Preliminary Results and Interpretations from EM-APEX Floats Deployed in Hurricane Frances, September 2004

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Three new, autonomous temperature (T), salinity (S) and velocity (V) floats that profiled the upper 200 m of the ocean were air-launched ahead of Hurricane Frances as it approached Turks and Caicos Islands. The floats, denoted as EM-APEX floats, were deployed 31 August 2004 in a line perpendicular to the forecasted path of the hurricane about a day ahead of the intense winds. Float 1636 was placed ahead of the eye; float 1633 was deployed about 50 km to the right (i.e., NNE); float 1634 was launched 100 km NNE of the storm's path. Initially, the floats profiled from the surface to 200 m and once to 500 m for 10 hours, then continued profiling to 200 m (about 1-h RT) with half inertial period (IP) excursions to 500 m while not broaching the surface for 5 days. After 5 days the floats surfaced and transmitted the data collected while submerged, the floats profiled to 500 m every half IP (i.e., every 16 h) until recovered later in September. The submerged operations ended about 0100 UTC on 6 September, at which time the accumulated observations were transmitted via Iridium satellites. Figure 1 shows two views of Frances as it passed over the EM-APEX floats.

Figure. 1: Two views of Hurricane Frances about the time it passed over the 3 EM-APEX floats.

The EM-APEX is the result of an ONR-supported SBIR collaboration between Webb Research Corp. (manufacturer of APEX autonomous profiling float) and APL-UW (which integrated measurements of motional induction to obtain velocity). Basically, the EM-APEX is a standard WRC APEX profiling float with the APL-UW subsystem for measuring motionally induced electric fields generated by the ocean currents moving through the vertical component of the Earth's magnetic field (Baker, D.J., 1979; Ocean Observations and Experiment Design, *in The Evolution of Physical Oceanography*, C. Wunsch and B. Warren, Eds., MIT Press). The T and S observations are obtained from the Sea Bird Electronics SBE-41 CTD. Electrodes on a right cylindrical shell surrounding the lower half of the float sense the motionally induced voltages. The voltages are amplified, digitized, processed into velocity components and stored within the float. Other measurements are magnetic compass and instrument tilt. Float position is determined by the GPS system when the float surfaces. The T, S, V, position and other observations are processed within the float and transmitted over the Iridium global cell phone system.

The purpose of the measurements is to determine the interactions between the atmosphere and ocean under hurricane conditions. The fluxes of momentum, freshwater and heat between the ocean and air are important to the evolution of the hurricane and the upper ocean. For example, the currents and turbulence generated by the wind stresses can deepen and cool the ocean's surface mixed layer, a process that can dampen the growth of the hurricane. Only rugged instruments and comprehensive measurements of the ocean's response to the hurricane are able to reveal the critical fluxes. The EM-APEX is a major step toward obtaining the needed *in situ* measurements. The air-launch capability, high quality ocean observations and rapid, bi-directional data link are vital improvements in the ability to observe and understand the interactions between the ocean and the atmosphere in a hurricane and other situations.

Figure 2: Left panel shows the EM-APEX and its developers, senior engineers Jim Carlson (L) and John Dunlap (R), during Puget Sound testing. Only the grey PVC shell with electrodes and the small turbine blades for instrument rotation are added to the exterior of Webb Research Corporation's APEX float. Right panel shows the EM-APEX in the bottom half of the air-launch container. The air-launch container is completed with the addition of the other half for the cardboard cylinder and a parachute. The container is held together with nylon straps that are released by salt blocks that dissolve in about an hour after being immersed in seawater.

Figure 3 presents half inertial period pairs of T, S, and V to 500 m before and after the arrival of the hurricane. The left panels show half inertial period profiles before the arrival of H. Frances. The variables for

