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The Redevelopment of a Warm-Core Structure in Erin: A Case of Inland Tropical Storm Formation

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ABSTRACT

Remarkable radar and satellite images are presented to illustrate the unusual inland reintensification of Tropical Storm Erin over Oklahoma during the evening of 18 August 2007 to the early morning hours of the 19th. Using a blend of objectively and subjectively produced analyses, the authors document the warm-core nature of the disturbance as it reorganized. The evidence presented suggests that attention on such disturbances should remain under tropical forecasting domains, even though presently accepted conventions preclude assigning tropical storm nomenclature to such a system.

1. Introduction

During the evening of 18 August 2007 to the early morning of the 19th, former Tropical Storm Erin dramatically reintensified over Oklahoma (Figs. 1 and 2), after weakening considerably over west Texas and eastern New Mexico. The remnants of tropical cyclone (TC) Erin reintensified about 500 mi (~800 km) in linear distance from landfall, after traveling approximately 700 mi (~1100 km) on a curving overland path (Arndt et al. 2009).

Twenty-four hour rainfall totals of 4–8 in (10.2–20.3 cm) were common over most of central Oklahoma (Fig. 3). Maximum sustained winds of nearly 25 m s^{-1} (with gusts >33 m s^{-1}) were recorded by the Oklahoma Mesonet (Fig. 4). In addition, this stage of Erin's lifespan also yielded a cluster of severe thunderstorm events, including tornadoes and convective wind gusts (Fig. 5).

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Erin was not reclassified as a tropical storm by the National Hurricane Center (NHC) (Brennan et al. 2009; Knabb 2008). The stated reason was that organized convection associated with Erin's inland reintensification phase was not judged subjectively to have lasted long enough temporally, and that a baroclinic short wave trough was speculated to have influenced the redevelopment of the system. Brennan et al. (2009) also mentions that the primary forcing for redevelopment was not the extraction of heat energy from the ocean, and implied that the fact the storm did not redevelop over a tropical ocean was a factor in the terminology used to classify the storm.[1]

[1] http://www.nhc.noaa.gov/aboutgloss.shtml: "A warm-core non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center. Once formed, a tropical cyclone is maintained by the extraction of heat energy from the ocean at high temperature and heat export at the low temperatures of the upper troposphere. In this they differ from extratropical cyclones, which derive their energy from horizontal temperature contrasts in the atmosphere (baroclinic effects)."

