4.3 AIR-SEA INTERACTION PROCESSES RELEVANT TO TROPICAL CYCLONE INTENSITY CHANGE

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1. INTRODUCTION

It is an important international priority to improve the forecasts of surface windfield, intensity, structure and storm surge in landfalling Tropical Cyclones (TCs) in order to successfully mitigate the detrimental physical impacts associated with these storms. Coastal population growth in the U.S. of 4-5% per year, is outpacing the historic 1-2% per year rate of improvement in official hurricane track predictions. While specific track prediction models have indicated a 15-20% improvement over the past 2-3 years, very little skill has been shown in the prediction of intensity change or windfield distribution(Neumann et al. 1997). For this reason, the average length of coastline warned per storm, about 570 km, has not changed much over the past decade, nor has the average overwarning percentage, about 75%. However, the average preparation costs have increased eight-fold in the past 7 years from $50M per storm in 1989 (Sheets 1990) to an estimated $300M per storm in 1996, or about $1M per mile of coastline warned (Jarrell et al 1992; Neumann et al 1997). The increasing potential for severe loss of life as coastal populations soar, and potential monetary losses of tens of billions of dollars requires that greater effort be directed to understanding all physical processes which play an important role in modulating hurricane windfields and storm surge at landfall.

A major source of difficulty in past efforts to predict hurricane intensity, windfields and storm surge at landfall has been the inability to measure the surface windfield directly and the inability to predict how it changes in response to external and internal forcing.The surface windfield must presently be estimated from a synthesis of scattered surface ship and/or buoy observations and aircraft measurements at 1.5 km to 3.0 km altitude (Powell 1980; Powell et al. 1996;Powell and Houston 1996). This task is complicated by variations with height of the storm's structure, such as the change with height of storm-relative flow due to environmental wind shear and to the variable outward tilt of the wind maximum with height.

2. BACKGROUND

We suggest that changes in the TC intensity and windfield will be brought about by (1) changes in the large-scale environmental conditions, (2) changes in the underlying boundary and/or (3) naturally-evolving internal dynamics. In this paper, we focus discussion on 2) above. One factor affecting hurricanes at landfall is the impact of upper ocean features offshore from the U. S. coastline and the degree to which they modulate TC-induced cooling of the upper ocean mixed layer. Direct linkages between TC intensity change and observed air-sea changes have been difficult to make due to the multiplicity of factors, above. In addition, detailed oceanographic and surrounding environmental observations in the atmosphere have been generally lacking from which to make comparisons. Innovative use of new observing technologies, mixing mobile observing in-situ platforms, such as drifting buoy arrays and airborne instrumentation, with new satellite observing platforms, are enabling critical features of air-sea and environmental interactions to be measured for the first time.

As TCs approach the U. S. mainland they often encounter warm ocean features such as the Gulf Stream, Florida Current, Gulf Loop Current and Gulf of Mexico warm eddies. Several cases suggesting a strong role of air-sea interaction processes on TC intensity changes have occurred in recent years, many of which have been landfalling situations. One especially significant case was Hurricane Andrew (1992), which gained strength as it passed over the Gulf Stream just before landfall on South Florida (Willoughby and Black, 1996).

Elsewhere in this volume, Shay, et al (1998) describe an innovative use of basin-wide climatology and TOPEX/Poseidon satellite measurements of geoid anomalies to observe these features, which are deep reservoirs of heat and moisture available to significantly intensify landfalling TCs, such as appeared to occur in Hurricane Opal (1995). Cold oceanic features along the shelf zone may also be encountered by TCs just before landfall which may act as an energy sink and weaken the storms just before landfall. Xie et al(1998) make innovative use of NOAA polar orbiting AVHRR satellite imagery to observe this situation in the case of Hurricane Fran,1996.

The interpretation of a TC's intensity change as it approaches landfall is frequently complicated by trough interaction and oceanic structure change occurring simultaneously. Elsewhere in this volume, Bosart, et al (1998) describe an innovative use of GOES-8 high density water vapor winds to observe an approaching trough interact with Hurricane Opal.