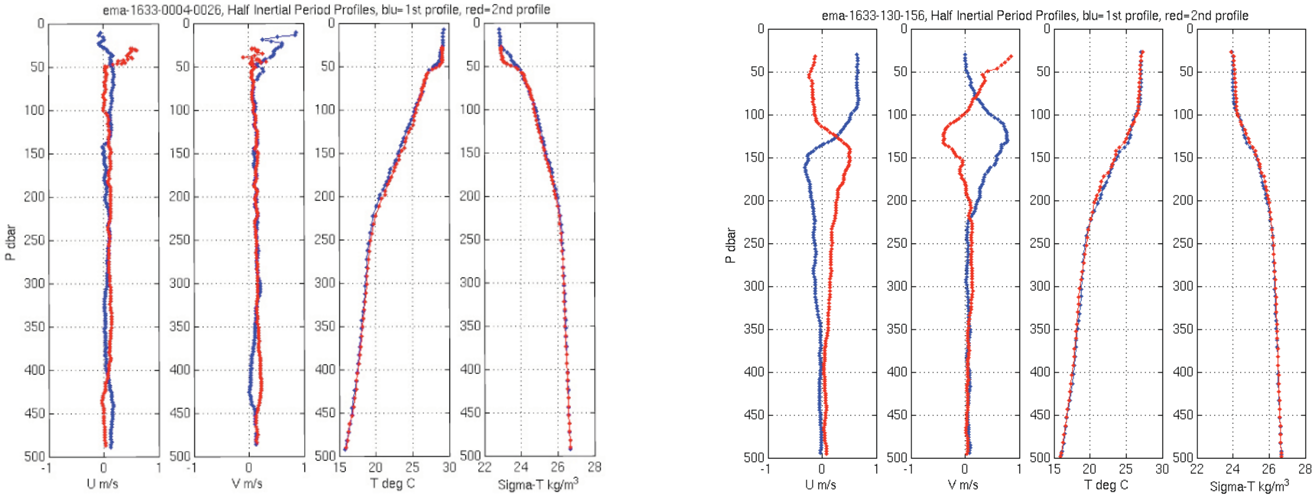

Figure 3: Half inertial period pairs of T, S and V profiles for Float 1633. The set of panels on the left are the before environmental conditions and the panels on the right are profile pairs after the hurricane had arrived. The blue lines are data from the first profile (first number in title; e.g, 004) and red is the second profile (e.g., 026). The velocity profiles are remarkably smooth considering the surface winds and exhibit the classic half inertial period mirror imagery. The velocity fits are over 50 seconds of electric field data.

the first profile in each pair are the blue lines, and the red profile was taken 16 hours later (half an inertial period). On the right are half-inertial pairs after the hurricane was forcing the ocean. There are several remarkable aspects to these data. First, note how smooth are the profiles. They are taken under hurricane induced surface gravity wave heights > 10 m with orbital velocities of several m/s. The velocity profiles were determined on board based on 50-s long fits to the slowly rotating electric field measurements. The result is velocity that has very little contamination from surface waves. Second, the “mirror imaging” of the velocity is very noticeable, revealing the dominant role of inertial motions.

Figure 4 contains over 200 profiles (Dn+Up) that show changes of upper ocean properties over the first 6 days. After this time they park at 500-m depth when not making the half IP profiles. There are many interesting features from these profiles, such as the pre-storm T and S SML thicknesses, growth and vertical propagation of IP motions (N.B. sloping phase lines with depth), and property changes in deepening SML caused by the hurricane.

