P3.19 PRELIMINARY OBJECTIVE ANALYSES USING THE NESDIS/CIRA TROPICAL CYCLONE INFRARED IMAGERY PART I: HURRICANE HARMONICS

James P. Kossin*

Cooperative Institute for Research in the Atmosphere (CIRA)
Colorado State University, Fort Collins, Colorado

1. INTRODUCTION

The NESDIS/CIRA tropical cyclone infrared (IR) imagery archive contains half-hourly, 4 km horizontal resolution, geostationary IR images of tropical cyclones that occured since the onset of the 1995 hurricane season (Zehr 2000). The present abstract introduces some preliminary results of analyses of this largely unexplored data set. By combining the IR data with information regarding storm position and track, a coherent depiction of the spatial and temporal structure of hurricane cloudiness can be demonstrated. Spatially dependent periodic oscillations are revealed, and new insights into the respective roles of the diurnal and semidiurnal oscillations are uncovered. Although the present results are preliminary, a controversial hypothesis, namely that the diurnal cycle may force only the hurricane cirrus canopy, and not the convection in the eyewall, is suggested.

2. DAILY VARIATIONS

By combining the half-hourly IR hurricane images with best track storm center fixes interpolated to the times of the images, azimuthal averages of equivalent blackbody cloud-top temperature (T_{BB}) can be calculated, and Hovmöller type diagrams (radius versus time) can be created (Fig. 1). Casual scrutiny of these diagrams immediately reveals periodic oscillations on a diurnal timescale, while closer inspection often reveals semidiurnal oscillations.

The diurnal oscillations are most obvious at larger distances from the storm center ($r > 200$ km) and are largely induced by the horizontal expansion and contraction of the cirrus canopy. The behavior of tropical cyclone cirrus canopies has been well documented (e.g., Browner et al. 1977, Muramatsu 1983, Lajoie and Butterworth 1984, Steranka et al. 1984), but the examples shown in Fig. 1 greatly facilitate the interpretation of these previous studies by *succinctly* capturing many of their results, including:

1)The areal extent of the cirrus canopy horizontally expands and contracts on a diurnal cycle.

2) The maximum area of the canopy typically occurs around 1600-1800 Local Mean Solar Time (LMST) in the Atlantic and Eastern Pacific basins. This agrees well with Browner et al. (1977).

3) The amplitude and radial extent of the canopy area oscillation often decrease as eye formation occurs. This result may extend the findings of Steranka et al. (1984) where the amplitude was found to decrease in multiple-storm composites of hurricanes versus composites in tropical storms.

4) Since canopy area oscillates diurnally, the phase of the diurnal cycle is systematically dependent on radial distance from storm center. Furthermore, it is clear from Fig. 1 that the phase is systematically dependent on choice of T_{BB} threshold. This may illuminate the reason that Reed (1983) found that in ordinary Pacific ocean convection, the time of maximum area of cloud top colder than -55°C was significantly out of phase with the time of maximum area of cloud top colder than -20°C.

5) The apparent speed of radial propagation of the T_{BB} features of the canopy can be explicitly calculated from Fig. 1 and is typically near ~ 10 m s^{-1}, in good agreement with Wexler and Merritt (1967), whose calculations based on limited data necessarily required numerous assumptions. It should be noted here that this expansion rate is not necessarily a direct measure of upper level outflow rates, just as the canopy contraction is not a measure of upper level inflow.

Each panel in Figure 1 essentially comprises a set of individual time series in 4 km radial increments. Objective time series analyses can then be performed at each radius. The results of such analyses for the 3 hurricanes in Fig. 1 are shown in Fig. 2, which displays the most significant harmonics at each radius. As expected from the subjective

* *Corresponding author address:* James P. Kossin, Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, CO 80523-1375; e-mail: Kossin@CIRA.colostate.edu

