

## Upper-Ocean Temperature Response to Hurricane Felix as Measured by the Bermuda Testbed Mooring

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### ABSTRACT

Hurricane Felix passed over the Bermuda testbed mooring on 15 August 1995, providing a unique opportunity to observe the response of the upper ocean to a hurricane. In the vicinity of Bermuda, Felix was a particularly large hurricane with hurricane-force winds over a diameter of about 300–400 km and tropical storm-force winds over a diameter of about 650–800 km. Felix moved northwestward at about 25 km h<sup>-1</sup> with the eye passing about 65 km southwest of the mooring on 15 August. Peak winds reached about 135 km h<sup>-1</sup> at the mooring. Complementary satellite sea surface temperature maps show that a swath of cooler water (by about 3.5°–4.0°C) was left in the wake of Felix with the mooring in the center of the wake. Prior to the passage of Felix, the mooring site was undergoing strong heating and stratification. However, this trend was dramatically interrupted by the passage of the hurricane. As Felix passed the mooring, large inertial currents (speeds of 100 cm s<sup>-1</sup> at 25 m) were generated within the upper layer. The *e*-folding decay timescale of the inertial currents was about 9 days. The mixed layer depth was about 15 m before the arrival of Felix and deepened to about 45 m within three days after Felix's passage; the temperature at 25 m decreased by approximately 3.5°–4.0°C. Large-amplitude temperature oscillations (~1.5°C) near the inertial period (inertial pumping effect) were set up by the hurricane in the seasonal thermocline resulting in vertical displacements of isotherms of approximately 15 m at 60–70 m. Comparative scale analyses of the upper-ocean responses to Hurricane Felix and Hurricane Gloria (1985) indicate that they have several similarities.

### 1. Introduction

The influence of sea surface temperature (SST) on the genesis, evolution, and intensity of tropical cyclones has received considerable attention (e.g., Chang 1979; Tuleya and Kurihara 1982; Emanuel 1986). Ginis (1995) has presented an extensive review of this topic and has indicated that a potentially significant constraint on predictions of tropical cyclones is the lack of understanding of the ocean's response to intense forcing. Both positive and negative feedbacks exist for the hurricane–ocean system because of sea surface cooling induced by strong forcing. Fully coupled high-resolution atmosphere–ocean models are needed to explore these complex interactions (e.g., Ginis 1995).

Open ocean response to intense forcing has been the subject of considerable theoretical and modeling efforts

(e.g., Gill 1982; Lighthill 1978; Price 1981, 1983; Price et al. 1994). However, the observational databases available for such studies are very limited because of the operational difficulty of doing shipboard measurements under such adverse conditions and the paucity of moored instrumentation. However, a few hurricanes have passed over moored instruments, but almost exclusively over relatively shallow waters [e.g., review by Ginis (1995)] where the dynamic response is quite different and more complicated because of topographic and boundary effects. To our knowledge, the only previous open ocean mooring observations of hurricane-forced dynamics were obtained by Brink (1989), who collected current data at depths from 159 to 1059 m at a location about 100 km from the path of Hurricane Gloria (1985) in the western North Atlantic. Although neither mixed layer nor wind observations were made, Brink's data are especially important for characterizing the response of the deep thermocline and the downward propagation of near-inertial energy without topographic influence. On 15 August 1995, Hurricane Felix passed over the Bermuda testbed mooring (BTM), providing another unique and important dataset.

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## 2. Methods

The BTM program was initiated in June 1994 and provides the oceanographic community with a common platform for the development and testing of interdisciplinary sensors, analyzers, and systems (Dickey 1995; Dickey et al. 1998). The BTM has several advantages. One of these is the capability of capturing extreme, episodic events, which are inaccessible to ships. The mooring site, which is coincident with the Joint Global Ocean Flux (JGOFS) Bermuda Atlantic Time Series (BATS) site, is ideal for several other reasons. For example, 1) a rich historical database is available for the area (Michaels and Knap 1996); 2) remote sensing data are available for the region (see Nelson 1998); 3) at a minimum, shipboard measurements are made at monthly intervals near the mooring (Michaels and Knap 1996); and 4) there is a documented need for high temporal resolution data at the site, which is of high ecological and biogeochemical importance and a focus for JGOFS observationalists and modelers.