3. THE RECORD HURRICANE SEASONS OF 1995-96

In over half of the 32 storms that occurred during the 1995 and 1996 hurricane seasons, significant intensity changes were associated with storm translation over SST boundaries, which were either pre-existing or created by previous storms. Many of these storms also experienced interactions with mid-latitude troughs during the same time period and has made it difficult to partition the physical processes responsible for the observed intensity changes. This section seeks

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to suggest a link, in selected storms, between changes in air-sea interaction processes and observed intensity changes.

In order to obtain some insight into this process, 10 cases were identified as 1) undergoing significant changes in air-sea fluxes due to changes in the SST field over which they moved and 2) having observations available to document a) the intensity change and b) the SST change. In 1995, these were Felix, Luis, Marilyn, Opal and Roxanne. In 1996, these were Bertha, Edouard, Hortense, Fran and Josephine.

Mobile drifting buoy arrays, provided by the National Data Buoy Center (NDBC) and described in The National Drifting Buoy Deployment Plan (Office of the Federal Coordinator, Silver Spring, MD), were deployed to adaptively sample 3 of these cases of suspected strong ocean interaction: Luis and Marilyn in 1995 and Fran in 1996. An array of 3 Wind Speed/ Direction (WSD) buoys and 7 CMOD mini-drifting buoys were deployed by WC-130 Air Force Reserve (AFRES) aircraft 550 km ahead of Hurricane Luis. The deployment was repeated in the same area for Marilyn 10 days later where a mix of 3 WSD's and 8 CMOD's were deployed. An additional deployment of 35 AXBT's and 3 CMOD's was conducted from a NOAA WP-3D as Marilyn passed over the pre-storm array, providing an unprecedented array of 16 working buoy platforms from which detailed surface wind, pressure, SST and ocean mixed layer depth fields were constructed. The buoy data, together with AVHRR images and FNMOC SST anomaly charts, showed a 4C decrease in SST's, resulting from Luis, which itself subsequently weakened as it uncovered the cold wake left by Felix one week earlier. Marilyn subsequently crossed Luis' wake at the time convection and attendant surface winds weakened, while at the same time, further enhancing the SST cooling created by Luis and Felix.

In 1995, two storms became quasi-stationary for several days: Felix, offshore from the Gulf Stream, and Roxanne, in the Bay of Campeche. Felix and Roxanne executed slow loops in their respective regions over several days generating SST changes on the order of 3-4°C. This created deep, cold SST pools due to sustained intense upward mixing of subsurface water. Both storms subsequently weakened as convective cloud development declined dramatically.

In 1996, 3 WSD's were deployed 300 km ahead of Fran, just seaward of the Gulf Stream, and adjacent to an offshore NDBC moored buoy. Together these data provided enhanced surface wind and pressure fields.Together with AVHRR images, these data also showed that Fran created a well-defined 2°C cold wake which was interrupted by passage over the Gulf Stream. Fran deepened after emerging from the cold wake created by Edouard five days earlier and then weakened as it approached the warm Gulf Stream. This corresponded to the advection toward the storm's inner core of cool, dry air, associated with a deep mid-latitude trough. In addition, winds ahead of the storm uncovered and amplified a cold shelf eddy on the shoreward side of the 'Charleston Bump' (Xie et al., 1998). A 5°C SST decrease resulted there which may have also played a role in the storm's weakening. This behavior contrasted markedly with the behavior of Hurricanes Andrew (1992), Jerry (1995) and Bertha (1996), which all intensified just before landfall as they moved over the Gulf Stream.

Also in 1996, Hortense deepened after crossing the cold wake left by Fran ten days earlier. Hortense crossed then paralleled the wake left by Edouard two weeks earlier. After uncovering the cold water in the wake just below the surface, Hortense weakened.

It is our conviction that complex air-sea interactions such as those that occurred during the 1995 and 1996 seasons need to be better understood through improved observational efforts if the hurricane intensity change problem is ever to be understood. Better observations are required of pre-existing ocean feature structure, ocean response to hurricanes, subsequent cold wake evolution and impact on following storms and air-sea flux processes in the hurricane boundary layer. A first step in this direction was taken during the 1997 season in Hurricanes Guillermo (EPAC) and Erika (Atlantic) where new GPS dropsondes were first deployed in quantity within the storms' inner core and subsequently deployed in conjunction with AXBT's. In this way, both atmospheric and oceanic boundary/mixed layer structure were simultaneously measured.

