Air-Sea Flux Estimation in High Wind Boundary Layers

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LONG-TERM GOALS

Our primary goal is to improve our understanding of air-sea surface flux processes in high winds, specifically in the complex conditions of tropical hurricanes where swell, sea spray and secondary boundary layer circulations play a role. Our ultimate goal and prime motivation for this work is to parameterize these new observations and improve the accuracy of hurricane intensity prediction.

OBJECTIVES

The objective of this work is to develop a new surface wave-dependent flux parameterization for the high wind hurricane boundary layer containing secondary (roll-vortex) circulations over fetch limited seas in the presence of sea spray and one or more swell components from an airborne platform. We propose to test the following hypotheses:

1) that surface momentum exchange coefficients increase with wind speed for moderate winds (>30 m/s), are enhanced by fetch-limited waves or opposing swell, but level off or decrease above a high wind threshold (>45 m/s), especially in quadrants where swell has a significant downwind component,

2) that compensating mechanisms for enhanced surface air-sea enthalpy fluxes over and above current parameterizations must exist for storm maintenance and growth above some high-wind threshold wind speed, and
3) that candidate mechanisms are separable and can be estimated, such as a) enhanced turbulent fluxes due to wave interactions, b) spray evaporation and c) secondary flow circulations (roll-vortex type).

APPROACH

Our approach is to implement a multifaceted observational program among several investigators to simultaneously measure air-sea fluxes using several independent methods while at the same time measuring two-dimensional surface wave spectra, as well as spray droplet spectra, in wind speed regimes ranging from 20-40 m/s, and possibly higher. The secondary goal is to use existing data sets to inter-compare various published wave-dependent bulk flux parameterizations, with and without wave age effects and with and without spray parameterizations, using never-before-available surface inputs from GPS dropsondes, AXBTs, model-generated as well as remotely-measured wave spectra and remotely-measured surface winds in gale- and hurricane-force conditions.

Flight track design and evaluation, bulk surface parameter measurement for surface flux estimation and atmospheric and ocean profiling will be lead by P. Black (HRD)- E. Uhlhorn (HRD/UM-CIMAS) will assist. This will include measurement of PBL wind, air temperature and specific humidity profiles from GPS sondes together with surface winds from the SFMR (HRD and UMASS versions) as well as mixed layer thermal profiles, sea surface temperature and upper ocean heat content from AXBTs. PBL continuous wind profiling and surface wind vector retrieval will be lead by D. McLaughlin (UMASS-MIRSL), with A. Zhang assisting, using the UMASS dual polarized, dual frequency Doppler scatterometer. Large-scale surface wind retrievals will be lead by P. Chang (ORA) using satellite scatterometry. Large-scale ocean heat content retrievals will be lead by G. Goni (PHOD) using satellite altimetry. Direct flux measurements will be lead by T. Crawford (FRD, J. French (FRD) and W. Drennan (UM-RSMAS). In a collaborative effort, K. Emanuel (MIT) will lead the effort to estimate boundary layer fluxes from GPS dropsonde profiles, including an initial assessment of this technique using recent data sets. R. Black (HRD) will collaborate with C. Fairall (ETL) in measurements of spray droplet spectra. Surface 2-D long-wave swell spectral measurements will be lead in a collaborative effort by E. Walsh (ETL/WFC). Measurements of surface wave dissipation due to wave breaking will be lead by Melville (SIO) in a collaborative effort using high-speed video imaging. E. Terrill (SIO) will lead a collaborative effort to obtain 1-D wind wave spectra using a laser altimeter, as well as ocean thermal and current profiles using subsurface floats. E. D'Asaro (UW) will lead a collaborative effort to measure ocean-mixing profiles using subsurface floats.

Our strategy will be to obtain new parameterizations of momentum, heat and moisture fluxes from these observations including accurate estimates of the exchange coefficients as a function of wind speed and to estimate the modulation of the fluxes by fetch-limited wind waves, long-wavelength swell, sea spray and PBL secondary circulations, i.e.'roll vortices'.

WORK COMPLETED

Flight pattern testing (P. Black, K. Emanuel)

A new flight pattern strategy of conducting a coordinated survey pattern using the two WP-3D's was tested and found to work very well operationally for the mapping of bulk boundary layer parameters with fine azimuthal resolution. The pattern involves flying the two P-3s along orthogonal legs during three coordinated penetration legs which rotate by 30 deg after each pass. This strategy is being considered as an alternative to coarse azimuthal resolution patterns with the two P-3's flying in tandem in a 'figure 4' pattern that rotates by 45 deg. This raises some flight safety issues in high winds.

The opportunity to test the stepped-descent pattern for flux estimation in along-wind and across-wind conditions did not present itself during the 2001 hurricane season. Neither did the opportunity to test an extended crosswind pattern in the presence of a RADARSAT overflight to assess the surface signatures and flux modulation of 'roll vortices' in the PBL. This objective will be a top priority for the 2002 season.

The collaborative retrospective study of Emanuel and Ranstrom shows that previous strategies for GPS sonde deployment is less than ideal for estimation of the ratio of enthalpy and momentum flux as a function of wind speed. Their initial work suggests deployment strategies will need to be altered in one of several ways to deploy sondes in the eyewall with very high spacial resolution: 1) install two 4-channel GPS receivers on one P-3, 2) fly two P-3's in tandem through the eyewall deploying sondes with the 4-channel receivers on different P-3's (a potential flight-safety issue) or 3) purchase an additional 4-channel GPS sonde receiver (~$50K).

A strawman implementation plan is being developed which will contain initial flight plan strategies based on these initial findings and will be open to discussion and modification during FY02 in the period leading up to the initial instrument test phase during the 2002 hurricane season.

Retrospective bulk flux study (P. Black, E. Uhlhorn)

A retrospective study of conventional bulk flux estimates from individual storms dating to 1997 has just begun. Cases with unique new surface data are being identified which contain 1) remotely measured surface winds, 2) SSTs from AXBTs, 3) surface wind, temperature and specific humidity from GPS dropsondes and 4) surface 2-D wave spectra. These measurements are being used to calculate retrospective surface fluxes with and without wave age parameterizations.

A landmark data set regarding hurricane PBL structure and a preview of the new flight pattern strategy was obtained in Hurricane Humberto on Sept 23-24, 2001. Coordinated flight patterns along 6 azimuths were flown by the two NOAA P-3s, the NASA DC-8, and NASA ER-2, together with AFRS WC-130. Over 220 detailed vertical PBL profiles were obtained from GPS dropsonde with fine radial resolution on the two days. Also measured were continuous remotely sensed surface winds, 2-D surface wave spectra, surface and subsurface ocean temperatures from AXBTs (coincident with GPS dropsondes) and 3-D wind fields from airborne Doppler radar. Humberto is now the prime case for retrospective surface flux calculations.

