Analysis on Tropical Storm Erin (2007) and the Diurnal Cycle in Post-Landfall Tropical Cyclones

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INTRODUCTION

Tropical Storm Erin (2007) was an unusual tropical cyclone (TC) that intensified over the state of Oklahoma. Prior research uncovered multiple factors responsible for Erin's strange re-intensification, such as abundant surface moisture producing a "brown ocean" effect (Arndt et. Al, 2009) , but little investigation into the diurnal cycle has been conducted. The diurnal cycle, which manifests in TCs through deeper convection as a result of cloud-top cooling (Melhauser and Zhang, 2014), has been investigated as a key component for TC behavior, through an understanding for which TCs undergo rapid intensification (RI) and which TCs could have higher rainfall rates. The diurnal cycle in TCs can be investigated through cyclical pulses of cloud-top cooling followed by intense cloud-top warming known as diurnal pulses, which begin to form in the inner core before propagating outward overnight. These pulses are theorized to have direct links with TC intensity, structure, and evolution (Dunion et. al, 2014). Rapid intensification of TCs, for example, shows a nocturnal preference and is associated with deep convective clouds, suggesting that increases in TC vortexes can be linked to diurnal convective trends (Wu et. al, 2020). The necessity for understanding the behavior of TCs once they make landfall is extremely important due to impacts on humans and population centers on land. As a result, we chose to investigate the diurnal cycle in Tropical Storm Erin (2007) using the Weather Research and Forecasting (WRF) model through sensitivity tests by modifying the diurnal cycle. We hypothesize that the diurnal cycle will inverse the timing of intensification overnight as viewed through rainfall totals.

METHODS

The WRF model, running version 4.1, was selected for its relative flexibility with modeling capabilities and efficiency with computation. A control run was simulated using ECMWF ERA5 boundary conditions and model forcing data, starting at 2007-08-17 at 21:00 UTC and continuing until 2007-08-20 09:00 UTC. The control run was run on a double nested grid of 6 km and 1 km . Furthermore, the control run was simulated using the Thompson Microphysics Scheme and the Noah-Multi Parameterization Land Surface Model scheme, which has shown significant improvement in surface to boundary layer interactions since the most recent modeling study on TS Erin (Krikken and Steeneveld, 2012). The control run was then analyzed through Python analysis of model rainfall rate output with NCEP/EMC 4 km Gridded Data (GRIB) Stage IV Data and comparison of the modeled storm track with NOAA Best Track data (Fig 1), to verify the accuracy of the control run. Additionally, reflectivity was calculated and plotted to showcase visual similarity between both the control run and the real storm.

A sensitivity test was then run through first editing WRF's RRTMG code by offsetting the timing of solar radiation by 12 hours, and then running a simulation using identical settings to the control run, including the same ERA5 reanalysis data. Verification of the sensitivity run against the control run was conducted through direct comparison of rainfall amounts, storm track data, and mean wind time series.

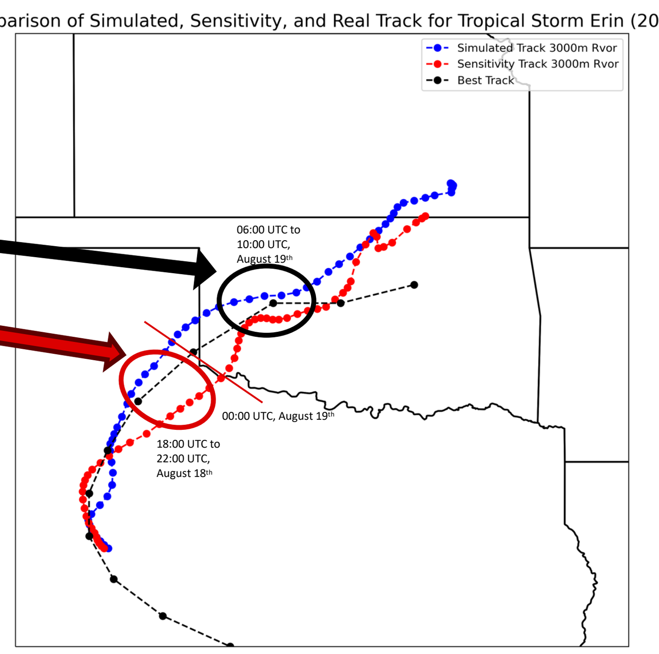

Fig 1. Control (blue), sensitivity (red), and NOAA Best Track (black) track points representing the center of Tropical Storm Erin. The simulated tracks were calculated using a tracking algorithm that manipulated relative vorticity from 50m, interpolated U and V wind files.

