P1.29 SURFACE THERMODYNAMIC OBSERVATIONS WITHIN THE TROPICAL CYCLONE INNER CORE

Joseph J. Cione* and Peter G. Black
NOAA/AOML/Hurricane Research Division
Miami, FL

1. INTRODUCTION

Up until very recently observations of the tropical cyclone (TC) boundary layer, especially within the inner core high wind regime, have been very rare. The lack of data within the TC boundary layer has forced theoreticians and TC modelers alike to make several assumptions regarding the thermodynamic structure of the low level TC inner core, including the critically important air-sea interface, where ocean-atmosphere exchanges of momentum, heat and moisture occur. Despite the lack of observations, it has been accepted as conventional wisdom by many that differences between surface air temperature (SAT) and sea surface temperature (SST) within the TC environment are relatively small (i.e. SST-SAT ~ 0-1°K) and do not vary much as a function of radial distance from the TC center (WMO, 1995; ONR, 1987; Hawkins and Imbembo, 1976; Miller, 1958). That is, any adiabatic or diabatic induced surface cooling experienced by the air parcel as it flows radially inward is effectively balanced by heat transfer from the sea and/or downward vertical mixing of relatively warm air above the surface (Frank, 1984, 1977; Malcus and Riehl, 1960).

However, a recent study by Korolev et al. (1990) suggests that there may be some functional dependence of SST-SAT values (herein referred to as Air Sea Contrast (ASC)) and the observed surface wind speed. Korolev et al. demonstrated that ASC significantly increased with increasing surface wind speed for two tropical storms. It is believed that this reduction in air temperature primarily occurred due to evaporation of sea spray into the low level air and, that this cooling was dramatically enhanced as the surface wind speed increased. While findings from this case study are significant, a more complete investigation utilizing composite analyses from many tropical systems (especially hurricanes) is necessary if we are to obtain an improved physical understanding of typical air-sea interaction processes occurring within the TC inner core. A major objective of this research is to construct multi-storm composite analyses of near-surface atmospheric and oceanic conditions observed in and around the TC inner core. More specifically, this study will investigate the validity and potential limitations associated with the conventional assumptions that near-surface radial inflow in hurricanes is approximately isothermal, and that that low level relative humidity is nearly uniform radially inward.

2. DATA

In order to create composite analyses of events that individually are quite rare (i.e. buoy observations of the TC inner core) surface observations covering several storms over many years needed to be included. To this end, an extensive marine/coastal surface observation database including over 8000 individual meteorological and oceanographic observations from more than 175 timeseries spanning 28 hurricanes from Eloise (1975) through Danny (1997) was recently constructed. This comprehensive database depicts ‘close encounters’ (CE) between hurricanes and fixed, drifting and moored buoy platforms. Most of this data was acquired from the National Data Buoy Center’s (NDBC) quality controlled, online archived buoy database (NDBC, 1995; Gilhousen, 1988) except for the WSD 1995/6 drifter buoy observations which were obtained directly from NDBC sources. In addition to the surface buoy/platform data, National Hurricane Center ‘Best Track’ TC positions were also incorporated into the CE database.

3. RESULTS

After stratifying observations by SST, it became readily apparent that ASC values for the SST>27°C subgroup noticeably increased inside 2.5 degrees from the TC center (see Fig. 1a). This finding was not found for observations having SSTs <27°C (not shown). It is also worth noting that on average, there is a slight mean decrease in SST inside 2.5 radial degrees (RD) on the order of 0-.5°C which acts to *reduce* ASC values (also not shown). Observations in Fig. 1a however clearly depict an *increasing* ASC trend inside 2.5RD, illustrating that significant air temperature cooling near the surface is occurring.

As previously mentioned, Korolev et al. (1990) showed that ASC was positively correlated with the

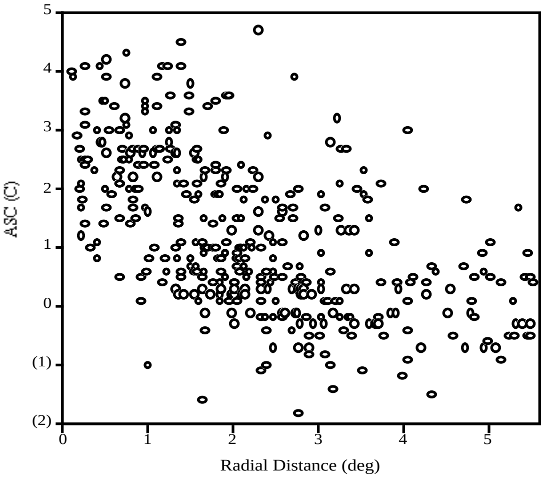

Figure 1a: The Air Sea Contrast (ASC) as a function of radial distance from the tropical cyclone center. ASC (in °C) is defined as SST minus the (10m) surface air temperature Only observations having SST> 27°C and 10m surface winds >10ms^{-1} are included. Radial distance is given in degrees latitude.