Continuous PBL wind profiling/ surface wind vector measurement (D. McLaughlin, A. Zhang)

The proposed FY01 activity for UMASS was to upgrade the UMass C and Ku-band airborne scatterometers into an Imaging Wind and Rain Airborne Profiler (IWRAP) to enable the instrument to image (in 3-D) atmospheric boundary layer winds and precipitation. Tasks for FY01 are:

1. **Boost the transmit power of C and Ku-band from 1 watt to 80 watts by integrating microwave power modules (MPM) into the C and Ku-band transmitters.**

The C and Ku-band power amplifiers have been ordered from Microwave Amplifiers Inc. (C-band solid state amplifier) and Northrop Grumman (Ku-band Microwave Power Module or MPM) and are scheduled to be delivered in October (for C-band) and November (for Ku-band) 2001 time frames. These modules will then be integrated into new RF transmitter boxes that have been fabricated. In the event these amplifiers are not delivered by their promised dates, we are able to install two smaller amplifiers currently available at UMass to provide 10W (C-band) and 20W (Ku-band) transmit power, on a temporary basis for system testing during planned NOAA WP-3 2002 winter storms flights for P. Chang (NOAA/NESDIS/ORA). The impact on IWRAP's sensitivity will be a 9dB reduction in signal-to-noise ratio (SNR) at C-band and 6dB SNR reduction at Ku-band.

2. **Incorporate a four channel digital receiver into the IWRAP C and Ku-band receivers to enable IWRAP to simultaneously record the Doppler/reflectivity profiles at four separate incidence angles (approx. 30, 36, 42 and 50 degrees incidence) and two frequencies.**

To date, we have completed approximately 70% of the work needed for digital receiver implementation. A block diagram of the digital receiver system is given in Figure 1. The progress associated with each major component of this system is given in Figure 2. We expect to finish the digital receiver integration by 12/01/01 to test the IWRAP system during 2002 NOAA/NESDIS/ORA flights (01/2002-03/2002).

Key to this development is processing firmware (Field Programmable Gate Array codes) being developed by Andraka Engineering, under subcontract. Since this is a critical subsystem in the IWRAP radar development, we will carefully monitor the subcontractor development of this task during October and November and use this status to rationally plan for the timing of the 2002 winter flights of the IWRAP system.

3. Incorporate high power internal calibration loops to IWRAP in order to record transmit waveforms and measure transmitter/receiver gain fluctuations.

This work has been completed.

4. Test and calibrate IWRAP at the UMass outdoor calibration range.

The test and calibration of the IWRAP system at the UMass outdoor calibration field will be carried out in early December 2001. This task will include observing corner reflectors at varying ranges and characterizing the system gain stability as a function of the instrument's internal temperature environment. This task is estimated to take two weeks.

5. Integrate IWRAP into the NOAA WP-3D aircraft.

Integration of IWRAP into NOAA WP-3D aircraft is scheduled to be carried out late December 2001.

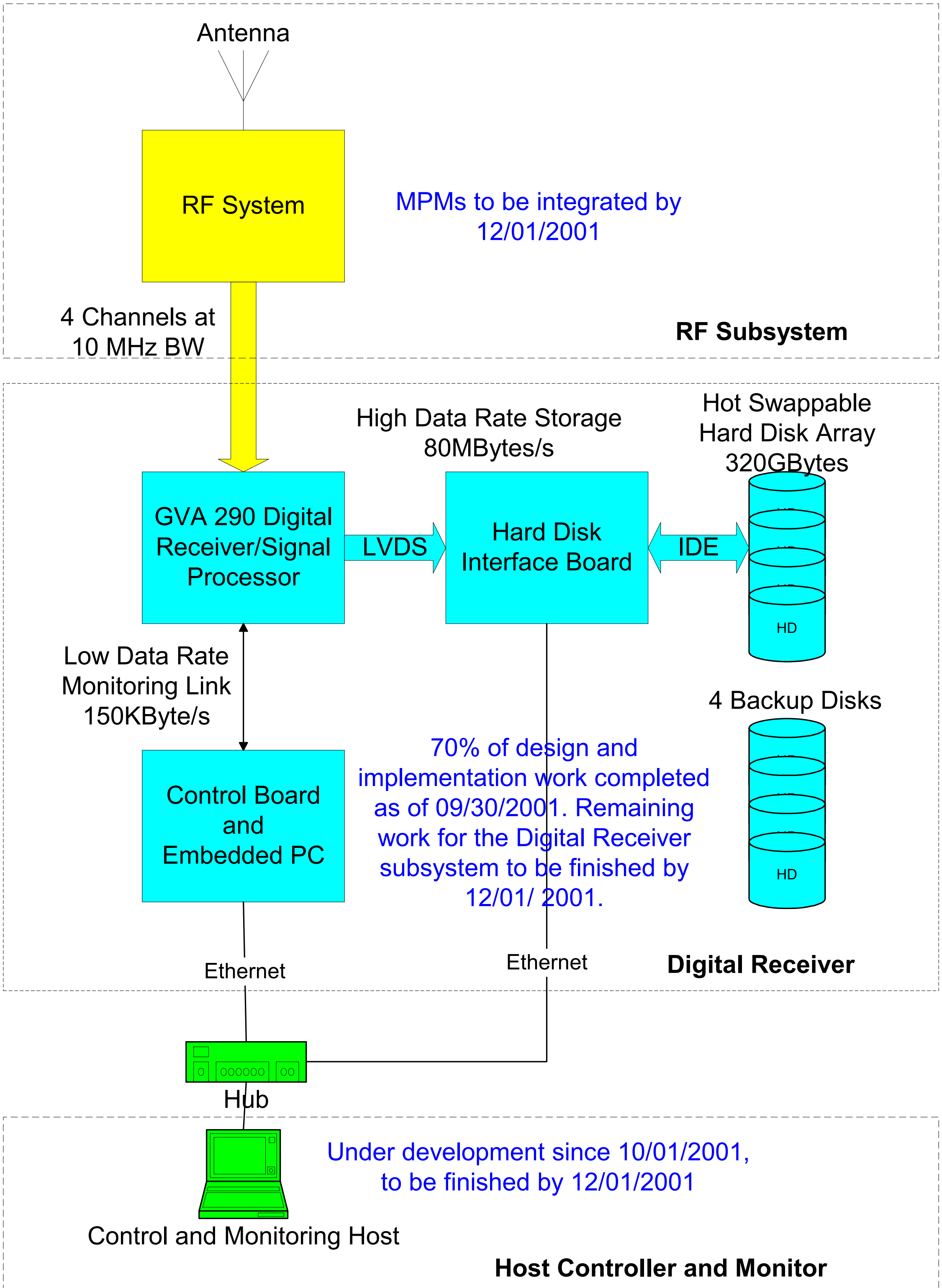

Figure 1. IWRAP System Diagram

- **USFMR Work**

Though not specifically addressed in our CBLAST proposal for FY01, UMass participated in Hurricane flights aboard NOAA AOC aircraft during August – October of 2001, refined system calibration and successfully tested a real-time transmission of surface wind data to the National HurricaneCenter. For future research archives, 8 flights were flown through 4 storms collecting a total of 460 Mbytes of data. These flights are listed in Table 1

