9C.2 Synthesis of major results from the Coupled Boundary Layer Air-Sea Transfer Experiment (CBLAST) in hurricanes (2003 -2004)

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1. MOTIVATION FOR CBLAST

CBLAST was an effort conceived by the Office of Naval Research (ONR) to fill a gap in our understanding of air-sea transfer processes at extreme wind conditions. Developed under an Accelerated research Initiative, CBLAST Hurricane was conceived to improve understanding of air-sea flux processes in extreme hurricane wind conditions. It was widely recognized that approximation of air-sea flux of momentum and enthalpy (heat and moisture) by bulk aerodynamic formulas involving exchange coefficients was well established only for winds slightly in excess of gale, i.e. tropical storm, force (17 m/s). Dependence of the drag coefficient and enthalpy exchange coefficient on wind speed was only well established to winds of 20 m/s (Large and Pond, 1976; Smith, 1980; Fairall et al, 2003). Yet extrapolations to winds over 60 m/s is common in hurricane models, both operational and experimental. These extrapolations have taken on a wide range of values, given the lack of observations. CBLAST was therefore conceived as a first step to reduce this gap in measurements and basic understanding.

The motivation of CBLAST was thus to 1) improve air-sea flux physical understanding, 2) improve air-sea flux parameterization and 3) through this effort to improve Tropical Cyclone (TC) intensity prediction. While significant progress has been made in improving forecasts of TC track over the past 30 years (Franklin et al 2003), little improvement in forecasts of TC intensity has been achieved (DeMaria et al. 2005). While many factors have contributed to the lack of intensity forecast skill, lack of basic understanding of three major areas is key: 1) environmental interactions with the surrounding atmosphere and underlying ocean, 2) internal dynamics such as eyewall replacement cycles and 3) physics of air-sea flux at the ocean surface. This latter is the focus of CBLAST, especially air-sea exchange at extreme winds and how it depends upon surface wave spectral characteristics, spray and foam production and secondary boundary layer circulations. This undertaking has taken on added significance and urgency in light of the new era of increased numbers of hurricanes (Goldenberg, et al, 1998) and the increased numbers of landfalling hurricanes in the past two years.

2. CBLAST CONCEPT AND OBSERVATION PLAN

Conceived in 2000, CBLAST became a cooperative project between ONR, NOAA and the Air Force Reserve Command (AFRC). ONR provided support for over 16 PI's (see Table 1.) from universities and government laboratories. NOAA provided aircraft flight hour support for two WP-3D research aircraft, expendable probes and Hurricane Field Program infrastructure. AFRC, through the 53rd Weather Reconnaissance Squadron, provided infrastructure support, specialized expertise in air deployment of large platforms and WC-130J and C-130J aircraft support.

Table 1. CBLAST Hurricane Principal Investigators

Aircraft Program

- 1. Peter Black (NOAA/AOML/HRD)- Chief Scientist, Flight Planning, Program Coordination, Dropsondes, SFMR
- 2. Paul Chang (NOAA/NESDIS/ORA)- Lead Scientist-Ocean Winds, IWRAP, satellite apps, SATCOM
- 3. Eric Uhlhorn (NOAA/AOML/HRD)- SFMR, AXBT
- 4. Chris Fairall (NOAA/ESRL/ETL)- Sea Spray, CIP
- 5. William Asher (U. Washington/APL)- Sea Spray, PDA
- 6. Kerry Emanuel (MIT)- Dropsondes, High Wind Flux, Theory
- 7. Edward Walsh (NASA)- Surface waves, SRA
- 8. Jeffrey French (U. Wyoming)- Turbulence, BAT
- 9. William Drennan (U.Miami/RSMAS/AMP)- Moisture Flux, LICOR
- 10. Stephen Frasier, Daniel Esteban, Rob Contreras (UMASS)- Remote Sensing, IWRAP, USFMR
- 11. James Carswell (Remote Sensing Solutions)- Remote Sensing, IWRAP
- 12. Ken Melville, James Lasswell (U. California/Scripps)-Surface wave breaking, foam coverage, MASS VIS and IR down-looking camera systems

Drifting Buoy/Float Program

- 13. Eric D'Àsaro (U. Washington/APL)- Ocean Mixing, gas exchange, Lagrangian Floats
- 14. Tom Sanford (U. Washington/APL)- Chief Scientist, ONR SBIR, ocean currents, EM APEX floats
- 15. Eric Terrill (U. California/Scripps)- Ocean acoustics, surface waves, ocean profiles, ARGO/SOLO floats
- Pearn Niiler, William Scuba (U. California/Scripps)- SVP Mimimet, ADOS drifting buoys
- 17. Gustavo Goni (NOAA/AOML/PHOD)- Satellite ocean heat content

