rho_a c_d U_{10}^2 \qquad (1)$$

where ρ_a is the density of air (1.26 kg/m^3) and c_d is the drag coefficient. The drag coefficient was computed using the formula presented in Large et al. (1995)

$$c_d = \begin{cases} 1.2 \times 10^{-3} & 0 \le U_{10} < 11\, m/s \\ (0.49 + 0.065 U_{10}) \times 10^{-3} & 11 \le U_{10} \end{cases} \qquad (2)$$

Strong wind forcing and inertial currents during and after the passages of tropical storms and hurricanes result in motion of the surface buoy and upper water column instrumentation, as a slack reverse catenary mooring design was used during the deployments discussed in this paper. With this design, the surface buoy stayed mostly within a 5 km watch circle after the passage of Hurricane Fabian. In order to account for this biasing effect, a velocity time series for the buoy position, V_{BTM}, (and indirectly the upper portion of the mooring) was estimated using System Argos satellite-based data. By necessity, it was assumed that the ADCP hung directly beneath the buoy and moved with the same motion as the surface buoy. We then added the velocity of the buoy/mooring from the recorded ADCP velocity, V_{ADCP}, to obtain the corrected water velocity, V_{corr}, i.e.

$$V_{corr} = V_{BTM} + V_{ADCP}. \qquad (3)$$

The bias effect was found to be up to 20% of the speed.

Analyses of Currents

All data showed a large percentage of energy near the inertial frequency (f = 1.059 cpd = 7.7 x 10^{-5} s^{-1} or inertial period of 22.8 h) after the passage of each cyclone. To further examine the near-inertial component of the currents, it is useful to isolate the inertial response. Therefore once the mooring motion bias was removed, all ADCP time-series data were low-pass filtered with a cutoff frequency of 4 cpd, well above the dominant inertial frequency of ~ 1 cpd. Then complex demodulation was performed near the inertial frequency, following the method described by Zedler et al. (2002) (see also Qi et al., 1995). Complex demodulation is useful to examine signals in which one dominant (and known) frequency is present. In this case the frequency is the local inertial frequency, f. Given a demodulation frequency σ and a complex velocity U = u + iv, this technique returns a time-dependent amplitude, A(t), and phase, φ(t). From σ and the time derivative of φ, we computed the true frequency of the original signal, ω, using the equation

$$\omega = \sigma + \frac{d\varphi}{dt} \qquad (4)$$

If σ=f, A(t) is the inertial current amplitude and we can compute the blue shift, ν , as

$$\upsilon = \frac{(\omega - f)}{f} = \frac{d\varphi / dt}{f} \qquad (5)$$

However in this case we cannot choose σ=f because our time-series are discrete and σ must be a multiple of the sampling frequency. We thus set σ = 1.0920 cpd, while at the BTM site f = 1.0624 cpd. Therefore, the blue shift is obtained from

$$\upsilon = \frac{(\varpi - f)}{f} = \frac{(\sigma - f + \frac{d\phi}{dt})}{f} = \frac{(0.0296 + \frac{d\phi}{dt})}{f} \qquad (6)$$

This technique allows resolution of frequency differences of 0.01f because, unlike conventional Fourier transformations, complex demodulation assumes the signal is composed of a single wave. Therefore, a relatively short (O(1 inertial period or IP)) signal can be used to achieve this high resolution (Levine and Zervakis, 1995) .

Complementary Satellite Observing Methods

Several different satellite-based sensors provide generally synoptic views of the ocean surface on scales relevant to tropical storms and hurricanes (i.e., Martin, 2005; Scharroo et al., 2005). The interpretation of BTM storm data sets is greatly enhanced by considering various satellite-based observations.

Satellite-based scatterometer data were used to obtain surface wind fields during the periods when Hurricane Fabian, Tropical Storm Harvey and Hurricane Nate were in the vicinity of the BTM. Wind fields were obtained from the SeaWinds scatterometer onboard ADEOS II (Hurricane Fabian only) and from the QuickScat satellites (for Hurricane Fabian, Hurricane Nate and Tropical Storm Harvey). ADEOS II was operational from April to October in 2003 and therefore data from that satellite are available only for Hurricane Fabian. Both QuickScat and ADEOS II gridded, Level-3 data provide twice daily images with a resolution of 25 x 25 km. The data were obtained from NASA's Physical Oceanographic Distributed Active Archive Center (PO.DAAC, http://podaac.jpl.nasa.gov/).

These data were used to construct time-series of the wind forcing experienced in the vicinity of the BTM during the passages of the storms. Data were available for the BTM site roughly twice each day on ascending and descending satellite passes. To obtain a time series of the wind velocity data, we first selected an appropriate time period for each storm. Then, for each pass within the time frame, the four data points closest to the BTM were selected and averaged together. If one or more of the four points were not available (because of a quality flag or an edge of the swath), then only those available were used for the averages. If no data were available for a particular pass, then no value was recorded in the time series.

Sea surface temperature (SST) distributions, which indicated cool surface storm wakes, were derived from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) satellite infrared imagery (available at NASA's Goddard Earth http://daac.gsfc.nasa.gov/). Due to heavy cloud cover caused by the storms, individual images frequently failed to provide clear images. Therefore, 8-day composite images were used. The gridded, Level-3, 4-km, 8-day composite SST data were obtained from PO.DAAC (http://podaac.jpl.nasa.gov/). In addition, ocean color images used for surface chlorophyll *a* fields are provided by NASA's Sea-viewing Wide Field-of-view Sensor (SeaWiFS; e.g. McClain et al. 1998; O'Reilly et al. 1998). Again, because of cloud cover individual images did not provide a clear view of the chl-a response. Therefore level 3, gridded, 8-day composite data were used (data obtained from NASA's Goddard Space Flight Center, http://seadas.gsfc.nasa.gov/)

4. Means for Comparing Tropical Storms and Hurricanes

Comparisons among the three storm data sets described here and those presented in past case studies are useful for several purposes. For example, comparisons among different storms allow us to distinguish which characteristics and variables are more effective in influencing upper ocean thermodynamic and dynamic responses, as well as air-sea interaction and fluxes. They can also provide modelers with general information that can be used for determining the accuracy of model simulations. It is important to emphasize that our mooring observations are limited to a single location and cannot capture the three-dimensional upper-ocean response. Several of the key factors thought to influence the upper ocean response to tropical cyclones and hurricanes have been outlined in previous papers (e.g., Price, 1981, 1983; Price et al., 1994; Dickey et al., 1998b). For the BTM site, these include:

1) Storm translation speed.
2) Winds stress field (maximum wind speed and radial distance to maximum winds)
3) Initial thermal and density structure of the upper-ocean (i.e., mixed layer depth, density gradients, and sea surface temperature). Presence of mesoscale eddies may also be important.
4) Orientation of storm path with respect to instrument platform (i.e., distance to study BTM site, and which side of the storm track the study site is on).

It is helpful to examine various relevant factors in relation to several parameters and non-dimensional numbers. Important early work on this topic by Price (1981, 1983) and Price et al. (1994) sought to isolate the factors that are most important in determining the upper ocean response to hurricane forcing by computing several non-dimensional numbers. This approach has subsequently been used for several other hurricane studies (e.g. Dickey et al., 1998b; Shay et al. 2000; Babin et al. 2004). Non-dimensional parameters can also provide guidance concerning scaling of equations and determining which variables are more important for the upper ocean response. Data used to compute non-dimensional numbers and various parameters for the present study were obtained from BTM mooring measurements and from National Hurricane Center (NHC) Tropical Cyclone reports, Forecasts/Advisories, and Best Track position estimates. For example, NHC information specific to the region of the BTM include: estimates of central pressures at storms' centers, storms' maximum wind speeds, storms' translation speeds, radial distances from storm centers to points of maximum winds, and radial distances to hurricane force winds. We have also used NHC data to compute distances of closest approach and relative directions of storm centers with respect to the BTM.

Several general characteristics of each storm while in the vicinity of the BTM are summarized in Table 1 for Hurricane Felix, Hurricane Fabian, Tropical Storm Harvey, and Hurricane Nate. In Table 2 we provide local estimates of atmospheric conditions and the resulting upper ocean response at the BTM as the storms passed over. For completeness, we provide definitions of some of these key non-dimensional and dimensional numbers. These include the Hurricane Hazard Index, the non-dimensional storm speed, the Burger number and the Rossby number.

The hurricane hazard index (HHI) was recently introduced by Kantha (2006) and provides a new continuous and open-ended scaling method that overcomes some of the limitations of the traditional Saffir-Simpson Hurricane Scale (SSHS). The following are limitations of the SSHS that the HHI seeks to overcome: 1) the integer values of the SSHS represent a range of wind speeds and central pressures, thus a few m s^{-1} change in wind speed can change the SSHS while the intensity and potential destructiveness of the storm will not change by much, 2) the SSHS saturates at the high end, and 3) the SSHS does not include any information about the size of the hurricane. The variables used to compute the HHI include maximum sustained near surface tangential wind speed, radius to hurricane winds, and the translational speed of the hurricane. The HHI is defined as

$$HHI = \left(R_{hurr} / R_0\right)^2 \left(V_{\max} / V_0\right)^3 \left(U_0 / U_h\right) \qquad (7)$$

where R_{hurr} is the radius to hurricane force winds, U_h is the translation speed of the storm, and V_{max} is the maximum velocity of tangential winds. Subscript 0 indicates reference values; R_0 = 96.6 km, V_0 = 33.1 m s$^-$1 and U_0 = 6.7 m s^{-1} (Kantha, 2006).

The non-dimensional storm speed, S, gives an indication of the time scale over which the ocean feels the direct impact of the storm. Following Price et al. (1994), S is defined as the ratio of the local inertial period, IP = 2π/f, to the hurricane residence time, $8R_{max}/U_h$, or

$$S = \frac{\pi U_h}{4 f R_{\max}} \qquad (8)$$

where U_h is the storm translation speed, f is the Coriolis parameter, and R_{max} is the radius to maximum wind stress. A value of S close to unity indicates that the resonance effect will be large and the right-hand bias more pronounced.