RESULTS

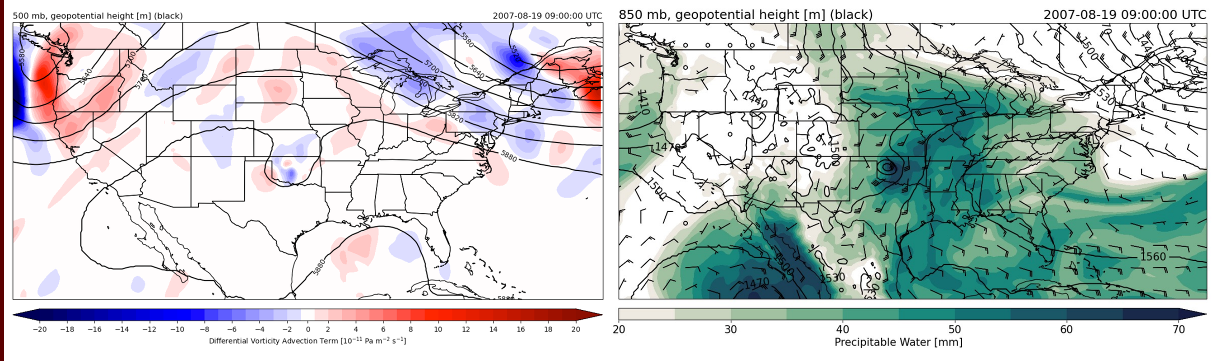

Fig 2. ERA5 Reanalysis Plots showing differential vorticity advection from 400mb to 700mb [left] and precipitable water at 850mb [right] during Tropical Storm Erin's time of intensification over Oklahoma at 2007-08-19 at 09:00 UTC.

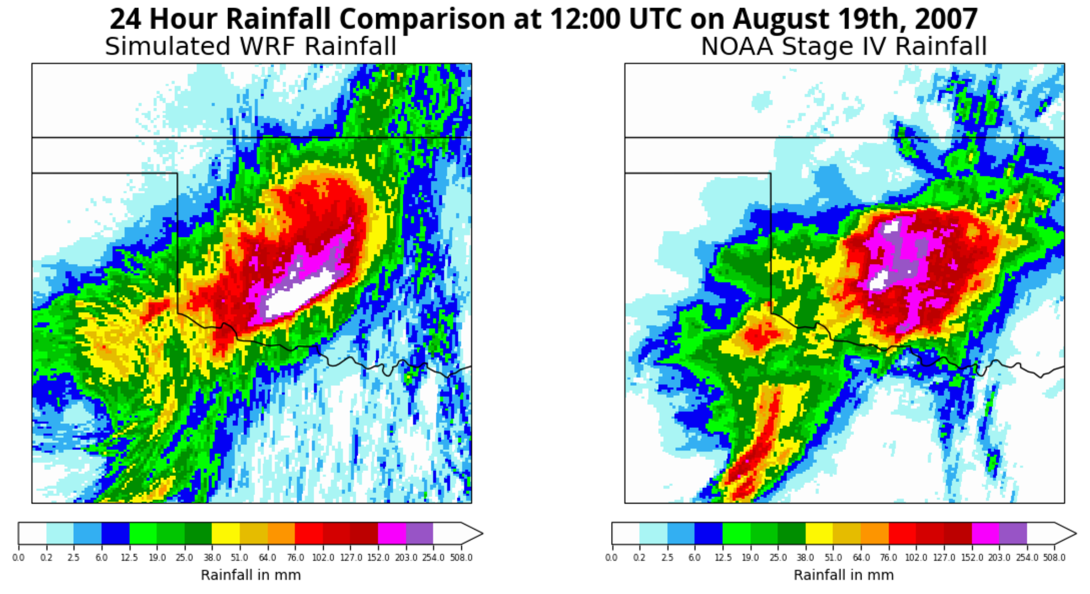

Fig 3. Coarsened WRF output rainfall from 2007-08-18 at 12:00UTC until 2007-08-19 at 12:00 UTC plotted next to NCEP/EMC 4 km Gridded Data Stage IV Data.