The BTM site is located 80 km southeast of Bermuda ( $31^{\circ}43.7'N$ ,  $64^{\circ}10.1'W$ ) in water of depth 4554 m. Mooring turnarounds take place every 3–4 months, with an approximate 1-week break in the time series observations, which is required for replacement of instrumentation. The mooring and its special telemetry are described in detail by Frye et al. (1996) and Dickey et al. (1998).

The mooring array used for Deployment BTM 3 (6 April 1995–23 August 1995) is illustrated in Fig. 1. The meteorological package included sensors for measuring wind speed and direction and air temperature (Coastal Climate Weatherpak). These variables were sampled every hour, recording 10-min average data. The peak wind gust (highest 3-s value every 10 min) was also recorded during this 10-min sampling period. This measurement is important particularly under high wind, high sea-state conditions, such as those experienced during passage of Hurricane Felix. Average wind speeds are about 20% lower than wind gust speeds according to our analysis. The wind anemometer and a downwelling spectral radiometer were located on the buoy at 4.5 m above the ocean surface. Estimates of wind speed at 10 m above the surface,  $U_{10}$ , are computed using a commonly used formula presented by Large et al. (1995).

During deployment of BTM 3, current speed and direction and temperature were measured at depths of 25 and 106 m using S4 (InterOcean) electromagnetic current meters. These were sampled at 2 Hz, and 1-min averages were stored every 30 min. Temperatures were also measured with self-recording temperature systems (TPODS, Brancker, Inc.) at 60, 120, and 150 m. These data were sampled every 15 min. Multivariable moored systems (MVMS; e.g., Dickey 1991; Dickey et al. 1993) recorded 3.75-min averages of physical and optical data at depths of 45 and 71 m. Physical data collected with the MVMS included vector-averaged currents [based on

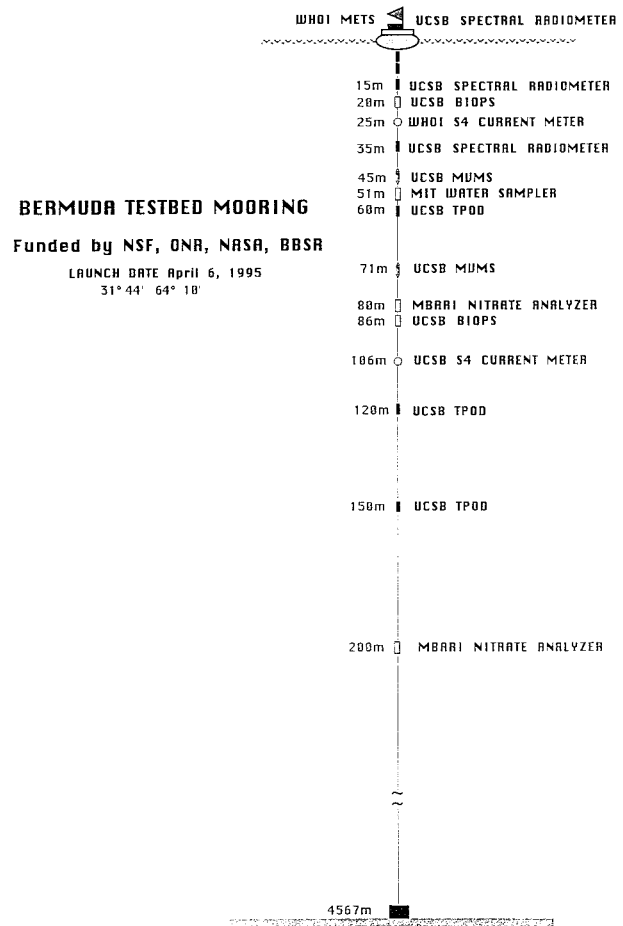


FIG. 1. Mooring schematic for the Bermuda testbed mooring for the period 6 April–25 August 1995. Relevant physical instruments include a surface meteorological system (METS), a surface spectral radiometer, subsurface multivariable moored systems (MVMS), S4 current meters, and subsurface temperature recorders (TPODS).