Corresponding author’s address: Joseph J. Cione, NOAA/AOML/HRD, 4301 Rickenbacker Causeway, Miami, FL 33196; e-mail: cione@aoml.noaa.gov surface wind speed for two tropical storms. However, observations from the CE database suggest that changes in ASC in and around the TC inner core may not always be related to changes in observed surface wind speed. After binning together all observations that had SSTs >27°C, surface wind speeds between 10-25ms^{-1} (>25ms^{-1}) and distances between 1-2.5RD (<1RD) it became clear that the observed increase in ASC inside 2.5RD illustrated in Fig. 1a almost entirely occurred between 1-2.5RD while ASC remained near constant or slightly decreased radially inward of 1RD (see Fig. 1b). This result was found *despite* the fact that average wind speeds were significantly lower for observations between 1-2.5RD (16.1ms^{-1}) when compare to average wind speeds inside 1RD (34.3ms^{-1}).

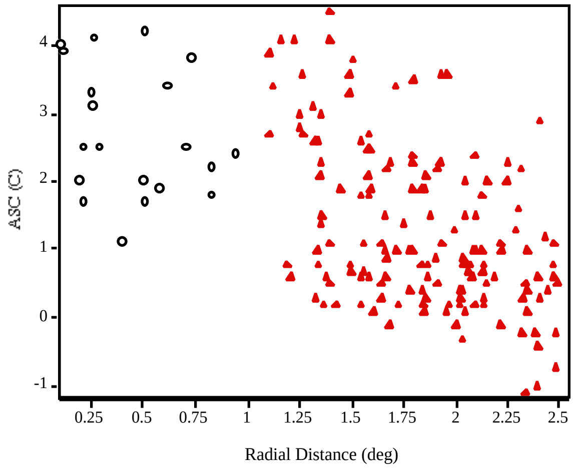

Figure 1b: As in Fig. 1a except observations having surface wind speeds >30ms^{-1} (between 10-25ms^{-1}) between 0-1RD (1.1-2.5RD) are only included.

These findings may in part be explained by Fig. 2 which illustrates relative humidity (RH) as a function of TC radial distance for 7 of the 28 hurricanes in the CE database that included measurements of surface dewpoint. All observations in Fig. 2 have SSTs >27^{o}C and surface winds in excess of 10ms^{-1}. While observations in Figures 1a and 1b illustrate that inflow at low levels near the TC inner core is not isothermal under certain conditions, Fig. 2 illustrates that surface RH is neither relatively constant nor approximately equal to 90% (illustrating the limitations of traditional assumptions regarding surface RH (WMO, 1995)). From this figure we see that RH values are approximately 85% from 2.5-3.5RD then noticeably drop off to near 70-75% just inside 2.0RD before recovering to near 90% at 1RD. Inside 1RD, RH observations rapidly increase to near saturation close to the cyclone center. The most significant finding in Fig. 2 is the noticeable drop off in RH inside 2.5RD from ~85% to near 75% between 1.5-2.0RD. The exact physical process(es) responsible for modifying and drying the air near the surface within this region are not explicitly accounted for. However, it is likely that interactions with (relatively dry) convective downdrafts associated with adjacent rain bands or nearby inner core convection is occurring or, that interactions with the local/large scale environment are enabling (relatively dry) air from aloft to reach the surface. In any event, if these low RH observations are truly representative, the potential implications are rather significant. The reduced RH values observed between 1-2RD would allow unsaturated air to dramatically cool further through a combination of enhanced evaporative cooling from sea spray and local precipitation. Figure 2 illustrates this 'potential cooling' through the use of a curve depicting the functional relationship between the dewpoint depression and RH for a given air temperature (in this case taken to be 27°C). This curve simply states that for a given temperature, the potential for additionally cooling, either by adiabatic or diabatic processes, is inversely proportional to RH. From Fig. 2, we see that average RH values of 75-80% observed between 1-2RD represent approximately 4.2°C of potential cooling. Similarly, observed RH values of ~90% near 1RD yield a potential cooling between 1.7-2.0°C. Assuming that typical low level inflow in a hurricane experiences similar RH increases (i.e. from ~75% to ~90%) between 1-2RD the net cooling would be about 2.5°C. Taking into account an initial ASC between 0.5-1.0°C at 2RD, an approximate estimate of ASC between 3.0-3.5°C at 1RD is obtained. To the first order, these estimates agree with typical observed ASC values illustrated in Figures 1a and 1b. However, between 0.25-1RD we see little evidence of further ASC increase despite additional *potential* cooling of ~1.7-2.0°C (associated with the observed RH increase from near 90% to saturation).