The experimental design consisted of two major observational components: 1) airborne in-situ and remote

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sensing instrumentation flown into hurricanes by the two NOAA WP-3D aircraft and 2) air-deployed surface drifting buoys and subsurface profiling floats. This was intended to provide a mix of 'snapshots' of inner-core hurricane conditions each day over a 2-4 day period together with a continuous time series of events at particular ocean locations. A third component, available based on operational needs, consisted of the hurricane synoptic surveillance program designed for improved track forecasting. It provided, on occasion, concurrent high-level NOAA G-IV jet aircraft flights in the hurricane environment, deploying GPS dropsondes to profile the steering currents and significant synoptic features, in addition to reconnaissance flights within the hurricane's inner core from the WC-130H operated by AFRC 53rd WRS. Polar-orbiting and geostationary satellite platforms provided additional remote sensing measurements in the hurricane's inner core and environment.

The aircraft component of CBLAST had two modules: a) an aircraft stepped descent module and b) an inner-core survey module. The former was designed focus on in-situ air-sea flux and sprav measurements, while the latter was to focus on largescale structure, eyewall flux budget measurements and documentation of internal dynamics. The centerpiece of this effort involved a multi-sonde sequence of 8-12 GPS dropsondes dropped from coordinated WP-3Ds flying in tandem at different altitudes. See Fig. 1 for a schematic of a typical flight plan. Each module consisted of several options related to precise experiment patterns dictated by prevailing conditions and available time on station. For instance, the stepped descents, down to as low as 70m above the sea, were only carried out in clear air conditions between rainbands.



Figure 1. CBLAST survey pattern showing planned expendable probe deployments along a 'figure 4' pattern relative to the storm's eyewall and rainband features. Location of planned stepped-descent patterns to measure boundary layer fluxes is shown schematically.



Figure 2. Vertical alignment of stepped descent flight legs along with expendable probe location along the 25 nmi (40km) leg length.

Both modules were complemented with an array of airborne remote and in-situ sensors. Air-deployed drifting oceanographic buoys and floats (auto-profiling oceanographic radiosondes) were designed to further complement the airborne in-situ and remote sensing of the air-sea interface. This air-deployment module consisted of arrays of sensors measuring continuous time series of surface and upper ocean conditions before, during and after hurricane passage. Together the aircraft and buoy/float array provided a unique description of air-sea fluxes, surface wave and upper ocean conditions in hurricane conditions never before achieved. The synoptic surveillance program provided observations on cases where environmental interactions were important, allowing research efforts to distinguish between intensity changes resulting from air-sea processes those interaction and resulting from environmental interactions with significant synoptic scale features in the near-storm environment. In a similar fashion, the inner core survey module provided observations of significant changes in the inner core dynamics occurring concurrently with observed air-sea processes. In principle this was to provide an overarching data base to allow intensity changes from air-sea interaction causes to be separable from those due to environmental interactions and internal dynamics.

3. CASE STUDIES

The CBLAST experimental effort began in 2000 with the development of six new airborne instrument systems, three new oceanographic float designs, 2 drifting buoy designs, the flight pattern strategy and the air-deployment strategy, including the WC-130J air-deployment certification and air-drop certification of 3 platform types. The new airborne instrument systems were 1) Best Atmospheric Turbulence (BAT) probe for fast response temperature and u,v,w wind components, 2) LICOR fast response humidity system, 3) CIP particle spectrometer and 4) Particle Doppler Analyser (PDA) for sea spray droplet observation, 5) Downward-looking MASS high-speed visible and infrared camera systems for wave breaking observations, 5) Scanning radar Altimeter (SRA) for

directional wave spectra, 6) Stepped and Simultaneous Frequency Microwave Radiometers (SFMR and USFMR) for surface wind speed and 7) the Integrated Wind and Rain Atmospheric Profiler (IWRAP) for continuous boundary layer and surface wind vector profiles.

These systems were built in 2001 and flighttested in 2002. Two storms, Edouard and Isadore, were flown in 2002, the first to test the new stepped-descent flight pattern strategy and the second to test extended low level flight pattern for detection of secondary roll circulations. The CBLAST field program began in earnest in 2003 with the survey flight pattern flown on 6 days by the two NOAA WP-3D aircraft together (a total of 12 fights) with 15 stepped-descent patterns flown within the hurricane boundary layer in Hurricanes Fabian and Isabel from a staging base in St. Croix, U.S. Virgin Islands. An additional 10 AFRC WC-130H reconnaissance flights and 3 NOAA G-IV surveillance flights were also flown during this period. A 2 X 4 array of 16 drifting buoys and 4 floats were deployed by the 53rd WRS from a WC-130J aircraft (Fig 3) ahead of Hurricane Fabian. The aircraft fleet in St Croix is shown in Fig. 3- the NOAA WP-3D crew and scientists in fig. 4.



