

Technical and Scientific Evaluation of EM-APEX in Hurricane Frances Final Report

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LONG-TERM GOALS

The EM-APEX is a new autonomous sensor platform capable of making long-duration measurements of ocean velocity profiles in inhospitable environments. This project aimed to increase our understanding of the capabilities of the EM-APEX as well as to advance our scientific understanding of air-sea interaction under hurricanes using the first dataset from the EM-APEX.

OBJECTIVES

- To characterize the velocity measurement capability of the EM-APEX, including the relative magnitudes of error contributions from electrode noise, package motion and instrument calibration.
- To characterize the suitability of the profiling float package for future measurement programs and additional sensors, including limits imposed by battery life, buoyancy control range, and high-frequency package motion.
- To examine the physics of air-sea interaction under a hurricane through observations of shear, mixed layer deepening and internal wave radiation.

APPROACH

The first set of floats, designed and developed by engineers Jim Carlson and John Dunlap at APL-UW, were deployed in Hurricane Frances as part of the 2004 CBLAST experiment (Figure 1). Four of these initial floats were deployed again in the 2005 EDDIES experiment (NSF) near Bermuda. In the light of these and other upcoming projects, a thorough evaluation of the initial EM-APEX datasets is essential. To do this we have (a) examined both the CBLAST and EDDIES datasets to learn about instrument performance. In addition, we have undertaken ongoing scientific analysis of the Hurricane Frances (CBLAST) data. Performance was primarily evaluated by comparing different components of the EM-APEX system (e.g., velocity sensors and accelerometers or velocity and GPS) while scientific analysis has made use of other datasets available from the CBLAST experiment, including the H*WINDS reanalysis and a numerical model by Jim Price at the Woods Hole Oceanographic Institution.

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14. ABSTRACT The EM-APEX, a new autonomous sensor platform, capable of making long-duration measurements of ocean velocity profiles in inhospitable environments, was the focus of this project, aimed to increase our understanding of the capabilities of the EM-APEX, as well as to advance our scientific understanding of air-sea interaction under hurricanes using the first dataset from EM-APEX. Our objectives, approach, scientific tasks, results, both scientific and technical, are discussed in this Final Report.						
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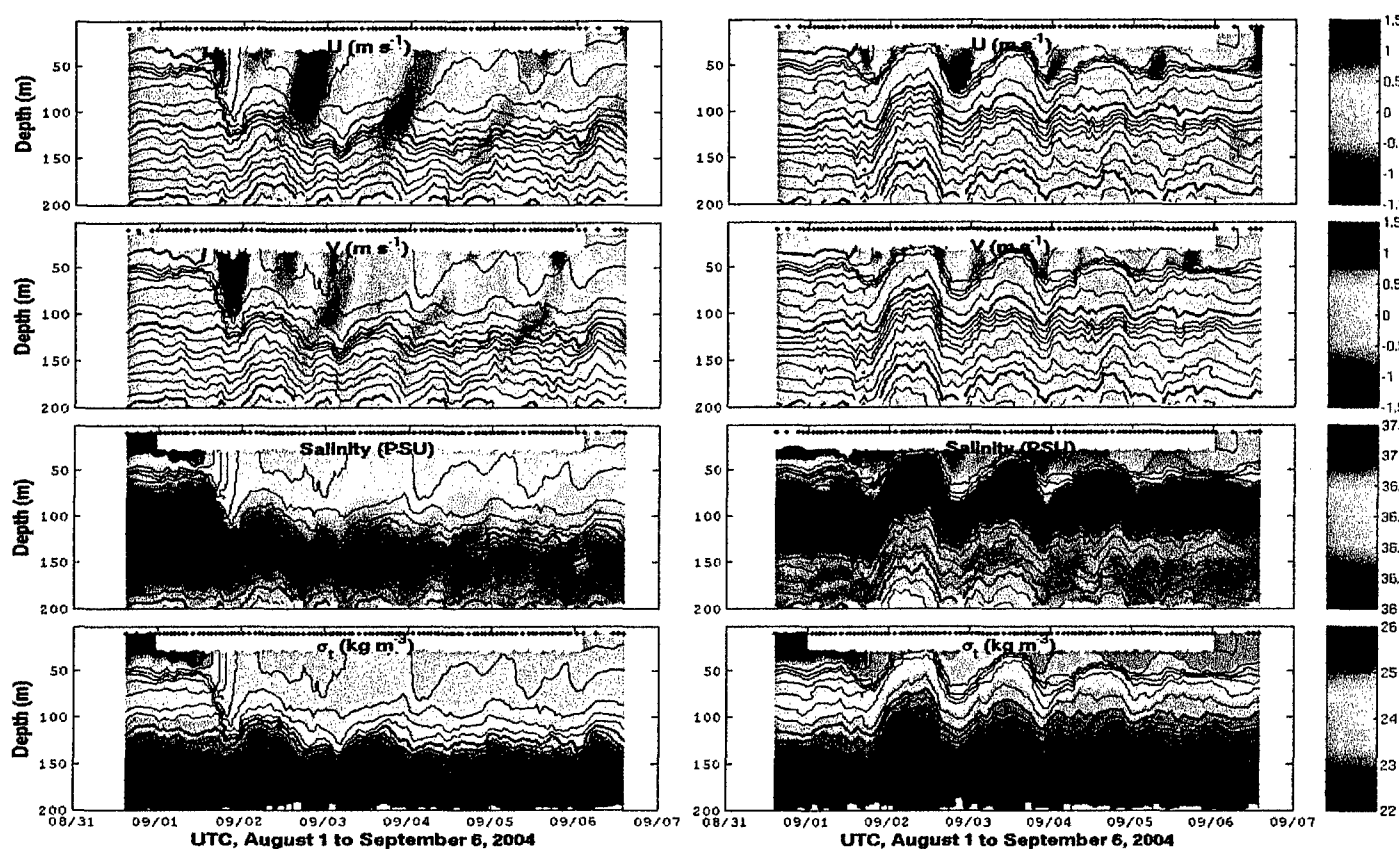