The Burger number, B, provides an indication of the degree of pressure coupling between the mixed layer currents and the thermocline current and is defined by Price et al. (1994) as

$$B = \frac{g' h_{max}}{4 f^2 R_{max}^2}. \qquad (9)$$

In equation (9), g' is the reduced gravity, defined as $g' = g\Delta\rho/\rho_0$, where $\Delta\rho$ is the density difference across the seasonal thermocline; $g = 9.8$ m s^{-2} is the acceleration due to gravity; h_{max} is the maximum mixed layer depth; f is the Coriolis parameter; and R_{max} is the radius to maximum winds. Note that for the purposes of this paper we have defined the mixed layer depth, MLD, as the depth at which temperature is 0.5 °C less than the surface temperature.

Finally, the Rossby number for mixed layer currents can be estimated following Price et al. (1994) as

$$Q = \tau/(\rho_o\, h_{max}\, U_h\, f), \qquad (10)$$

where τ is the maximum wind stress, ρ_o is the density within the mixed layer, h_{max} is the maximum mixed layer depth, U_h is the storm translational speed, and f is the Coriolis parameter. Large values of Q indicate that advective effects are relatively important opposed to planetary rotational effects.

Closest Approach

For each storm the time of closest approach and minimum distance to the BTM was determined using the NHC's Best Track data. The Best Track data reports latitude and longitude every six hours (0000, 0600, 1200, 1800Z) and is accurate to 0.1°. To determine the minimum distance to the BTM, we first chose two Best Track points (p_1 and p_2) such that the point of closest approach will occur between these to points. The point of closest approach to the BTM is defined as the point on the line connecting p_1 and p_2 that minimizes the distance to the BTM. The distance between this point and the BTM is defined as the minimum distance between the storm and the BTM. To compute the time of closest approach, we assume that the storm translated at a constant velocity, U_h, between p_1 and p_2. U_h was computed as the distance between p_1 and p_2 divided by the time between these points (6 hrs). By using this computed translational speed, it was possible to obtain a rough estimate of the time when the storm center reached the point of closest approach.

5. Results

Tropical Storm Harvey, Hurricane Nate, and Hurricane Fabian are discussed next. The overall characteristics of each storm are described using direct observations from the BTM, as well as complementary NHC and satellite data. For each storm, the wind and barometric data are discussed first, followed by the upper ocean thermal and current responses. It is important to note that each storm has unique inherent aspects, and furthermore, the relative position of the BTM with respect to each path was different for each storm. For the present study, it is worth keeping in mind that Tropical Storm

Harvey passed almost directly over the BTM, with an eastward average translation speed of roughly 6.3 m/sec (Figure 3). Hurricane Nate passed about 123 km to the southeast of the BTM, with a northeastward average translation speed of 6.7 m/sec. In this case, the BTM was located to the left of the storm's path (Figure 5). Hurricane Fabian passed about 102 km to the east of the BTM, which was located to the right of the storm's path, and it translated northward at 8.6 m/sec (Figure 7). Clearly, the BTM site experienced different types of atmospheric forcing conditions and thus the upper-ocean responses are unique for each storm. This is advantageous from the perspective of providing analysts and modelers distinct realizations. However, comparisons between the BTM data sets must be done carefully as upper ocean responses to intense storms are highly dependent on the relative positions of the moving storms and the observing platform, namely the BTM in this case. As already discussed, upper-ocean responses to hurricane forcing are more dramatic to the right of hurricane paths than to the left of their paths. Interestingly, JPL modelers have already used BTM data sets for intercomparisons by examining upper ocean responses to hurricanes from the perspectives of 'virtual moorings' as well as from the BTM (Yi Chao, personal communication).

5.1 Tropical Storm Harvey

Tropical Storm Harvey originated from a tropical depression that first appeared on 2 August 2005, centered 600 km (320 n mi) southwest of Bermuda. Harvey strengthened to a tropical storm with maximum sustained winds of 20 m/s (40 kt) at 0600 UTC 3 August with its center located 460 km (250 n mi) southwest of Bermuda (storm center at 29.5° N, 68.6° W). Shortly after 0600 UTC 4 August, Harvey passed 75 km (40 n mi) south of

Bermuda (storm center at 31.6° N, 65.0° W) with maximum sustained winds of 26 m/s (50 kt) and a central pressure of 995 mb, while traveling on an eastward, north-eastward path. Twelve hours later (1800 UTC 4 August) Harvey reached its peak intensity of 28 m/s (55 kt) with a central pressure of 994 mb at 240 km (130 n mi) east of Bermuda (storm center at 32.0° N, 62.1° W). After gradually drifting first eastward then northward for several days, Harvey obtained extratropical cyclone status on 9 August, when it was 900 km (490 n mi) southeast of Cape Race, Newfoundland before dissipating on 13 August.

By applying the method described in section 3 to the NHC's Best Track data, we conclude that the center of Harvey passed 5 km to the north of the BTM site at 0928 UTC 4 August 2005 with a translation speed of 6.3 m s^{-1}. The 4 August 0900 NHC Forecast/Advisory (number 8) placed the center of Harvey 40 km west of the BTM with maximum sustained winds of 26 m/s (50 kt) and central pressure of 995 mb. At nearly the same time, QuickScat measured maximum winds of 24.5 m/s (48 kt, Figure 3), in good agreement with the NHC best track estimate. We can therefore conclude that the BTM site likely experienced the maximum wind forcing of Tropical Storm Harvey with sustained winds of 26 m/s.

Barometric Pressure and Winds

The barometric pressure time series at the BTM site is shown in Figure 4a. Pre-storm values were near 1020 mb. As Harvey approached the BTM, the pressure decreased slowly before experiencing a sharp drop just before 3 August (YD 215). The minimum pressure measured by the BTM was 995 mb at 0700 UTC 4 August (YD 216). Barometric pressure values returned to pre-storm conditions within a few days, e.g. by 8 August (YD 220). Unfortunately, due to instrument failure *in situ* wind measurement from the BTM anemometer are not available for the period when Tropical Storm Harvey was in the vicinity of the BTM (the same problem occurred for Hurricane Nate). For this reason, a time series of wind velocity was constructed from QuickScat data in the proximity of the BTM using the method described in section 3 (Figure 4b and c). Prior to Harvey's arrival, wind near the BTM was light (< 5 m s^{-1}) and towards the west. No data are available from noon 2 August (YD 214) through 3 August (YD 215) because of gaps in QuickScat coverage. The next available satellite data are from late 3 August (YD 215), when the wind was toward the north around 7 m s^{-1}. The wind then dropped below 5 m s^{-1} at 1000 4 August (YD 216), close to the time when minimum pressure was measured at the BTM site (Figure 4a). Wind intensity then increased to 10 m/s (20 kt) while rotating 180°, blowing toward the south. The dip in wind speed at 1000 along with the 180° change in direction supports the assertion that Harvey passed nearly directly over the BTM mid-morning on 4 August. After Harvey's passage, the winds slowly turned towards the west and finally towards the north by 13 August (YD 225), remaining around 5 m s^{-1} (10 kt) for the rest of the sampling period.

Temperature Structure

The MODIS SST image shown in Figure 3 indicates patchy SST cooling occurring after the passage of Tropical Storm Harvey. A cool swath of ~26 °C SST, 100 km wide and 400 km long is apparent on the right hand side of the storm track east of the BTM site.

Maximum cooling of roughly 2.5 °C occurred about 50 km southeast of the site. It is therefore unlikely that the BTM experienced the maximum SST cooling and upper-ocean thermal response.

The mixed layer depth (MLD) prior to the passage of Tropical Storm Harvey was around 10 - 15 m as shown in Figures 9 and 10. It began to deepen around 3 August (YD 215) and by 4 August (YD 216) it was between 19 and 34 m (note that no temperature sensors were located between these two depths) and it remained within this depth range for roughly one week (Figures 4d and 10). The MLD returned to near pre-storm conditions by about 13 August (YD 225), while still retaining a strong diel cycle. The mixed layer temperature cooled by 1.5 °C from 28 °C to 26.5 °C after Harvey's passage (Figure 4d). Despite the almost direct hit by Harvey, it is believed the BTM did not experience the maximum ML response to Harvey, which occurred to the right of the storm track.

Prior to the passage of Harvey, seasonal warming was observed within and immediately below the ML, as evidenced by temperature data at the 34 and 45 m depths (not shown here). Harvey disrupted this warming trend and warming did not resume until almost three weeks later. The 34- and 45-m sensors recorded large temperature oscillations near the inertial period (Figure 4d), and showed an average decrease of 0.5 °C during the week immediately after Harvey's passage. At both depths, the near-inertial oscillations began around 4 August (YD 216), with peak amplitudes of > 1.5 °C and 1 °C for the 34-m and 45-m sensors, respectively. These maximum amplitudes occurred between 6 and 13 August (YD 218-225) before decreasing and reaching their minima around 20 August

(YD 232). Interestingly, near-inertial oscillations were still evident when Hurricane Nate passed to the south of the BTM about 3 weeks later on 8 September (YD 251). The 750-m temperature sensor showed a 0.5 °C rise followed by a 1 °C drop (not shown), coinciding with the passage of Harvey. Sensors below 750 m (1250 and 1500 m) showed no response to Harvey.

Currents

The upper ocean current response to Tropical Storm Harvey is illustrated in Figure 4e) to h). All depths showed an increase in energy near the inertial frequency, but the times when the amplitudes of the near inertial currents peaked covaried with depth. The eastward (u-component) and northward (v-component) current components are 90° out of phase with the u-component leading, indicating near-inertial counter-clockwise motion. This phase relationship between u- and v-components is evident in all of the data sets described in this paper. At 27 m, currents rose rapidly around 1200 UTC 4 August (YD 216), just after Harvey passed over the BTM, and decayed slowly (Figure 4f). Large inertial oscillations persisted for several days with peak values of 35 cm/s. By 19 August (YD 231), these currents decayed to around 15 cm/s.