Figure 3. Deployment of a drifting buoy package from an AFRC WC-130J aircraft.



Figure 4. CBLAST aircraft fleet in St. Croix consisting of two NOAA WP-3D aircraft and the AFRC Wc-130J aircraft. The latter was used to air-deploy the drifters and floats ahead of Hurricanes Fabian (2003) and Frances (2004).



Figure 5. NOAA WP-3D crew and scientists in front of one of the WP-3D aircraft.

An engine failure due to salt build-up occurred near the end of the 6th flight resulted in new safety regulations requiring a chemical engine wash after each flight below 340 m. CBLAST flights in 2004 continued, but were restricted to flight levels above the boundary layer. The CBLAST flights in 2004 were in Hurricanes Frances on 5 days, Ivan on 4 days and Jeanne on 3 days. The key success in 2004 was the air-deployment by the 53rd WRS of 38 drifting buoys (30 Minimet; 8 ADOS) and 16 floats (10 ARGO/SOLO; 2 gas flux; 2 Lagrangian; 2 EM/APEX) in Hurricane Frances.

4. KEY RESULTS FROM THE AIRCRAFT COMPONENT

The principal results from the aircraft component of CBLAST was the estimation from direct eddy correlation measurements of surface momentum and enthalpy flux from two new airborne instrument packages: the Best Atmospheric Turbulence Probe (BAT) and the LICOR fast response humidity probe, shown mounted on the WP-3D aircraft in Fig. 6. The results were obtained during the stepped-descent patterns that were flown in Hurricanes Fabian and Isabel in 2003. Details of these results are presented in French, et al (2006) and Drennan et al., 2006. There were a total of 12 stepped descent patterns flown on 6 days in the two storms from which 48 independent estimates of Cd and 41 estimates of Ce were derived from measured fluxes and SFMR estimates of U10, the ten-m surface wind. Several surprising results emerged from these measurements. First, Cd leveled off and decreased slightly with wind speed at approximately 22-23 m/s, a considerably lower threshold for the leveling off of Cd at 33-35 m/s based on the Powell (2003) and Donelan, et al., 2004 studies (Fig. 7). Further, the estimated Cd values appeared to be independent of storm quadrant differing little between young growing waves in the right-rear quadrant in a swell-following environment to the right front and right-rear quadrants where the local sea became older, less steep and higher, and also encountered swell at increasing crossing angles of up to 90 degrees (Walsh, et al., 2001). Second, the flux measurements for both momentum and moisture appeared to be approximately constant with height within the hurricane boundary layer. Third, the Ce results above 20 m/s agreed almost exactly with the HEXOS results (DeCosmo, et al., 1996) for wind speeds below 20 m/s suggesting that Ce is

constant with wind speed u to hurricane force conditions of approximately 33 m/s.



Figure 6. Location of the BAT turbulence probe and LICOR fast response humidity probe on the WP-3D aircraft.



Figure 7. Drag coefficient estimates derived from CBLAST stepped-descent flight legs in Hurricanes Fabian and Isabel (2003). The asterisks represent average values in 2.5 m/s bins. The red squares are from flight legs in the right-front quadrant of the storms, green plus signs from the right-rear quadrant and the blue diamonds from the left-front quadrant. The dotted line represents Large and Pond, 1979 (LP) extrapolated to 35 m/s winds. Peak winds for LP were 22 m/s.



Figure 8. Ce as a function of wind speed for a combination of HEXOS and earlier observations in addition to CBLAST estimates in Hurricanes Fabian and Isabel.

When CBLAST Cd and Ce results are compared with other studies (Fig. 9), one can see that they represent a doubling of the wind speed range of observations previously available, which is a significant achievement. It is apparent that the CBLAST high-wind Cd values represent significant departure from prior estimates. It also becomes obvious that while CBLAST extended the range of prior observations, a further doubling of the wind speed range is required to estimate fluxes in hurricane conditions from CAT 1 to CAT 5. It is in this range that physical processes may depart significantly from moderate hurricane wind conditions as the importance of sea spray increases dramatically, a process that little is known about at present.