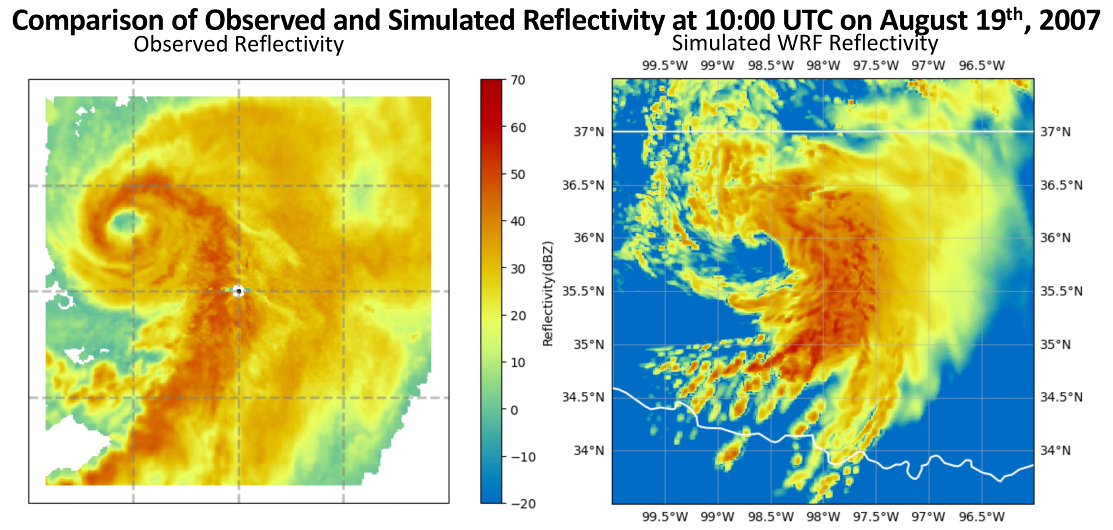

Fig 4. NEXRAD Level II Observed Reflectivity (dBZ) at 10:03 UTC from the KTLX radar in Oklahoma City [left] plotted next to derived reflectivity product from WRF simulated output at 10:00 UTC [right].

There was a high level of moisture in the region around the time of intensification (06:00 UTC until 10:00 UTC on August 19th, 2007), as viewed through the 750mb Precipitable Water ERA5 reanalysis plot. The DVA plot shows the cyclone is not engendered by a digging trough but rather existing as its own shortwave after landfall. (Fig 2). Comparison of rainfall values (Fig 3), which were calculated as the total rainfall falling between August 18th, 2007 at 12:00 UTC and August 19th, 2007 during the period of intensification, shows concentrated amounts above 100mm over central and eastern Oklahoma in both the simulated and observed rainfall totals. Additionally, areas of rainfall eclipsing 203mm are centered around a similar region in central Oklahoma, with the overall shape of heavy rainfall patterns on the simulated portion mimicking the observed values. The structure of spiraling rainbands and overall wider precipitation on the eastward side of the storm are **sufficiently modeled** in the real case as well (Fig 4). As a result, when considering the precision of the simulated track (Fig 1), **the control run is thoroughly verified** and close enough to observations for a sensitivity test.

