ENTHALPY FLUXES DURING TROPICAL CYCLONES IN THE CARIBBEAN SEA RELATIVE TO OCEAN VARIABILITY

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1. INTRODUCTION

Tropical cyclones (TC) are known to intensify over areas of high ocean heat content (OHC; *Leipper and Volgenau,* 1972) in which sea surface cooling is minimal during mixing. The deeper mixed layer associated with higher OHC (less vertical mixing) maintains enhanced enthalpy flux into the storm (*Shay and Uhlhorn*, 2008). However, the classical TC intensification hypothesis, known as wind-induced surface heat exchange (WISHE), does not consider the ocean's heat content, moisture, or its vertical structure as a source for enhanced heat flux. Instead WISHE proposes that wind stress within the storm acts to increase the enthalpy flux from ocean to atmosphere. This heat transfer adjusts the low-level atmospheric pressure gradient and increases the wind speed, reinitiating a positive feedback.

TC intensification is also possible independent of WISHE (*Montgomery et al.*, 2009). Numerical studies found that intensification can occur from moisture differences at the air-sea interface altering enthalpy flux, enhancing the low-level atmospheric buoyancy, and increasing the wind stress. *Cione et al.* (2013) argues that sea-to-air moisture disequilibrium and enthalpy flux is dominated by low-level atmospheric moisture and not by the moisture at the ocean interface (i.e. the atmosphere is drier). Conversely, *Jaimes et al.* (2015) shows that moisture at the ocean

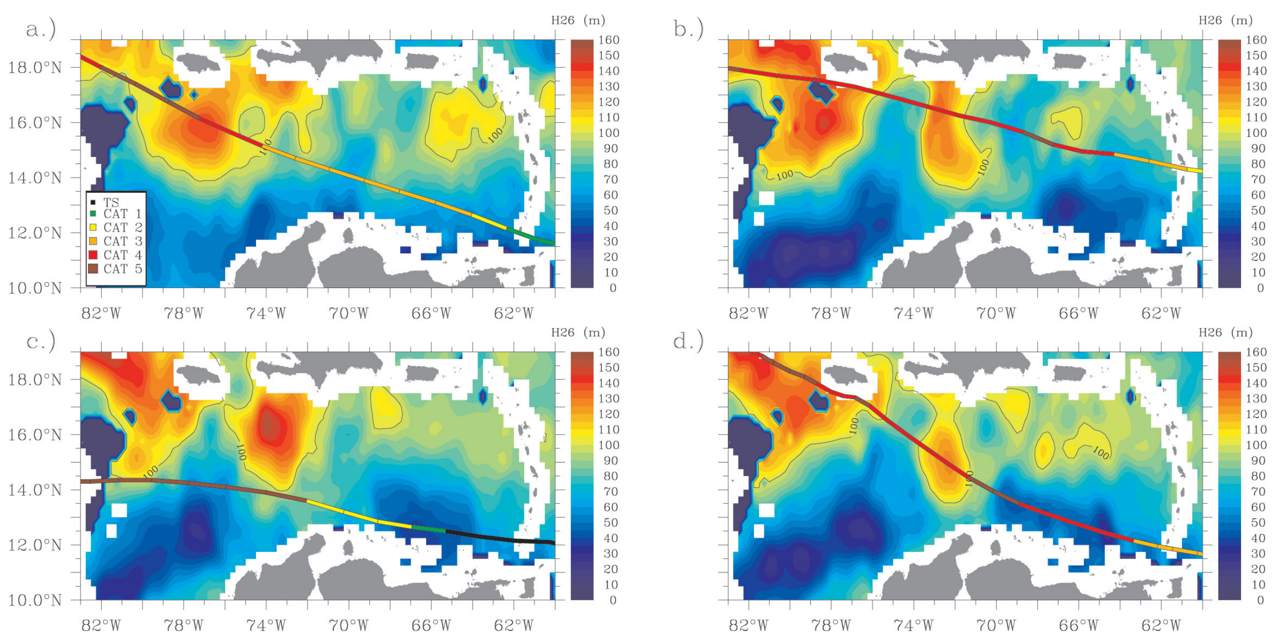

Figure 1. Tracks of a) Emily (2005), b) Dean (2007), c) Felix (2007), and d) Ivan (2004) over 26°C isotherm depth (H26) field within the Caribbean Sea. Black contours indicate 100m depths. H26 is used in the calculation of OHC.