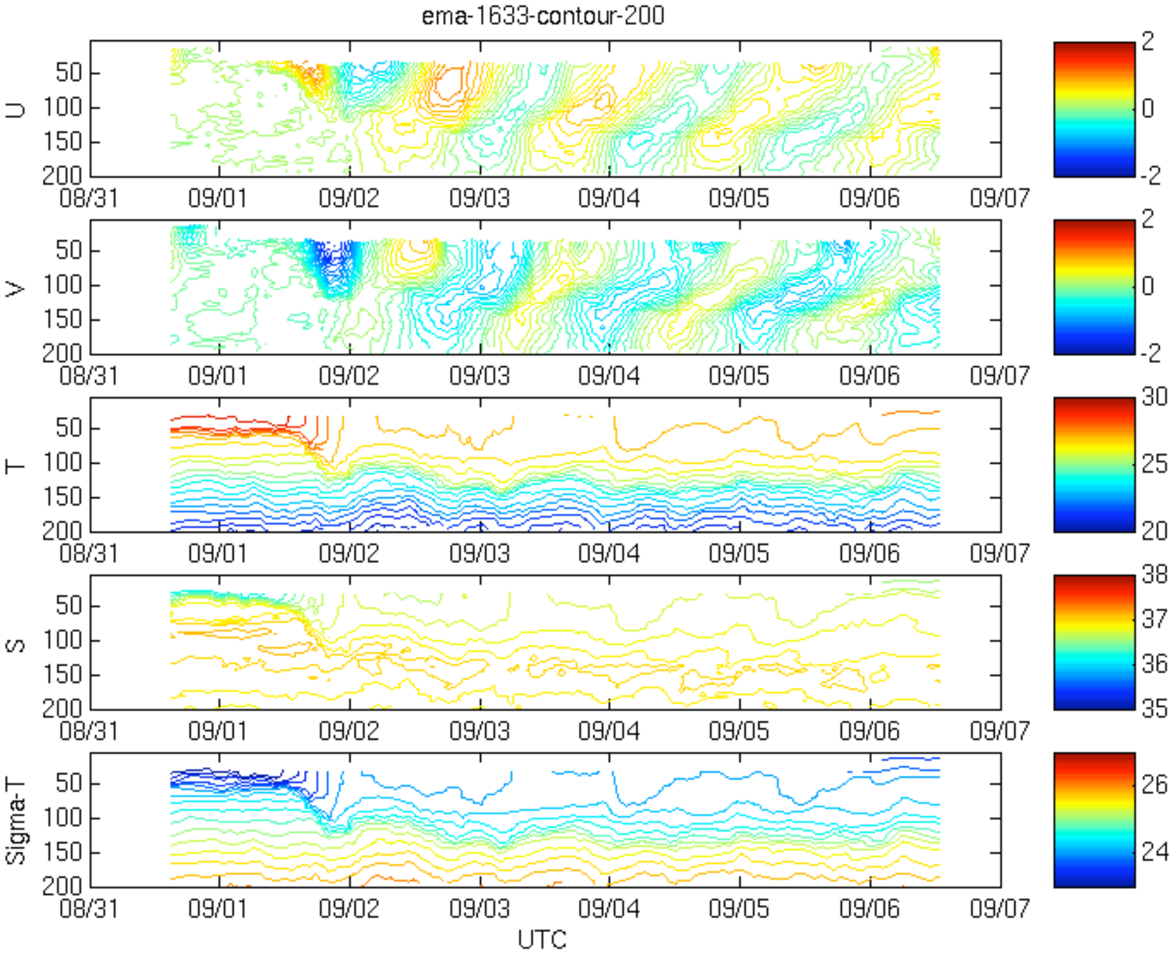

Figure 4: Contour plots of U (east) and V (north) velocity components (m/s) vs. depth and time. Also, T, S and sigmat (density) are displayed. Only for the first 10 hours and last 14 hours was the EM-APEX profiling from the surface to depth; during the hurricane the float turned around before reaching the surface.

Figure 5 displays the information in terms of color shading, rather than as colored contour lines. Both figures show the rapid deepening of the surface mixed layer (SML) and its changes in water properties. The initial conditions exhibit a stable thermocline and little motion. Late on the first of September (UTC), strong and time dependent winds induce SML inertial period motions. The SML begins to mix with the cooler, more saline water below producing a 2 C cooling and an increase in salinity. Both changes increase SML density.