Below 30 m, the current response to Harvey was weaker (Figure 4 g and h) than at the shallower depths. The strongest inertial currents did not occur below 30 m until 0000 17 August (YD 217), roughly 12 hrs after Harvey's closest approach to the BTM. Inertial currents decreased with depth below 45 m. At ~75 m, these oscillations were near 15 cm/s. As already noted from the temperature data, inertial oscillations with amplitudes larger than pre-storm values remained until Hurricane Nate passed by the BTM site on 8 September (YD 251).

5.2 Hurricane Nate

Hurricane Nate's origins can be traced back to a tropical wave that moved off the African coast on 30 August 2005. On 7 September, Nate reached hurricane strength (winds > 33 m/s) about 415 km (225 n mi) south-southwest of Bermuda (28.9 °N, 66.2 °W). Nate then accelerated northeastward at 5-8 m s^{-1} (10-15 kt) and passed 200 km (110 n mi) southeast of Bermuda (33.5 °N, 63.8 °W) at 1200 UTC 8 September (Figure 5). Nate reached its peak intensity of 41 m/s (80 kt) with a central pressure of 979 mb at 0000 UTC 9 September (32.6 ° N, 61.1 °W). After turning east-northeastward Nate began to weaken and by 9 September, it was downgraded to a tropical storm once again.

From the method described in section 3 using Best Track data, we estimate that Nate passed 123 km southeast of the BTM at 1500 8 September. At this time the eye was centered at 30.9 °N, 63.3 °W and was moving toward the northeast at 6.7 m s^{-1}. The 1200 and 1800 Best Track maximum wind speed and central pressure were reported to be 39 m s^{-1} (75 kt) and 982 mb, respectively. These results are summarized in Table 2.

Barometric Pressure and Winds

Figure 6a shows the time series of barometric pressure at the BTM before, during and after the passage of Nate. Pressure remained steady near 1014 mb prior to Nate's arrival. It then began to drop on 8 September, and reached its minimum value of 1000 mb at 1400 on 8 September (YD 251). Pressure rose back to a value near 1020 mb after Nate's passage, and remained steady for the next 12 days.

As noted earlier the anemometer on the BTM failed during deployment 22 so *in situ* winds are unavailable, however a well resolved time series was constructed from SeaWinds data in the vicinity of the BTM (Figure 6b and c). Prior to Nate's passage, the BTM area experienced light winds (< 5 m/s) towards the west. Winds began picking up on 7 September (YD 250) and reached a maximum value of near 20 m s^{-1} at 1000 on 8 September. Over the next 24–hrs, the winds decreased to 5 m s^{-1} while rotating clockwise 180°, ending up towards the east. Data were not available again until late 10 September when winds were light (<5 m s^{-1}) again.

Temperature Structure

The MODIS SST image (Figure 5) showed less intense SST cooling than after Tropical Storm Harvey (Figure 3). Although the BTM appears to be situated in an extreme cool wake in the satellite imagery, this appears to be a data quality issue since the BTM time series does not show such cooling (Figure 6d).

The initial MLD prior to the passage of Hurricane Nate was near 22 m (Figures 9 and 10), but shortly after 1200 8 September (YD 251), the ML had deepened to roughly 33 m. After the passage of Nate, the upper portion of the seasonal thermocline oscillated near the inertial frequency for almost a week (Figure 10b). Virtually no change in temperature was recorded for depths shallower than 20 m, but strong near-inertial oscillations were seen in the 34-m depth record (Figure 6d). Beginning early on 8 September, the 34-m temperature rose from about 24 °C to about 28 °C and then oscillated between these values (~2 °C amplitude) for 5 days before decreasing in amplitude The 45-m sensor showed similar oscillations, but with much smaller amplitudes (~ 1 °C). The 71-m and 100-m sensors showed some evidence of near-inertial pumping between 9 September and 14 September (YD 252-259), but otherwise remained unchanged. Virtually no response was observed in the 150, 200, and 250-m sensors. The 750-m sensor showed a slight increase in temperature (~ 0.5 °C) on 9 September (YD 252), but quickly dropped again; the 1250- and 1500-m sensors' temperatures remained unchanged (data not shown). Only slight cooling in the ML was recorded by the BTM after Nate's passage (Figures 9 and 10). Satellite SST imagery does show surface cooling in the wake of the hurricane by as much as 2 °C, but only minimal cooling in the vicinity of the BTM.

Currents

The BTM's ADCP horizontal current time series records are shown for Hurricane Nate at selected, representative upper ocean depths (18, 27, 33, and 75 m) in Figures 6e through h. Increased velocity oscillations near the inertial frequency were clearly evident for these depths beginning after 8 September (YD 251), but the timing and amplitudes of these oscillations varied with depth. A sharp transition at the 33-m depth appears to separate the response of the upper water column from the response of the lower water column. At depths shallower than ~33 m, the response to Nate was nearly immediate. Near inertial currents at 15 m began to increase slightly before Nate's arrival. However, at all the other depths down to 33 m, currents increased very near the time of Nate's closest approach. Maximum values in the upper water column exceeded 25 cm/s, and occurred roughly between 9 September and 13 September (YD 252-256), before decaying to 15 cm/s amplitude oscillations by 16 September (YD 259).

The current response at depths greater than 33 m was different from those at shallower depths. Although inertial currents did increase around the time of Nate's closest approach, the greatest values did not occur until 11 days later, around 19 September (YD 262). The largest values were seen at the 39-m depth with inertial currents near 30 cm/s; values of 25 cm/s were observed to depths of 60 m. Below 80 m, the inertial response was very small, with currents not much larger than pre-storm conditions.

5.3 Hurricane Fabian

Hurricane Fabian evolved from a tropical wave that emerged from western Africa on 25 August 2003 and reached hurricane status (winds > 33m/s or 64 kt) on 30 August at 16.3° N, 45.6° W. Fabian reached its peak intensity on 1 September when the eye was 490 km east-northeast of the northern Leeward Islands (19.0° N, 57.3° W) with estimated wind speeds of 64 m/s (125 kt) and a central barometric pressure of 942 mb. These characteristics made hurricane Fabian a category 4 storm on the Saffir-Simpson scale. The minimum central pressure of 939 mb was measured at 2245 UTC 3 September with the center at 23.2° N, 63.0° W. Fabian then translated west to west-northwest before turning north-northwestward (Figure 7). The hurricane struck Bermuda at 2000 UTC 5 September as a category 3 storm with winds of 51 m/s (100 kt) and a central pressure near 950 mb. Eyewitness reports confirm that the eastern fringe of Fabian's eyewall passed over the western end of the island between 1945 and 2115 UTC. Fabian continued northward and then north-northeastward before losing hurricane status on 8 September while located 1300 km east-northeast of Cape Race (51.7° N, 36.0° W).

Using the NHC Best Track data and the method described in section 3, we estimate that Fabian passed 102 km west of the BTM on September 5 around 1850 UTC. At this time the eye was centered at 32.0° N, 65.2° W and moving at 8.6 m s^{-1} to the north. The reported maximum sustained winds at 1800 UTC were 54 m s^{-1} (105 kt) and the central pressure was 950 mb.

Barometric Pressure and Winds

The BTM measured a drop in atmospheric pressure from pre-storm levels of 1020 mb to a minimum of 986 mb around 1600 UTC 5 September. Barometric pressure then rose again, but had a small second dip centered around 7 September (YD 250) with a value of 1011 mb (Figure 8a).

Three different wind measurements were obtained during Hurricane Fabian. *In situ* measurements from the BTM meteorological station recorded pre-storm conditions until winds peaked during Fabian's passage. Unfortunately, the wind sensor failed shortly after Fabian hit the BTM (Figure 8b). However, satellite scatterometer data from both ADEOS II and QuickScat were recorded. The BTM's wind sensor (mounted 4.3 m above the sea surface) recorded maximum sustained winds of > 30 m/s (> 58 kt) with gusts greater than 35 m/s (68 kt) at 1500 5 September (Figure 8b) These winds are 35 m s^{-1} and 40 m s^{-1}, respectively when adjusted to 10-m height above sea level. The SeaWinds satellite scatterometer (onboard ADEOS II) passed over the BTM at 1430 UTC and measured maximum winds (computed for 10 m above ocean surface) near the BTM of 27 m/s (52 kt). According to Yueh et al (2003), this estimate may be a substantial underestimate do to heavy rainfall in the hurricane. At that time, the maximum wind speed recorded by SeaWinds for Fabian was 34 m/s (66 kt). All data showed that winds quickly decreased to roughly pre-storm levels by 7 September (YD 250) and remained < 10 m/s for the remainder of the observational period under consideration, except for a slight increase after 13 September (YD 256). It is not surprising that the various wind speed reports are somewhat at variance with each other, as different methodologies were used to measure wind speed.

All wind measurements showed a clockwise wind vector rotation from a predominantly westerly direction to a northerly wind direction over a 48-hour period. Data from both wind-sensing satellites show further counterclockwise rotation afterwards. SeaWinds data revealed easterly winds about mid-day on 6 September (YD 249) before turning northerly again for three days. By 12 September (YD 255), the winds were again out of the west and at pre-storm wind speeds.

Temperature Structure

Sea surface cooling in the wake of Hurricane Fabian was observed in both remotely sensed and in situ temperature records. A MODIS eight-day composite SST image shows a cool swath centered about 100 km to 150 km to the right of the hurricane track (Figure

7). The swath is roughly 200 km wide and its SST is ~3° C cooler than the surrounding waters. BTM data shown in Figure 8d indicate that at 2 m and 8 m, temperatures dropped by ~3 °C during the latter part of 5 September (YD 248). Temperatures at these depths, which were well within the mixed layer, remained near 25 °C through 7 September (YD 250) before slowly increasing. At the same time the drop in near surface temperature occurred, temperatures in the depth range of 19 – 72 m increased and then cooled. All temperature records collected within this depth range are clearly characterized by near inertial oscillations. The mixed layer cooled and deepened down to at least 47 m shortly after the SST drop in temperature; this is evident in the large increase in temperature (up to about 25 °C) recorded by the 47-m sensor. The 57-m temperature evolution was very similar to those at depths of35 and 47m, except that it was not incorporated into the ML and remained about 1 °C cooler. The 101-m sensor showed near-inertial oscillations starting at the same time the SST cooling occurred (1200 UTC 5 September). These oscillations persisted for 7 days until 13 September (YD 256), with the largest amplitude being ~ 1.5 °C. However, the average temperature remained nearly constant. Temperatures at the 151-m and 201-m sensors remained virtually unchanged during the whole period. Interestingly, a large increase in temperature of 2.5 °C was recorded at 700 m (data not shown) starting around 4 September (YD 247), peaking at 1900 UTC on 5 September (YD 248). After that, the 700-m temperature started to decrease, but did display inertial oscillations. The 700-m temperature returned to pre-storm values by 12 September (YD 255).