Figure 1: Upper-ocean response to Hurricane Frances observed by EM-APEX floats 1633 (left panel) at the radius of maximum winds and 1636 (right panel) beneath the center of the storm.

WORK COMPLETED

Technical Tasks. The following evaluations have been made:

1. Velocity sensors—to check for gross errors in wiring or coding, to refine calibration coefficients and processing procedures, and to characterize the final measurement accuracy.
 - a. Examine velocity fit (demodulation) residuals for noise levels (see Fig. 3, left panel).
 - b. Compare redundant electrode channels for component quality and calibration (Fig. 2).
 - c. Compare down vs. up profiles for calibration check and noise level (Fig. 2).
 - d. Compare integrated subsurface velocity with GPS displacement (Fig. 5).
2. Attitude sensors—to assess the accuracy of heading and tilt measurements as well as the ability to diagnose actual instrument accelerations and magnetometer errors.
 - a. Compare laboratory accelerometer calibrations to mean in-water values to determine ballasting tilts (varying from float to float but steady over time; Fig. 3, right panel).
 - b. Characterize instrument tilts while profiling, including oscillation at the float rotation frequency, increased tilting in the surface wave field due to asymmetric drag, and additional contributions from surface wave orbital accelerations (Fig. 3, right panel).
 - c. Examine magnetometer accuracy and potential for correcting hard and soft iron errors.
3. Longevity—to evaluate potential future missions and advantages of enhanced battery technology (lithium cells). Battery usage for both CBLAST and EDDIES deployments has been used to model power consumption under different profiling modes.

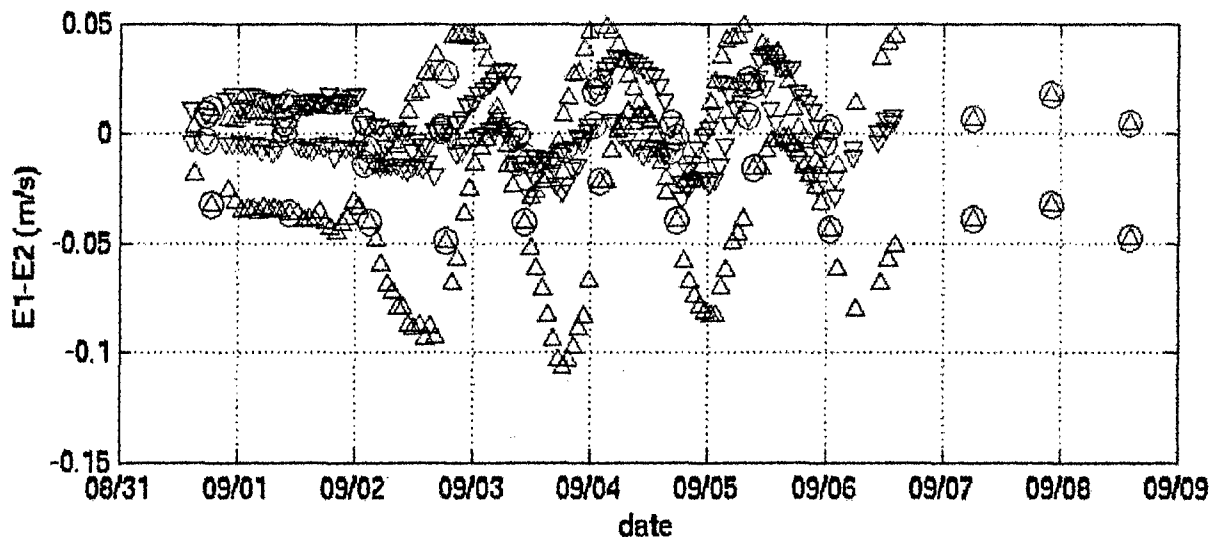


Figure 2: Velocity differences between the two perpendicular electrode channels from EM-APEX 1633 averaged below 100 m depth. Red indicates east-west (U) velocity differences and blue north-south (V) differences. Upward and downward pointing triangles indicate ascending and descending profiles, respectively. Circles indicate 500 m deep profiles, while the rest are 200 m deep. The figure shows differences of up to 0.1 m/s between the two channels and between adjacent down and up profiles, modulated by the rotating inertial currents of up to 1.4 m/s shown in Fig. 1. These differences point to errors in the calibration angles and electric field sensitivity coefficients used in processing the EM-APEX data and can be used to correct the data to achieve the highest quality measurements. Since the errors are less than 10% of the hurricane-driven currents they do not change the essential picture of Fig. 1.