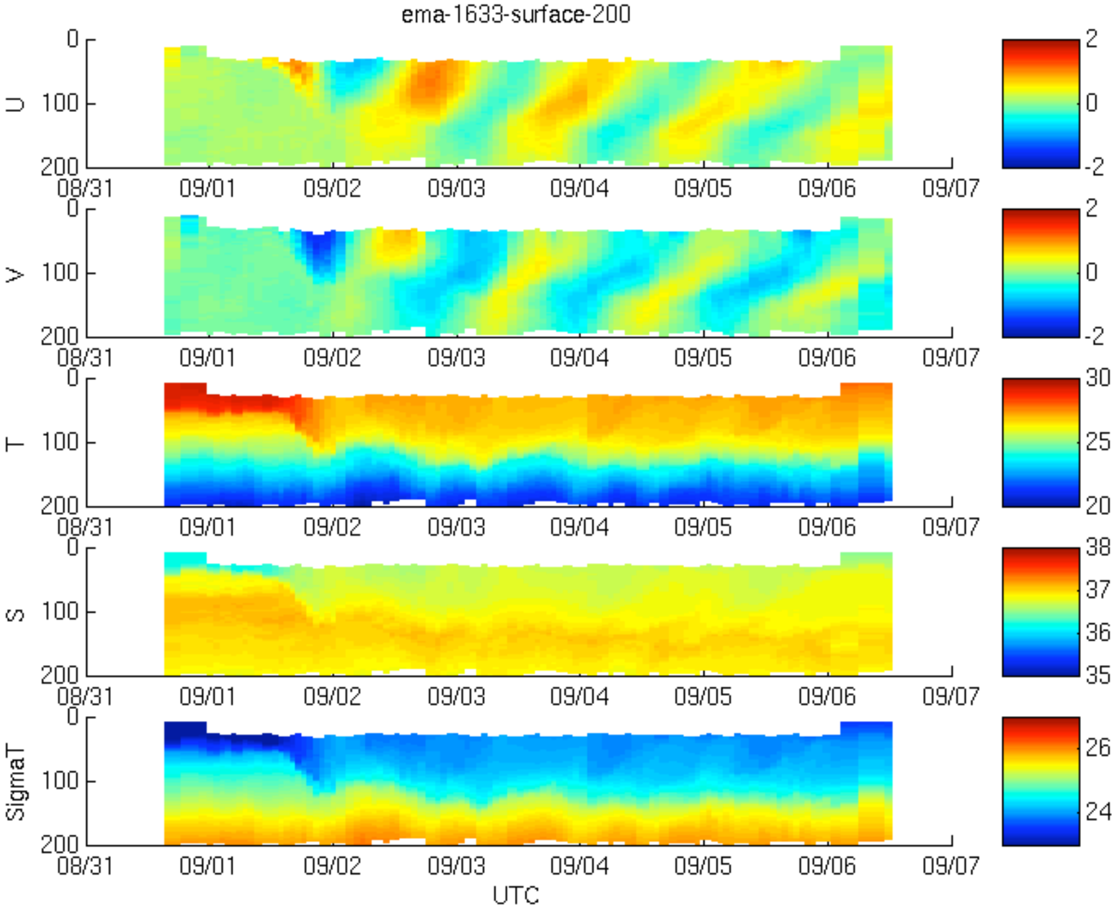

Figure 5: Color surface displays of the same data as in Fig. 4.

Adding velocity information greatly expands the ability to understand how the hurricane interacts with the ocean. Velocity often reveals how and why things happen, not just what happened. That is, the physical process responsible for the observed T and S changes is usually one involving transport, propagation and mixing and other processes involving velocity. The utility of the velocity measurements in understanding hurricane-ocean interactions is illustrated in Fig. 6. This figure displays the changes in upper ocean density (sigmat-1025 kg/m^3) and a diagnostic of the causative process. Note above 50 dbar, the density increased by about 1 kg/m^3, while from 50 to 150 dbar it decreased by about 0.5 kg/m^3. So the net change over 150 dbar is about zero. It appears that this is due to vertical mixing, as opposed to lateral advection of different water. The diagnostic variable is the gradient Richardson number, Ri. The quantity is a measure of the ability of the shear of horizontal current to overcome the stability of stratified seawater and cause overturning and mixing. Mathematically it is N^2/S^2 where N is the Brunt-Vaisala frequency (proportional to vertical density gradient) and S is the magnitude of the vertical gradient or shear of horizontal currents. A value of 1/4 is thought to be a necessary condition for shear instability. The Ri is large before the storm (profile 26), except in the SML where N is small. However, after the hurricane arrives, Ri becomes small, hovering around 0.25 at numerous depths down to 150 dbar. This is the same zone over which the density is observed to change. It seems likely that shear instability is responsible for the vertical mixing observed. It should be remembered that each profile is a snapshot. However, Fig. 7 shows similar evolution of the SML over time.