The vertical temperature structure at the BTM site before and after (i.e., maximum temperature response) Hurricane Fabian is shown in Figures 9 and 10. The initial mixed layer depth was 20 m. The ML began deepening around 1200 UTC 5 September (YD 248) and by 6 September (YD 249) it was on average 50 m (Figures 9 and 10). It oscillated (at approximately the inertial period of 22.8 h) near the 50-m depth for about 2 days before shoaling to less than 20 m by September 8 (YD 251). By this time, the ML had cooled by 2 °C, reaching temperatures of about 26 °C.

Currents

During the Hurricane Fabian event, currents were recorded in 3-m vertical bins from 21 to 192 m; however, for clarity only four current records from representative depths (30, 60, 90, and 120 m) are shown in Figure 8e-h. Currents at the BTM site prior to the onset of hurricane-related winds were quite modest (< 5 cm/sec), and only small inertial currents were evident. Just before 1200 UTC 5 September (YD 248), currents began to increase, reaching their maximum values between 48 m and 63 m at 1100 UTC 6 September (YD 249). The largest current speeds were greater than 150 cm/s, peaking at 160 cm/s at depths of 51 and 57 m (Figure 8 c-f). Between 1200 UTC 5 September (YD 248) and 0000 7 September (YD 250), the ADCP data for depths shallower than about 48 m were obviously contaminated, most likely due to bubble entrainment caused by hurricane force winds and the accompanying wave field. For this reason, they are not shown in Figure 8. It is very likely that the mixed layer currents peaked during this period, and therefore the reported maximum velocities are probably an underestimate of the maximum mixed layer currents produced by Fabian.

Currents remained above 30 cm/s for several days after Fabian's passage; however, both the duration and the intensity of near-inertial currents generally decreased with depth to at least 90 m. The most intense and longest-lived inertial currents were seen in the 27 – 48 m records, where they did not drop below 30 cm/s until 0600 UTC 15 September (YD 258). The time period during which they remained above 30 cm/s was almost ten days (11 inertial periods; again, the inertial period at the BTM site is 22.8 h). It is interesting to note that inertial currents at 90 m were somewhat smaller than those observed at 120 m. At 99 m, currents fell below 30 cm/s by 12 September (YD 255), resulting in a total time above 30 cm/s of five and a half days. Below 129 m, only a small trace of the response was recorded.

5.4 DIH Content

The depth integrated heat (DIH) content of the upper-ocean was greatly influenced by the passage of the storms. Figure 9a shows linearly interpolated temperature profiles. The solid lines show the average profiles computed from a 24-hr period immediately before each storm, $T_0(z)$, while the dashed lines are the 24-hr averaged profiles measured during the maximum temperature response to each storm, $T_1(z)$, which occurred roughly 24-48 hrs after the storms' closest approaches. In all three cases the passages of the storms resulted in a cooling of the upper layer (mixed layer). The most dramatic cooling occurred in the case of Fabian, with the ML cooling by more than 3.5 °C and a decrease in temperature observed down to 40 m. The ML cooling was less pronounced after the passage of both Harvey and Nate (~ 0.5 °C).

Temperatures below the ML increased by 2.5 °C after both Nate and Fabian. The maximum temperature increase occurred at 34 m for Nate and at 72 m for Fabian. Temperatures remained fairly constant below the ML after the passage of Harvey.

The DIH anomaly can be obtained from the temperature profiles by integrating the temperature anomaly ($T_1(z) – T_0(z)$) over an appropriate depth range and multiplying it by the density and specific heat of seawater. Thus, as in Zedler (1999), we compute the DIH anomaly as:

$$DIH = \rho_0 c_{pw} \int_{z_1}^{z_2} (T_1(z) - T_0(z))dz \qquad (11)$$

Here ρ_0 is the density of seawater and c_{pw} is the specific heat of seawater, so that $\rho_0 c_{pw}$ = 4.1 MJ °C^{-1} m^{-3}. Integration is performed over depths z_1 to z_2 (z is positive downward), so that negative values indicate a heat loss and positive values indicates a heat gain within the specified depth range.

In order to examine the separate contributions of mixed layer cooling and upper thermocline warming, two depth ranges were chosen for integration: a shallow depth range, which extended from the surface to the depth at which the temperature anomaly becomes positive; and a deeper depth range, which extended from the bottom of the shallow range to 150 m, where the temperature anomaly approaches zero. The shallow range effectively quantifies the ML cooling occurring after the passage of storm and is therefore denoted DIH_{ML}. The deeper range quantifies the upper thermocline warming, which occurs after the passage of the storm, and is therefore denoted DIH_{TC}. The net DIH anomaly is the sum of these two values.

These depth ranges and their corresponding DIH values are summarized for each storm in Table 3. In the case of Tropical Storm Harvey, an additional calculation was required. For this storm, T_0 and T_1 below the ML depth (~20 m) were very similar (Figure 9a). Therefore, a second set of ranges was chosen, so that it was possible to better resolve the ML cooling after the passage of Harvey. The new set of depth ranges was chosen to be the same as for Nate. The DIH_{ML} and DIH_{TC} values computed with respect to these new depth ranges are labeled Harvey* in Table 3.

Figures 9b through d show heat content anomaly as a function of depth. The values displayed in these profiles are directly proportional to the temperature anomalies and hence reflect the same structure. The DIH anomaly is the integral of these profiles. All three storms showed heat loss in the ML but the largest loss was experienced after Fabian where DIH_{ML} = -399 MJ m^{-2}. The large ML heat loss in the Fabian case is similar to that observed for Hurricane Felix at the BTM site in 1995, where DIH_{ML} = -326 MJ m^{-2} over the depth range [0, 29] (Zedler, 1999). Hurricane Nate had a much smaller ML heat loss, roughly -31.4 MJ m^{-2}. Using the [0, 20] depth range for Harvey, the ML heat loss was -43.0 MJ m^{-2}, therefore it was similar to that of Nate. Both Fabian and Nate showed large

DIH gains below the ML. For Fabian. DIH_{TC} = 318.0 M Jm^{-2} and for Nate DIH_{TC} = 249.0 MJ m^{-2}. While this is expected in the Fabian case because of its size, it is somewhat unexpected for Nate as indicated in the Discussion section. Harvey showed a slight loss of heat below the ML with DIH_{TC} = -22.1 MJ m^{-2}. Over the whole depth range (0 m to 150 m), both Fabian and Harvey showed negative DIH anomalies of -81.2 MJm^{-2} and -65.1 MJ m^{-2} respectively, while Nate had a large gain of heat with DIH_{150} = 218.0 MJ m^{-2}.

6. Discussion

The data sets presented here offer unique information concerning the thermal and dynamic responses of the upper ocean to hurricane forcing in the open ocean. The common features present in these data sets include: i) deepening of the mixed layer; ii) redistribution of heat between the mixed layer and upper thermocline; iii) near-inertial oscillations in temperature and current records. Each of these processes occurred to a varying degree at the BTM site depending upon the specific storm. The differences in responses at the BTM site are dependent not only upon the physical properties of the storm (i.e. size, intensity, and translations speed) and pre-existing oceanographic conditions (i.e. stratification, currents, etc.), but also on the orientation and distance of the storm track in relation to the BTM site. Thus interpretation, analyses, and model utilization of these data sets must be done carefully and in proper context.

The strongest and most pronounced response of the present BTM observations occurred with the passage of Hurricane Fabian. Fabian produced the largest currents (> 100 cm s^{-1}), DIH_{ML} values (-399.0 MJm^{-2}), and SST change (3.5 °C). This is not surprising since Fabian was the strongest of the storms considered here based on both the Saffir-Simpson Hurricane Scale and the HHI (see Table 1). Additionally, the BTM was positioned near the location of expected maximum ML current response at a distance102 km ($2.2R_{max}$) to the right of the storm track (Price, 1983). In contrast, both Harvey and Nate had less intense responses. Maximum currents were moderate (> 30 to 35 cm s^{-1}), DIH_{ML} values were smaller (-43.0 MJ m^{-2} and -31.4 MJ m^{-2}, respectively) and the SST changes at the BTM site were less pronounced (1.5 °C and 0.5 °C, respectively).

Although many of these differences are due to storm size and intensities (both Harvey and Nate were much smaller and less intense storms than Fabian and Felix), some of the differences were due to the location of the BTM in relation to the storm track. Tropical Storm Harvey passed almost directly over the BTM. Although the region experienced Harvey's maximum winds stress (τ_{max} = 1.7 N m^{-2}), the BTM likely did not record the maximum ML current response, which probably occurred to the right of the storm track. At Nate's closest approach, the BTM site was 140 km away from the storm center and located on the left-hand side of the storm track. Therefore, not only did the BTM site experienced lower wind stress, but also the counterclockwise rotating wind stress vector worked against the clockwise rotating inertial current field produced by the storm. For this reason, the dynamic response recorded at the BTM site was most likely much lower than the maximum response.

6.1 DIH content

All three storms showed ML heat loss. Such cooling can be the result of latent and sensible heat transfer to the atmosphere and by transport of heat into the upper thermocline through turbulent mixing, although the former likely accounts for a relatively small percentage of heat loss (Price, 1981). If heat is removed from the ML and transported down into the upper thermocline through turbulent mixing, then the upper thermocline should warm. Such warming occurred after Fabian and Harvey (and Felix), and the thermocline warming was the same order of magnitude as the ML cooling. The net DIH change for Fabian and Harvey were -81.2 and -65.1 MJ m^{-2} respectively (see Table 3).