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interface dominates moisture disequilibrium in areas of high OHC, sustaining enhanced enthalpy flux to the TC and assisting in its rapid intensification (RI). The authors also found that maximum enthalpy flux was collocated over regions of high OHC and moisture disequilibrium instead of regions of high momentum flux during RI. This implies that WISHE was not the dominant mechanism during RI, and that deep, warm water sustained SST and moisture at the ocean surface to provide sufficient buoyancy to the atmosphere and impact intensity.

In this context, we investigate the upper ocean's role in modulating enthalpy flux, air-sea moisture disequilibrium, and wind stress during 4 different TCs over the Caribbean Sea: Ivan (2004), Emily (2005), Dean (2007), and Felix (2007). All four TCs encounter different oceanic regimes while in the basin, in particular a large warm eddy (Figure 1). We also examine if a relationship exists between intensity change, the ocean's vertical structure, and the air-sea moisture difference.

2. METHODS

Global positioning systems dropwindsonde (referred to as dropsonde) data is used to calculate air-sea fluxes. Data is acquired from U.S Airforce Reconnaissance (USAFR) flights, NOAA WP-3 flights, and NOAA G-IV flights for dates that coincide with the TC residing over the Caribbean Sea. The 10-m variables of wind speed, specific humidity, and temperature are extracted from each profile. The dropsonde locations are projected into a storm coordinate system (*Jaimes et al.,* 2015).

Data points are separated into "clusters". A cluster is defined where dropsonde coverage is over most quadrants of the TC, for the same time period such that data is sampled within the same day, and that the inner core of the storm is resolved. Additionally, a cluster must be located over a different ocean environment than the previous cluster. This approach allows us to investigate how the storm's intensity changes over time with respect to different ocean regimes.

Momentum and enthalpy fluxes are calculated for each dropsonde within a cluster using bulk aerodynamic formulas to estimate fluxes of momentum (τ), enthalpy (Qh), heat (Ql), and moisture (Qs):

$$\tau = \rho_a C_d U_{10}^2$$

$$Ql = \rho_a L_v C_q U_{10}(q_{sst} - q_a)$$

$$Qs = \rho_a C_p C_h U_{10}(SST - T_{10})$$

$$Qh = Ql + Qs$$

where q_{SST} is the saturation specific humidity at SST and q_a is the saturation specific humidity of the air at 10m. Coefficients C_q, C_h, and C_d are based on the Coupled Boundary Layer Air-Sea Transfer (CBLAST) experiments (*Bell et al.,* 2012). Daily SST [*JPL MUR MEaSUREs Project*, 2010] is extracted for the location of each dropsonde within a cluster to calculate air-sea fluxes.

Latent and sensible heat flux, momentum flux, moisture disequilibrium *($dq=q_{SST}-q_A$)*, and air-sea temperature difference *($dT=SST-T_{10}$)* are computed and objectively analyzed (*Hankin et al.,* 2015) to create a continuous field for each variable within a cluster. These and other atmospheric variables are compared to OHC (*Myers et al.,* 2014) and wind speed for the same locations and times. This comparison allows us to investigate if regions of maximum enthalpy flux are collocated in space with OHC or momentum flux.