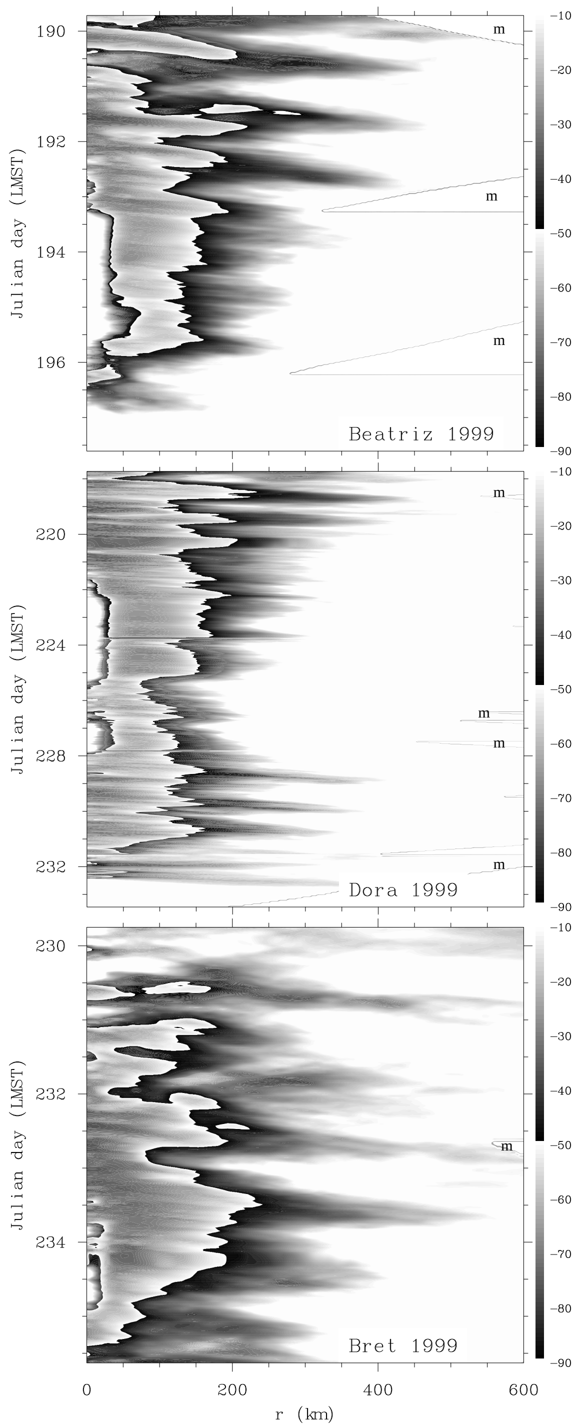

Figure 1: Hovmöller (radius versus LMST) diagrams of azimuthally averaged T_{BB} in eastern Pacific hurricanes Beatriz 1999 and Dora 1999, and Atlantic hurricane Bret 1999. Averages are with respect to interpolated best track center. The small "m" denotes missing values. Values along the label bars are in degrees Celsius.

scrutiny of Fig. 1, T_{BB} evolution at outer radii away from the eyewall ($r > 200$ km) is generally dominated in all three storms by the diurnal harmonic. However, closer to the convection near $r = 100$ km, *the diurnal harmonic becomes insignificant* and T_{BB} variation in Hurricanes Beatriz and Bret is *dominated by a semidiurnal harmonic.* No significant periodic oscillations are evident at inner radii in Hurricane Dora.

Figures 3 and 4 show T_{BB} time series at $r = 100$ km in Beatriz and $r = 40$ km in Bret. The phase of the planetary pressure tide S_2 is shown on each figure and is aligned with T_{BB} evolution, that is, colder cloud tops occur when the local pressure is lower (S_2 is minimum). The phase of the semidiurnal oscillations in Beatriz and Bret exhibit little dependence on radial distance from the storm center. This is physically consistent with the local effects of S_2.

At this point, it has been shown that T_{BB} away from the hurricane eyewall oscillates diurnally, while T_{BB} in the convective region near the eyewall can exhibit a dominant semidiurnal cycle. What might be driving this convective cycle? Aircraft data from Hurricane Elena 1985 (chosen because of relatively good temporal sampling) shows that θ_e in the eye and eyewall can oscillate semidiurnally (Fig. 5). The amplitude of the semidiurnal harmonic is about 1 K in the eyewall on the 850 hPa flight-level surface. The phase is physically consistent with S_2, that is, higher θ_e occurs when the pressure is lower. If the amplitude of the θ_e oscillation depends on height, then the passing of the S_2 pressure wave may cause small lapse rate changes. In an eyewall that is moist-neutral (angular momentum and θ_e surfaces are approximately parallel), a small change in static stability might effect large changes in the convection.

The notion that hurricane convection is not diurnally forced is speculative and controversial, and requires further work to confirm or deny. It may be that a diurnal cycle of low level convergence is too small in amplitude to measurably affect the strongly convergent hurricane low level circulation. It is not yet clear whether the diurnal cycle of cloud top cooling and associated lapse rate variability plays any role in the present results. Spectral analyses of large composites of the irregularly sampled flight-level data in the lower and middle levels are currently underway, and will hopefully be illuminating in questions of semidiurnal lapse rate changes. The robustness of results using the satellite imagery archive is currently being thoroughly tested using data from additional hurricanes.