EG&G vector measuring current meter, see Weller and Davis (1980)], temperature, and conductivity (Sea-Bird Model SBE-4). Other bio-optical (Dickey et al. 1998) and chemical (Jannasch et al. 1994) measurement systems were deployed, but are not discussed here. These systems also provided temperature data. To summarize, the in situ physical data relevant to the present analysis include currents at 25, 45, 71, and 106 m and temperature at these same depths plus depths of 60, 120, and 150 m.

## 3. Results

Hurricane Felix had its origin as a tropical wave off the African coast 6 August 1995 and reached hurricane force winds about 800 km north-northeast of the Leeward Islands on 11 August. Air Force Reserve hurricane hunter planes made 24 flights into Felix, collecting meteorological data. Felix was a particularly large hurricane with hurricane force winds over a diameter of about

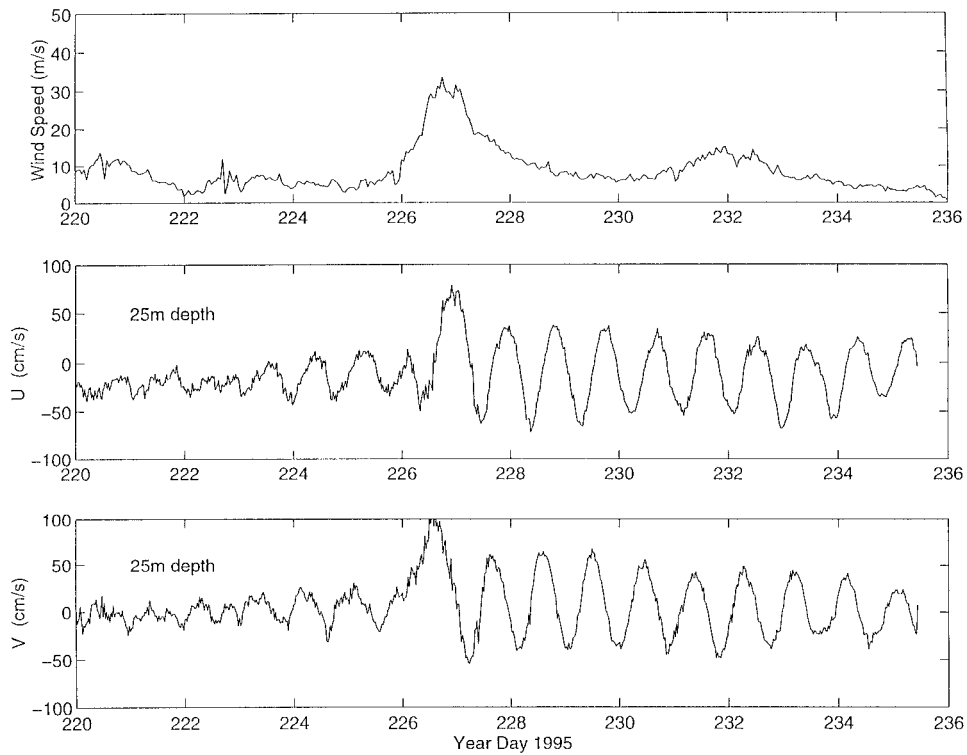


FIG. 2. Time series (top to bottom) of (a) wind speed, (b) zonal current at 25-m depth, and (c) meridional current at 25-m depth.