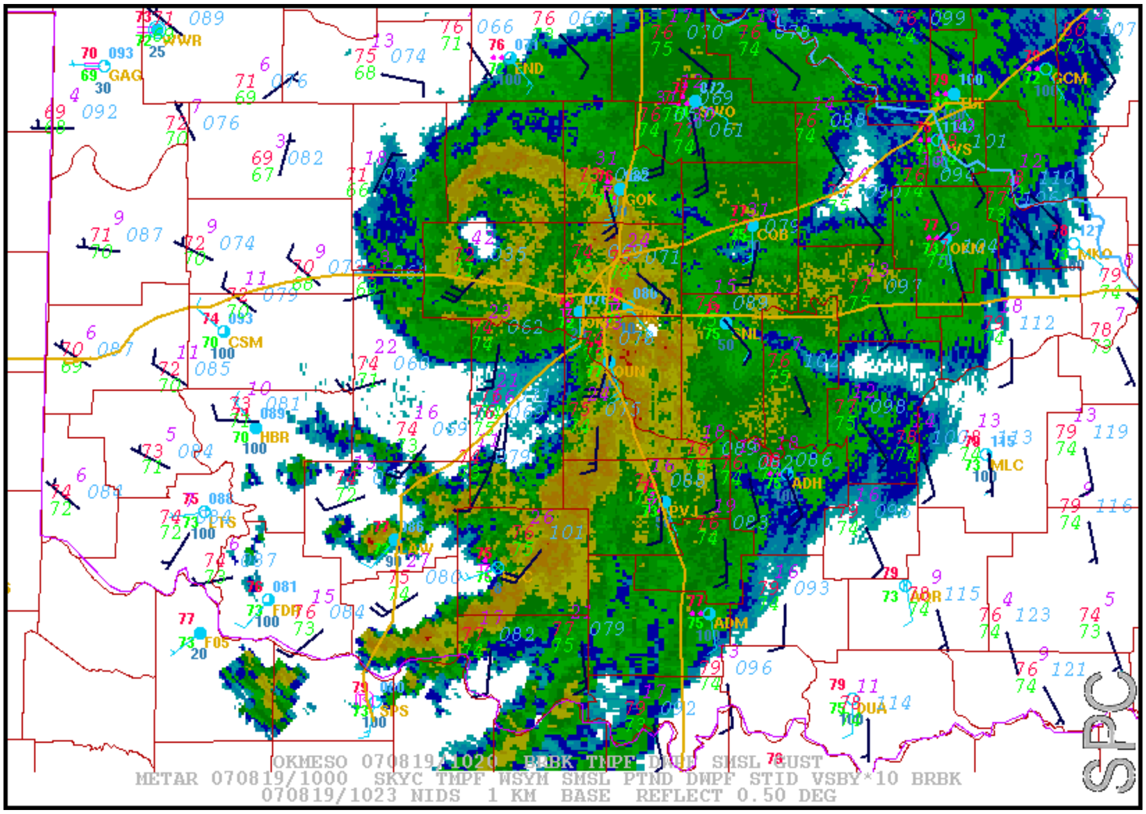

Figure 1. Base reflectivity (0.5° tilt) from KTLX (Oklahoma City WSR-88D) at 1024 UTC 19 August 2007, with conventionally plotted METAR and Oklahoma Mesonet surface data. Thermal quantities in °F. Wind barbs represent 10 kt (5 m s^{-1}). *Click image to enlarge. Click here for an animation from 0403-1330 UTC.*

A few tropical cyclones have maintained tropical storm intensity as far north as southern Oklahoma, including the Galveston storm of 1900 and Carla of 1961 (Jarvinen et al. 1984; data updates are available online via http://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html). TC Felice of 1970 produced damaging winds of 20-25 m s^{-1} in an eyewall-like feature documented by NSSL WSR-57 radar (Jessup 1971)[2]; however it is unknown whether this was a case of inland reintensification.

Previous studies (e. g., Bassill and Morgan 2006) have shown that when surface conditions over a continent are favorable, reformation of a tropical system can take place. Emanuel et al. (2008) described and modeled the inland reintensification of TC Abigail over Australia in 2001, containing a very similar precipitation geometry and eye as in Erin's Oklahoma stage, except in Southern-Hemispheric mirror image. However, documentation of such an extent of redevelopment in North America has been sparse. Monteverdi and Edwards (2008) suggested that during its transit across Oklahoma, Erin intensified its warm-core characteristics, and showed a radar and satellite evolution consistent with tropical cyclones.

The purpose of this manuscript is to extend the analyses in Monteverdi and Edwards (2008) and to further document the warm-core structure of Erin at the time of its redevelopment. Many of the features of the storm will be illustrated with unusual imagery. Using a blend of subjective and objective analyses, we will show that the redeveloped storm had a structure indistinguishable from that of a maritime tropical storm. The view of the authors on NHC's decision not to reclassify Erin as a tropical storm, as outlined in Knabb (2008), will also be presented.

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[2] HURDAT data, by contrast, classify Felice specifically as a tropical depression in Oklahoma, instead of either a remnant low or tropical storm.