Scientific Tasks. Progress was made on analysis of several aspects of air-sea interaction in hurricanes with results presented in seminars at oceanographic institutions and at scientific meetings. Processes studied include:

1. Mixed layer cooling and deepening, including evaluation of gradient Richardson numbers (Figs 1 and 6).
2. Comparison with upper-ocean model of Jim Price (Fig. 6), including:
 - a. Mixed-layer deepening;
 - b. Mixed-layer cooling;
 - c. Vertical motion of isopycnals (inertial pumping); and
 - d. Super-inertial response due to finite forcing region.
3. Evaluation of drag coefficients by (i) testing the Price et al. (1994) model forced with different wind stress parameterizations and (ii) directly comparing the observed mixed layer acceleration with the wind stress (Fig. 7).
4. Inertial wave wake, including both mixed-layer energy peak, which propagates downward and a second deep (lower mode) energy layer forced by inertial pumping (Fig. 8).
5. Surface wave distribution and relationship to remotely-sensed wave spectra (Fig. 4).

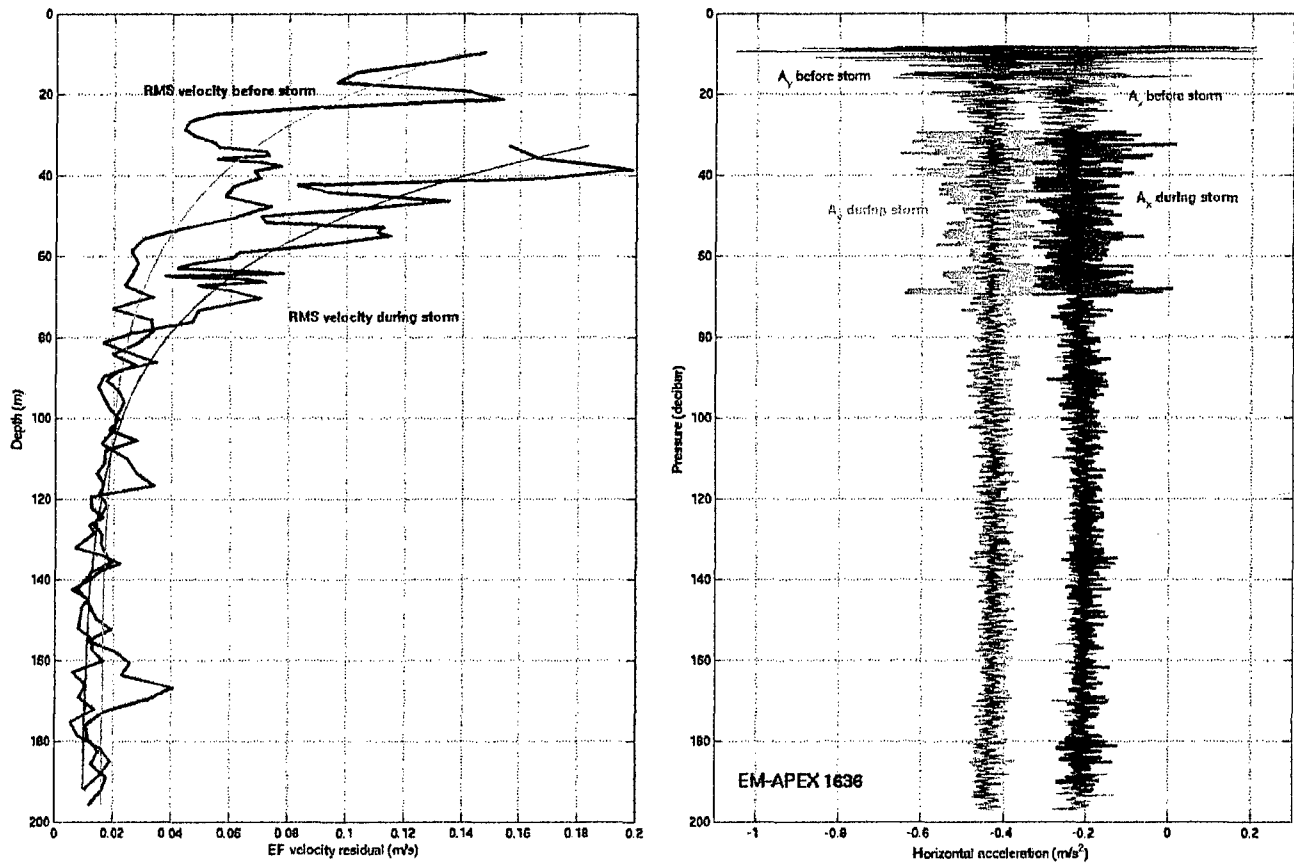


Figure 3: EM-APEX measurements through the surface wave field during contrasting wind and wave conditions under the Hurricane Frances track (from float 1636). The left panel shows velocity residuals after demodulating the horizontal electric field measurements over a 50-s window—essentially giving a combination of the higher-frequency variability and electrode noise. The exponentially-decaying part (thin curves) is interpreted as resulting from a single dominant surface wave amplitude and period (see Fig. 4 for timeseries of these). The right panel shows horizontal (in the float's frame of reference) accelerations recorded at 1 Hz. The depth mean indicates a steady floating tilt of nearly 3° due to the float's internal mass distribution, while the increasing variability near the surface is due to the surface wave field. From the EF-inferred significant wave heights of 1 m and 4 m for the pre-storm