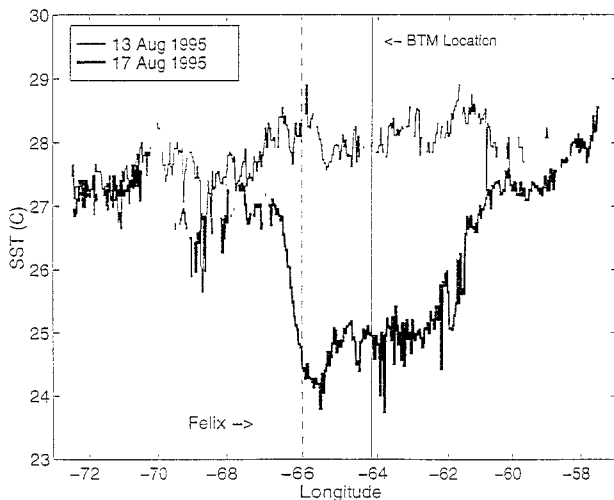


FIG. 3. Sections of SST ( $^{\circ}\text{C}$ ) along  $31.75^{\circ}\text{N}$  from 3-day composite images of AVHRR-derived SST, centered on 13 August 1995 or year day 225 (thin line) and August 17 or year day 229 (thick line). Felix crossed this latitude at approximately  $-66.5^{\circ}$  longitude (indicated by a vertical dashed line) near 0000 UTC 15 August or year day 227, with peak winds near  $135\text{ km h}^{-1}$ . The Bermuda testbed mooring location was very near the center of the cold SST swath (indicated by a solid vertical line).

300–400 km and tropical storm force winds over a diameter of about 650–800 km. A minimum barometric pressure of 930 mb and maximum surface wind speeds of  $220\text{ km h}^{-1}$  (category 4 on the Saffir–Simpson scale) were measured when Felix was about 500 km south-southeast of Bermuda at 1800 UTC 12 August. Felix then moved northwestward in a nearly straight line path at about  $25\text{ km h}^{-1}$ . Barometric pressure gradually increased and maximum wind speeds decreased as the eye passed about 65 km and 100 km southwest of the BTM and the island of Bermuda, respectively. Wind speed peaked over the BTM on 15 August (year day 227) at about  $135\text{ km h}^{-1}$  or  $38\text{ m s}^{-1}$  (Fig. 2).

Satellite SST (high-resolution Advanced Very High Resolution Radiometer) maps (Nelson 1998) show that a swath of cool water was left in the wake of Felix. The SST was roughly  $3.5^{\circ}$ – $4.0^{\circ}\text{C}$  cooler in the wake, which was roughly 400 km wide (Fig. 3). Remarkably, the BTM was located almost perfectly in the center of Felix’s wake. The center of the hurricane wake was located about 200 km to the right of the trajectory of the eye of the hurricane. Interestingly, two large surface temperature features (about 250 km in diameter) were left in the wake as indicated in SST images of 20–22 August (year days 232–234). These clockwise rotating features may be related to inertial current oscillations described below.