Table 1. USFMR Participated Flights in NOAA 2001 Hurricane Field Program

Flight	Date	Storm/(MISSION)	Data Amount (MegaBytes)
1	09/10/01	Erin	72.8
2	09/15/01	Gabrielle	54.5
3	09/16/01	Gabrielle	36.1
4	09/19/01	(KAMP)	39.8
5	09/22/01	Humberto	78.5
6	09/23/01	Humberto	62.3
7	09/24/01	Humberto	60.9
8	10/07/01	Iris	55.8

The proposed FY02 activity is to

1. **Develop software for processing IWRAP profile data into backscatter images and wind field maps.**

We have started this work on 10/01/2001. This software will process the measurements from the scatterometers into high resolution surface backscatter images, high resolution wind vector field maps and retrieve the 3-D wind field from Doppler measurements of precipitation. This code will serve as the basis to realize real-time processing of the high resolution 3-D and surface wind fields during CBLAST deployment in FY03 – FY04.

2. **Participate the 2002 HFP with IWRAP and USFMR.**

We plan to install the IWRAP and USFMR systems on to the NOAA WP-3D aircraft in December 2001 to participate in the 2002 NOAA/NEDIS/ORA winter storm flight experiment. This will serve as an engineering check of IWRAP hardware and software to prepare for hurricane flights that will take place in August-October of 2001. If necessary, modifications to the IWRAP system will be made during summer 2002 to ensure successful operations during 2002 HFP flights.

3. **Add dual polarization capability to the IWRAP system.**

The dual polarized antennas have been ordered from Ball Aerospace ($139K, funded by Oregon State University/NASA) and are scheduled to arrive at UMass in January 2002. We are currently working on a design to add dual polarization imaging capability to the C-band and Ku-band spinners. (The current spinning mechanisms use single RF channel rotary joints to pass radar signals between the spinning antenna and the non-rotating RF electronics in the radar). Two approaches are being considered at this point. The first is to replace the single channel RF rotary joints with dual channel joints to pass both polarizations. To date, we have been unable to locate a dual channel rotary joint that will accommodate the wide bandwidth of the IWRAP system (bandwidths needed to frequency-scan the antennas are 500MHz at C-band and 1GHz at Ku-band). We are pursuing a lead from Q-par Angus Ltd. The second design option is to install a polarization switch on the spinning dual-polarized antenna and use a single channel rotary joint with slip rings. The power and control signals of the polarization switch will be passed through the slip rings.

We plan to finish the dual-polarization upgrade for the spinners during the spring of 2002 then install the dual polarized antennas into the radar prior to hurricane flights.

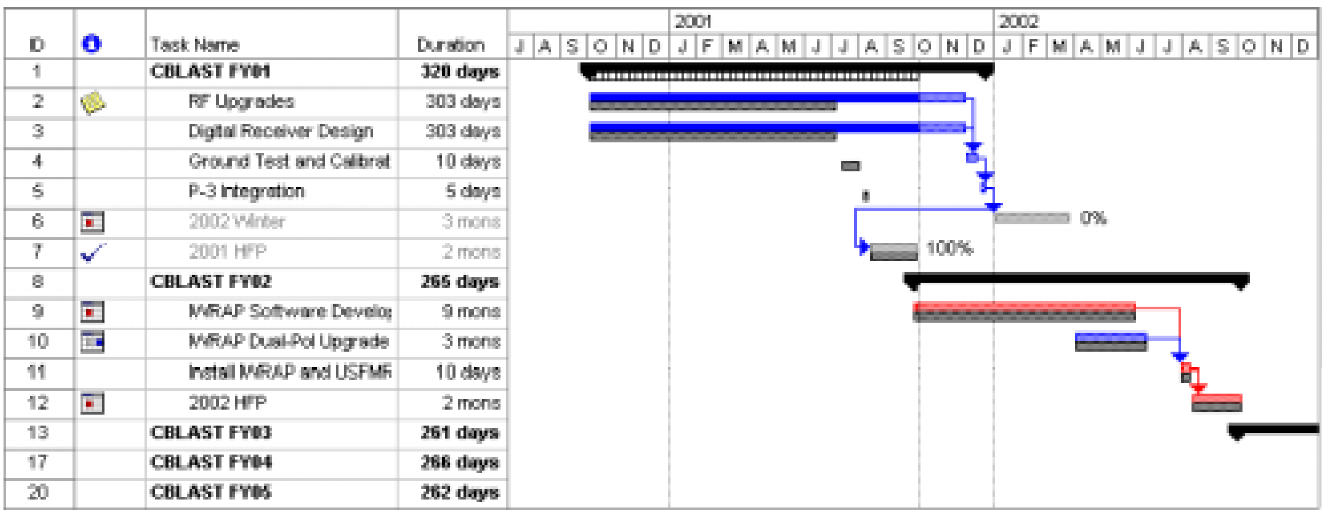

Figure 2. UMass CBLAST Project Schedule

Gray bars denote the original proposed schedule.
Blue and red bars denote current plan (shaded color) and progress (solid color).
Black bars denote summary tasks.

NOTES:

a. 2001 HFP involved the UMass SFMR only and resulted in the data set summarized in Table 1.

b. 2002 winter flights will involve both the SFMR and the IWRAP. A detailed plan for flight hours to test IWRAP and collect precipitation measurements will be made in conjunction with Dr. Paul Chang, representatives of NOAA HRD, and CBLAST collaborators.

c. 2002 HFP will involve both the UMass SFMR and IWRAP instruments.