RESULTS

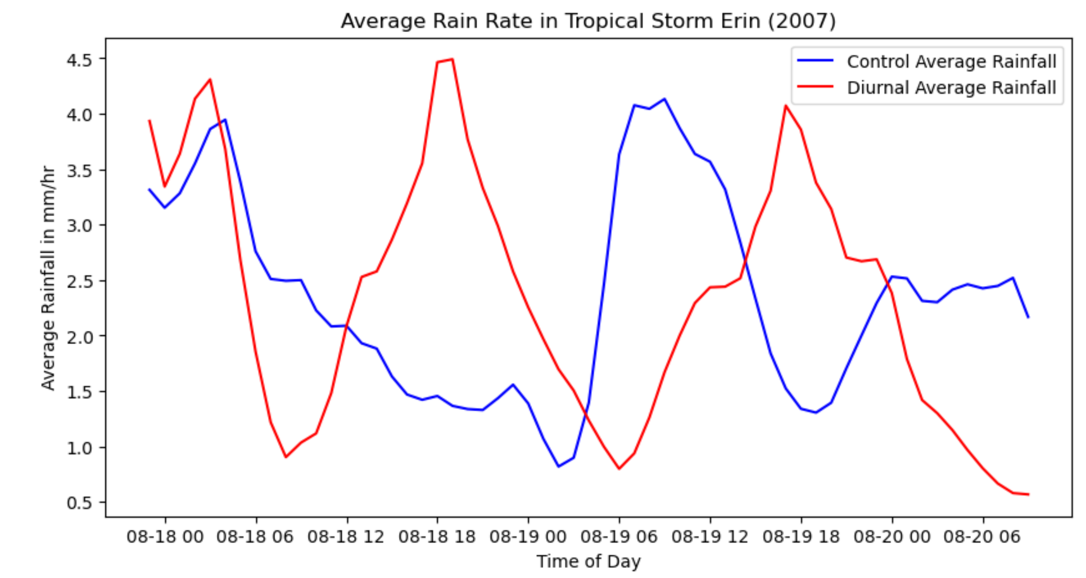

Fig 5. Averaged derived hourly rain rate in mm/hour between the control run (blue) and the sensitivity run (red) from 2007-08-17 and 2008-08-20 with an annual radius of 2º latitude.