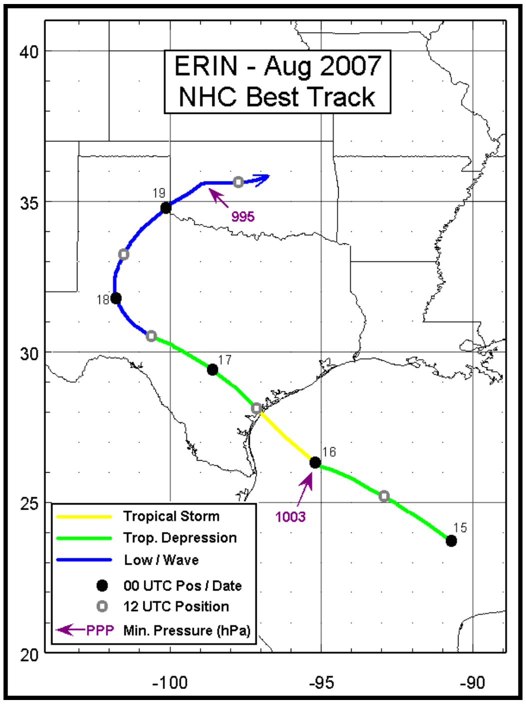

Figure 2. Track of Erin's center at 6 h intervals and NHC classification (see legend), 15–19 August 2007 (adapted from Knabb 2008). *Click image to enlarge.*

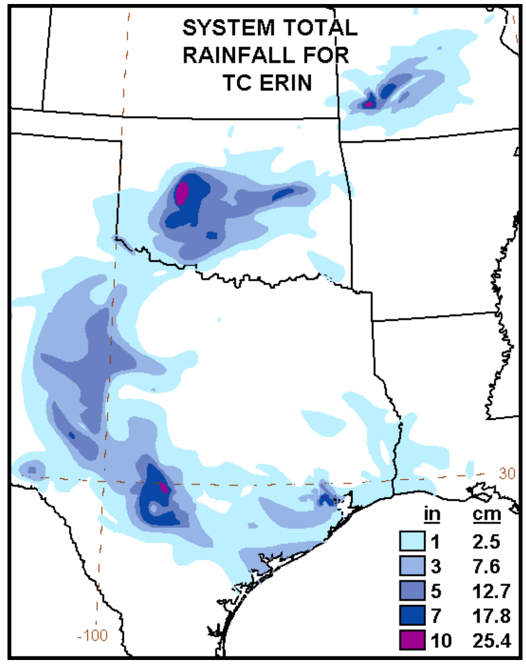

Figure 3. Total rainfall for TC Erin, 18–19 August 2007, per legend. Max record was 12.81 in (32.54 cm) near Eakly, OK, within the purple shading. Adapted from Hydrometeorological Prediction Center analysis.