Web Based Data Archive for the C-Blast Project (A. Zhang)

The goal of this effort is to provide and maintain a central web-based data archive that will allow secure access to the data collected by CBLAST investigators during the remaining 4-year span of this program. We also plan to provide web pages describing the ONR CBLAST program for the general public and scientific communities. The web server will implement access control and allow only CBLAST team members to download/upload data sets from/into the data archive. Two terabyte RAID systems will be used to store CBLAST data.

UMASS has received the first Terabyte RAID system from MegaHaus and been setup at UMass/MIRSL computing lab. The second one will be added in 2003. The web server machine has been ordered from ASL and will arrive in October 2001. For web development, we plan an structure similar to our CPRS (Cloud Profiling Radar System) data archive web site which serves a data volume similar to that to be collected for CBLAST. Our CPRS web site can be found on the web at http://abyss.ecs.umass.edu/cprs-web. To access the data archive section of the web, use the following guest account:

username: guest
password: cprsdata

Professional web interface design for the CBLAST web server has been budgeted and will be carried out by web designer Tom Sweeney at the Engineering Computer Service at University of Massachusetts. A site developed by Tom Sweeney, showing an example of his work, can be found at http://www.ecs.umass.edu/development.

A meeting or conference call will be held to collect user requirements and finalize data formats and other specifications from our various CBLAST partners.

We plan to finish the web site development prior to the 2002 winter storm flights. The data collected during these flights will be archived and served from the UMass CBLAST web site.

We plan to connect the CBLAST web server to the Internet2 backbone at University of Massachusetts. This will allow consistent high speed access to the data archive and avoid internet traffic generated by university students.

Retrospective analysis of UMASS CSCAT/KSCAT high wind ocean backscatter (J. Carswell, P. Black)

The UMass CSCAT, KUSCAT and SFMR were flown on the NOAA N42RF aircraft for the 1999 hurricane research/reconnaissance flights through Hurricanes Brett, Dennis and Floyd. CSCAT and KUSCAT collected NRCS measurements simultaneously at approximately 20, 30, 40 and 50 degrees incidence, while conically scanning at 80 RPM. The SFMR provided wind speed and rain rate estimates at an one hertz. Every eight NRCS scans (6 seconds) were averaged together to reduce fading noise. The SFMR wind speed and rain rate estimates were also averaged over the same period. Fig. 3 illustrates the measurement geometry.

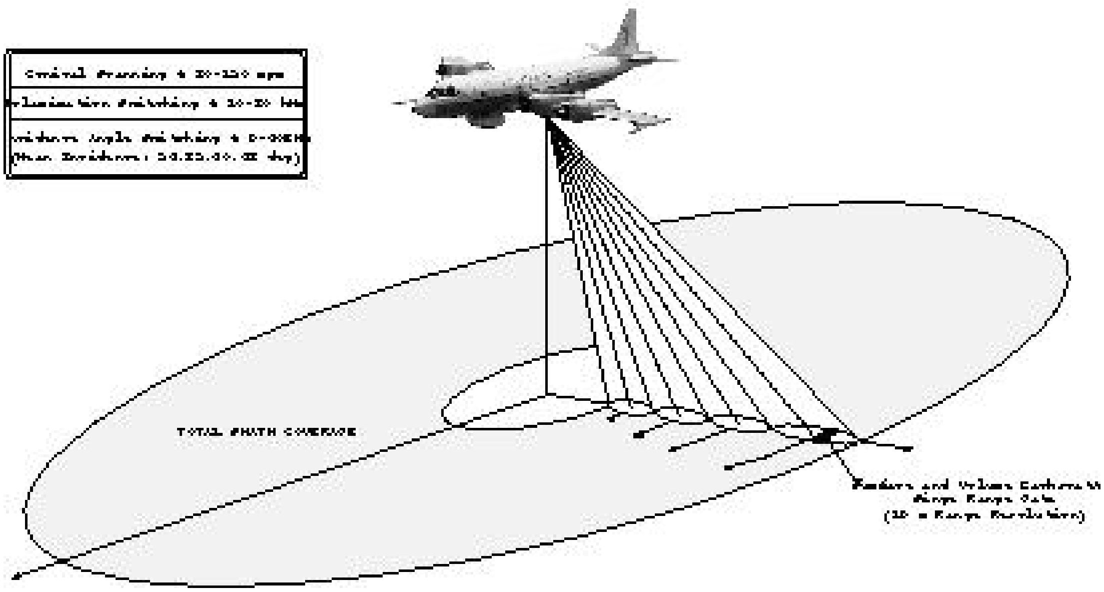

Figure 3. Scatterometer/SFMR observing geometry.

From the averaged NRCS scans, the mean NRCS (A0) at the four angle and two frequencies was calculated and collocated with the averaged SFMR wind speed and rain rate estimates. The mean NRCS measurements were filtered to exclude all events were the rain rate exceeded 3 mm/hr. An atmospheric attenuation correction was applied to the filtered mean NRCS based on the SFMR rain rate, and the corrected mean NRCS measurements were binned into 3 m/s wind speed bins based on the SFMR wind speed estimates and averaged.

Figures 4 and 5 plots the C and Ku-band averaged mean NRCS at 43.5 and 40.9 degrees incidence, respectively, versus the SFMR wind speed. The circles represent the averaged NRCS value for the wind speed bin and the vertical lines show the standard deviation of the measurements within the wind speed bin. Model functions CMOD4, CMOD4HW, NSCAT1 and NSCAT2 are overlaid. CMOD4 under predicts the mean NRCS for winds above 15 m/s. These measurements clearly show a saturation occurring at 45 m/s for CSCAT; above this wind speed the mean NRCS no longer increases. This is consistent with all four angles. Since both the C and Ku-band measurements show a saturation at the same wind speed, surface attenuation due to foam cannot be causing this effect.

We propose that the surface drag coefficient is decreasing at the high wind speeds. This is consistent with the conclusions of Emanuel from the initial budget analysis of the retrospective GPS dropsonde data.