4. HURRICANE OPAL

Hurricane Opal represented the classic dilemma to forecasters in attempting to assess TC intensity change. An upper trough was approaching Opal as it entered the warm Gulf of Mexico. This is illustrated schematically in Fig. 1. The question was how would the trough effect intensity change and how would air-sea interaction effects modulate this interaction. Even in hindsight, this is a difficult question to answer.

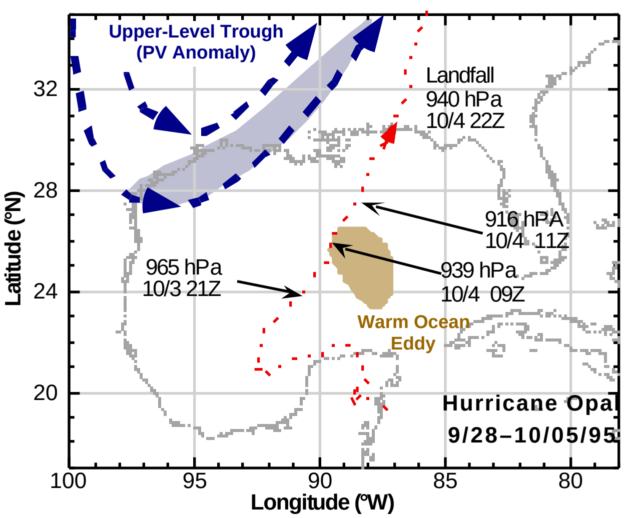

Figure 1. Schematic showing upper trough and jetstreak positions (dashed streamlines and elongated shading, respectively) relative to Opal about 1200 GMT, 3 October, 1995. Opal's track (dotted line) and approximate eddy location (oval-shaped shading) based on Topex/Poseidon are also shown.

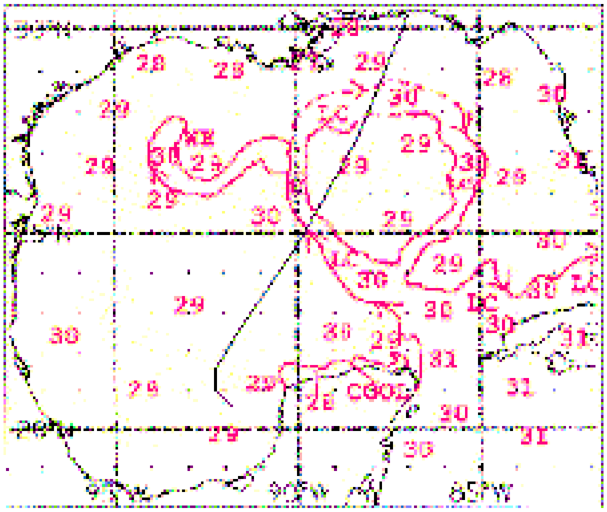

Figure 2. Ocean feature analysis for 26 September, 1995 showing spot SST values (°C) and Loop Current/eddy complex in central Gulf.

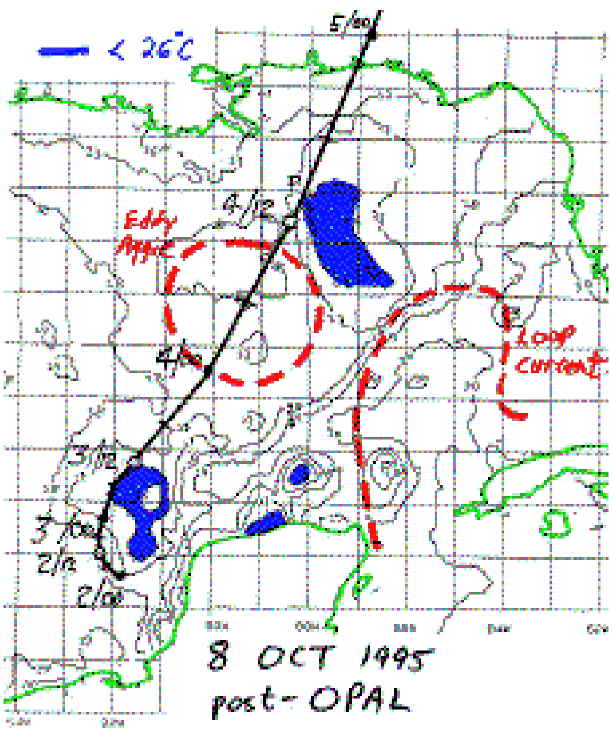

Figure 3. SST analysis (°C) for 8 October, 1995. Shading is for SST<26°C. Dashed lines show estimated Loop Current and Eddy Aggie locations. Solid line is Opal's track with closed circles for 00 GMT positions, open circles for 12 GMT locations and tics for 6-hourly positions.