and during-storm profiles, respectively, wave orbital accelerations of 0.15 and 0.52 m/s^2 are expected at the surface, decaying to 0.06 and 0.16 m/s^2 at 30 m. The observed accelerations at 30 m are somewhat above these levels, indicating a mixture of orbital accelerations and instrument tilt due to asymmetric drag or wave shear.

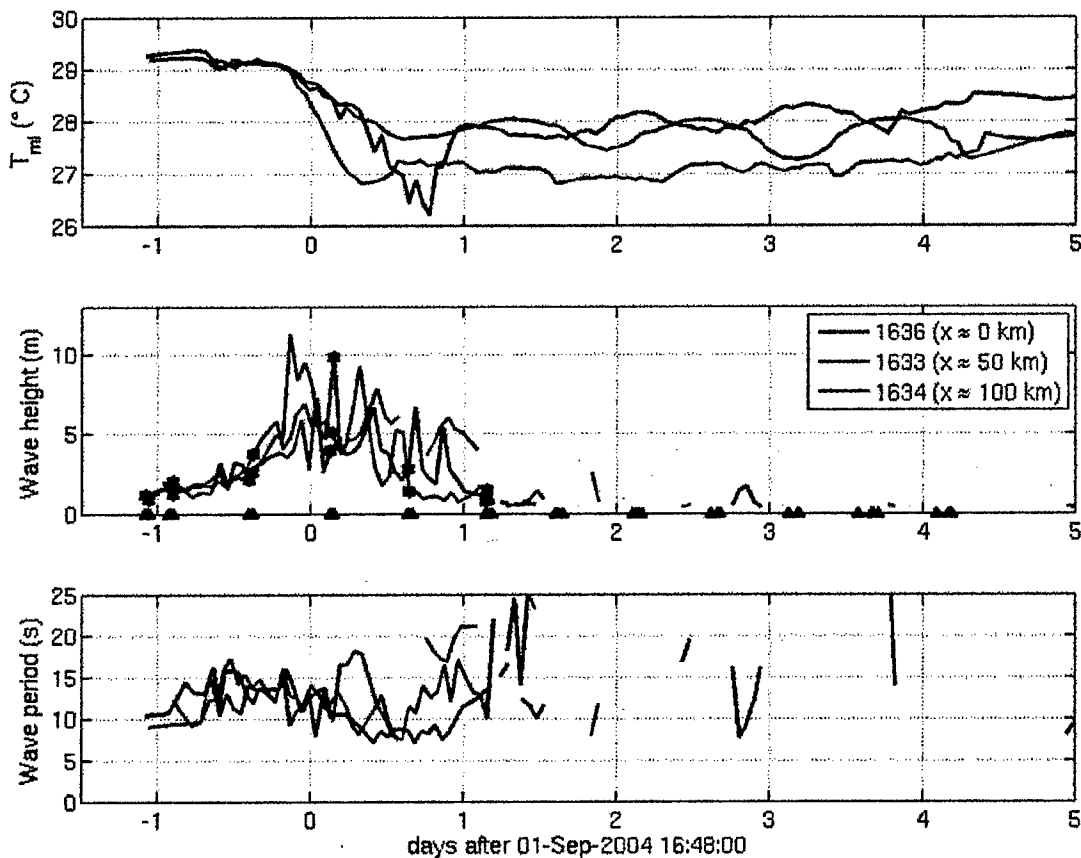


Figure 4: Timeseries of mixed-layer temperature (top panel), significant wave height (middle panel) and surface wave period (bottom panel) at each of the three EM-APEX floats in Hurricane Frances. The observations detail the growth of the surface wave heights and nearly steady, if not decreasing, periods in advance of the storm (which was centered over the line of floats at the zero point on the time axis). After the storm passage, the confused nature of the surface wave field resulted in the exponential fitting method becoming unreliable (missing data in latter half of the lower two panels). However, high-frequency accelerometer and velocity data recorded at the times marked with triangles can be used to reconstruct surface wave properties using more sophisticated methods.

RESULTS

Technical Results.

- a. Laboratory (standing) accelerometer calibrations show mean in-water tilts to be 1–3°, varying from float to float but steady over time (Fig. 3).
- b. Variable tilts in deep water are seen at the rotation frequency ($\pm 0.2^\circ$) and in the surface wave field ($\pm 4^\circ$ at 10 m depth under 1 m SWH waves; Fig. 3).
- c. CBLAST: Maximum duration attained by a single float was 150 round-trip profiles to 200 and 500 m, 90 km vertical distance traveled, just over 50% of batteries remaining.
- d. EDDIES: Maximum duration attained by a single float was 240 round-trip profiles to 150–200 m, 80 km total vertical distance traveled, batteries fully used.
- e. Subsurface navigation by integrating the continuous velocity measurement has the potential to improve positioning significantly over dead reckoning (Fig. 5).