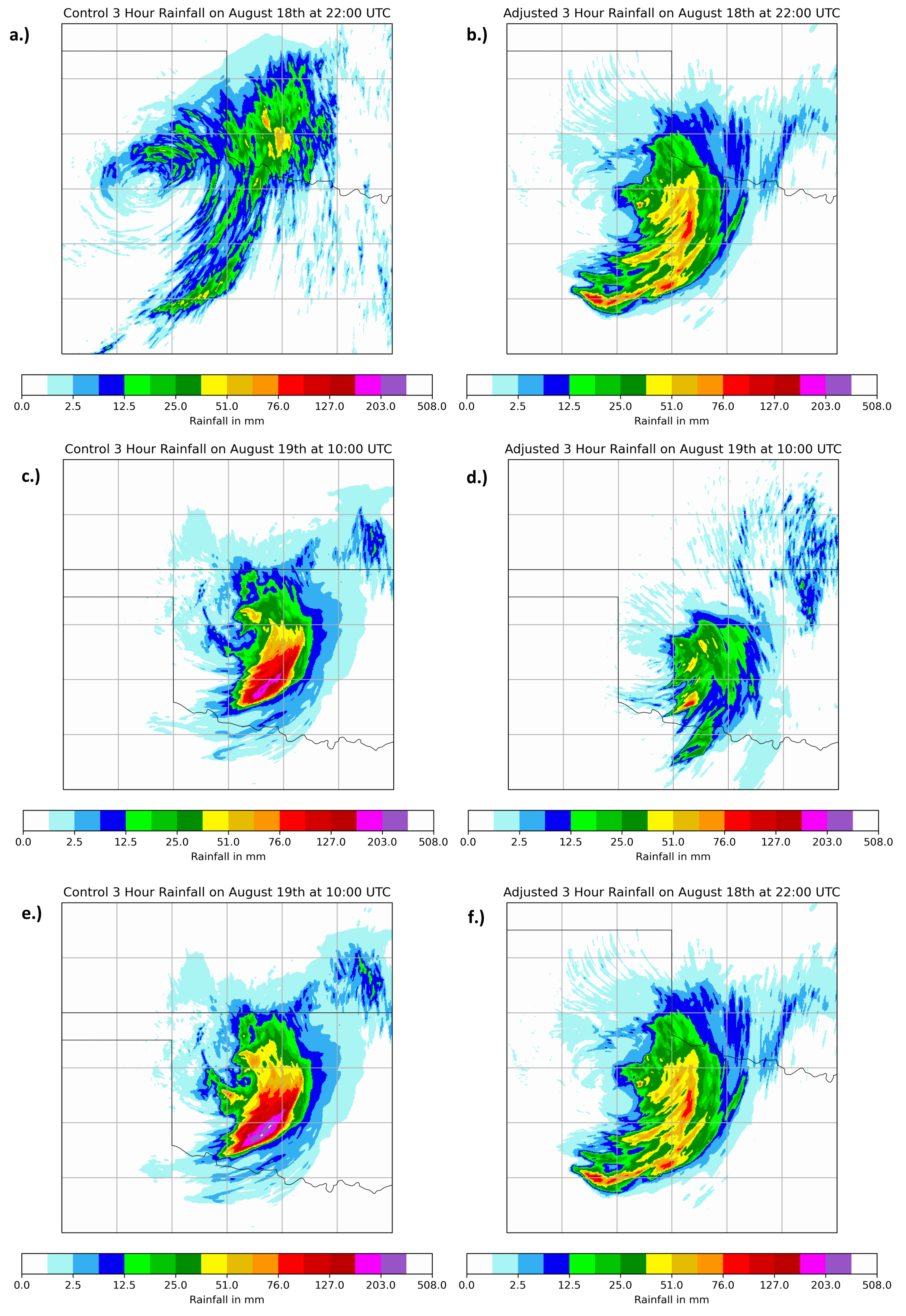

Fig 6. Derived rainfall comparison from the WRF control and sensitivity run on 2007-08-18 at 22:00 UTC (a, b), on 2007-08-19 at 10:00 UTC (c, d), and a comparison of peak intensity for the control run (e) and the sensitivity run (f).

RESULTS

To investigate the differences in intensity between the control run and sensitivity run, averaged rain rate was calculated by masking out all rainfall values outside of 2º latitude from the center of the TC, subtracting consecutive timesteps to calculate the hourly rain rate, and averaging all the data across the domain to produce an average rain rate time series for each timestep (Fig 5). Rainfall rate can be generalized as a proxy for intensification and has increasing trends closer to the inner eyewall (Xi et. al, 2023). The time series shows a cyclical pattern developing for the two simulations, with rainfall maxima peaking nocturnally for both runs.

- The peak for the control run, which is arbitrarily selected as above 3.5 mm per hour, lasts from 06:00 UTC until 10:00 UTC on August 19th.
- The sensitivity run, which is offset by 12 hours, shows the maximum peak occurs approximately from 18:00 UTC until 22:00 UTC on August 18th. The period of maximum rainfall intensity is **precisely 12 hours earlier on the sensitivity test than the control run**.

Furthermore, given the only change to the code was through altering the timing of solar radiation, we can infer that diurnally driven variations of solar radiation play an important role in the timing of Tropical Storm Erin's intensification. These rainfall rates can be visualized through the various subplots on Figure 6, which shows 3-hour rainfall at the latest timestep for each run's peak intensity compared to the corresponding run.

- At 22:00 UTC on August 18th, the control run (6a) shows significantly lower values than the sensitivity test. The sensitivity test (6b) shows most of the rain confined to the southeast quadrant of the TC and **significantly wider areas of heavier precipitation**.
- At 10:00 UTC on August 19th, the control run (6c) shows a significantly stronger signal for rainfall, centered primarily in the southeast quadrant. The shape of the rainfall accumulations is closer to the peak intensification of the sensitivity run (as compared on Fig 6e and 6f). The sensitivity test is significantly weaker at 10:00 UTC on August 19th than at 22:00 UTC on August 18th.