However, Bosart, et al (1998) produce a convincing argument, using high-density water vapor winds to analyze the details of the upper troposphere interaction, to show that a jet streak associated with the trough produced and enhancement of the divergence over the storm just before rapid deepening commenced near 1800 GMT, 3 October. The work of Shay, et al (1998) show that just after this time, the storm passed over a warm Gulf of Mexico eddy, dubbed "Eddy Aggie" by oceanographers. Using sea surface height anomalies from TOPEX/Poseidon measurements and an innovative new technique to infer mixed layer depth, they calculate the change in ocean mixed layer heat potential. Their results show a large change in mixed layer heat content and contend that the fluxes into Opal had to be enhanced during its passage over the eddy.

This feature was well known to oceanographers, who had been following its pinching-off process from the Loop Current since late Spring using the TOPEX data and AVHRR polar-orbiting satellite data. But the feature was largely unknown to hurricane forecasters since it did not appear in summertime SST analyses. Only in an ocean feature analysis (courtesy Jennifer Clark, formerly NESDIS), was the LOOP Current/Eddy Aggie complex discerned prior to Opal's passage over the Gulf. Shown in Fig. 2, this analysis represents features faintly visible in AVHRR images from 26 September, one week prior to Opal's passage over the eddy. This product was discontinued by NOAA at the end of September.

An SST analysis performed at NHC (courtesy Mike Hopkins) on October 8, 4 days after Opal's eddy passage, shows (Fig. 3) the pattern of cooling caused by the storm off the Yucatan coast, southwest of the eddy and around the northeast perimeter of the eddy. The Loop Current and eddy locations in Fig 3 were estimated from a combination of the TOPEX data and an interpolation between Fig. 2 and the first images of the eddy/Loop Current complex in late November (Fig. 4). Note, from the analysis that no significant surface cooling occurred in the area of the eddy. Yet, the analysis of Shay et al (1998) show that a large change in the ocean upper layer heat content took place. Therefore, large fluxes of heat and moisture had to occur as the storm passed over this eddy. This evidence shows that a deep reservoir of warm ocean water can supply almost infinite amounts of heat energy without themselves being depleted.

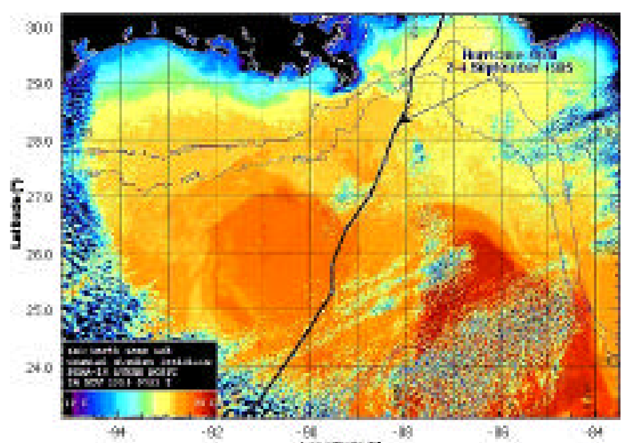

Figure 4. AVHRR image of Eddy Aggie courtesy of LSU Coastal Studies Institute, Earth Scan Laboratory for 26 November, 1995. Opal's position at 3-h intervals are shown by open circles.

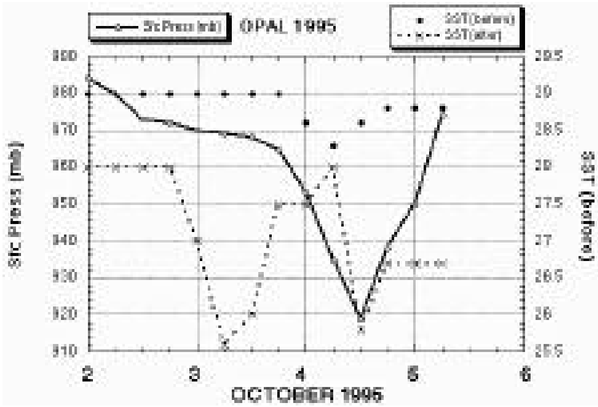

Figure 5. Time series of minimum surface pressure, together with SST along Opal's track before (September 26) and after (October 8) storm passage.