3. RESULTS

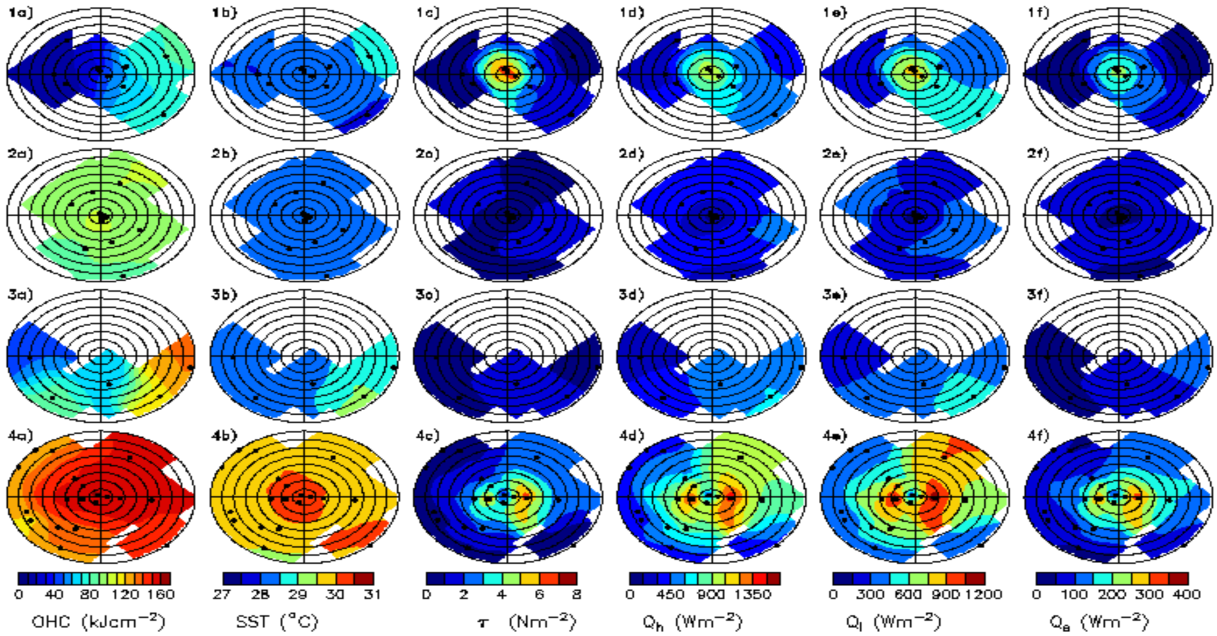

Figure 2. Along track variability of OHC (a), SST (b), wind stress (c), enthalpy (d), latent (e), and sensible (f) heat fluxes during Hurricane Ivan, for clusters 1 (top row) to 4 (bottom row). Circles are for radial distances of 1 Rmax. Grid points farther than 4.375 Rmax away from the nearest data point are set to "undefined" and masked white. Dropsonde locations are indicated with black circles.