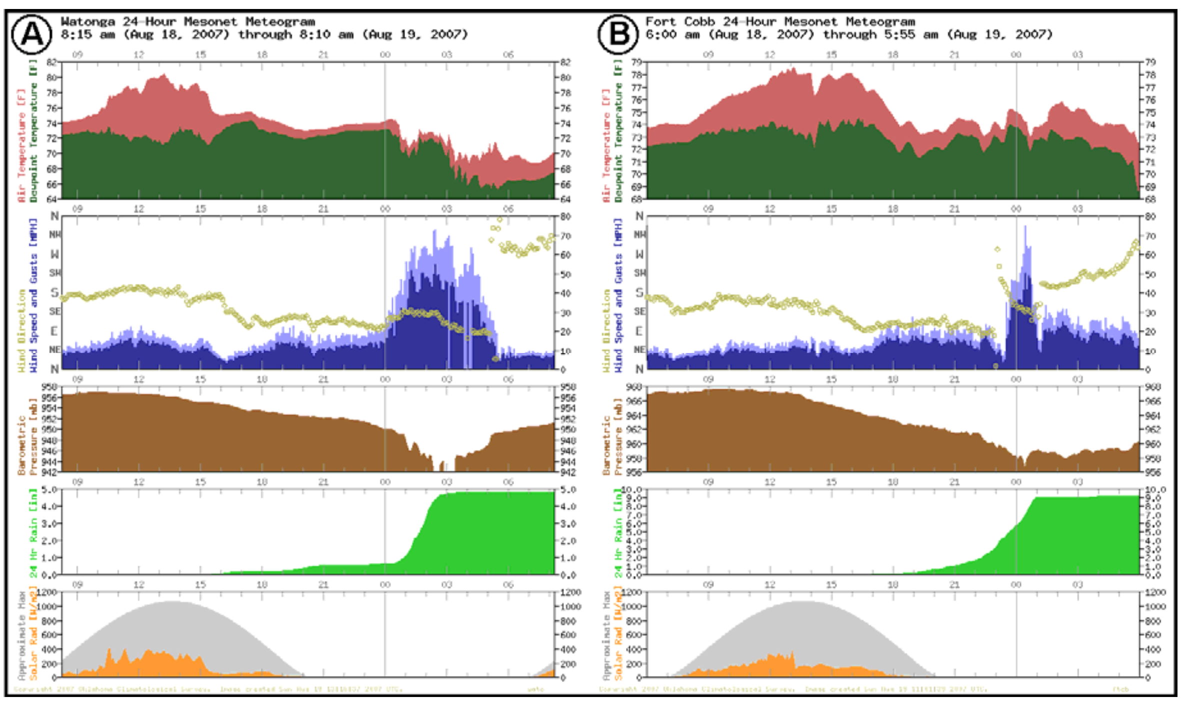

Figure 4. Oklahoma Mesonet meteorograms from a) Watonga and b) Ft. Cobb, OK, showing sharp pressure fall and strong wind shift between 1000 and 1300 UTC (0300 to 0600 CDT) as eye of redeveloped Tropical Storm Erin passed. Note gusts between 70–80 mph (31–36 m s^{-1}) at both locations. *Click image to enlarge.*

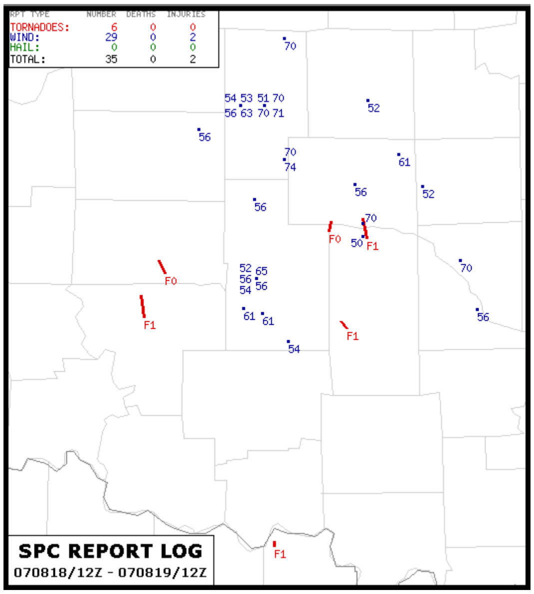

Figure 5. Map of severe local storm reports for 1200 UTC 18 August to 1200 UTC 19 August 2007. Red paths denote tornadoes translating primarily northward, with F (EF) Scale ratings. Blue dots signify convective wind gusts ≥50 kt (25 m s^{-1}) severe criteria, with values in kt. No hail reports occurred with this phase of Erin's lifespan. Data courtesy Storm Prediction Center. *Click image to enlarge.*

2. The reintensification of Erin

Arndt et al. (2009, hereafter A09) provided a detailed account of the unusual redevelopment of Erin over Oklahoma on 18–19 August 2009. In addition, we believe that this case is also singularly remarkable because it represents an example of the formation of a tropical storm over land, one with greater intensity than the oceanic TC ever had.

A09 indicated that key features in the redevelopment of Erin included latent heat release, both associated with local evapo-transpiration in the development area and with the moisture advection of air with high equivalent potential temperature (θ_e) into Oklahoma. These findings and speculations are consistent with those presented in Monteverdi and Edwards (2008).