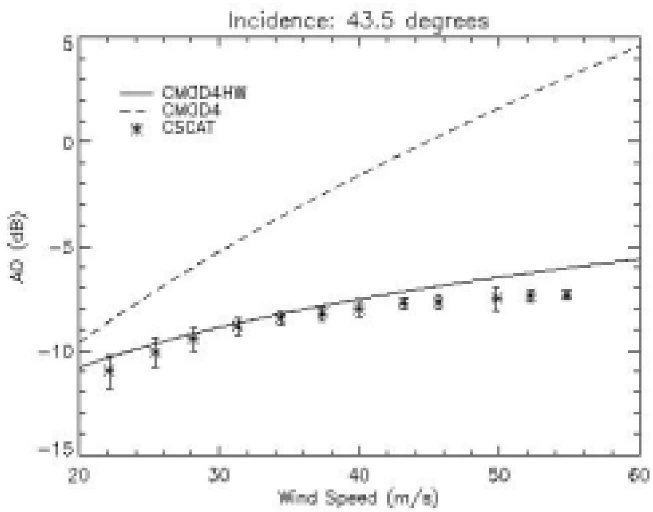

__Figure 4. High wind CSCAT observations from NOAA WP-3D in hurricanes compared with standard (dashed) and high wind ERS2 CSCAT model function.__

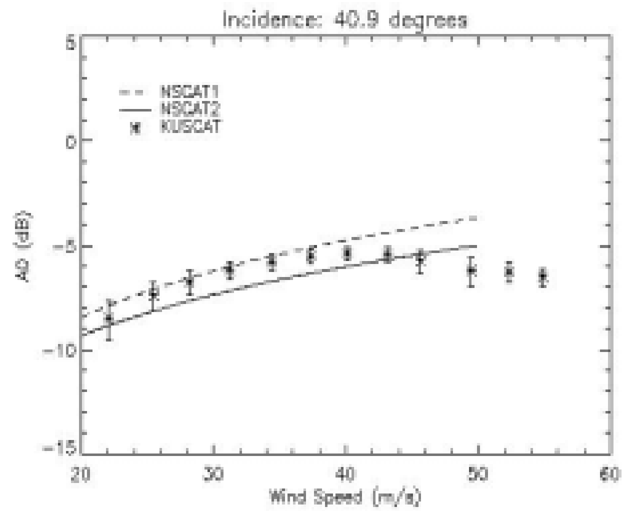

__Figure 5. High wind KSCAT observations from NOAA WP-3D in hurricanes compared with standard (dashed) and high wind K-band Quikscat model function.__

Large-scale surface wind fields (P. Chang)

New Quikscat data files have been made available that contain not only rain flagged data, but images of normalized backscatter fields and all retrieved wind aliases along a Quikscat swath (see P.Chang web page). This will allow storm relative de-aliasing of tropical storm wind fields, resulting in the best fit alias relative to the storm center to be chosen rather than that based on the Aviation global initial analysis, which frequently incorrectly locates the storm center. Collaborating HRD scientists (M. Powell) intend to utilize this new information to assist in objectively analyzing hurricane surface wind fields radialy outward from the gale force wind radius.

Large-scale ocean heat content (G. Goni)

The work being done on this research is to produce estimates of the Hurricane Heat Potential, using a combination of TOPEX/POSEIDON and ERS2 altimeter-derived sea height anomaly and climatological hydrographic data within a two-layer reduced gravity ocean approximation. The hurricane heat potential is a parameter proportional to the integrated vertical temperature between the surface and the 26C isotherm, which is the approximate sea surface temperature needed for a storm to sustain hurricane strength. Specific research objectives are now focused to determine the hurricane heat potential in the Caribbean Sea, Gulf of Mexico and tropical Atlantic, and with special emphasis on warm core rings, the Loop and Florida currents and the Gulf Stream. The close relationship that exists between the dynamic height and the ocean mass field allows these two parameters to be used within a two-layer reduced gravity ocean model to monitor the upper layer thickness, which is defined to go from the sea surface to the depth of the 20C isotherm. Although there are other factors controlling the sea height anomaly, it is assumed here that most of its variability is due to changes in the depth of the main thermocline, and to steric and barotropic effects. The thermal profiles are constructed using near-real time sea surface temperature composites, altimeter-derived upper layer thickness and wind-derived estimates of mixed layer depths. Near-real time sea height anomaly data from three altimeters are provided by NOAA/NESDIS and used to estimate the depth of the 26C isotherm and the hurricane heat potential. Estimates of these parameters are posted daily during hurricane season to help forecasters and researchers on identifying regions of possible hurricane intensification in: http://www.aoml.noaa.gov/phod/cyclone/data/

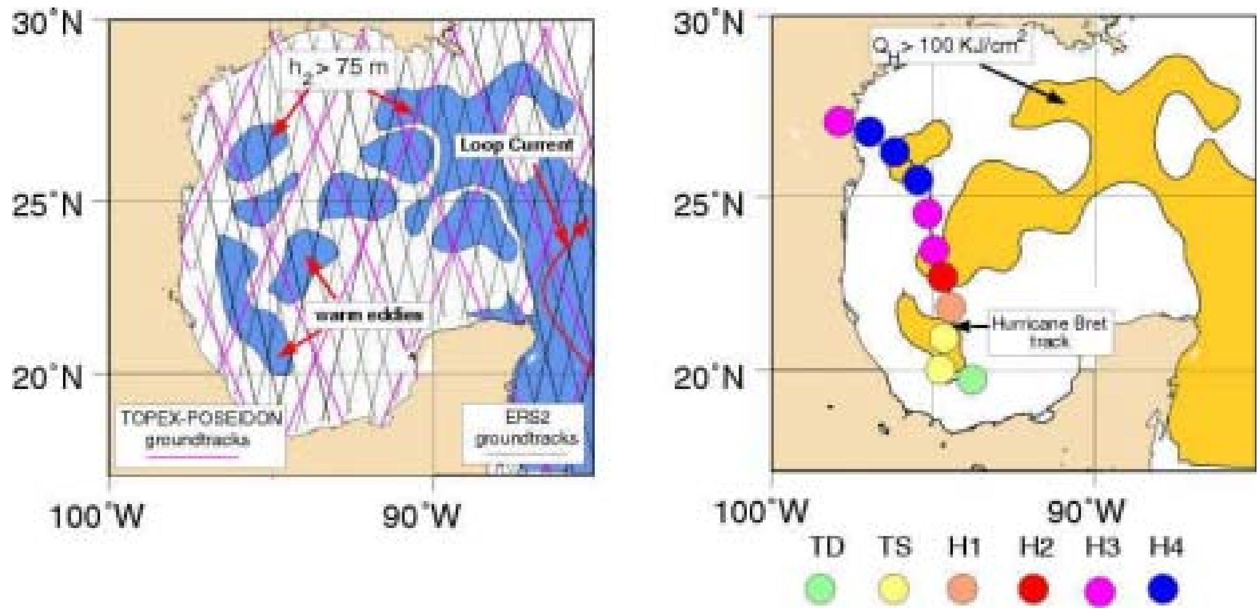

Figure 6. Altimeter-derived upper layer thickness during Hurricane Brett, August 10-18, 1999 (left) with the shaded blue areas indicating values larger than 75 m. The altimeters' ground tracks are superimposed. Altimeter-derived hurricane heat potential during August 10-18, 1999 (right) with the shaded yellow areas indicating values larger than 100 KJ/cm**2. The track of Hurricane Bret, from 00 GMT, Aug 19 to 00 GMT, Aug24, is superimposed with positions every 12 hours. The locations on the track when Bret became a tropical depression (TD), tropical storm (TS), and hurricane (H), with numbers referring to intensity categories on the Saffir-Simpson scale.