Nate showed a different response. The DIH decreased in the ML after Nate (value was similar in magnitude to that of Harvey), but a large positive DIH anomaly was observed in the thermocline. This resulted in a positive net DIH anomaly of 218.0 MJ m^{-2}.

One possible mechanism that may account for this increased is advection. There is a small warm anomaly in the 71 m and 100 m temperature records for Nate that lasts for about a week centered on day 254 with a value of 0.5 °C (see Figure 6d). This anomaly may reflect the presence of downwelling or horizontal advection of warmer waters at the BTM site. This could result from the horizontal transport of ML waters toward the BTM after Nate's passage. A convergence of ML waters at the mooring site may have depressed the isotherms in the vicinity of the BTM. This would result in a warming of the thermocline while still allowing for ML cooling. Due to the different relative positions of the BTM with respect to the storm track, in the case of Harvey the same process may have produced an opposite response. Since Harvey was almost a direct hit, the wind stress induced divergence likely led to transport of ML waters away from the storm track resulting in a doming of the isotherms below the ML at the BTM site. This can be seen in the BTM temperature time series as a cool temperature anomaly in the 45 m, 71 m, and 100 m records (Figure 4d).

6.2 Ekman Pumping and Isopycnal Displacement

As reviewed in the introduction, Ekman pumping is an important component of the post-storm current and temperature response of the ocean to hurricanes. Ekman pumping is caused by divergence in the ML velocity field. The impulsive pumping action produces isopycnal displacements at near the inertial frequency (e.g., Price, 1981). This process is clearly manifest in the large oscillations in the temperature records at the BTM site (Figures 4d, 6d and 8d). The 34 m and 71m temperature records after the passages of Harvey and Nate show the clearest examples of this effect. In the case of Fabian, although inertial oscillations are present in the temperature record, turbulent mixing and redistribution of heat in the upper-ocean makes their interpretation more difficult. By using the magnitudes of these oscillations and the vertical temperature gradient (*dT/dZ*), it is possible to estimate the amplitude of the vertical isothermal (isopycnal) displacement, η, as

$$\eta = \Delta T \Big/ \frac{dT}{dZ} . \qquad (12)$$

Here ΔT is the amplitude of the temperature oscillations. The vertical temperature gradient was determined from BTM temperature profiles shown in Figure 9. Using the pre-storm profiles and our temperature time series, we have estimated the amplitudes of η for various depths. Table 4 shows the results of these calculations for Harvey, Nate, and Fabian. Hurricane Fabian's temperature response (Figure 8d) was dominated by entrainment, and thus clear inertial period temperature oscillations are more difficult to discern. Because the magnitude of oscillations varied with time after Hurricane Fabian, the values in Table 4 were computed using the maximum oscillation observed and therefore only represent one cycle, whereas after Harvey and Nate the magnitudes of oscillations were fairly stable and better represent the average isopycnal displacement which took place after the storm passage. Additionally, during deployment 18 (the Fabian case) temperature sensors on the BTM were located at 35, 47, 72, and 101 m as opposed to 34, 45, 71, and 100 m during deployment 22 (the Harvey and Nate case); however, this should have only a small effect on the calculations. Because the 34-m BTM temperature sensor was partially within the ML after Nate, and just below the ML after Harvey, these records provide a good estimate of the oscillations at the base of the ML. For both cases, the isopycnal displacement was ~10 m. After Fabian, the MLD deepened to greater than 35–m; therefore, temperature at 35-m did not show strong near-inertial oscillations until almost one week after the storm passage. At this time isopycnal displacements were about half those of the Harvey and Nate values. At 45 m the amplitude of oscillations varied between 4 m (in the Nate case) to 10 m (in the Harvey case). The greatest variation in isopycnal displacement was observed in the 71 m records with 20 m isopycnal displacements after Hurricane Fabian and 10 m oscillations after Harvey and Nate. At 100 m the temperature response to Tropical Storm Harvey was small and therefore estimates of isopycnal displacement were not computed. The Fabian and Nate response showed similar displacements of 7 – 8 m.

Estimates of vertical velocity, w, were also computed from the isopycnal displacements by dividing the peak-to-peak isopycnal displacement (2η) by half an inertial period (0.5IP), i.e.

$$w = \frac{4\eta}{IP} \qquad (13)$$

where IP is the local inertial period of 22.8 hours. Vertical velocities were on the order of 10^{-4} m s^{-1} although at 71-m following Hurricane Fabian, vertical velocity is estimated to be as large as 10^{-3} m s^{-1}.

Scaling estimates of isopycnal displacement can also be determined by using the following formula given by Price et al. (1994),

$$\eta = \frac{\tau}{\rho_0 f U_h} \qquad (14)$$

where τ is the magnitude of the wind stress, ρ_0 is the density of seawater (1035 kg m^{-3}), f is the local Coriolis parameter and U_h is the translation speed of the cyclone (e.g., Price et al., 1994). Figure 11 shows results for our study using the SeaWinds wind field data from Figures 3, 5, and 7. In all cases, the SeaWinds derived estimates for isopycnal displacement were smaller than those derived from temperature records. The largest discrepancy is seen for Tropical Storm Harvey. The SeaWinds derived estimates had values between 2 and 4 m while temperature derived estimates were 10 m. This is likely due to the small size of Tropical Storm Harvey, which makes it difficult to fully resolve relevant scales of winds using in the SeaWinds data. Although the absolute magnitudes of the isopycnal displacements appear to be underestimates, this method is useful to examine the spatial extend of isopycnal disturbances after the passage of intense storms. The Hurricane Fabian case (Figure 11, left panel) clearly shows a right-hand bias in the response that coincides with the SST response in Figure 7 and the Hurricane Nate response extends well to the left of the Hurricane track, consistent with the BTM temperature time series.

6.2 Inertial Currents

By inspecting Figures 4e-h, 6e-h, and 8e-h, it is evident that the dominant frequency in the horizontal components of the current velocity in all three storms is near the inertial frequency (IP = 22.8 hr). To further investigate this signal, complex demodulation, as described in the Methods section, was applied to the current data relevant to the three principal storms of this study. However, because of the presence of secondary frequency modes and a smaller inertial response in the cases of Tropical Storm Harvey and Hurricane Nate, interpretations of the results are more difficult for those storms and are not discussed further. Inertial currents derived from the complex demodulation analysis for Hurricane Fabian are shown in Figure 12. Inertial currents in the ML are available only after 2 inertial periods following Fabian's closest approach because of ADCP instrument bubble contamination issues.

Amplitude

The inertial current field in the wake of Hurricane Fabian was marked by strong currents at all depths. Within the mixed layer, currents most likely peaked 1 or 2 IPs after the storm passage. Unfortunately, ADCP data are not reliable during that period, but from the available data we can observe mixed layer, near-inertial currents > 50 cm s^{-1} and as high as 70 cm s^{-1} that last for a week after the storm passage. If we assume that maximum mixed layer inertial current velocities were on order of 100 cm s^{-1}, the e-folding time scales for current amplitudes are 9 days (9.5 IP). Below the ML, the inertial current amplitudes reached their maximum values between depths of 40 and 80 m, with the largest amplitudes near 100 cm s^{-1} about 1 IP after Fabian's closest approach. Currents within this depth range had slightly shorter e-folding times scale of about one week. Moving deeper, current amplitudes decreased with depth and maximum currents occurred at slightly later times. Below 120 m, the response was much weaker but still well above 10 cm s^{-1}. An interesting feature appeared around YD 252, when larger amplitude velocities can be seen penetrating to 130 m. It is unclear if this is an actual feature of the response or an artifact in the current data (possibly caused by inadequate removal of mooring motion). Further investigation will be needed to determine this.

Phase

The vector field (white arrows) in Figure 12 represents relative phase, φ, of the complex demodulated currents. By inspecting the relative phase, we can divide the inertial current response into three different zones. Figure 13 shows the time series of relative phase at different depths after Hurricane Fabian passed the BTM site. Different colors indicate the three different zones. The red lines show calculated relative phase values for the shallower depths (48 to 78 m). Within this depth interval, the relative phase is fairly constant with both time and depth. A transition layer can be identified below this layer (blue lines, 81 – 126 m). This transition layer is marked by a strong gradient in phase with depth. In the case of Fabian, we can observe a 90° clockwise rotation in phase over a depth range of 40 m (from 90 m to 130 m). Below this transition layer the currents become more uniform in both phase and amplitude (black line, 129 – 186 m).

Negative variations of phase with depth ($d\varphi/dz < 0$) indicate that deeper currents lead shallower currents. This occurs because the entire vertical current structure is rotating clockwise (anti-cyclonic). Figure 14 shows six snap-shots of the vertical current structure over a single inertial period. This vertical current structure has been reported in other studies (e.g. Leaman and Sanford, 1975; Pollard, 1980; Price, 1994; Shay 1998) and below the mixed layer can be interpreted as the result of the downward propagation of near-inertial internal waves produced by the hurricane.

Blue Shift

In each of the three layers, the slope of the phase generally increases with time (Figure 13). As reviewed in section 3, we have computed the dominant frequency in the signal, ω, through complex demodulation and from the slope of the phase, dφ/dt, we have estimated the blue shift. In the upper layer (48 – 78 m), the phase is a nearly linear function increasing with time between days 249 and 256 with an average slope of 0.024 cpd. This indicates a blue shift of ν = 0.050. The phase in the transition layer is more complicated. From day 249 through day 251 the phase increases with time but decreases with depth. Furthermore, dφ/dt also decreases with depth. The blue shift values range from ν = 0.047 at the top of the transition layer, to ν = 0.028 at the base of the transition layer (taken to be 126 m). Shortly after day 251, a decrease in phase occurs, followed by a second rise that peaked on day 254. The bottom layer had a structure similar to that of the transition layer, except for the depth dependence on φ. From day 249 to day 251, the slope was fairly constant indicating a blue shift ν = .028. But as for the transition layer, a decrease is followed by a steady increase after day 251. The cause of the large variations of phase after day 251 in the transitional and thermocline layers is unknown but does coincide in time with the tongue of large amplitude inertial currents that penetrates below 130 m.