Figure 9. Cd (left axis) and Ce (right axis) as a function of wind speed. Plotted are CBLAST values of Cd (red diamonds) and Ce (blue inverted triangles) compared with recent Cd estimates from Powell, 2003 (black line, open triangles), Donelan, et al., 2004 (blue line, open triangles), an average of Large and Pond, 1976 and smith, 1980 (heavy black line) and HEXOS for ocean depths of 18 (dotted line) and 30 m (dashed line) and Ce values for HEXOS (DeCosmo, et al., 1996- black crosses) and TOGA/COARE (Fairall, et al., 2003- black solid triangles). Also shown are very preliminary Cd and Ce budget estimates (dotted pink and dash-dotted light blue, respectively) from Emanual and Fairall ongoing studies.

One implication of the new Cd and Ce observations as well as the somewhat tenuous extreme wind estimates is that the ratio of Cd/Ce, hypothesized by Emanuel, 1996 to be an important parameter in estimating hurricane potential intensity, decreases to values on order of 0.5-0.6 tropical storm and CAT 1-3 hurricane conditions before increasing to values close to 1.5 at CAT 5 conditions. This effect is being investigated further by Montgomery, et al., 2006.



Figure 10. Ratio of Cd/Ce derived from CBLAST measurements as well as an average of prior values below 20 m/s and estimated values based on budget estimates at winds above 50 m/s.

The Scanning Radar Altimeter (SRA) on the P3 aircraft recorded huge data sets on the 2D wave spectra in all quadrants of CBLAST storms in 2004 and in Fabian in 2003. Typical of those results was the image in Fig. 11 from the front guadrant of Hurricane Fabian near 200 m altitude which shows the predominant 200 m swell propagating to the upper left of the image. Superimposed on the swell is the local sea with wavelengths of about 75 m crossing it at a 90 degree angle and propagating toward the lower left. This is typical of conditions depicted in Fig. 12, which illustrate 3 sectors of distinctly different 2D wave spectra, discussed by Walsh, et al., 2001. The spectra in sector I tend to be tri-modal with 2 swell peaks and the local sea. The spectra in sector II tend to be unimodal with the swell following within 30 degrees of the local sea. The spectra in sector III tend to be either bior uni-modal depending on whether the local seas is resolved. The swell tends to propagate at about a 90 degree angle to the local sea in this region.



Figure 11. Swath of wave elevations from SRA during Fabian from 200 m flight altitude during Fabian, 2003. Scale of aircraft is shown at 1 km along track, 0.2 km cross track position.



Figure 12. Analysis of SRA swell direction of propagation, wave height (dashed black contours) and wave steepness (solid blue contours) for Hurricane Bonnie.

Strong evidence was found for the existence of roll vortex secondary boundary layer circulations in hurricanes. Complementing the CBLAST flights in 2002-2004 were a number of RADARSAT and ENVISAT SAR passes (see Fig. 13) over the storms which all showed streaks in the radar backscatter with wavelengths on the order of 800-1000 m. These were most prominent in the front semicircle of the storm. From a 120 m flight leg in Hurricane Isadore 2002, the u'w' vertical cospectrum was computed. The first part of the leg was in the radial direction toward the eye and showed a very coherent peak in the spectrum near 900 m, in close agreement with the scales from the SAR images (fig. 14). This peak disappeared when the aircraft turned and flew along wind. Ongoing studies (J. Zhang, personal

communication) suggest these features may play an important role in boundary layer fluxes.



Figure 13. RADARSAT SAR image (top) from right-front quadrant of Hurricane Fran, similar to that obtained for Hurricane Isadore, 2002. Spectrum of wavelengths from ENVISAT image of Hurricane Isadore, 2002. Arrow indicates peak in aircraft-derived spectrum in fig. 14.



Figure 14. Spectrum of vertical momentum flux along a 120 m altitude radial flight leg into Hurricane Isadore, 2002.

5. KEY RESULTS FROM THE DRIFTING BUOY/FLOAT COMPONENT

The 54 buoys and floats deployed into Hurricane Frances in 2004 yielded a wealth of information on ocean structure and structure changes induced by the hurricanethe first ever evolutionary 4D ocean structure observations beneath a hurricane. The buoys and floats revealed a warm anticyclonic eddy directly in the path of the storm which was flanked by cooler cyclone features.