Investigations into several hurricanes, such as Opal (1995, Shay, et al., 2000) and Bret (1999), above, have shown a strong correlation between rapid intensification and regions of enhanced ocean heat potential due to warm eddies. In the case of Bret, the storm intensified by 3 categories on the Saffir-Simpson scale during the 36 hours of passage over the high heat potential region in excess of 100 KJ cm^{-2} associated with a warm eddy remnant which broke off from the Loop Current 9 months earlier.

Future work includes the estimates of a mixed layer depth using surface heat fluxes and wind speeds, estimates of the barotropic component of the sea height using simultaneous altimeter and hydrographic observations, sea surface temperature obtained at the Coast Watch Caribbean node at NOAA/AOML, and comparison of results against different model estimates.

Direct flux measurements in hurricanes using BAT probe (T. Crawford and J. French- ARL/ FRD)

The primary objective for FY2001 was to acquire, build and test the instrument package and data system that will be used to obtain measurements of momentum, sensible and latent heat from the aircraft. Initial work focused on purchasing the necessary equipment, including a computer system, data acquisition boards, serial boards, various electronic components for the instruments, and GPS systems. Much of this work was accomplished by early to mid-summer. Work continued on the assembly of various components of the instrument package, including the data system itself, the BAT housing, the Infrared Gas Analyzer (IRGA, for high frequency water vapor measurements) and electronic control circuitry.

With much of the system assembled, testing is beginning as we move into FY2002. We have been working in close coordination with the NOAA Aircraft Operations Center as instrument mounting is the next major hurdle in this project. Critical decisions have been made regarding placement of instruments such as the IRGA, the Everest infrared sea-surface temperature device, and the GPS-attitude antennas. The P3 is currently flying missions as FY2001 winds down. In the coming weeks we will address concerns regarding mounting the BAT on the nose boom and electrically isolating and shielding the front electronics to protect from lightning strikes.

The data system is nearly identical to the one recently re-designed for the LongEZ which proved highly successful in CBLAST-Low during summer 2001. The success with the LongEZ system and current testing of the P3 system leaves us confident that we are ready to mount the system whenever the aircraft comes available, likely spring 2002. This should leave sufficient time for testing purposes before deployment in the 2002 hurricane season.

Direct flux measurements in hurricanes using the Radome-Mounted Gust Probe and LICOR fast response humidity sensor (W. Drennan, UM/ RSMAS)

As part of the Hurricane component of the Coupled Boundary Layers/Air-Sea Transfer (CBLAST) Defense Research Initiative, two NOAA WP-3D aircraft will be instrumented for the measurement of turbulent fluxes. This proposal is aimed at enhancing the flux measurement system currently installed on the WP3Ds to include latent heat (or humidity) flux. Latent heat flux is known to be a key parameter governing the intensity change of hurricanes. However, there is little information regarding its behavior at high winds. Furthermore as pointed out by Emanuel (1995), the high wind speed behavior of latent heat flux that is required for good model performance contradicts current experimental evidence, which is based on data collected at more moderate winds. Hence direct measurements of latent heat flux in the high wind regime are of great importance, with direct application to improved storm intensity forecasting.

The turbulence flux package currently existing on the WP3Ds consists of a gust probe system mounted on the nose radome which, when coupled with a motion package located in the fuselage, is used to derive momentum flux. Here we propose to enhance this system with a fast response humidity sensor (LICOR-7500) which will be mounted in the radome, in close proximity to the gust probes. The LICOR will be modified for aircraft usage, ensuring compatibility with existing onboard systems. This instrument will yield fast response humidity which, when combined with the vertical velocity measured using the gust probe, will allow the latent heat flux to be calculated. We further propose adding a full motion package (BEI) in the radome. This will reduce the errors involved in correcting the gust probe signals for aircraft motion, and hence yield improved flux estimates.

Discussions have been held with WP-3D engineers at NOAA/AOC regarding turbulent flux equipment currently installed on WP-3Ds. Sample flux data from the existing system has been obtained, and assessment of the data quality has begun. Methods of enhancing the existing flux system to include latent heat flux measurements are under way.

Microphysical measurements of sea spray droplet distributions (R. Black, NOAA/HRD in collaboration with C. Fairall, NOAA/ETL, J. Hudson, DRI and J. Lawrence (Univ. Houston)

Most of the droplet spectral measurement work on the WP-3 aircraft in FY01 was focused on the installation and data evaluation from the FSSP probe for small particle sampling and the new NASA HVPS probe (http://www.specinc.com/services.htm) for cloud and precipitation droplet sampling. HRD will be working with C. Fairall during FY02 on the installation of the CIP probe (http://www.dropletmeasurement.com/caps.htm) for measurement of spray droplet spectra (also see collaborations below).

Jim Hudson's CCN counter (DRI, Reno NV.) measured CN, CCN, and the particle volatility from altitudes of 12,000' - 18,000' in FY01. These measurements indicated that outside the eyewall at altitude the CCN/CN ratio was quite high (~ 80%) in relatively clean air, with total CN concentrations of ~200 - 300/cc. In the eye of Humberto, however, the CN concentrations were sharply higher (~ 500 - 800/cc) and the CCN/CN ratio was much smaller, as CCN concentrations remained in the 100 - 200 cc range. The volatility test he did indicated that these particles were NOT sea salt. The CN/CCN counts were about double on the landward side of the storm VS. the seaward side, indicating that the aerosol from the continent was affecting the storm. Preliminary plans for follow on years, contingint on continued NASA funding, are to fly this system in the PBL and test for variations with height in salt concentrations of the aerosols.

Preliminary collaborations with J. Lawrence at University of Houston have taken place and preliminary studies have been undertaken of a new instrument for measurement of salinity content in precipitation liquid water. Initial discussions with AOC engineers have taken place and several locations on the P-3 for possible installation have been investigated.