6.3 Richardson Number and Shear

Vertical entrainment is caused largely by vertical shearing of currents and it results in both relative cooling of the upper mixed layer waters and heating in the entrained upper thermocline waters. Shear-induced mixing occurs where gradient Richardson numbers are reduced to a critical threshold value (nominally ¼). When this occurs, the cooler thermocline waters below the mixed layer are turbulently mixed or ‘entrained’ into the warmer mixed layer waters causing a cooling throughout the mixed layer. Conversely, the warm mixed layer waters are mixed with the cooler thermocline waters causing a net warming in the upper thermocline. Hurricane Fabian data provide a clear example of this phenomenon. In Figures 8d and 10c, temperatures in the mixed layer (down to the 35 m sensor) dropped by as much as 3 °C while sensors below the mixed layer (to a depth of 101 m) measured increases in average temperature after the passage of Fabian.

The gradient Richardson, Ri, is computed as N^2/S_v^2, where N is the Brunt-Vaisala frequency and S_v is the vertical shear computed as

$$S_v = \sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2} \qquad (15)$$

where u is the zonal velocity component and v is the meridional velocity component. Figure 15a through c show time series of the vertical distribution of the square of the Brunt-Vaisala frequency (top), the square of the vertical shear of horizontal currents (middle), and Ri number (bottom) during Hurricane Fabian. The 3 m binned ADCP data were used for shear and interpolated temperature data were used for Brunt-Vaisala frequency. From Figure 15c we can clearly see that Ri was below 0.25 down to a depth of 130 m from day 249 through 254.

6.4 *Ocean Color in the Wake of Hurricane Fabian*

Previous studies have shown that under certain circumstances, the upwelling and entrainment produced by hurricanes can trigger significant ocean color and/or phytoplankton bloom wakes (e.g., Iverson, 1977; Hoge et al., 2002; Babin et al., 2004; Walker and Leben 2005; Son et al. 2006). The mechanisms that have been postulated to explain ocean color wakes include 1) phytoplankton blooms, and 2) transport or entrainment of chlorophyll and/or colored dissolved organic matter (CDOM) into surface layers. Among the three storms considered here, Hurricane Fabian produced the most significant ocean color wake as indicated in Figure 16. This figure shows a SeaWifs 8-day composite image of chlorophyll concentration for Sept. 6 through 13 (YD 249-256). There is a large chlorophyll increase after the passage of Hurricane Fabian and the spatial extent of this increase coincides with the cool SST wake produced by Fabian shown in Figure 7.

The typical depth range for the deep chlorophyll maximum layer (DCML) at the BATS site near BTM is between 60 and 120 m (Steinberg et al. 2001). The surface waters in the oligotrophic Sargasso Sea are relatively nutrient poor during the late summer months, when seasonal stratification is near its maximum and only trace amounts of nitrate are present above 100 m. However, at depths greater than 150 m, nitrate values can exceed 2 μmol/kg (Steinberg et al., 2001). In particular, a profile from BATS cruise 179 in mid-August, which was obtained just a few weeks before the passage Hurricane Fabian, showed a linear increase of nitrate+nitrite concentrations from undetectable levels at 100 m to 2.6 μmol/kg at 200 m (http://bats.bbsr.edu/). If hurricane induced vertical mixing is deep enough, both the phytoplankton at the DCML and the relatively nutrient-rich waters below the thermocline can be entrained into the surface layer. This nutrient injection into the euphotic zone could set favorable conditions for the development of a phytoplankton bloom. Figure 15c shows that the Richardson number was below ¼ down to 130 m for several days after the passage of Fabian. Mixing thus appears to be deep enough to account for the onset of a phytoplankton bloom. Together with the vertical advection of the DCML, this might explain the higher chlorophyll levels in the wake of Hurricane

Fabian shown in Figure 16. The BTM's 10-m flourometer showed a small peak after the passage of Fabian confirming the SeaWiFS data. The 34-m BTM flourometer data displayed a rapid increase in chl-a concentration after Fabian, but the magnitude and persistence of the signal after the passage make the data questionable from that point onward because of possible biofouling. Strong vertical mixing was not observed at the BTM in the cases of Nate and Harvey and no significant chlorophyll increases were observed in SeaWiFS images or BTM flourometer data after their passages.

7. Summary

The upper-ocean response to three tropical cyclones was examined here. All three storms shared several qualitatively similar dynamic responses. In all cases, the large wind stress induced elevated upper ocean currents (up to at least 100 cm s^{-1} in the case of Fabian). Large near-inertial oscillations in the temperature records showed evidence of Ekman pumping and isopycnal displacements of at least 10 m. Mixed layer deepening occurred after each storm to depths of 45 m. In all three cases, the mixed layer DIH heat decreased after the storm passage indicating a transport of heat out of the ML into the atmosphere, but primarily into the upper thermocline. Both Fabian and Harvey showed a net loss of DIH (when integrated down to 150 m) up to 81.2 MJ m^{-2}, but somewhat surprisingly Hurricane Nate's response showed a large increase in net DIH of 218 MJ m^{-2}. Satellite images show a distinct asymmetric response in SST after each storm, with more intense SST cooling on the right-hand side of the storm track and maximum SST cooling of 4 °C.

Although each storm was unique in size and intensity and many of the differences in response were due to those variables, it is important to emphasize that the distance from the storm center and the orientation of the storm trajectory in relation to the BTM were important factors that need to be heeded when comparing the specific ocean responses. Harvey passed almost directly over the BTM and clear evidence of isopycnal doming was seen in the temperature record. On the other hand, Hurricane Nate passed far to the right of the BTM, leaving a fairly weak (but comparable to Harvey) response and a deepening of isopycnals. Hurricane Fabian was the largest storm, with the largest currents and temperature response. For this event, the BTM was situated on the right hand side of the storm track at a distance where maximum current response is expected.

The present data sets are quite unique and are anticipated to be of great value for developing, testing, and calibrating open ocean models applied to the problem of upper-ocean response to tropical storms including hurricanes and typhoons and hurricanes. Such work will help to increase our understanding of the ocean-atmosphere interaction beneath tropical cyclones to better predict their paths and intensities as well as their influences on the biogeochemistry and ecology of the upper ocean and perhaps global climate change.

Acknowledgements

We thank Derek Manov, Frank Spada, Songnian Jiang, and John Kemp for their significant contributions and Francesco Nencioli, Libe washburn, Dave Siegel, Yi Chao, and Sarah Henkel for their useful comments on the manuscript. Support for this research was provided by the National Science Foundation Ocean Technology and Interdisciplinary Coordination and Chemical Oceanography Programs (TD: OCE-9627281, OCE-9730471, OCE-9627277), the National Ocean Partnership Program (TD: N40000149810803), the Office of Naval Research Ocean Engineering and Marine Systems Program (Dan Frye: N00014-96-1-0028), and the University of California, Santa Barbara (to T. Dickey, UCSB).

References List

Anthes, R.A., R.W. Corell, G. Holland, J.W. Hurrell, M.C. MacCracken, and K.E. Trenberth, Hurricanes and Global Warming -- Potential Linkages and Consequences, *Bulletin of the American Meteoroligocal Society*, *87* (5), 623-628, 2006.

Babin, S.M., J.A. Carton, T.D. Dickey, and J.D. Wiggert, Satellite evidence of hurricane-induced phytoplankton blooms in an oceanic desert, *Journal of Geophysical Research*, *109*, 2004.

Brink, K.H., Observations of the Response of Thermocline Currents to a Hurricane, *Journal of Physical Oceranography*, *19*, 1017-1022, 1989.

Church, J.A., T.M. Joyce, and J.F. Price, Current and Density Observations across the Wake of Hurricane Gay, *Journal of Physical Oceanography*, *19*, 259-265, 1989.

Conte, M.H., T. Dickey, J.C. Weber, R. Johnson, and A. Knap, Transient physical forcing of pulsed export of bioreactive material to the deep Sargasso Sea, *Deep Sea Research I*, *50*, 1157-1187, 2003.

Conte, M.H., N. Ralph, and E.H. Ross, Seasonal and interannual variability in deep ocean particle fluxes at the Oceanic Flux Program (OFP)/Bermuda Atlantic Time Series (BATS) site in the western Sargasso Sea near Bermuda, *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, *48* (8-9), 1471-1505, 2001.

Dickey, T., G. Chang, C. Moore, A. Hanson, and D. Karl, The Bermuda Testbed Mooring and HALE-ALOHA Mooring Programs: Innovative Deep-Sea Global ObservatorieS, *Marine Technology Society*, 2006.

Dickey, T., D. Frye, H. Jannasch, E. Boyle, D. Manov, D. Sigurdson, J. McNeil, M. Stramska, A. Michaels, N. Nelson, D. Siegel, G. Chang, J. Wu, and A. Knap, Initial results from the Bermuda Testbed Mooring program, *Deep-Sea Research Part I-Oceanographic Research Papers*, *45* (4-5), 771-794, 1998.

Dickey, T., D. Frye, J. McNeil, D. Manov, N. Nelson, D. Sigurdson, H. Jannasch, D. Siegel, T. Michaels, and R. Johnson, Upper-ocean temperature response to Hurricane Felix as measured by the Bermuda testbed mooring, *Monthly Weather Review*, *126* (5), 1195-1201, 1998.

Dickey, T.D., and J.J. Simpson, The Sensitivity of the Upper Ocean Structure to Time Varying Wind Direction, *Geophysical Research Letters*, *10* (2), 133-136, 1983.

Emanuel, K., Increasing destructiveness of tropical cyclones over the past 30 years, *Nature*, *436*, 686-688, 2005.

Foltz, G.R., and M.J. McPhaden, Unusually warm sea surface temperatures in the tropical North Atlantic during 2005, *Geophysical Research Letters*, *33*, 2006.