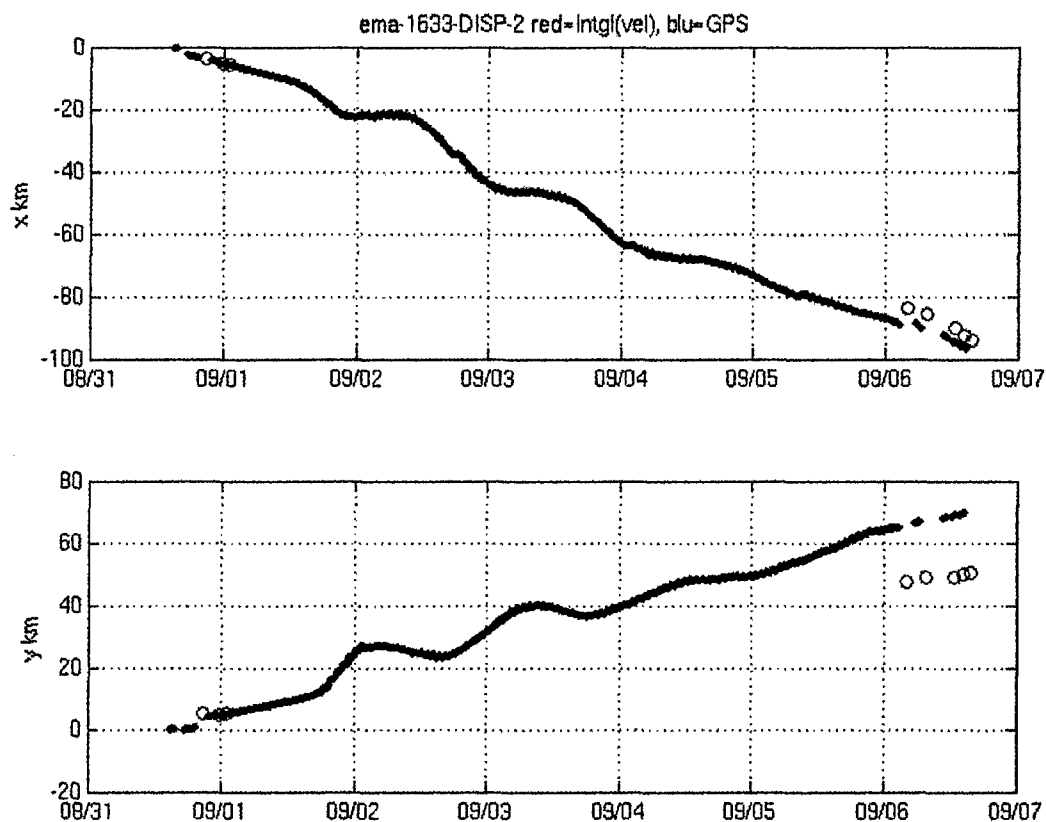


Figure 5: Subsurface navigation of the EM-APEX during the 5-day period following Hurricane Frances, during which all three floats were instructed to cycle continuously between 30 m and 200 m, with round trips to 500 m every 16 hours (1/2 inertial period), without coming to the surface. Plotted are east (x, upper panel) and north (y, lower panel) displacements of float 1633 inferred from an integration of the profile velocity data, along with GPS positions obtained at the beginning and end of the subsurface interval. The results indicate that the relative velocity profile obtained by the electromagnetic method is quite close to the absolute velocity in a deep water environment with little barotropic flow. To obtain absolute velocity, the EM velocities are combined with the GPS displacement (i.e., the 0.14 m/s inferred mean north drift becomes 0.10 m/s absolute velocity), allowing the continuous EM measurement to improve the back-estimation of the float's meandering trajectory in the strong inertial currents during the subsurface interval.

Scientific Results. The following are the principal scientific results to date from the EM-APEX measurements in the Hurricane Frances dataset:

1. Upper-ocean acceleration in Hurricane Frances produced an initial mixed layer deepening with minimal change in heat content (i.e., through a 1-D process; Fig. 6).
2. Comparison with the upper-ocean model used by Price et al. (1994), yields a favorable comparison (Fig. 6) of:
 - a. Mixed-layer deepening;
 - b. Mixed-layer cooling;
 - c. Vertical motion of isopycnals (inertial pumping); and
 - d. Super-inertial response due to finite forcing area. This is in contrast to a 1-D model, which produces incorrect shear, deepening and current frequency.