However, Brennan et al. (2009) and Knabb (2008) concluded that the redevelopment of Erin over Oklahoma was consistent with that expected of a tropical system in an intermediate stage in a transition to becoming a baroclinic disturbance. There were several key issues that Brennan at al. (2009) suggest were fundamental to the redevelopment. They stated:

"…The upper-level forcing was apparently a dominant mechanism, but since the system was clearly nonfrontal over Oklahoma, designating it as an extratropical cyclone is the most appropriate solution…."

Knabb (2008) also stated:

"…The upper-level forcing was apparently a dominant mechanism, which is in contrast to tropical cyclones that are maintained primarily by extraction of heat energy from the ocean….".

Leaving aside a discussion of the details of these explanations, we simply note that much of the preliminary evidence presented in Monteverdi and Edwards (2008) contradicted the notion that some sort of transition to an extratropical system explained Erin's behavior. A detailed examination of Erin's structure while the storm was over Oklahoma would clarify these issues. But we must also note the allusion to the source for the energy fueling tropical storms, as stated by Knabb above, namely the heat energy (i.e., of latent heat) from the ocean. We believe this is a key point.

3. Essential features of warm-core systems

Tropical cyclones contain sea level expressions of warm-core systems. As such, they have a three-dimensional structure consistent with the classical surface thermal low, as outlined in many textbooks [e.g., Bluestein (1993, pp. 187–188)] and in many observational studies (e.g., Hawkins and Rubsam 1968).

Palmén and Newton (1969, p. 369) state unequivocally, "…the formation of a warm core is the first decisive sign of tropical cyclone formation…." While alluding to the linked role of sea surface temperature fields, and the excessive boundary layer water vapor associated with evaporation off a deeply mixed tropical ocean, they do not mention the formation of such systems over tropical ocean areas as a necessary condition for the usage of the terminology "tropical cyclone."

The three-dimensional characteristics that distinguish warm-core from baroclinic systems have been documented in many studies (e.g., Bosart and Bartlo 1991). Warm-core systems tend to be associated with: a) surface low pressure areas weakening with height; b) collocation of lows in the mid to lower troposphere with thickness ridges or tongues, θ and θ_e maxima, and surface temperature maxima; c) collocation of surface mass divergence fields with the center of the cyclones at each level in the troposphere; d) a vertical "stacking" of the lows at successive height levels; and e) a weakening wind field with height.

4. Radar and satellite signatures of warm-core structure

Erin developed an eye about the time that near-hurricane force winds were observed (Figs. 1, 6 and 7). The radar and infrared-satellite presentations of Erin during the period from 0000–1100 UTC 19 August 2007 were consistent with the formation of strong convection and rapid surface development documented for developing tropical systems (e.g., Zehr 1987). Expansion and cooling of cloud tops occurred for nearly nine hours through 0840 UTC, with warming from ~1040 UTC onward (Fig. 6). The near-explosive generation and expansion of the area of coldest cloud tops was simultaneous with reintensification of the surface cyclone (seen below).

Radar imagery (Fig. 7, animation of Fig. 1) clearly shows an eye in the reflectivity field at the same time the storm strongly reintensified with a warm-core structure. This was the only time during the system's lifespan, whether oceanic or overland, that a closed eye clearly appeared. Plotted METAR and Oklahoma mesonet surface data (Figs. 1 and 8) illustrate the closed wind circulation collocated with Erin's eye.

5. Evidence of warm-core structure

At the surface (Fig. 8), except for the storm-scale cold pools generated by convection around the center of the storm (and evidenced by the outflow boundaries), the temperature field indicates that the cyclone had a warm-core. Despite the relatively high ambient relative humidity and θ_e of tropical cyclones (TCs), cold pools have been documented to develop within spiral rainbands of hurricanes over water, e.g., the ~12 K subcloud-layer θ_e deficits found by Barnes et al (1983). The presence of convective cold pools, therefore, does not preclude tropical character or classification of the TC; though aggregate, upscale cold pool growth on the meso-β scale may have contributed to ultimate weakening after 1200 UTC.