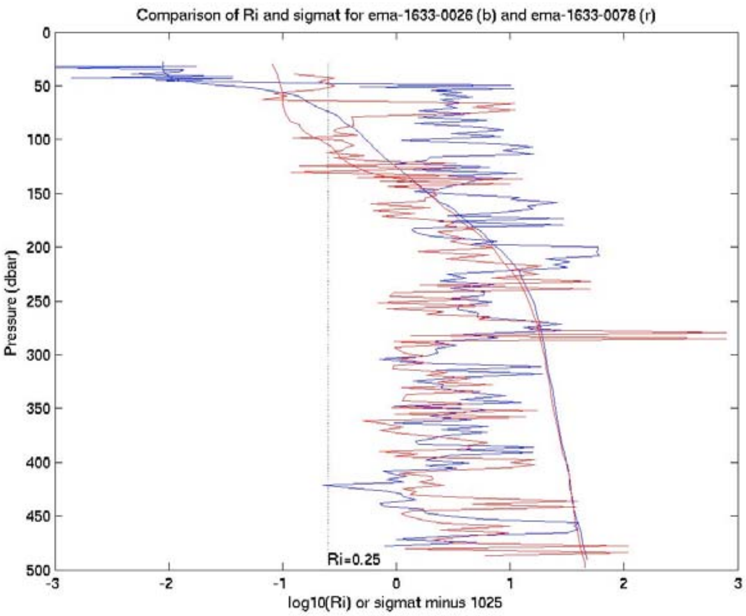

Figure 6: Vertical profiles of density and Ri from float 1633 before (profile #26 - blue) and after (profile #78 - red) the hurricane arrived. Profile 78 is 32 hours after the profile 26. The changes in density (displayed as density – 1025 kg/m^3) appear to be caused by vertical mixing resulting from shear instability as diagnosed by the gradient Richardson number.

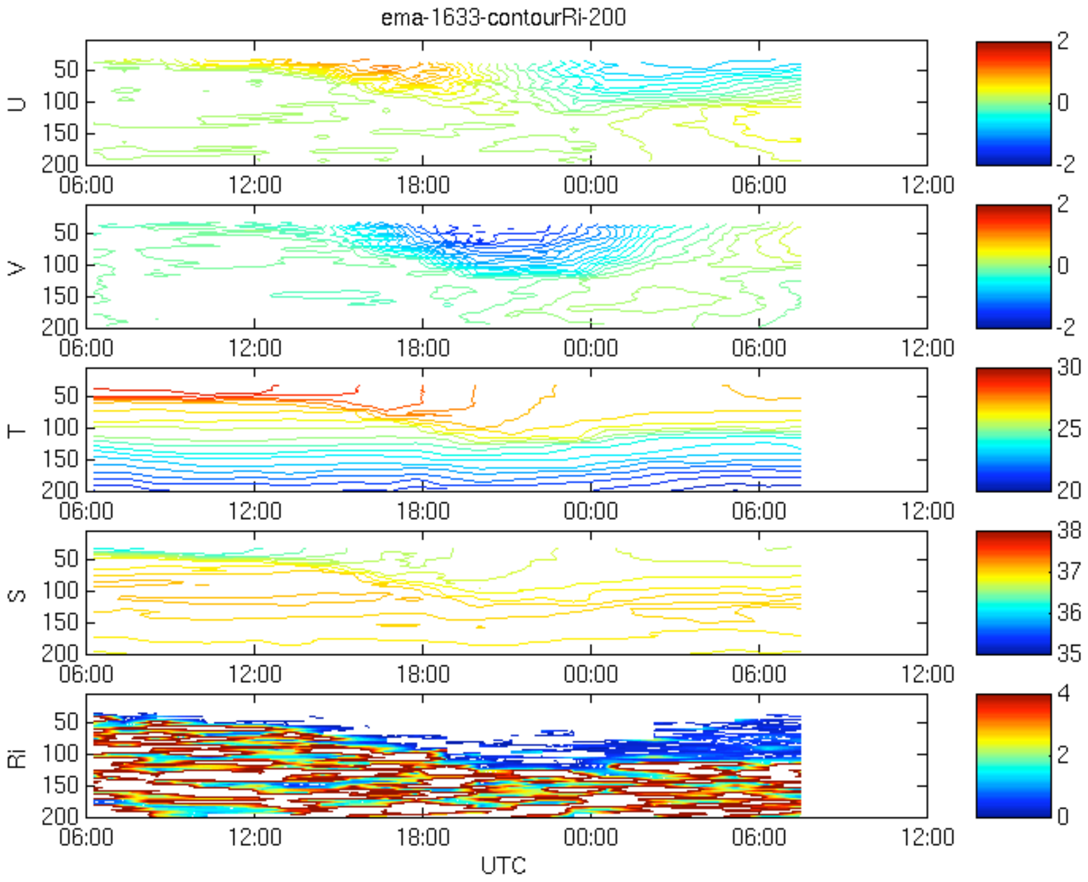

Fig. 7: H. Frances arrived at float 1633 around 1200 UTC on 1 September 2004. The upper ocean was accelerated by the wind stress resulting in rapid increases in velocity and vertical shear, a decrease in temperature and an increase in salinity. Both of the changes in water properties are consistent with the vertical mixing demonstrated by the low values of the Richardson number. The blue regions are those in which Ri < 1, often ~ 0.25. Regions in which N^2 is less than 3×10^{-5} s^{-2} are blanked to deemphasize already well-mixed and weakly stratified layers. There appears to be some restratification shallower than 100 m after the hurricane departed.