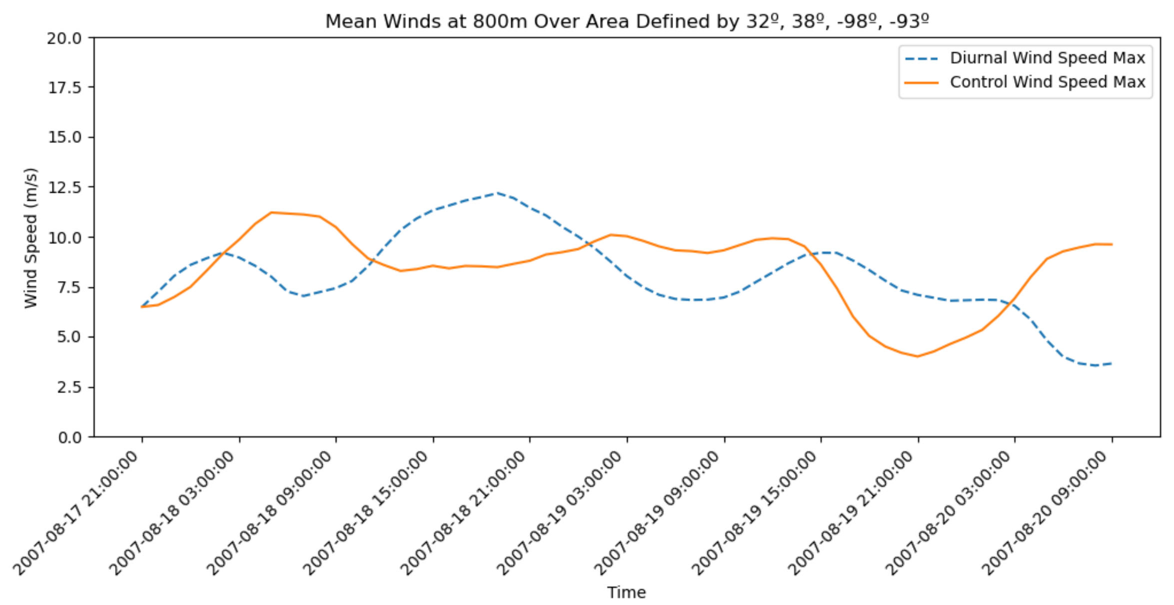

Fig 7. A cross section of the Great Plains Low Level Jet during Tropical Storm Erin's intensification. The wind speed values were averaged across the region for the control run (orange) and the sensitivity run (blue).

As a result, it can be inferred that the storms both intensified into TC systems offset by approximately 12 hours. While **these results are indicative of diurnal variability**, there are still questions on the role of the Great Plains Low Level Jet (GPLLJ) in the intensification of Tropical Storm Erin. The GPLLJ existed nocturnally over the region Tropical Storm Erin moved into and was responsible for some level of moisture advection. Offsetting the solar radiation results in an offset in the timing of the GPLLJ as well (Fig 7). As such, it is still unclear the relative magnitude the impact of the GPLLJ had on Tropical Storm Erin's overland intensification compared to tropical dynamics.

CONCLUSIONS

As a result of a simple code change which offset solar radiation by 12 hours, the timing of intensification changed from 06:00 UTC-10:00 UTC on August 19th, 2007 to 18:00 UTC to 22:00 UTC on August 18th, 2007. The new timing of intensification is approximately during the same solar timing, which indicates that there is a direct correlation between diurnally driven solar radiation and Tropical Storm Erin's intensification. While the role of the GPLLJ and the importance of shortwave cloud-radiative feedback remains to be determined, their similar influence from the diurnal cycle still allows for the conclusion that **the changing of the solar clock led to a change in the timing of intensification**, as verified through rainfall totals. The findings help strengthen that Tropical Storm Erin maintained its tropical characteristics through its overland intensification. Furthermore, given the framework used, it can be theorized that in tropical-like systems, the nocturnal preference for rapid holds true regardless of surface type. Future work should investigate similar landfalls using case studies or idealized model ensembles, as well as conduct larger scale data analysis on landfalling and post-landfall intensification timings to understand the frequency of this correlation. Additionally, studies investigating shortwave cloud-radiative feedback and separating surface forcing from the GPLLJ could further our understanding on the relative role of the diurnal cycle on Tropical Storm Erin's overland intensification.

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