Fig 5 together with Fig 3 show that the storm center moves into the eddy just after rapid deepening has commenced, most likely triggered by the enhanced trough-induced upper divergence. By 1200 GMT, 4 October, the troughªenhanced divergence is gone, but the rapid deepening still continues because of the enhanced surface fluxes over the eddy. The fluxes are immediately cut off as the storm exits the eddy by 1200 GMT, 4 October and moves into the stormªcooled water. Convection quickly dies out and rapid filling commences.

One is tempted to conclude, that given the proper observations, this type of intensity change scenario could be diagnosed ahead of time. However, one other factor to be noted based on analysis of SSM/I 85-GHz images, is that a concentric eyewall cycle was occurring, apparently triggered by the trough interaction (Willoughby and Black, 1996; Willoughby et al 1982) such that the inner eye had shrunk to the point of dissipation by 1300 GMT, 4 October, just as the cold water effect might have resulted in filling. Perhaps the cold SSTs prevented a further contraction of the outer concentric ring of convection and limited any subsequent deepening prior to landfall. Certainly, the issue of the relative role on intensity change of trough interaction, air-sea interaction and internal dynamics deserves considerable further research through enhanced observational efforts.

5. HURRICANE COLD WAKE PRODUCTION AND STORM ASYMMETRIC STRUCTURE

The extent and magnitude of the cold SST region produced by hurricanes has been shown (Black, 1983; Black and Shay, 1995) to be a crescent-shaped region with maximum SST decrease located in the right-rear quadrant. Maximum cooling ranges from 1.5-6°C, depending on the speed of motion of the storm and the underlying mixed layer structure. The radial extent of maximum cooling was shown to range from the radius of maximum winds outward to 2.5 times the radius of maximum winds (R_{max}). The pattern is a consequence and mixing, upwelling and horizontal advection, with strongest cooling in the right-rear quadrant a consequence of combined upwelling and mixing processes. Beyond 2.5 R_{max}, the pattern is modulated by internal inertia-gravity waves. These conclusions were based on hundreds of AXBT observations in dozens of storms over a 20-year period from 1971 to 1991.

Of relevance to the present discussion is the inference that the cooling pattern can be strongly modulated by pre-existing oceanic features. The extent of this modulation depends on the oceanic structure of the feature and the speed of the storm.

In the case of Opal's passage over Eddy Aggie and the Loop Current, its forward speed accelerated from nearly stationary on 2 October to over 10 m s^{-1} by landfall on 4 October. The effect of the eddy on the storm and vice versa can be quite different for slow moving storms passing over the center of the eddy and for storms passing to the left and right of the eddy.

A summary of these differences is shown in Fig. 6, based on case studies in Black (1983) and in Shay, et al., 1992 for Hurricanes Anita (1976), Allen (1980) and Gilbert (1988). This schematic (Panel A, Fig 6) shows that a slow moving storm may in fact extract all of the available heat potential above 26°C from the mixed layer within an eddy and through the upwelling process bring cold sub-thermocline water to the surface, weakening the eddy circulation by also weakening subsurface horizontal temperature gradients at the edge of the eddy, as was the case for Hurricane Anita. A faster moving storm (panel B), such as Opal, may not be able to cool the eddy at all, but simply extracts enhanced heat and moisture from the eddy, while cooling the perimeter of the eddy dominated by shallower mixed layers.

However, a storm moving near average speeds of 5 m s^{-1} passing to the left of a warm eddy (Panel C) may generate strong cooling along the eddy boundary as a result of complex interactions of storm-generated currents and the eddy currents acting in opposite directions. Such a case was observed for Hurricane Allen and later documented in Hurricane Gilbert with AXCPs (Shay, et al 1992). Finally, a storm moving to the right of a warm eddy (Panel D) may generate only weak cooling at the eddy periphery.