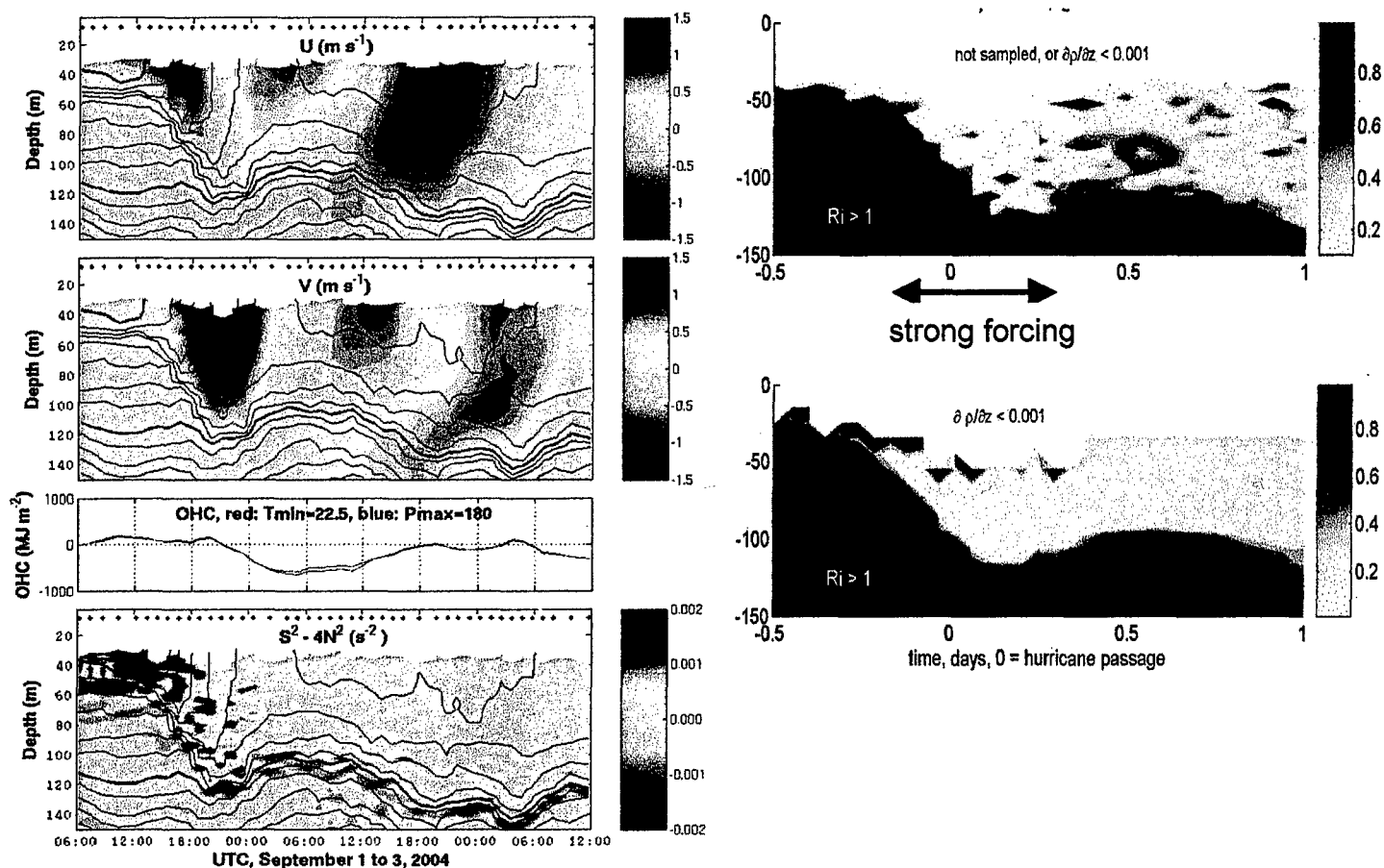


Figure 6. Left panels: A detailed view of the initial upper-ocean response at EM-APEX 1633 (50 km to the right of Hurricane Frances' track), where the strongest winds and strongest inertial response occurred. OHC (ocean heat content) was approximately constant during the initial mixed layer deepening, before 3-D effects (upwelling due to surface divergence) became evident. $S^2 - 4N^2$ (or "reduced shear") illustrates a shear dominated mixed layer during the deepening phase followed by marginal stability ($S^2 - 4N^2 = 0$, or $Ri = 1/4$) without further mixing after the storm has passed. Right panels: Verification from the Price et al. (1994) model that $Ri = 1/4$ conditions persist long after the mixed layer has ceased to deepen. The upper panel shows the float 1633 observations of Richardson number (Ri), while the lower panel shows Ri from the model.

3. Wind stress parameterizations with leveling or decreasing drag coefficient at high winds agree better with observed mixed layer cooling and acceleration (Fig. 7).
4. Near-inertial waves radiated from Hurricane Frances appear in both a narrow (100 m in depth) beam emanating from the mixed layer and a deeper layer below 200 m.

IMPACT/APPLICATIONS

This evaluation work on the EM-APEX will be of considerable value in planning future experiments using the floats, as well as in assessing the potential for operational use of the floats as environmental sensors in support of naval operations or in a climate monitoring capacity (e.g., as a contribution to the global Argo array).