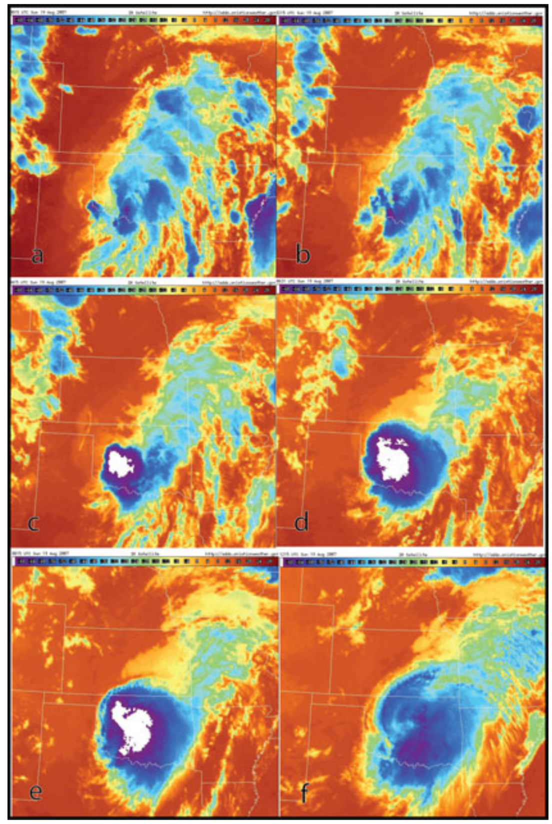

Figure 6. Enhanced infrared satellite images at: a) 0040, b) 0240, c) 0440, d) 0640, e) 0840, and f) 1040 UTC 19 Aug 2007, thermal scales in ºC. Expansion and cooling of cloud tops occurred through 0840 UTC, with warming from about 1040 UTC onward. Courtesy Aviation Weather Center. *Click on image to enlarge.*

Trajectories computed using the HYSPLIT (Draxler and Rolph 2003) model with parcel-following relative humidity (RH) (e.g., Fig. 10) indicate that parcels entering the circulation of the storm, when it was over southwestern Oklahoma, had been moist for their entire paths from the Gulf coast area and northern Texas into the core region of Erin. The ending time and location of the trajectory shown (1000 UTC 19 August at Oklahoma City, east of the center) were chosen to match most closely the formation of the radar eye seen in Fig. 6 and to represent the immediate inflow sector of Erin. One easily can infer the three prior diurnal heating cycles in the along-trajectory RH calculations. Even at 18 UTC the day before, when the parcel appeared to be in a pronounced RH dip related to diurnal heating, values remained above 60%; and the parcel RH remained between 75%–90% for most of the 72 h prior to its arrival in Erin's core region. This analysis is consistent with what is expected in the spiral arms of convection of a developing tropical system (Barnes et al. 1983; Powell 1990).