Therefore, a range of possible effects on storm intensity may result from passage over a pre-existing warm eddy such as Eddy Aggie in the Opal case. The fact that it moved rapidly over the center of the eddy suggested that while cooling of the eddy perimeter took place due to strong mixing, that the deeper mixed layers and shorter period of strong mixing allowed Opal to extract energy from the eddy without changing its structure, as shown by Shay, et al (1998). However, other cases such as Anita, Allen and Gilbert produced different scenarios.

Given the four different possible ocean response scenarios discussed above, another factor affecting storm intensity is how the atmospheric PBL asymmetric structure is arranged. Historically, one is lead to expect the strongest convection and highest surface winds to be located in the right-front quadrant of the storm, with maximum inflow and vertical motion in the right-rear quadrant. Aircraft observations over the last 20 years have shown that this is not always the case. Detailed

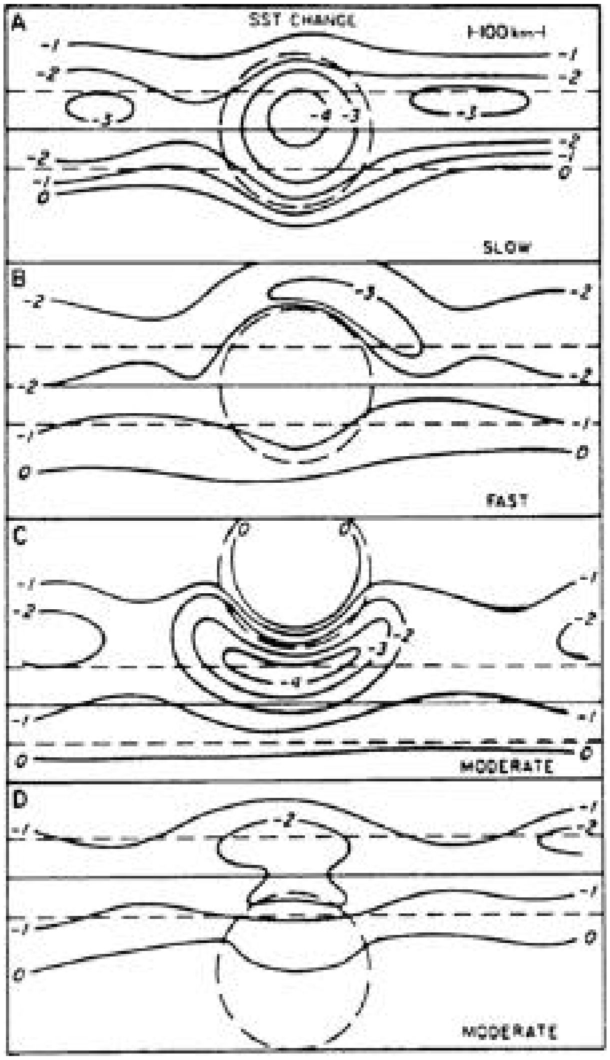

Figure 6. Schematic of SST change (°C) induced by a tropical cyclone moving across an oceanic warm eddy for a) fast-moving storm, U>7 m s^{-1}, b) slow moving storm, U< 3 m s^{-1}, c) moderate-moving storm, 3<U< 7 m s^{-1}, moving to the left of the eddy and d) moderate-moving storm, 3<U< 7 m s^{-1}, moving to the right of the eddy. Parallel dashed lines are the radius of maximum wind. Circular dashed line in the eddy perimeter.

airborne Doppler radar studies have shown that variations in the environmental vertical shear may cause considerable variability of the location of the strongest convection, maximum winds and quadrant of strongest inflow and vertical motion.

For instance, along track shear such as observed in Hurricanes Norbert (1984) in the eastern Pacific, Celia (1973) in the Gulf of Mexico and Emily (1994) off the North Carolina coast, produce surface wind maxima in the left quadrant of the storm with maximum inflow and vertical motion in the left-front quadrant. These variations can lead the inflowing air to acquire different properties due to fluxes from the surface. If the inflowing air to the eyewall first passes over the cold wake produced by the storm, it may not be sufficiently buoyant to support eyewall convection. If, on the other hand, the strongest inflowing air at the surface bypasses the cold wake and travels unaffected all the way to the eyewall, much more vigorous inner core convection might be expected.