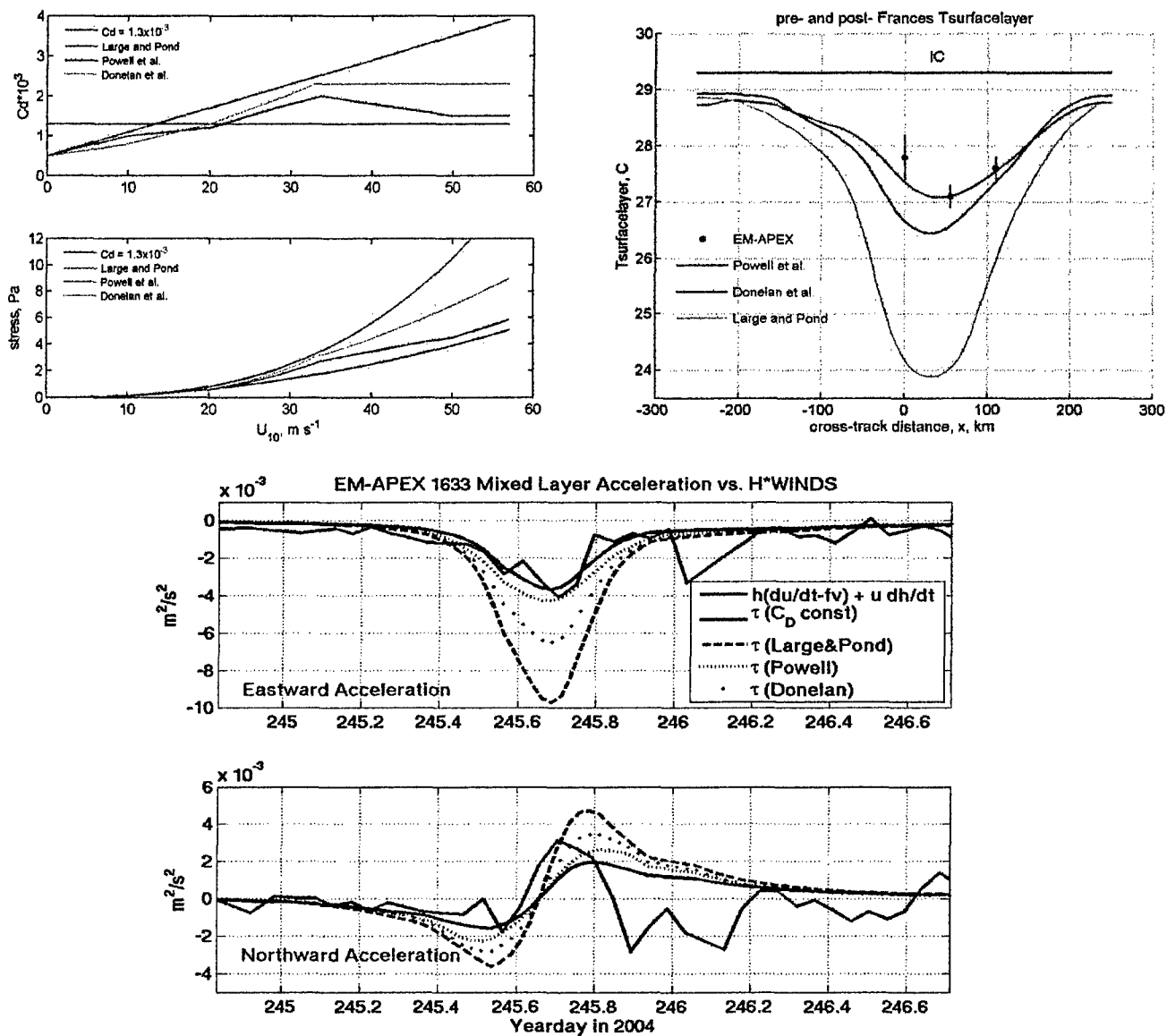


Figure 7: Evaluation of wind stress (drag coefficient) parameterizations using the EM-APEX measurements under Hurricane Frances. The two panels at the upper left show the drag coefficient (C_d) and wind stress as a function of wind speed predicted by several proposed parameterizations. The upper right panel illustrates the evaluation of three of these using the modeled and observed overall cooling in the wake of the storm. The lower two panels illustrate an alternative method comparing the instantaneous mixed layer acceleration observed by an EM-APEX float to the wind stress at the same location. In both cases, the parameterizations which saturate or decrease C_d at high wind speeds appear to give better comparisons with the observations.