Gill, A.E., On the behavior of internal waves in the wakes of storms., *Journal of Physical Oceanography* (14), 1129 - 1151, 1984.

Hoge, F.E., and P.E. Lyon, Satellite observation of Chromophoric Dissolved Organic Matter (CDOM) variability in the wake of hurricanes and typhoons, *Geophysical Research Letters*, *29* (19), 2002.

Hoyos, C.D., P.A. Agudelo, P.J. Webster, and J.A. Curry, Deconvolution of the Factors Contributing to the Increase in GLobal Hurricane Intensity, *Science*, *312*, 94-97, 2006.

Iverson, R.L., Mesoscale oceanic phytoplankton patchiness caused by hurricane effects

on nutrient distribution in the Gulf of Mexico., in *Oceanic Sound Scattering Predictions*, edited by N.R. Anderson, and B.J. Zahuranec, pp. 767-778, Plenum Press, 1977.
Jiang, S., T. Dickey, D.K. Steinberg, and L. Madin, Temporal variability of zooplankton biomass from ADCP backscatter time series data at the Bermuda Testbed Mooring Site, *Deep-Sea Research II*, *In press*, 2007.
Kantha, L., Time to Replace the Saffir-Simspon Hurricane Scale?, *Eos*, *87* (1), 3, 2006.
Knutson, T.R., and R.E. Tuleya, Comments on "impacts of CO2-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective scheme" - Reply, *Journal of Climate*, *18* (23), 5183-5187, 2005.
Kuwahara, V.S., P.G. Strutton, and T. Dickey, Radiometric and bio-optical measurements from moored and drifting buoys: measurements and data analysis protocols, in *Ocean Optics Protocols for Satellite Ocean Color Validation*, 2004.
Landsea, C., Hurricanes and global warming, *Nature*, *438*, 2005.
Landsea, C., Counting Altlantic Tropical Cyclones Back to 1900, *Eos*, *88* (18), 2007.
Large, W.G., and G.B. Crawford, Observations and Simulations of Upper-Ocean Response to Wind Events During the Ocean Storms Experiment, *Journal of Physical Oceanography*, *25* (11), 2831-2852, 1995.
Leaman, K.D., and T.B. Sanford, Vertical Energy Propagation of Inertial Waves - Vector Spectral Analysis of Velocity Profiles, *Journal of Geophysical Research*, *80* (15), 1975-1978, 1975.
Levine, M.D., and V. Zervakis, Near-Inertial Wave Propagation into the Pycnocline during Ocean Stroms: Observations and Model Comparision, *Journal of Physical Oceanography*, *25*, 2890 - 2902, 1995.
Mann, M.E., and K. Emanuel, Atlantic Hurricane Trends Linked to Climate Change, *Eos*, *87* (24), 233, 2006.
McClain, C.R., M.L. Cleave, G.C. Feldman, W.W. Gregg, S.B. Hooker, and N. Kuring, Science quality SeaWiFS data for global biosphere research, *Sea Technology*, *39* (9), 10-16, 1998.
McGillicuddy, D.J., A.R. Robinson, D.A. Siegel, H.W. Jannasch, R. Johnson, T. Dickeys, J. McNeil, A.F. Michaels, and A.H. Knap, Influence of mesoscale eddies on new production in the Sargasso Sea, *Nature*, *394* (6690), 263-266, 1998.
McNeil, J.D., H.W. Jannasch, T. Dickey, D. McGillicuddy, M. Brzezinski, and C.M. Sakamoto, New chemical, bio-optical and physical observations of upper ocean response to the passage of a mesoscale eddy off Bermuda, *Journal of Geophysical Research-Oceans*, *104* (C7), 15537-15548, 1999.
Michaels, A.F., and A.H. Knap, Overview of the US JGOFS Bermuda Atlantic Time-series Study and the Hydrostation S program, *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, *43* (2-3), 157-198, 1996.
O'Reilly, J.E., S. Maritorena, B.G. Mitchell, D.A. Siegel, K.L. Carder, S.A. Garver, M. Kahru, and C. McClain, Ocean color chlorophyll algorithms for SeaWiFS, *Journal of Geophysical Research-Oceans*, *103* (C11), 24937-24953, 1998.
Piekle Jr., R.A., C. Landsea, M. Mayfield, J. Laver, and R. Pasch, Hurricanes and Global Warming, *Bulletin of the American Meteoroligocal Society*, *86* (11), 1571-1575, 2005.

Pollard, R.T., Properties of near-surface interail oscillations., *Deep-Sea Research*, *17*, 813 - 821, 1980.
Price, J.F., Upper Oean Response to a Hurricane, *Journal of Physical Oceranography*, *11*, 153-175, 1981.
Price, J.F., Internal Wave Wake of a Moving Storm. Part I: Scales, Energy Budget and Observations, *Journal of Physical Oceanography*, *13*, 949-965, 1983.
Price, J.F., T.B. Sanford, and G.Z. Forristall, Forced Stage Response to a Moving Hurricane, *Journal of Physical Oceanography*, *24*, 233-260, 1994.
Qi, H., R.A. DeSzoeke, C.A. Paulson, and C.C. Eriksen, The Structure of Near-Inertial Waves during Ocean Storms, *Journal of Physical Oceanography*, *25*, 2853 - 2871, 1995.
Scharroo, R., Satellite Altimetry and the Intensification of Hurricane Katrina, *Eos*, *86* (40), 366, 2005.
Shapiro, L.J., and S.B. Goldenberg, Atlantic Sea Surface Temperature and Tropical Cyclone Formation, *Journal of Climate*, *11* (4), 578-590, 1998.
Shay, L.K., G.J. Goni, and P.G. Black, Effects of a warm oceanic feature on Hurricane Opal, *Monthly Weather Review*, *128* (5), 1366-1383, 2000.
Shay, L.K., A.J. Mariano, D. Jacob, and E.H. Ryan, Mean and Near-Inertial Ocean Current Response to Hurricane Gilbert, *Journal of Physical Oceanography*, *28*, 858 - 889, 1998.
Sholkovitz, E.R., and P.N. Sedwick, Open-ocean deployment of a buoy-mounted aerosol sampler on the Bermuda Testbed Mooring: Aerosol iron and sea salt over the Sargasso Sea, *Deep-Sea Research Part I-Oceanographic Research Papers*, *53* (3), 547-560, 2006.
Siegel, D.A., T.K. Westberry, M.C. O'Brien, N.B. Nelson, A.F. Michaels, J.R. Morrison, A. Scott, E.A. Caporelli, J.C. Sorensen, S. Maritorena, S.A. Garver, E.A. Brody, J. Ubante, and M.A. Hammer, Bio-optical modeling of primary production on regional scales: the Bermuda BioOptics project, *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, *48* (8-9), 1865-1896, 2001.
Son, S., T. Platt, H. Bouman, and D. Lee, Satellite observation of chlorophyll and nutrients increase induced by Typhoon Megi in Japan/East Sea, *Geophysical Research Letters*, *33*, 2006.
Steinberg, D.K., C.A. Carlson, N.R. Bates, R. Johnson, J., A.F. Michaels, and A.H. Knap, Overview of the US JGOFS Bermuda Atlantic Time-series Study (BATS): a decade-scale look at ocean biology and biogeochemistry, *Deep-Sea Research II*, 1405-1477, 2001.
Stramska, M., and T.D. Dickey, Short-term variability of the underwater light field in the oligotrophic ocean in response to surface waves and clouds, *Deep-Sea Research Part I-Oceanographic Research Papers*, *45* (9), 1393-1410, 1998.
Trenberth, K.E., Uncertainty in Hurricanes and Global Warming, *Science*, *308*, 1753-1754, 2005.
Walker, N.D., R.R. Leben, and S. Balasubramanian, Hurricane-forced upwelling and chlorophyll a enhancement within cold-core cyclone in the Gulf of Mexico, *Geophysical Research Letters*, *32* (18), 2005.
Webster, P.J., G.J. Holland, J.A. Curry, and H.-R. Chang, Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment, *Science*, *309*, 1844-

1846, 2005.
Yueh, S.H., B.W. Stiles, and W.T. Liu, QuikSCAT wind retrievals for tropical cyclones, *IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING*, *41* (11), 2616-2628, 2003.
Zedler, S.E., Observations and Modeling of the Ocean's Response to Hurricane Felix at the Bermuda Testbed Mooring, Master of Arts thesis, University of California, Santa Barbara, Santa Barbara, CA, 1999.
Zedler, S.E., T.D. Dickey, S.C. Doney, J.F. Price, X. Yu, and G.L. Mellor, Analyses and simulations of the upper ocean's response to Hurricane Felix at the Bermuda Testbed Mooring site: 13-23 August 1995, *Journal of Geophysical Research-Oceans*, *107* (C12), 2002.
Zheng, X.B., T. Dickey, and G. Chang, Variability of the downwelling diffuse attenuation coefficient with consideration of inelastic scattering, *Applied Optics*, *41* (30), 6477-6488, 2002.

Table Captions

Table 1. Comparison of Tropical Storm Harvey, and Hurricanes Nate, Fabian, and Felix general characteristics. For Harvey, Nate and Fabian, values are taken from the NHC Forecast/Advisories closest to the time when the storms were at their nearest approach to the BTM site unless otherwise noted. Values for hurricane Felix adapted from Dickey et al. (1998) unless otherwise noted. Note that since Harvey was a Tropical Cyclone, the SSHS, HHI and R_{hurr} are not applicable; also R_{max} is not well defined and thus difficult to determine.

[a] HHI computed using formula in Kantha 2006, see text for explanation.

[b] ΔSST estimated from 8-day MODIS composite images.

Table 2. Local observations at the BTM site during each storm's closest approach. Distance and direction from the BTM are computed from NHCs best track estimates of the storm centers. Maximum sustained winds for Felix and Fabian are from the BTM anemometer, and from SeaWinds for Harvey and Nate. Wind stress is computed from eq. 1 in text. All other values are *in situ* data from the BTM.