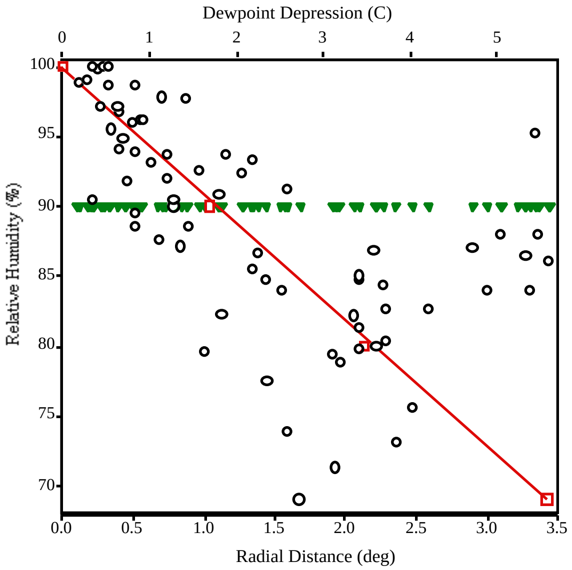

Figure 2: The relative humidity (in %) as a function of radial distance (in degrees latitude) from the tropical cyclone center. Also included is a curve depicting dew point depression (SST minus surface air temperature, in °C) as a function of RH. Upside down triangles are included as reference, representing 'constant RH' of 90%.

In order to get an improved understanding of relevant air sea interactive processes within the TC inner core it is appropriate to calculate θ_E as a function of RD. This is especially true inside 1RD where the composite radius of maximum winds and associated pressure gradients are located (i.e.~0.7-0.75RD) (not shown). Figure 3a illustrates a composite radial depiction of θ_E out to 2.5RD for observations exhibiting surface wind speeds >10ms^{-1} and SSTs > 27°C. Also illustrated in Fig. 3a for comparative purposes, is the θ_E radial profile that results if we assume that low level flow is isothermal, in near equilibrium with the sea (i.e. ASC=const=1°C) and RH remains constant at 90%. Clearly, the 'observed' horizontal profile illustrates significant reductions in θ_E relative to the 'assumed' profile. The difference between these profiles dramatically increases between 1.0-1.5RD and reaches a maximum value of ~17K near 1RD (see Fig. 3b). It should be noted that within this same region we also observe the most rapid increases in ASC and RH (see Figures 1b and 2). These findings further support the contention that much of the ASC increase observed between 1.0-1.5RD is likely a result of evaporative cooling of anomalously dry air near the surface (potentially from both local precipitation and interaction with sea spray). Figures 3a and 3b also show that 'observed' θ_E increases much more rapidly relative to 'assumed' θ_E inside 1RD. In fact, differences between observed and assumed θ_E are dramatically reduced by nearly 12K from ~17K at 1RD to near 5K at ~0.25RD. These findings suggest that a significant degree of low level cooling (warming) is occurring between 1-2RD (0.25-1RD) which is not accounted for if we assume near-surface TC inflow is isothermal, in near equilibrium with the sea and maintains uniform RH radially inward.

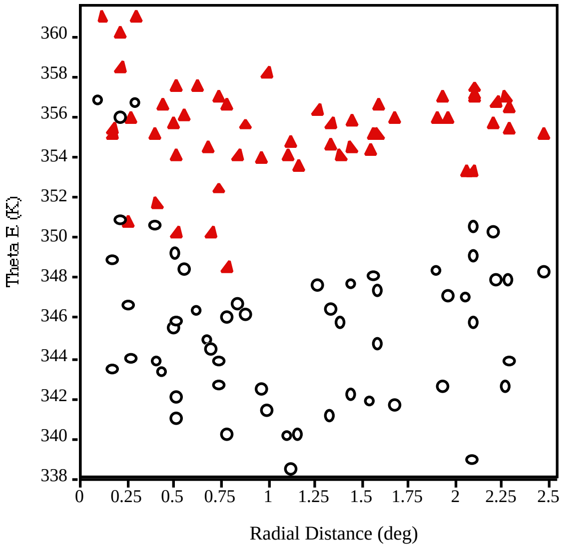

Figure 3a: θ_E **(K) as a function of radial distance using observations (open circles) and 'assumed values' (upright solid triangles) where ASC=constant=1°C and RH=constant=90%. Observations having SST> 27°C and 10m surface winds >10ms^{-1} are included. Radial distance is given in degrees latitude.**