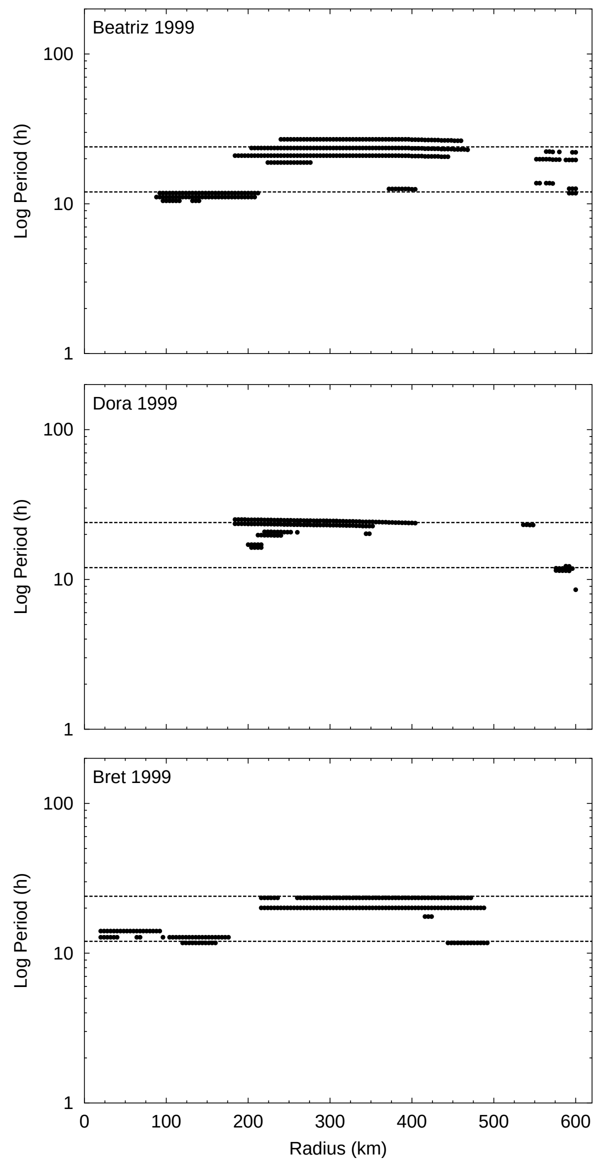

Figure 2: Results of spectral analyses of T_{BB} time series at each radius (from storm center) in Hurricanes Beatriz, Dora, and Bret 1999. Points represent the most significant harmonics. The dashed lines denote periods of 12 and 24 h.

3. CONCLUDING REMARKS

1) Consistent with previous studies, application of the NESDIS/CIRA tropical cyclone infrared imagery archive to T_{BB} time series shows a distinct diurnal cycle in the cold cloud of the hurricane environment.

2) The diurnal oscillation in cold cloud appears to be largely due to the evolution of the hurricane's cirrus canopy which oscillates in areal extent as it is affected by diurnal radiative and subsidence pro-

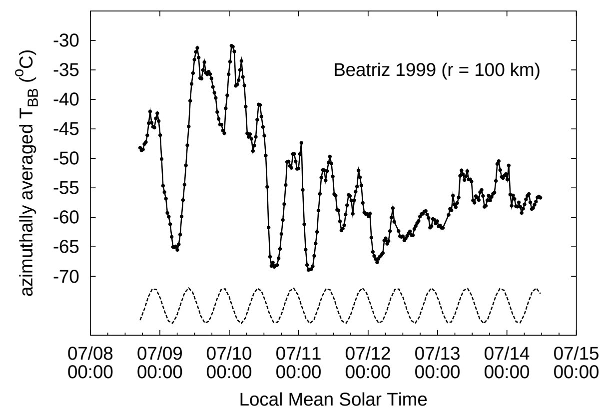

Figure 3: Time series of azimuthally averaged T_{BB} in Beatriz at $r = 100$ km. The lower sinusoidal curve (dashed) shows the phase of the semidiurnal pressure tide (S_2).