RESULTS

Black, borrowing on the work of other HRD scientists, F. Marks, S. Feuer and M. Black, has developed and tested a strawman strategy for CBLAST survey patterns by the two NOAA WP-3s for PBL flights to test new instrumentation in FY02 and beyond. **Black** has also devised a strawman plan of stepped descents and ascents in different wind regimes for direct flux and sea spray measurement in the PBL, allowing extrapolation of surface values. The testing of these stepped descent patterns remains a goal for FY02. **Emanuel** has suggested a deployment strategy for GPS dropsondes that would result in optimal estimation of the ratio of surface enthalpy and momentum exchange coefficients. Testing of this strategy is also a goal for FY02.

Black and Uhlhorn, working with other HRD scientists, deployed over 150 pairs of AXBTs and GPS dropsondes in 4 storms during the 2001 hurricane season, a strategy which is planned for CBLAST flights in FY02 and beyond. This allowed bulk variables to be profiled from flight level, typically 3.5 –

4 km, to 300-m depth in the ocean. This strategy allows for concurrent bulk flux estimates as well as defining PBL stability and regions of storm induced ocean surface and mixed layer cooling. Results of these 'combos' indicate that air-sea temperature differences increase with wind speed to approximately gale force and then remain constant at higher winds in the inner core.

A persistent problem with GPS sondes using the conventional differential GPS has been encountered by HRD over the past 3 years. Only 50% of wind data has been retreived in the eyewalls of CAT 3 and above storms due to strong low level wind shear. M. Black of HRD has acquired a number of 'next generation' full up GPS sondes for testing as well as a new receiver and laptop based software. These will be tested in 2002 in an effort to improve reliability in the high wind boundary layer. The new sondes require a longer averaging period and hence coarser vertical resolution.

AXCPs and AXCTDs were not deployed in 2001 by **Shay, Jacob and Black**, but results from the previous two seasons, supported jointly by NSF and NOAA, indicate the profound importance on hurricane intensity change of identifying deep warm pools such as the Loop Current, gulf Stream and warm anticyclonic eddies. A continuous supply of deep warm water is expected to result in different flux profiles, and a different impact on intensity change, than a shallow ocean mixed layer with decreasing heat supply during the coarse of measurement. Additional probes supplied by NSF in 2001 were not used and may be available for use during CBLAST tests in FY02, contingent on continued NSF support.

The AXCP and AXCTD measurements have the potential for greatly complementing the Lagrangian floats being developed by **D'Asaro and Nystuen** and by **Terrill, Melville and Sherman**. D'Asaro proved theability to deploy floats ahead of Hurricane Dennis and retrieved data via Argos that showed and combination of mixing events at the surface and base of the mixed layer together with advection in the middle of the mixed layer. Cycling of the float between the surface and base of the mixed layer at about 20 minute intervals suggested the presence of Langmuir, or roll vortex circulations, within the ocean mixed layer. Advanced float design has been completed and instrumentation added to measure surface winds and rain acoustically as well as wave spectra and salinity (density). This system coupled with the float design of Terrill et al. that will profile the mixed layer every 4-6 hours, should provide a powerful Langrangian tool for diagnosis of mixed layer processes during the passage of a hurricane.

An open issue regarding the float deployment is the means of float deployment and recovery. Initial tests by **D'Asaro** used a private sky-diving aircraft, an approach only viable for storms close to land. The logistics of using AFRS WC-130 aircraft remain to be resolved. The latter would provide flexibility of experimentation on storms far removed from the coastal USA.

Chang has developed a web page to make available in real time all Quikscat aliases plus the field of ocean backscatter for the purpose of independently diagnosing the correct large scale surface wind vector in tropical storms.

Goni has developed and refined a web page for real-time, large-scale ocean heat content depiction over the western north Atlantic, Caribbean Sea and Gulf of Mexico.

Crawford and French have purchased hardware and begun the fabrication stage for development of the BAT probes for measuring turbulent momentum flux as well as latent and sensible heat flux directly from the NOAA WP-3 aircraft. Installation issues have been discussed with engineers at AOC.

Completion of the probes and installation on the aircraft is anticipated prior to the 2002 hurricane season.

Drennan has obtained existing data from the radome-mounted gust probe system on the NOAA WP-3 aircraft and become familiar with the formats. He has discovered that the Lyman- alpha system is no longer supported, leaving a gap in the aircraft ability to obtain independent estimates of water vapor flux. He has discussed the situation with AOC engineeers and developed a plan for replacing the lyman-alpha system with a LICOR system. He has also discussed installation issues and found a suitable location for mounting near the radome pressure ports. A proposal was written and submitted for funding. A decision has not yet been made.

McLaughlin and Zhang, replacing Carswell who accepted a new position in private industry, have tested a new and improved version of the SFMR for surface wind and rain estimation- called the USFMR- during the 2001 hurricane season, showing successful performance except for a minor problem with USFMR radome integrity, a problem that prevented routine real-time wind estimation for NHC, and that will be corrected during FY02. They have also purchased hardware and nearly completed fabrication of a new design for their dual-frequency scatterometer system, CSCAT and KSCAT, to convert it into a dual-frequency, dual-polarization Doppler wind profiling system called Imaging Wind and Rain Airborne Profiler (IWRAP). This will enable the instrument to image (in 3-D) atmospheric boundary layer winds and precipitation, and produce continuous PBL wind profiles along the aircraft flight track.

Zhang has purchased the hardware for a web-based data archive and begun development of the software. The first terabyte RAID system has been set up and a second is on order. This effort will provide and maintain a central web-based data archive and will allow secure access to the data collected by CBLAST investigators during the 5 year span of this program. Completion of the web site and initial testing with aircraft data sets from FY02 winter storms flights is expected by January, 2002.

R. Black worked in conjunction with NASA collaborators and AOC engineers to install and test an improved system for cloud and precipitation particle spectra, the HVPS system, and the FSSP probe for small particle spectra. This will complement The CI system purchased by **Fairall and Asher** for installation on the WP-3 in FY02. **R. Black** also worked with Hudson of DRI on the collection of hurricane aerosol CCN and CN data in 2001 and the formulation of a plan for 2002 to use the system for sea salt aerosol concentration measurements and typing. This would complement a proposed system by Lawrence for a rain water salinity measurement system.

IMPACT/APPLICATIONS

The work of **Black** on flight pattern strategies will define the initial patterns to be flown by NOAA WP-3 aircraft in the initial phase of the project. The work of **Emanuel, Ranstrom and Black** will define the strategy for deploying GPS dropsondes and obtaining vertical profiles of bulk parameters. The work of **Ulhorn and Black** on retrospective flux calculations will serve as a baseline for new flux estimates to be obtained from CBLAST flights.