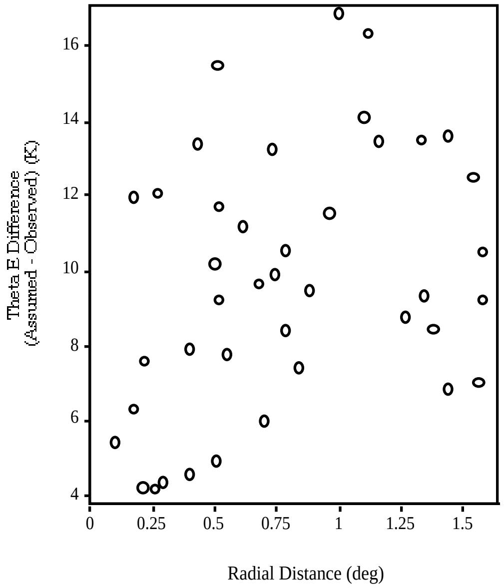

Figure 3b: The 'θ_E difference' (assumed θ_E minus observed θ_E, in K) as a function of radial distance (in degrees latitude). As is Fig. 3a, only observations having SST> 27^{o}C and 10m surface winds >10ms^{-1} are included.

In order to help explain the more rapid increase in θ_E inside 1RD (relative to the assumed θ_E profile), Fig. 4 is presented which illustrates the radial distribution of the difference between observed surface fluxes of heat and moisture and assumed surface fluxes of heat and moisture (where ASC=const=1°C and RH=const=90%). The standard bulk aerodynamic expressions used to calculate the scalar fluxes of heat (H_S) and moisture (H_L) are:

$$H_S = r\, C_p\, C_H\, (SST - T_{A10m})\, U_{10} \qquad (1)$$

$$H_L = L_v\, C_E\, (q_{SST} - q_{A10m})\, U_{10} \qquad (2)$$

Where r is the density of air, C_p is the specific heat of air at constant pressure, L_v is the latent heat of vaporization, SST is the sea surface temperature, T_{A10m} is the air temperature at 10m, U_{10} is the wind speed at 10m, C_H and C_E are the dimensionless coefficients of heat exchange and moisture exchange and q_{SST} and q_{A10m} are the saturation mixing ratio at the SST and the actual mixing ratio of the air at 10m, respectively.

In Fig. 4, we see that relative to the assumed latent heat flux (LHF), significant positive LHF anomalies exist from ~0.25-2.5RD. In addition, positive anomalies of sensible heat flux (SHF) > 250Wm^{-2} are also observed inside 1RD. Figure 4 illustrates that 'observed' LHF was substantially enhanced at radial distances between 1.0 and 2.5RD (where RH values were well below saturation and surface air temperatures noticeably decreased). Under these conditions of initially low RH, relatively low SHF and moderately increasing wind speeds (i.e. ~12-25ms^{-1}), enhanced, *net* low level cooling (most likely resulting from evaporation of sea spray and local precipitation) seems to be both plausible and supported by the observations. Inside 1RD we see that positive SHF anomalies dramatically increase while positive anomalies of LHF are significant up to ~0.4RD. It was suggested previously that as RH increases from 90% to near saturation inside 1RD the potential for additional cooling between 1.7-2.0^{O}C was

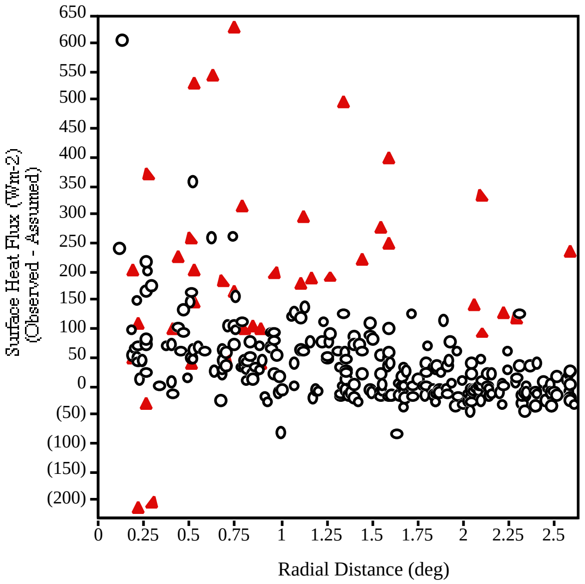

Figure 4: The difference between the observed surface heat flux and the 'assumed' surface heat flux (where ASC=constant=1^{O}C and RH=constant=90%) as a function of radial distance. Sensible (latent) heat flux differences are given as open circles (filled upright triangles). Flux values and radial distances are in Wm^{-2} and degrees latitude, respectively. Only observations having SST> 27^{O}C and 10m surface winds >10ms^{-1} are included.