Prior to the passage of Felix, the mooring site was

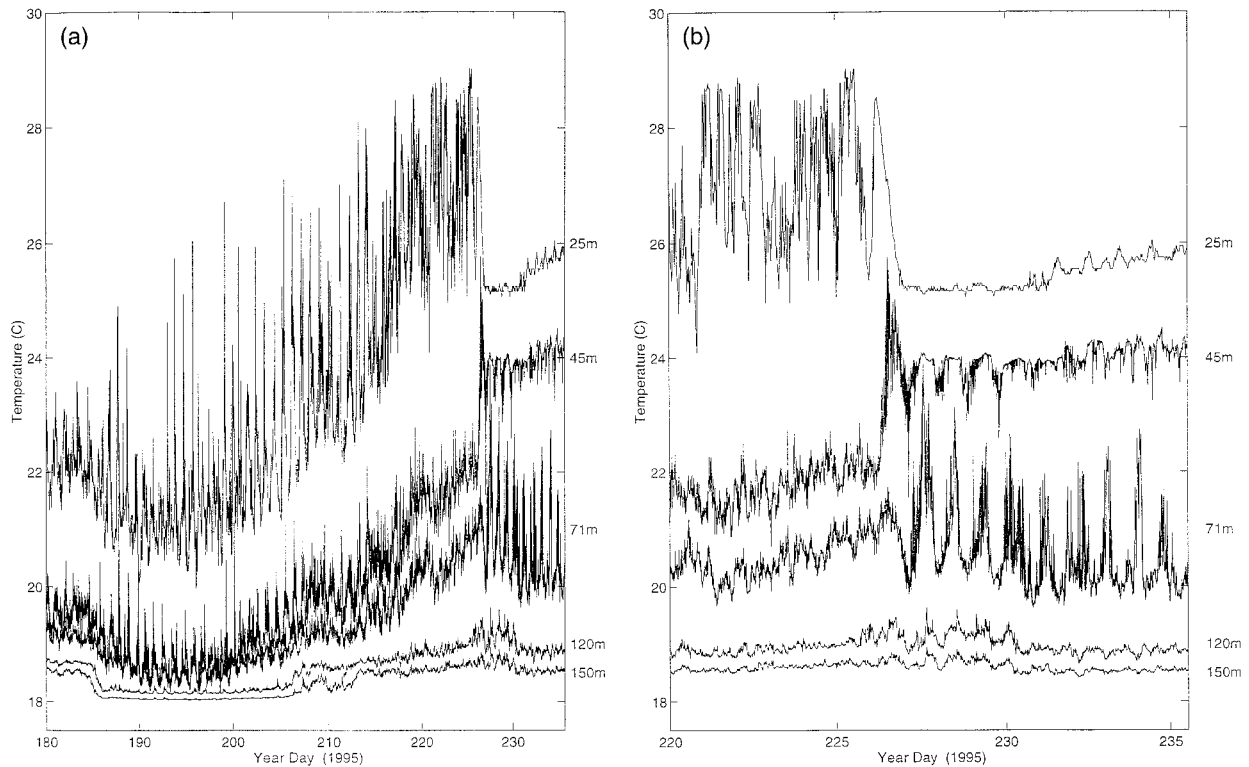


FIG. 4. (a) Time series of temperature at depths of 25, 45, 71, 120, and 150 m from 29 June (year day 180) through 24 August (year day 236). (b) Same as (a) except for time period from 8 August (year day 220) through 24 August (year day 236).

undergoing strong seasonal heating and stratification (Fig. 4a) consistent with observed minimal cloudiness (based on surface radiometer data) and increasing air temperature. However, this trend was dramatically interrupted by the passage of the hurricane on 15 August (year day 227). As Felix passed the mooring, large inertial currents were generated within the upper layer as indicated by the 25-m current meter record (speeds of  $100 \text{ cm s}^{-1}$ ; Fig. 2). Inertial currents are set up by the onset of intense localized wind stress and have a period of approximately 22.8 h at our site. The current shear is greatest at the base of the mixed layer where deep cooler waters are entrained into the mixed layer resulting in cooling of the surface layer. The mixed layer depth was about 15 m on 21 July (year day 202) according to CTD profile data and may have been shallower just prior to the arrival of Felix. The mixed layer deepened to about 45 m within three days after Felix's passage according to both mooring (Fig. 4b) and CTD data. The temperature at 25 m decreased by  $3.5^{\circ}\text{--}4.0^{\circ}\text{C}$  and the temperature at 45 m increased by about  $2^{\circ}\text{C}$  through the mixing process. Temperatures at 71 m and greater depths decreased slightly.

Interestingly, large-amplitude temperature oscillations (internal gravity waves near the inertial period) were set up by the hurricane in the seasonal thermocline below the mixed layer and are especially evident in the 71-m time series (Fig. 4b) and the horizontal currents

(Fig. 2). This effect is called inertial pumping and the vertical amplitudes of the waves are estimated to be roughly 15 m.

#### 4. Discussion

The analysis of this unique dataset is preliminary. Here, the focus is on the upper-ocean temperature response. Price et al. (1994) have depicted the upper-ocean response of a hurricane as a two-stage process. The first is a forced period of intense local mixing, which lasts for about half a day and the latter is a relaxation phase after passage of the hurricane when nonlocal, three-dimensional processes occur as part of a primarily baroclinic response. The temperature response at the mooring is influenced by several different processes. For example, mechanical mixing causes local entrainment of deeper cooler waters in a one-dimensional sense; however, nonlocal dynamics associated with upwelling, horizontal advection, and horizontal pressure gradients can affect the observed temperature structure (e.g., Greatbatch 1985). In addition, wind stress rotation rate and the timing of the arrival of hurricane force winds with respect to ongoing inertial current oscillations can affect the upper-ocean temperature response.

Energy in the mixed layer disperses in the wake as near-inertial internal waves that propagate into the thermocline (e.g., Brink 1989). As indicated by Price

TABLE 1. Comparison of Hurricane Felix and Hurricane Gloria. Values used for Hurricane Felix are from 15 August 1995 and for Hurricane Gloria are from 26 September 1985 (Price et al. 1994). Note that best estimates of variables and parameters are presented.