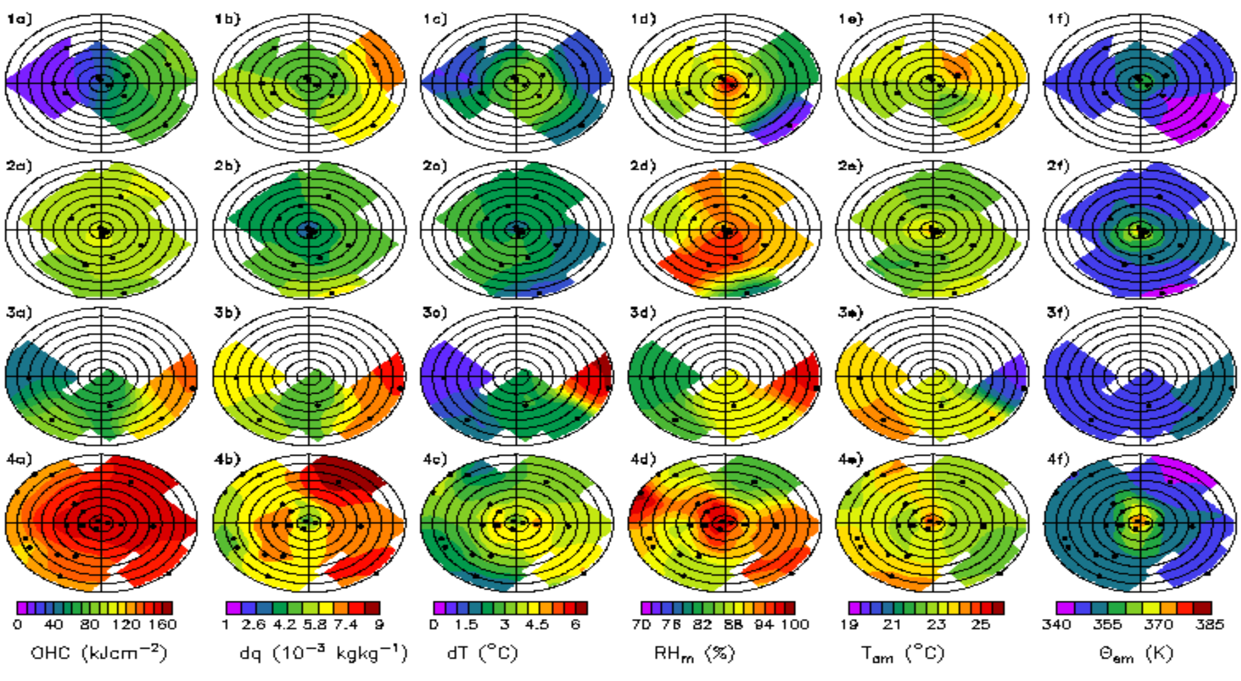

Figure 3. Same as in Figure 2 but with OHC (a), moisture disequilibrium (b), air-sea temperature difference (c), and lowest 100mb average of relative humidity (d), air-temperature (e), and equivalent potential temperature (f).

Observations during Hurricane Ivan (2004) indicate that maximum momentum and enthalpy fluxes are collocated in space within the inner 2 Rmax (radius of maximum winds), regardless of the ocean structure or atmospheric environment it traverses (Figure 2). However, as Ivan encounters areas of high OHC (> 90 kJcm^{-2}) or where an OHC gradient exists, enthalpy fluxes and moisture disequilibrium mimic the structure of OHC for regions outside of 2 Rmax during steady intensification periods (non-RI) (Figure 2). The collocated structure is especially apparent when Ivan encounters high OHC values within a warm-core eddy and in the western Caribbean (Figure 2). Furthermore, enthalpy fluxes over the entire storm are significantly greater over areas of high OHC (~150 kJcm^{-2}) compared to areas of relatively lower OHC (~60 kJcm^{-2}) for the same wind stress (Figure 2). This suggests that areas of high OHC assist in maintaining enhanced enthalpy flux, independent of wind stress.

When moisture from the atmosphere (q_a) and ocean (qsst) are examined separately, cluster-averaged qsst is 25% larger than qa when Ivan is over regions of high OHC (Figure 3). Additionally, moisture at the ocean surface steadily increases as Ivan moves into areas of deep, warm water. Both of these findings suggest that moisture across the air-sea interface is influencing total moisture disequilibrium.

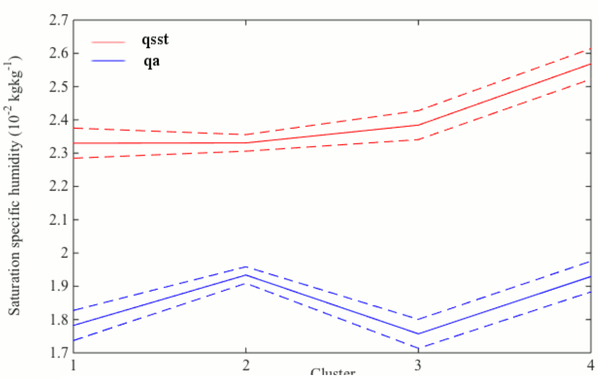

Figure 4. Characteristics of moisture disequilibrium; dq=qsst-qa. Solid lines are cluster-averaged values. Dashed lines are ± 1 standard deviation for the corresponding variable

4. CONCLUDING REMARKS

Regions of high OHC assisted in maintaining enhanced enthalpy flux within Ivan, independent of wind stress. In these regions, moisture disequilibrium and latent heat flux structure are more similar to OHC than momentum flux for distributions outside of 2 Rmax during steady intensification periods. Moreover, the saturation specific humidity at SST increases gradually as Ivan moves over areas of high OHC, suggesting the ocean structure is influencing this variable and total air-sea moisture difference. Similar analyses are applied to Hurricanes Emily (2005), Dean (2007), and Felix (2007) to examine if the phenomena found in Ivan apply to other storms in the Caribbean. Future work consists of forming a non-dimensional relationship between oceanic variability, enthalpy fluxes, and storm parameters to quantify the ocean's influence on a TC.

5. REFERENCES

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