Table 3. Observed depth integrated heat (DIH) anomaly based on post-storm minus pre-storm BTM temperature profiles. Negative values indicate heat loss. Cooling intervals are defined to be from the surface to where the temperature anomaly becomes positive and is meant to represent mixed layer cooling. Warming intervals extend from immediately below the cooling interval to 150 m and represent upper thermocline warming. DIH_{150} is the sum of DIH_{ML} and DIH_{TC}.

[a] These values were calculated using a different cooling and warming interval to better represent the mixed layer cooling observed after Harvey's passage, see text for explanation.

Table 4. Isopycnal displacement calculations for various depths after Tropical Storm Harvey and Hurricanes Nate and Fabian at the BTM site. T_{max} and T_{min} are the maximum and minimum temperature oscillation values estimated from figures 4d, 6d, and 8d. ΔT is one half $T_{max} - T_{min}$. dT/dz is computed from linearly interpolated temperature profiles immediately before the storm passage. η and w are the isopycnal displacement and upwelling values, respectively, as described in the text.

[a] Temperature records for Hurricane Fabian were at 35, 47, 72, and 101 m.

Figure Captions

Figure 1. Top Panel: Tropical storms and hurricanes that passed within 400 km (blue circle) of the BTM (red star) from 1851 though 2005. Bottom panel: Tropical storms and hurricanes that passed within 400 km (black dashed lines are 200 and 400 km radii) of the BTM (red star) from1995 through 2005. Tracks of Hurricane Felix (cyan), Fabian (green), Harvey (blue), Nate (magenta), and Florence (red) are highlighted.

Figure 2. BTM instrumentation diagram during deployment 22 (May 13 – September 27, 2005) when Tropical Storm Harvey and Hurricane Nate passed the BTM. Depths of temperatures sensors (T), fluorometers (Fl), PAR sensors, and ADCP are shown. A similar configuration was used when Hurricane Fabian passed by during deployment 18 in 2003. Note, only selected instruments discussed in this paper are shown. Inset is a map showing the BTM position relative to the Hydrostation S and BATS sites and Bermuda.

Figure 3. Track of Tropical Storm Harvey (black line, black dots every 6 hours) near the BTM. Color shading is MODIS 8-day composite SST beginning on day 217. Vectors are SeaWinds 10-m wind velocity from 1000 UTC Aug. 4. The position of the BTM is shown with the black dot in the center of the image.

Figure 4. Atmospheric and oceanographic observations during Tropical Storm Harvey. a) BTM barometric pressure, b) SeaWinds wind speed near the BTM, c) SeaWinds wind direction near the BTM, d) BTM temperature time series (sensors depth: 2, 4, 11, 19, 34, 45, 71, 100, 150, and 201 m), e)-h) Currents at the BTM for selected depths , u-component in red, v-component in blue.

Figure 5. Track of Hurricane Nate near the BTM (black line, black dots every 6 hours). Color shading is MODIS 8-day composite SST beginning on day 249. Vectors are SeaWinds 10-m wind velocity from 2200 UTC Sept. 8. The position of the BTM is shown with the black dot in the center of the image.

Figure 6. Atmospheric and oceanographic observations during Hurricane Nate. a) BTM barometric pressure, b) SeaWinds wind speed near the BTM, c) SeaWinds wind direction near the BTM, d) BTM temperature time series (sensors depth: 2, 4, 11, 19, 34, 45, 71, 100, 150, and 201 m), e)-h) Currents at the BTM for selected depths , u-component in red, v-component in blue.

Figure 7. Track of Hurricane Fabian near the BTM (black line, black dots every 6 hours). Color shading is MODIS 8-day composite SST beginning on day 249. Vectors are QuickScat 10-m wind velocity from 2200 UTC Sept. 5. The position of the BTM is shown with the red dot in the center of the image.

Figure 8. Atmospheric and oceanographic observations during Hurricane Fabian. a) BTM barometric pressure, b) SeaWinds on ADOES II (black) and QuickScat (red) and BTM *in situ* wind speed (blue), c) SeaWinds and BTM *in situ* wind direction d) BTM

temperature time series (sensors depth: 2, 8, 19, 35, 47, 57, 72, 101, and 151 m, e)-h), Currents at the BTM for selected depths, u-component in red, v-component in blue. Note the change in scale in h).

Figure 9. a) BTM pre-storm (solid) and post-storm (dashed) temperature profiles for Fabian (red), Harvey (blue), Nate (green). b) – d) Change in depth integrated heat content (post-storm – pre-storm).

Figure 10. Linearly interpolated temperature contours. Black line is ML depth, white line is 26 °C isotherm. a) Tropical Storm Harvey, b) Hurricane Nate, c) Hurricane Fabian. x-axis is year day for a) 2005, b) 2005, c) 2003.

Figure 11. SeaWinds derived estimates of isopycnal displacement for Hurricane Fabian (left), Tropical Storm Harvey (middle), and Hurricane Nate (right). The BTM location is indicated with black dot in the center of each image.

Figure 12. Complex demodulated (inertial) currents during and after Hurricane Fabian. Demodulation frequency σ = .0455 cyc/h. Colored contours are amplitude. Vector field is relative phase of the inertial currents. A 180° phase change with depth is evident during the strongest inertial current response (day 249 through 255). Note phase becomes less significant as amplitude gets small.

Figure 13. Relative phase of inertial currents in response to Hurricane Fabian at all depths. The blue shift is proportional to the time derivative of phase. Forced layer: 48 – 78 m (red), transition layer 83 – 126 m (blue), thermocline layer 129 – 186 m (black). Phase generally increased with time, indicating a positive blue shift and decreased with depth, indicating a downward propagation on an internal wave.

Figure 14. ADCP current profile over 1 inertial period (22.8 hrs) beginning 1.8 IP after Fabian's closest approach. The velocity profile is shaped like a right-hand spiral that rotates clockwise with time. Notice the maximum velocities occur between 50 and 100 m (magnitudes > 100 cm/s) and the velocities at depth lead the shallower velocities by a half a cycle. Note the shallowest vector is at 21 m.

Figure 15. Richardson number calculation after Hurricane Fabain. (top) log of the square of the buoyancy frequency, (middle) log of the square of the vertical shear, (bottom) Richardson's number. Blue box in the middle and bottom panels is where data is not available due to bubble contamination.

Figure 16. SeaWiFS 7-day chlorophyll concentration (day 249-256) near Bermuda after Hurricane Fabian.

Tables

Table 1. General Storm Characteristics While in the Vicinity of the BTM

Parameter	Symbol	Units	Harvey	Nate	Fabian	Felix
Saffir-Simspon hurricane scale	SSHS	--	--	1	3	1
Hurricane hazard index[a]	HHI	--	--	0.2	6.5	2.3
Maximum sustained winds	V_{max}	m s^{-1}	26	39	54	38
Maximum winds stress	τ_{max}	N m^{-2}	1.7	5.8	14.7	5.4
Radius to hurricane force winds	R_{hurr}	km	--	37	134	120
Radius to maximum winds	R_{max}	km	--	28	46	61
Central pressure	p_c	mb	995	982	950	964
Translation speed	U_h	m s^{-1}	6.3	6.7	8.6	6.9
SST change[b]	ΔSST	°C	2.5	3	3.5	3.5

Table 2. Observation at the BTM

Parameter	Symbol	Units	Harvey	Nate	Fabian	Felix
Distance from the BTM	--	km	5	123	102	90
Direction from the BTM	--		N/A	SE	W	W
Time of closest approach			Aug. 4 0928	Sept. 8 1453	Sept. 5 1847	Aug. 14 2140
Maximum sustained winds	U_{BTM}	m s^{-1}	26	20	30	38
Maximum winds stress	τ_{BTM}	N m-2	1.7	0.6	4.5	5.18
Pressure	p_{BTM}	mb	995	1000	986	N/A
Initial MLD	h_0	m	8	22	20	17
Maximum MLD	h_{max}	m	23	35	50	45
Mix layer currents	U_{ml}	m s^{-1}	25	27	60	50
ML temperature change	ΔT_{BTM}	°C	1.5	<0.5	3.5	3.5
Density change across the thermocline	Δρ	kg m^{-3}	2.3	3	3	2.6
Reduced gravity	g'	m s^{-2}	0.022	0.029	0.029	0.025
Nondimensional Numbers						
Nonodimensional storm speed	S	--	1.6	2.4	1.9	1.2
Mixed layer Burger Number	B	--	0.01	0.05	0.03	0.01
Rossby Number	Q	--	0.15	0.31	0.43	0.22

Table 3. Observed Depth Integrated Heat Anomaly

	Cooling interval [m]	DIH_{ML} (MJ m^{-2})	Warming interval [m]	DIH_{TC} (MJ m^{-2})	DIH_{150} (MJ m^{-2})
Harvey	0 - 61	-81.9	61 - 150	16.8	-65.1
Harvey[a]	0 - 20	-43.0	20 - 150	-22.1	-65.1
Nate	0 - 20	-31.4	20 - 150	249.0	218.0
Fabian	0 - 41	-399.0	41 - 150	318.0	-81.2

Table 4. Isothermal Displacement and Upwelling

Depth	T_{min}	T_{max}	ΔT [°C]	dT/dz [°C/m]	η [m]	w [cm/s]
34 m						
Harvey	22.0	25.3	1.7	-0.175	9.42	0.046
Nate	24.0	27.5	1.8	-0.182	9.62	0.047
Fabian[a]	24.0	25.5	0.8	-0.159	4.71	0.023
45 m						
Harvey	21.3	23.0	0.9	-0.080	10.68	0.052
Nate	22.5	24.0	0.8	-0.185	4.05	0.020
Fabian[a]	22.0	24.5	1.3	-0.142	8.81	0.043
71 m						
Harvey	20.0	20.8	0.4	-0.043	9.38	0.046
Nate	20.3	21.7	0.7	-0.064	10.98	0.054
Fabian[a]	22.0	24.5	1.3	-0.060	20.70	0.101
100 m						
Nate	19.4	19.8	0.2	-0.024	8.18	0.040
Fabian[a]	19.1	19.5	0.2	-0.030	6.76	0.033