possible. However, observed ASC values do not increase and in fact may slightly decrease inside 1RD (See Fig. 1b). This occurs despite the fact that the most dramatic increase in surface wind speed is observed inside 1RD approximately between 0.3-0.7RD. It is likely that the rapid onset of saturation near 0.5RD enables significant latent heat release to occur at or near the surface which, in conjunction with enhanced values of SHF (now ~30% of the total heat flux inside 1RD), act to effectively counter surface air temperature cooling that results from adiabatic expansion and evaporation inside 1RD.

4. SUMMARY AND FUTURE WORK

These preliminary findings illustrate that between 1-2.5RD low level TC inflow is neither isothermal nor in near equilibrium with the sea. Much of the surface air temperature cooling that results within this region is likely attributable to enhanced low level evaporation that is made possible by the rapid onset of low level drying inside 2RD (possibly arising from interaction with relatively dry convective downdrafts or other local/large scale processes responsible for vertically transporting relatively dry air to the surface).

To the first order, it appears that inside 1RD the assumption of isothermal inflow near the surface does apply since typical ASC values of 3°C remain relatively constant radially inward of 1 degree (despite the fact that near surface wind speeds dramatically increase within this region). While the inflow in this region maybe typified as near isothermal at the surface, the air is clearly not in thermodynamic equilibrium with the sea (i.e. ASC ~3°C). As a result, significant surface fluxes of heat and moisture occur within this high wind regime. In addition, as the air approaches saturation near 0.5RD it is probable that significant latent heat release occurs very close to the surface. It is suggested then, that since observed surface air temperatures remain relatively constant inside 1RD, low level warming from latent heat release, in conjunction with substantial SHF inside 1RD is closely balanced by surface cooling arising from adiabatic expansion and near-surface evaporation.

It is hoped that these initial findings and conceptual ideas will be thoroughly investigated, tested and expanded upon in the very near future using data obtained from the newly acquired GPS dropsondes. These revolutionary instruments can be deployed in regions of high wind and precipitation which will enable us for the first time to get highly detailed observations of the TC inner core.

Acknowledgments: The authors would like to thank Sam Houston (HRD) and Mike Burdette (NDBC) for their assistance in obtaining the 1995/6 WSD drifting buoy observations as well as Dr. Hugh Willoughby (HRD) for several insightful discussions.

5. REFERENCES

Frank, W.M., 1977a: The structure and energetics of the tropical cyclone. I: Storm Structure. *Mon. Wea. Rev.*, **105**, 119-1135.

Frank, W.M., 1984: A composite analysis of the core of a mature hurricane. *Mon. Wea. Rev.*, **112**, 2401-2420.

Gilhousen, D.B., 1988: Quality control of meteorological data from automated marine stations. Preprints of Fourth International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology, Miami, FL, 113-117.

Hawkins, H.F., and S.M. Imbembo, 1976: The structure of a small intense hurricane - Inez, 1966. *Mon. Wea. Rev.*, **104**, 418-442.

Korolev, V.S., S.A. Petrichenko, and V.D. Pudov, 1990: Heat and moisture exchange between the ocean and atmosphere in Tropical Storms Tess and Skip. *Soviet Meteor. Hydrol.*, **3**, 92-94 (English translation).

Malkus, J.S., and H. Riehl, 1960: On the dynamics and energy transformations in steady--state hurricanes. *Tellus*, **12**, 1-20.

Miller, B.I., 1958: On the maximum intensity of hurricanes. *J. Meteor.*, **15**, 184-195.

National Data Buoy Center, 1995: Automated data quality control checks and procedures of the National Data Buoy Center. NOAA Technical Report.

ONR, 1987: A Global View of Tropical Cyclones. Office of Naval Research 185pp. (Ch. 2 pp 36).

WMO, 1995: Global Perspectives on Tropical Cyclones. Tech. Doc. WMO/TD No. **693**, *World Meteor. Organ.*, Geneva, 289pp. (Ch. 2 pp 45-47).