The message from these observations is that not only does EM-APEX reveal the changes to the upper ocean but also helps diagnose the causations. This ability to distinguish among various possible processes, such as lateral advection, inertial pumping or vertical mixing, derives from the new velocity measurements along with the conventional T and S observations. Further analysis will examine the relationship between wind stress estimated from surface winds vs. the change in upper ocean momentum. The latter is the observable consequence of the time integrated wind stress. Few measurements have been made in hurricane wind stress conditions. We intend also to make detailed comparisons between the observations from the 3 EM-APEX and numerical models of ocean response to hurricanes. For example, float 1636 was nearly under the eye of the storm. It obtained a very dramatic time series as the hurricane passed overhead. The base of the mixed layer oscillated strongly with peak-to-peak excursions over 50 m. This response was caused by "inertial pumping", arising as water experiences convergence and divergence under the rapidly changing wind stress vector as the eye passed over. This is in contrast to the mixing by shear instability at float 1633.

The combination of T, S and V profiling would be a significant addition to many process and long-duration ocean observation programs, such as envisioned under GOOS and operating in ARGO. The EM-subsystem is rugged, low power and inexpensive. It has been designed to operate within the battery capacity of current APEX floats in the ARGO program. In ARGO it could provide direct estimation of vertical diffusivities though a parameterization based on 10-m shear and strain necessary for understanding gas transfer. Near real-time and long duration observations of ocean properties and dynamics will support better numerical modeling, storm forecasting, operational oceanography, process studies and basic research.

Examples of notable benefits from the EM-APEX in studies of the ocean are listed below. Examples that duplicate uses for T and S profiles alone are not included. The EM-APEX provides

V(z) measurements from an autonomous, profiling platform capable of deployment in remote situations and severe conditions for long duration; operational depth > 2000 m are anticipated for APEX; V can be absolute when a down profile follows an up with GPS fixes on each surfacing; mimics a slowing drifting current meter mooring with CTD
means for addressing questions of ocean dynamic processes responsible for changes based on velocity observations (e.g., advection, <u'w'>, Ri, K_v) of use for understanding the evolution of ocean properties
spatially distributed observations around shipboard studies or extension of observation duration beyond normal ship-based capabilities
estimates of horizontal density gradients via geostrophy ($V_z \propto \rho_x$), of potential value for constraints to numerical models (along with T, S and ρ), especially effect with profiles spaced half an inertial period to isolate the geostrophic profile
corrections for the lateral displacements of the float during traverses to and from park depths (i.e., improves accuracy of **<V>** computed at the park depth)
estimates of vertical diffusivity K_v via a shear and strain parameterization
estimates of directional SGWs, SML slab motion and SML shear
shear and stability through the "transition zone" at the SML base (i.e., Richardson numbers and parameters for mixed layer deepening)
velocity and density over much of the water column for determinations of energy flux (i.e., <v'p'>), especially for internal tides
rapid profiling over many weeks with internal storage of data for support of process studies, such as complementing nearby shipboard measurements
bi-directional communication permits mission modification and "store and forward" data communication
guidance for 'steering" floats by selecting park depth at which flow is in the desired direction to allow float to stay in region longer
GPS for accurate float location and surface velocity estimation
cost effective and valuable addition to standard, commercially produced instrument making technology available to scientific and operational community
rapid or easy deployment, such as from aircraft or commercial vessels

I hope you find this note informative and suggestive of potential future applications. The future of this technology depends at this stage on acceptance by the community. Webb Research Corp will need to be convinced that my enthusiasm is shared by potential users. I encourage feedback on this note be sent to Doug Webb at WRC or to me. I hope that the EM capability will become an option on WRC commercial floats and widely available to the oceanographic community.