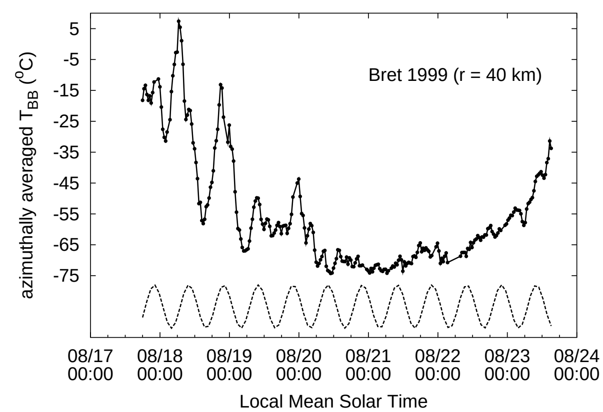

Figure 4: Time series of azimuthally averaged T_{BB} in Bret at $r = 40$ km, and the phase of S_2 (dashed).

cesses. Since the canopy's size oscillates diurnally, the phase of the diurnal cycle is systematically dependent on radial distance from storm center.

3) The amplitude of the diurnal signal also has a strong dependence on radial distance from storm center, and can become insignificant near the convective region (eyewall). *This may indicate that hurricane convection is not necessarily diurnally forced*, as suggested in previous studies.

4) Near the eyewall, a semidiurnal oscillation can dominate the power spectrum of the T_{BB} time series. The phase is aligned with the planetary pressure tide S_2, that is, the minimum T_{BB} occurs nearly simultaneously with the minimum perturbation surface pressure.

5) Time series of 850 hPa flight-level data in the eye and eyewall of Hurricane Elena 1985 show significant semidiurnal oscillations of θ_e, consistent

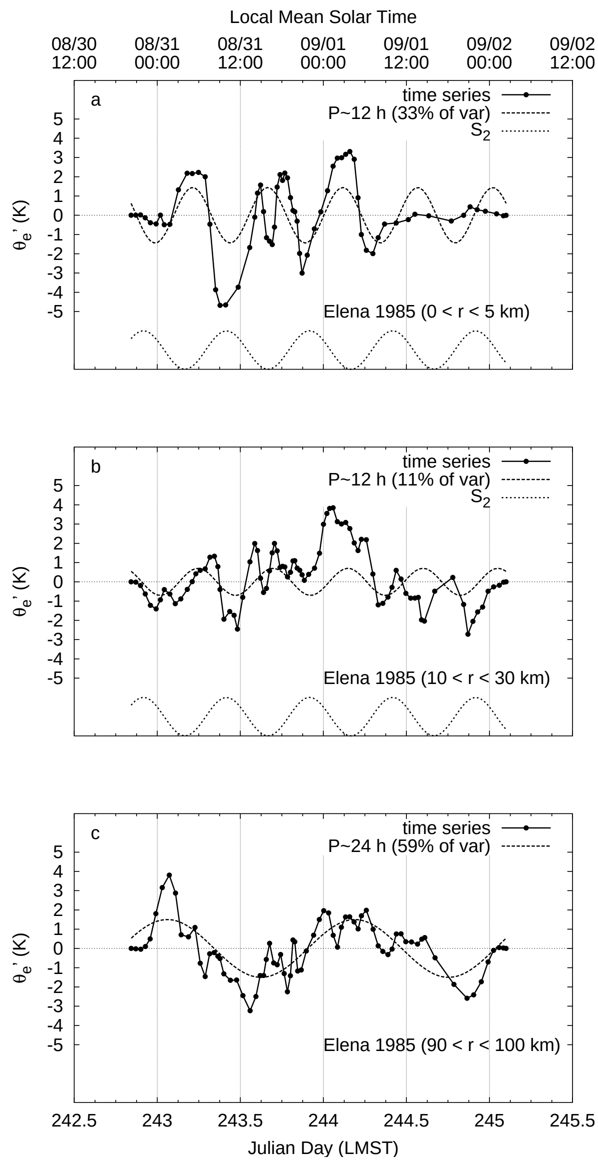

Figure 5: Time series analyses of perturbation θ_e, with respect to LMST, measured by aircraft at 850 hPa flight level in Hurricane Elena 1985. a) Average θ_e' in the eye ($0 \leq r \leq 5$ km) (solid), and the most significant harmonic ($\sim$ 12 h period) (long dash). The lower sinusoidal curve (short dash) shows the phase of the semidiurnal pressure tide (S_2). b) Same as a), but for average θ_e' in an annulus representing the eyewall region. c) Average θ_e' near the outer limit of the flight level radial leg data. Here, the most significant harmonic is diurnal ($\sim$ 24 h period).

with the satellite derived T_{BB} oscillations in Hurricanes Beatriz and Bret. The low-level θ_e is maximum when T_{BB} (and perturbed surface pressure) is minimum. It is hypothesized that the local pressure oscillation caused by S_2 might change local lapse rates by affecting θ_e differently at different heights. Such systematic lapse rate changes might explain the semidiurnal oscillation noted in T_{BB} in the convective regions of some hurricanes.

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