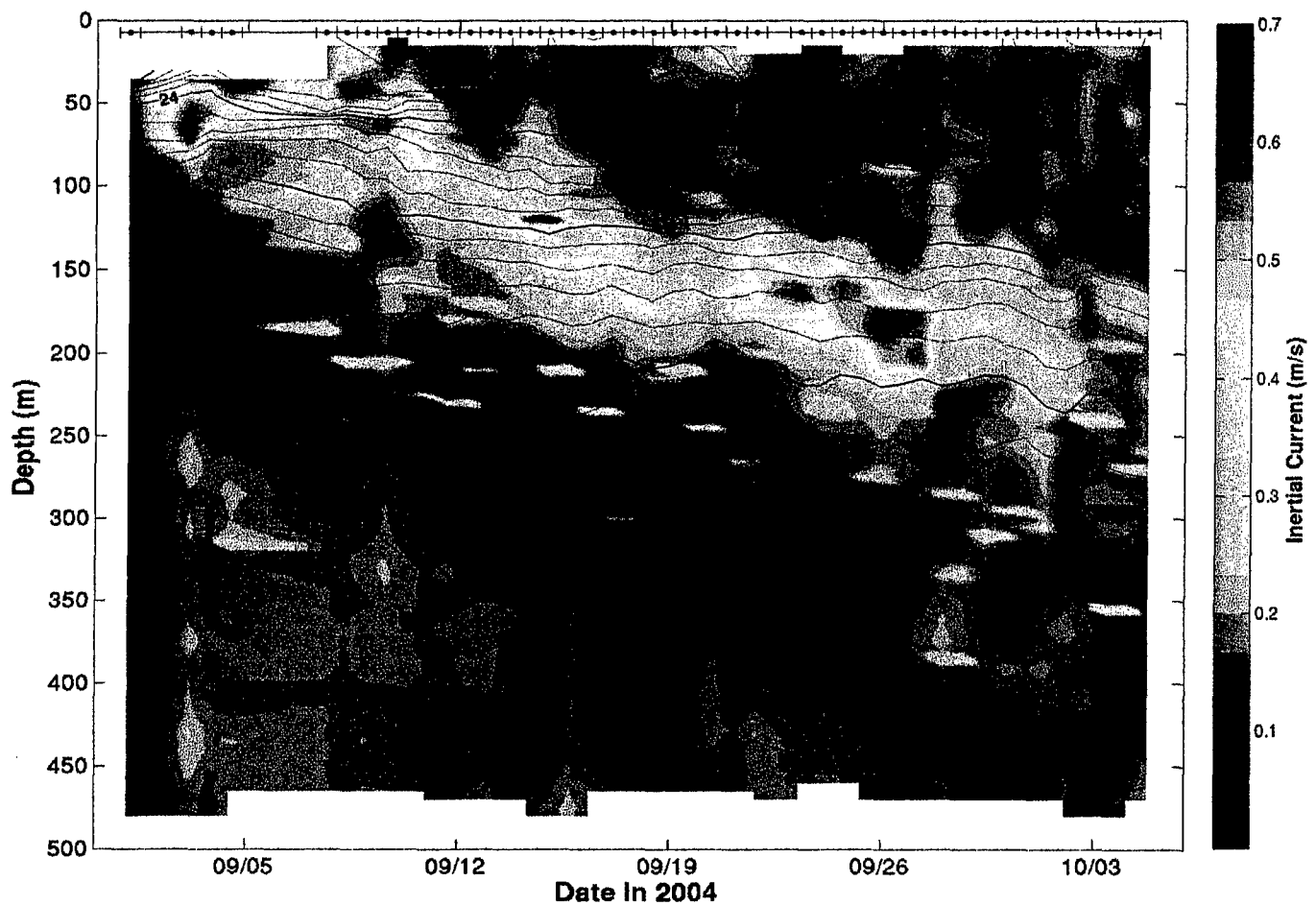


Figure 8: Observation of what appears to be downward radiation of near-inertial energy in the wake of Hurricane Frances. The quantity plotted is the inertial current amplitude inferred from differencing velocity profiles separated by $\frac{1}{2}$ an inertial period. Features of note include both the beam of near-inertial energy emanating from the base of the mixed layer at the time of the storm (9/2/2004) and the simultaneously-appearing deeper energy in the 200–500 m depth range which also propagates downwards. Downward propagation of near-inertial energy is also indicated by the upward phase slopes in the U and V velocity panels of Figs. 1 and 6. Solid lines indicate the evolution of the mean density structure at the float's position. Note that the float did move about 250 km during this period, so the radiated energy likely results from the integrated effect of the storm along a broad section of its track.

The analysis of the hurricane data is making clear the utility of the EM-APEX as an autonomous platform for sensing of upper-ocean conditions in extreme wind and wave states. The information on upper ocean mixing, drag parameterizations, and radiated internal waves is expected to contribute to improvements hurricane intensity forecasts, although the full benefit of the measurements will likely come after a future experiments using a larger array than the 3 floats deployed in CBLAST.

TRANSITIONS

The EM-APEX was developed through an ONR SBIR (small business innovative research) grant to Webb Research Corporation (WRC; Doug Webb) and APL-UW (Tom Sanford). The first set of floats, designed and developed by engineers Jim Carlson and John Dunlap at APL-UW, were deployed in CBLAST in 2004 and again in EDDIES in 2005. A second set of floats was built in 2006 by WRC for other users (Eric Kunze, Univ. Victoria, and Steve Riser, UW), and a number of floats are planned to be purchased (by APL-UW and others) from WRC for new experiments. At least two projects—the ONR Archipelago Straits DRI (Girton) and an NSF gas transfer study (D'Asaro)—have been funded to purchase EM-APEX and 4 more are under review.

RELATED PROJECTS

ONR EM-APEX Development (Webb)
ONR CBLAST DRI (D'Asaro, Terrill, Niiler, Black, Walsh, and others)
ONR Hurricane Modeling (Price)
NSF EDDIES Finestructure SGER (Girton)
ONR Archipelago Straits DRI (Girton)

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