Variable or parameter	Felix	Gloria
Radius to maximum wind $R$ (km)	61	70
Maximum wind speed $U_{10}$ ( $\text{m s}^{-1}$ )	38	36
Translational speed $U_H$ ( $\text{m s}^{-1}$ )	6.9	6.8
Local Coriolis parameter $f$ ( $\text{s}^{-1}$ )	$7.7 \times 10^{-5}$	$7.0 \times 10^{-5}$
Mixed layer depth scale $h$ (m)	45	50
Density change across thermocline $\Delta\rho$ ( $\text{kg m}^{-3}$ )	2.6	4.0
Isopycnal displacement in thermocline $\eta$ (m)	10	8
Mixed layer velocity scale $U_{\text{ml}}$ ( $\text{m s}^{-1}$ )	1.0	1.6
Alongtrack scale $L_i$ (km)	90	97
Nondimensional storm speed $S$	1.2	1.1
Nondimensional Burger number $B$	0.01	0.02
Nondimensional Mach number $C$	3.6	3.4
Nondimensional parameter $k$	1.4	1.4
Nondimensional mixed layer Rossby number $Q$	0.2	0.2

(1983), thermocline-depth response is likely observable and interpretable only when wind forcing is intense and isolated so that other effects are small in comparison. Such is clearly the case for Hurricane Felix.

The determination of the relative importance of these various processes will require application of models. However, preliminary scale analyses can provide some useful insights. Basic scaling factors and nondimensional parameters are presented here with relevant values in parentheses. Comparisons with Hurricane Gloria (1985), which had similar characteristics to Felix, are presented below (see summary in Table 1). It should be noted that the parameters estimated for Gloria are based on a modeled wind field and a single air-deployed expendable current profiler (AXCP) survey (26 September 1985) as input for an ocean model simulation (Price et al. 1994). Gloria, one of the most powerful hurricanes in its decade (wind speeds of  $36 \text{ m s}^{-1}$  and currents of  $170 \text{ cm s}^{-1}$ ), traveled well to the west of Felix's track and eventually crossed the Gulf Stream and progressed up the eastern seaboard of the United States.

The wind-driven horizontal velocity in the mixed layer,  $U_{\text{ml}}$  ( $100 \text{ cm s}^{-1}$ ), can be estimated (Price 1983) as

$$U_{\text{ml}} = \frac{\tau R}{\rho h U_H}, \quad (1)$$

where  $\tau$  is the wind stress magnitude (5.18 Pa),  $R$  is the radius to maximum stress,  $h$  is the mixed layer depth (45 m), and  $U_H$  is the translational speed of the hurricane ( $6.9 \text{ m s}^{-1}$ ). Wind stress is calculated using the formula (e.g., Price et al. 1994)

$$\tau = \rho_a(0.49 + 0.065U_{10}) \times 10^{-3}U_{10}^2, \quad (2)$$

where  $\rho_a$  is density of air ( $1.26 \text{ kg m}^{-3}$ ) and  $U_{10}$  is maximum wind speed ( $38 \text{ m s}^{-1}$ ). The radius of maximum wind speed is estimated using Eq. (1) to be 61

km. These values are comparable to those obtained for Hurricane Gloria (e.g., Price et al. 1994). The alongtrack scale of Felix can be estimated as

$$L_i = \frac{U_H}{f}, \quad (3)$$

giving a value of 90 km. The nondimensional storm speed  $S$  provides an indication of the timescale over which the ocean experiences the hurricane's wind stress and is relevant to generated inertial motions. Price et al. (1994) define  $S$  as

$$S = \frac{\pi U_H}{4fR}, \quad (4)$$

where  $f$  is the local Coriolis parameter ( $7.67 \times 10^{-5} \text{ rad s}^{-1}$ ). Our estimate of  $S$  is 1.2, which is quite similar to that of Gloria. With this value of  $S$ , the wind stress changes on a timescale comparable to the local inertial period (22.8 h).