The capability to measure the storm scale asymmetries and the environmental vertical wind shear may thus play an important role in understanding intensity changes due to air-sea interaction processes. Such a capability is now at had with the advent of the NOAA G-IVSP aircraft. With the advent of the aerosonde program (Greg Holland, personal communication). this capability may soon exist operationally on a world-wide basis.

6. AIR-SEA TEMPERATURE DIFFERENCES AND HIGH WIND BOUNDARY LAYER STRUCTURE

Yet another wrinkle in the understanding of tropical cyclone (TC) intensity change due to air-sea interaction processes is the recent observations from moored buoys during the passage of TCs. This topic is also discussed in Cione and Black, 1998. Observations first discussed by Black, Holland and Pudov (1993) from moored NDBC buoys in the Gulf o f Mexico and the U.S. East Coast and from an oceanographic research ship in the South China Sea showed that the sea minus air temperature difference as a function of wind speed in TC's was not a constant 1°C or less, as historically accepted, but increased to as much as 5°C for winds above hurricane force, i.e. 32 m s^{-1}. This implies that adiabatic cooling which occurs as surface air parcels spiral inward toward lower pressure in the hurricanes' inner core is not balanced by heat flux from the sea, as previously thought.

Holland (1997) has indicated that these results may raise estimates of the Maximum Potential Intensity (MPI) for tropical cyclones by as much as 40 mb for strong storms with estimated MPI of 890 mb. Gray (1995) has indicated that the lower theta-e values implied by a 4°C sea minus air temperature difference and assumptions of relative humidities near 90 %, is in agreement with theta-e values calculated from the Shea and Gray aircraft radial leg data set. This leads to the conclusion of higher MPI values than previously estimated, in agreement with Holland (1997).

Additional observations concerning this issue from two new data sources are now available. The previously reported moored NDBC buoy measurements during hurricane passage in the Gulf of Mexico and off the Atlantic U. S. East Coast south of the Gulf Stream are shown in Fig 1 together with a best fit polynomial regression curve. As mentioned, these results have confirmed earlier measurements made in two typhoons by Pudov (Pudov and Petrichenko, 1988; Korolev, et al., 1990; Pudov and Holland, 1997) from research ships in the South China sea.

In Hurricane Erika (1997) GPS dropsondes were dropped for the first time concurrently with AXBTs, enabling direct measurements of 10-m level air-sea temperature differences to be measured in the hurricane inner core and eyewall region independently of a buoy platform. These points are plotted on Fig. 7 and show excellent agreement with the buoy data.

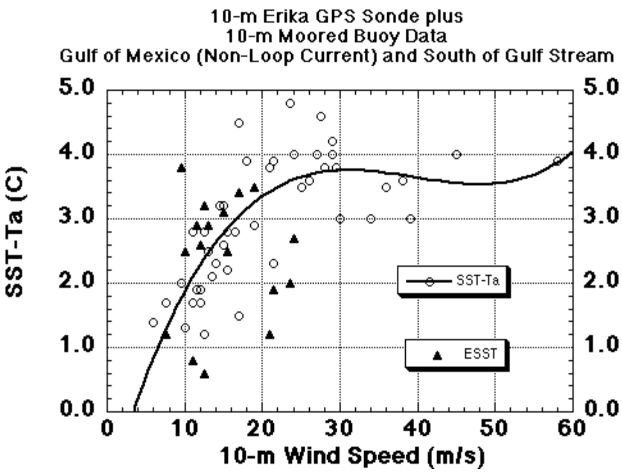

Fig. 7. Scatter plot and regression curve for moored buoy observations at the 10-m level in hurricanes in the Gulf of Mexico outside the deep, warm Loop Current and from buoys off the U. S. East Coast south of the Gulf Stream. Superimposed on the moored buoy data (circles) are the GPS dropsonde and AXBT data from Hurricane Erika, 1997 (triangles).