Ocean mixing was well resolved by the floats. Beneath a hurricane, mixing can significantly reduce sea surface temperatures from the pre-storm values. Fig. 15 shows the evolution of upper ocean temperature under the strongest winds of Hurricane Frances. It combines the vertical temperature profiles from an EM-APEX float with the nearby temperature measurements from the two Lagrangian floats. The strong wind and wave forcing directly generates turbulence in the upper 20-40m of the ocean. The Lagrangian floats are advected by the large-eddy velocities of this turbulence, repeatedly cycling across the turbulent layer and thereby tracing its depth and intensity (red and blue lines). Turbulent velocities are 0.1 m/s rms at the height of the storm, with the strongest downward jets reaching 0.3 m/s. The turbulent layer extends to 50m at the height of the storm. However, the changes in temperature, indicate that mixing extends to 120 m (magenta line). Measurements of shear by the EM-APEX floats (not shown) show a nearly critical Richardson number down to 120m, indicating a key role for shear instability in this deeper mixing. The one dimensional heat budget requires even deeper mixing as shown by the yellow dashed line. A more detailed analysis indicates that horizontal heat fluxes become important as the magenta and yellow-dashed lines diverge, indicating a transition of the boundary layer heat budget from vertical to three-dimensional.

The net effect of this strong ocean mixing is to cool the ocean surface, potentially reducing the enthalpy flux to the hurricane. The combined data from the floats and drifters is used to map the amount of cooling in Fig. 17. Cooling is most intense to the right of the storm center, with a cold wake spreading outward behind this region. The leading edge of this wake forms an SST front approximately 50 km wide which moves with the storm. The eye of storm is at the edge of this front, so that cooling at the eye is only about 0.5°C compared to the maximum of 2.5°C. SST gradients of up 2°C exist across the inner 50 km of the storm, with a temperature range of about 27.5-30°C. These data suggest that rather than specifying the SST at the hurricane inner core, it may be more useful to think in terms of the location of the SST front that exists beneath the core. Small changes in the location of this front relative to the core may have large effects on the enthalpy flux driving the storm.



Figure 15. Cooling of SST beneath hurricane Frances in storm-centered coordinate system. White dots show storm-relative locations of float and drifter data. Storm motion is to left. Colors show mapped SST change from pre-storm value. Contours show wind speed.



Figure 15. Evolution of the temperature structure of the upper ocean near the radius of maximum winds of Hurricane Frances. a) Wind speed and atmospheric pressure from HRD HWIND analysis at the two Lagrangian floats. b) Temperature contours (black and gray), trajectories of Lagrangian floats (red and blue) and depth of the mixed layer measured (magenta) and from a vertical heat budget (yellow dashed).

6. FUTURE PLANS FOR CBLAST HURRICANE

The analysis of CBLAST hurricane data sets has just begun. Continued support for analysis efforts is being provided by ONR and NOAA through the U.S. Weather Research Program (USWRP). Additional fundamental research will be ongoing in the years ahead for efforts such as merging 2D wave spectra from the SRA and the 1D wave spectra from the ARGO/SOLO floats to estimate the high frequency portion of the wave spectrum in hurricanes and to relate differences by quadrant to the observed wave spectra. Additional analysis of the GPS sondes from the multisonde deployments in the hurricane eyewall for the purpose of estimating eyewall air-sea flux via budget calculations and form that and SFMR surface wind, SST and specific humidity estimates to arrive at additional Cd and Ce estimates for extreme winds in excess of 50 m/s. Work will continue on the diagnoses of boundary layer secondary circulations, i.e. 'roll vortices' and the variability by storm quadrant from additional spectral analysis of Bat and LICOR data from along and cross wind flight legs as well analysis of IWRAP boundary layer wind profiles to address vertical structure issues of this phenomenon. Continued synthesis of drift buoy, float and satellite observations of ocean features in the path of Fabian and Frances will continue, including efforts to improve ocean mixing parameterizations in hurricane conditions.

Efforts to estimate fluxes at the top of the hurricane boundary layer will begin. Using the suite of BAT and LICOR turbulence instrumentation now available for both NOAA Wp-3D aircraft, additional measurements will be sought over the coming years to fill the many gaps in the CBLAST data and to continue to focus on the parameterization with wind speed, wave conditions and roll vortex effects. These observations will accompany new observations of sea spray droplets from any possible low level flights using the new suite of cloud microphysical spectrometer probes presently being improved on the P3 Aircraft- opening the possibility of extending sea spray studies.

The focus will also shift toward integrating existing and anticipated results on air-sea flux parameterization into the evolving HWRF operational model at the NOAA Environmental Prediction Center (EMC) as that model comes on line operationally and begins to build a data base with existing parameterization schemes. Similarly, efforts to integrate CBLAST results into the navy NOGAPS model effort and the Navy version of WRF. Special efforts will begin to asses the impact of the new air-sea parameterization schemes on hurricane intensity.

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