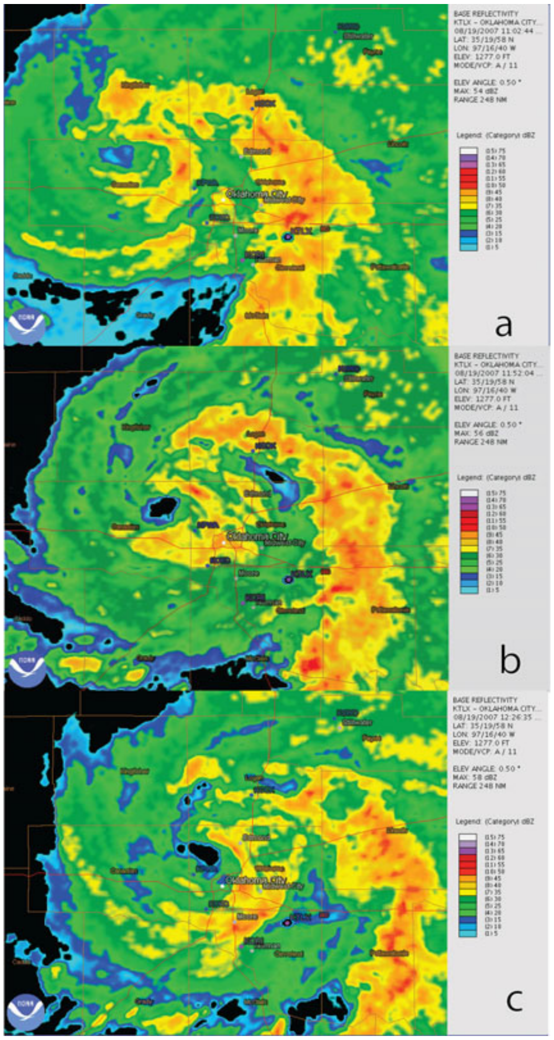

Figure 7. (Base reflectivity (0.5° tilt, values in legends) from KTLX for a) 1102, b) 1152 and c) 1224 UTC, representing snapshots of the evolution of the precipitation-free eye of TC Erin over central Oklahoma. *Click image to enlarge.*

Other trajectories, also for 72 h prior, were run at 1000 UTC from within 1º latitude and longitude north, west and south of center, as well as for the eye position (not shown). All trajectories indicated that the parcels traveled from within the antecedent, tropically characterized, boundary-layer air mass across eastern Texas, Louisiana and the northwestern Gulf of Mexico, with diurnal oscillations of RH along the overland segments of the trajectories.

By contrast, similarly positioned trajectory analyses relative to Erin's center, near its westernmost inland position at 0000 UTC 18 August (not shown), depicted increasing parcel RH with each nocturnal-diurnal cycle, following overland paths from central Texas. Parcels originating 72 h earlier (00 UTC 15 August) had their source within a drier continental air mass that preceded the influx of tropical air into the region; this influx of tropical air was associated with Erin itself. These analyses and surface observations also indicate that, through fortuitous geospatial geometry, Erin left behind the maritime tropical air mass accompanying its landfall, then reacquired it via long-trajectory inflow over favorably moist terrain once the system recurved eastward over Oklahoma.

To assess environmental and thermal-core characteristics more thoroughly over the region, subjective hand analyses were performed of mandatory-level upper-air observations at those synoptic rawinsonde release times bracketing Erin's inland intensification phase: 0000 and 1200 UTC 19 August 2007 (i.e., Fig. 11 and accompanying link). The actual subjective analyses are reproduced here for accuracy. Warm-core character was indicated strongly at 500 hPa. Erin was at least 700 km away from the closest midlatitude shortwave perturbations (over the Dakotas and northern Nebraska) of clearly baroclinic character (e.g., those involving baroclinicity evident at 700 hPa at 0000 and 1200 UTC). The 700-hPa analysis, with supplemental profiler and radar winds, shows a low over the eastern Texas Panhandle, close to the surface cyclone center. This strongly contrasts with the low position northwest of Amarillo that is implied by objectively analyzed 700-hPa isohypses in Fig. 5b of Arndt et al. (2009), depicting a closed contour over the northwestern Texas Panhandle and western Oklahoma Panhandle.

The nearest lower-tropospheric (e.g., 925 and 850 hPa) frontal zones at each synoptic time were ~900 km poleward from Erin's center position, indicating a distinct lack of baroclinicity associated with Erin. Lower- to middle-tropospheric moisture (e.g., dewpoints at 925–500 hPa levels) also was maximized in and near Erin, as should be expected with a tropical cyclone.