Further confirming this relationship are observations from nearly 12 drifting buoys air-deployed ahead of Hurricanes Luis and Marilyn in 1995 and Fran in 1996. Fig 8 shows the relationship between 1-m level measurements of air-sea temperature difference as a function of estimated 10-m wind (from 1-m anemometer measurements). One sees the same increase of air-sea temperature difference with wind speed as in Fig 1, except commencing at a higher wind, a result which may be due to the assumptions inherent in the Liu boundary layer model used for extrapolation. Interpretation of these observations is now much more promising with the successful deployment of the new GPS dropsonde with reliable wind, temperature, humidity and pressure measurements every one-half second to within less than 10 m of the surface. Innovative, successful

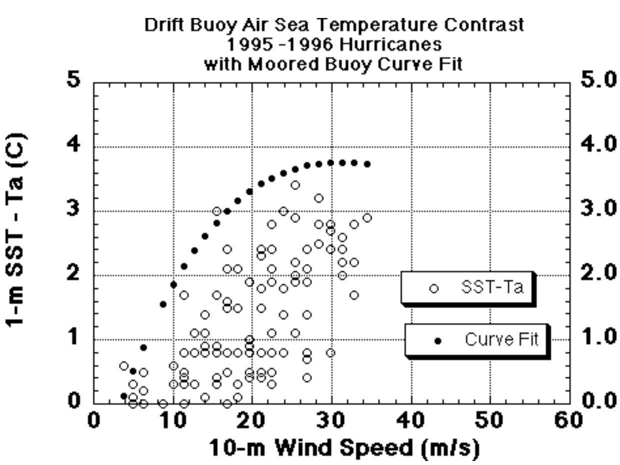

Fig 8. Scatter plot of observations at the 1-m level from drifting buoys in Hurricanes Luis and Marilyn in 1995 and Fran in 1996. Regression curve from Fig 7 is superimposed.

deployments of these sondes were made for the first time NOAA WP-3D and G-IV aircraft in the inner core of EPAC Hurricane Guillermo (1997) by James Franklin and Michael Black or HRD. Additional deployments were made on 3 days in Hurricane Erika.

Preliminary analysis of a few of the eyewall soundings have revealed several new and unusual boundary layer structures. Shown schematically in Fig. 9a, three eyewall soundings indicate low-level wind maxima below 100 m. Fig 9b illustrates the consistency among the three soundings of these features in vertical profiles of dry static energy, specific humidity and wind speed. They show elevated specific humidity in a thin layer below the wind maxima. Nearly all high wind soundings show this feature. Most eyewall soundings also showed a deeper layer of constant theta, or dry static energy. Many soundings show a second wind maximum above this layer near 1200 m. These wind observations are consistent with Australian tower observations in the inner, high-wind core of tropical cyclones first reported by Wilson (1979) and recently discussed by Kepert and Holland (1997). These data showed a low level wind maximum consistently at the 60-m level, as well as a wind maximum near the to of the 400-m tower.

The observation of a thin layer of elevated specific humidity in the high wind region beneath the eyewall is very suggestive of a spray layer which may enhance evaporation in the >90% relative humidity air. The existence of a wind maximum above this layer indicates that upward vapor fluxes in the boundary layer may be controlled more by shear-induced turbulence at the top of the high specific humidity layer than by direct flux from the sea. Sea spray processes such as discussed by Fairall, et al {1994) may become important. Additional analysis of this revolutionary new data source should lead to profound new insights into the workings of the hurricane eyewall boundary layer.

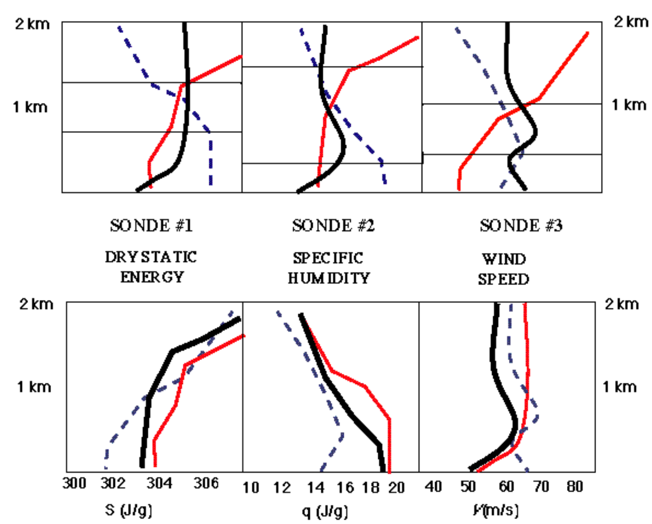

Fig. 9. GPS dropsonde profiles of dry static energy, mixing ratio and wind speed for the north eyewall of Hurricane Guillermo arranged by sounding (a) and by parameter (b).

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