The degree of pressure coupling between the mixed layer current and the thermocline current is indicated by the Burger number (e.g., Price et al. 1994) or

$$B = \frac{g'h}{4f^2R^2}, \quad (5)$$

where  $g'$  is reduced gravity ( $0.025 \text{ m s}^{-2}$ ) based on density change across the thermocline or  $\Delta\rho$  ( $2.6 \text{ kg m}^{-3}$ ). The Burger number is estimated for Felix to be 0.01. This is less than the value for Gloria and indicates that the pressure coupling is relatively weak, likely because of the large hurricane diameters. Price et al. (1994) show that the decay and  $e$ -folding time for mixed layer currents (through energy dispersion) are directly dependent on the Burger number. That is, for smaller-Burger number cases, the nonlocal dynamics of the relaxation phase are not as important during the forcing stage. The  $e$ -folding timescale for Felix is about 9 days according to our direct measurements. The decay of inertial oscillations has been the subject of several studies that have suggested various processes that may contribute to the decay [e.g., downward energy flux into the thermocline (Price 1983; Brink 1989); small-scale dissipation (Gonella 1971); and the  $\beta$  effect (D'Asaro 1989)]. This aspect will be considered in future analyses of this dataset.

Upwelling, which is driven by the wind stress curl, is the most important process causing density changes in the thermocline through divergence of upper-layer transport. The degree of upwelling associated with hurricane passage is indicated by the Mach number  $C$ , as given by Price et al. (1994):

$$C = \frac{U_H}{c}, \quad (6)$$

where  $c$  is the gravest mode internal wave phase speed. Using  $c = 1.9 \text{ m s}^{-1}$ ,  $C$  is 3.6 for Felix, which again is comparable to the value estimated for Gloria. Thus,

upwelling is likely not particularly important directly beneath either hurricane as each is relatively fast moving. The importance of upwelling has also been examined by Greatbatch (1985), who defined the parameter  $k$ , which is a ratio of the time over which upwelling takes place or  $f^{-1}$  to the time over which entrainment of deeper waters occurs or  $L/U_H$ . Parameter  $k$  is defined as

$$k = \frac{U_H}{Lf}, \quad (7)$$

where  $L$  is the horizontal scale of the storm. For Felix,  $k$  is estimated to be 1.4. This implies that since Felix is a moderately fast moving hurricane, upwelling of water can enhance cooling of the mixed layer for a few hours when entrainment is occurring.

A Rossby number for mixed layer current may be estimated according to Price et al. (1994) as

$$Q = \frac{\tau}{\rho_0 h U_H f}. \quad (8)$$

The mixed layer Rossby number for both Felix and Gloria is 0.2. Thus, nonlocal or advective effects are likely not important during the forcing and early decay stages.

The displacement of isopycnals in the seasonal thermocline (Price et al. 1994) can be estimated as

$$\eta = \frac{\tau}{\rho_0 f U_H}, \quad (9)$$

giving  $\eta = 10$  m. The vertical amplitude of near-inertial internal gravity waves estimated from our temperature time series (Fig. 4b) and CTD temperature profiles (using mean temperature gradient) made a few days after Felix's passage is about 15 m.

The position of maximum cooling has often been observed to be biased or displaced to the right of the path of hurricanes (e.g., Greatbatch 1985; Cornillon et al. 1987; Price et al. 1994). This was the case for Felix as indicated in Fig. 3 as the center of the swath of reduced temperature was offset by about 200 km. The rightward bias of Gloria was about 80 km. Several explanations for these biases have been forwarded (e.g., Chang and Anthes 1978; Price 1981; Price et al. 1994). However, the primary reason for these asymmetries is related to the wind stress vector rotation, which is effectively clockwise on the right side of tracks and often in near resonance with the inertially rotating mixed layer during hurricane passage (e.g., Dickey and Simpson 1983; Price et al. 1994). This effect is most likely to occur when the nondimensional speed  $S$  is  $O(1)$  as it was for both Felix and Gloria.

To summarize, few hurricanes have passed over heavily instrumented moorings, particularly in the open ocean. The scaling parameters computed with our dataset are similar to those primarily based on modeling results by Price et al. (1994) for Hurricane Gloria of

1985. The rich mooring and satellite datasets collected during this study will be the subject of several more studies including modeling of the coupled ocean-atmosphere system and assessments of modification of biogeochemical cycles in the Sargasso Sea.

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