The deployment of AXBT and GPS sonde pairs, or ‘combos’, by **Black and Uhlhorn** allows air-sea stability to be stratified by radius and storm quadrant, identifying regions of storm-induced cooling and allowing flux measurements to be placed in proper context.

The significance of using the next generation GPS sondes would be to improve reliability and accuracy of PBL wind profiles in the eyewalls of strong storms. The new sondes are also 25% more expensive than the present differential sondes.

The impact of the AXCP and AXCTD expendable probe deployments of **Shay, Jacob and Black** is to provide a Eulerian grid of ocean current and density observations for assessment of ocean mixing and heat potential before, during and after hurricane passage. The lagrangian float measurements of **D'Asaro and Nystuen** and **Terrill, Melville and Sherman** directly measure the mixing events and ocean profiles continuously over time during storm passage, but at varying distances from the storm center, as well as surface winds and waves. The two approaches offer a powerful tool for diagnosing important ocean mixed layer processes taking place at the same time as atmospheric turbulence measurements, airborne wave measurements of **Walsh and Wright,** wave breaking measurements of **Melville and Terrill** and sea spray measurements of **Fairall and Asher**, together with **R. Black**.

The impact of the web-based data archive by **Zhang** will be to provide a central site for easy archive and retrieval of CBLAST data sets by all CBLAST PIs in near real time. It will also provide for a central Hurricane CBLAST web site for Pis to use in describing initial results of their studies.

The significance of **Chang's** development for large scale surface wind assessment is to make available the observations necessary for the development of a wind de-aliasing scheme of specific use in tropical cyclones, eliminating bad alias selection by the global algorithm in general use. This task is being considered for development as part of HRDs objective surface wind analysis program.

The significance of **Goni'**s heat potential web page is to provide large scale fields to guide in the observational strategy and placement of expendable probes for optimal estimation of changing ocean heat content within the tropical cylone inner core.

The impact of the development of turbulence sensors mounted on the NOAA WP-3 nose boom by **Crawford and French** and turbulence sensors mounted on and near the aircraft nose radar by **Drennan** is to provide a unique capability to make two independent measurements of turbulent fluxes in the high wind region of a hurricane for the first time ever. If successful, this will be a landmark development and provide the pivotal data for relating in-situ fluxes to bulk surface parameters. This in turn will lead to improved parameterizations of surface fluxes for use in numerical models.

The impact of the nearly-completed IWRAP system by **McLaughlin and Zhang** will be significant in its ability to provide continuous wind and rain profiles along the flight track extending to the surface. It will enable the flux measurements and GPS sonde observations of wind and thermodynamics at discrete points along the flight track to be placed in the context of strong gradients, especially in the eyewall. The system will provide truly vertical profiles rather than slant-wise profiles provided by the GPS sondes as they are advected by the strong winds. In concert with the USFMR, this system will allow complete mapping of hurricane surface winds for co-location with surface wave spectra measured by **Terrill's** laser altimeter and **Walsh and Wright's** SRA. These instruments will also providethe bulk variables for comparison with in-situ turbulence measuements of **Crawford and French** and **Drennan** as well as the sea spray measurements of **Fairall and Asher** working together with **R. Black.**

The impact of **R. Black's** work with Hudson and possibly Lawrence is to develop systems that would unequivically identify small particles measured by Fairall and Asher as truly sea spray particles, differentiating them from fresh rain water.

TRANSITIONS

This work is serving to prepare for initial instrument testing and installation as well as flight pattern testing in the second hurricane CBLAST year next summer.

RELATED PROJECTS

An Observational and Modeling Study of Air-Sea Fluxes at Very High Wind Speeds (K. Emanuel and W. Ranstrom, MIT and P. Black, HRD)

Hurricane Wave Topography and Directional Wave Spectra in Near Real-Time- a collaborative NOAA/HRD – NASA/WFF effort (E. Walsh and W. Wright, NASA/WFF)

Air-Sea Coupling Mechanisms In Tropical Cyclones- a collaborative effort funded by NOAA and NSF (L. Shay and D. Jacob, UM/RSMAS, P. Black, NOAA/HRD)

Measurement of the Sea Spray Droplet Size Distributions at High Winds (C. Fairall, NOAA/ETL; W. Asher, UW/APL)

Lagrangian Float Deployments into the Ocean Beneath a Hurricane (E. D'Asaro and J. Nystuen, UW/APL)

Autonomous Profiler Measurements of the Air-Sea Interface in Very High Sea States (E. Terrill, W. K. Melville, J. Sherman SIO)

Whitecaps and wave-breaking in high winds (W. K. Melville and E. Terrill, SIO)

SUMMARY

For 2002, HRD has been allocated 35 flight hours for research by NOAA/OAR. However, NESDIS/ORA has purchased 70 flight hours for microwave remote sensing algorithm development (Chang) as well as satellite scatterometer intercomparisons in hurricanes (and 70 more hours for high winds in winter storms). These hours are expected to provide enough flying time in hurricanes to conduct the instrument testing for CBLAST.

Major progress has begun on achieving CBLAST high wind objectives. Flight patterns have been designed and tested and studies completed suggesting expendable sonde deployment strategies. Additional flight pattern testing is needed for the PBL turbulence and sea spray measurements. These will be refined in the insuing months as an implementation plan is developed. Hardware has been purchased and fabrication is ongoing for the IWRAP continuous wind profiling system and the BAT turbulence probe. The radome gust probe system is undergoing evaluation and a proposal to augment the system with water vapor flux capability is awaiting a decision. Computer equipment for the web-based archival system has been received and software development has begun. Testing of IWRAP and the web based archival system is planned for the 2002 winter storms flight program.

Initial indications from several studies are that the surface drag coefficient does not continue to increase with wind speed above about 30 m/s. It appears that sea spray plays an important role in enthalpy flux into the hurricane PBL. The role of surface swell and PBL secondary circulations appears important as well for surface fluxes. It is increasingly clear that current hurricane numerical models use a surface flux parameterization that is at odds with recent observations.

It appears important to continue to monitor water mass changes beneath moving hurricanes to place the planned new observations of surface fluxes into proper context. A sufficient supply of AXBTs for monitoring thermal structure is on hand. However, NSF support for AXCP and AXCTD expendable probes exists only for the coming season. Substantial progress has been made on the development of subsurface floats for monitoring ocean thermal and current profiles and turbulent mixing in a lagrangian framework.

REFERENCES

None

PUBLICATIONS

None

PATENTS

None