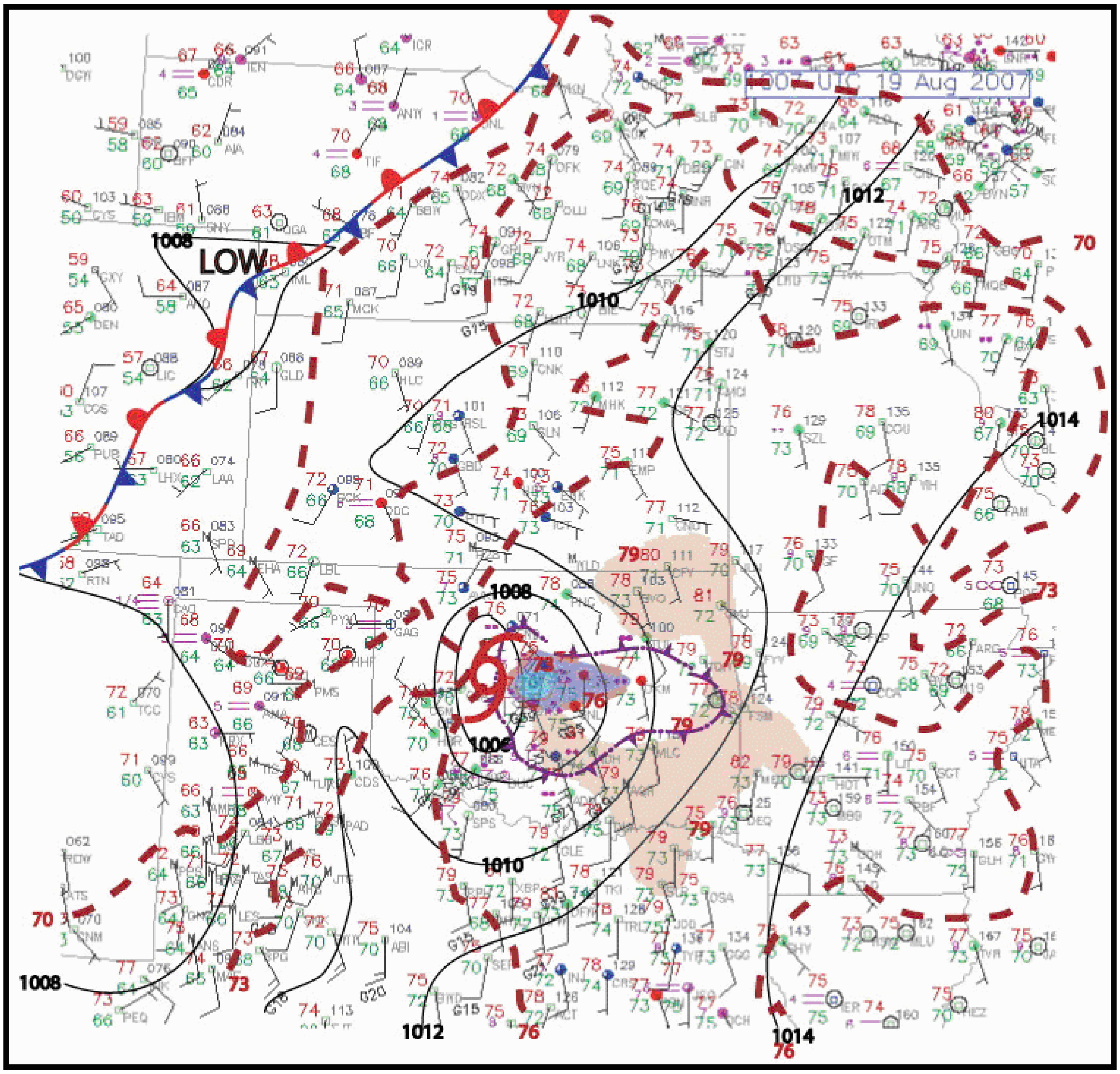

Figure 8. Subjective analysis of isobars (black) and isotherms (dashed red) at 1007 UTC 19 August 2007. Red shading indicates area with temperatures exceeding 79 ºF (26 ºC); blue shading outflow pool with temperature less than 73 ºF (23 ºC). *Click image to enlarge.*

At 250 hPa, a subtle trough is evident in cyclonically curved flow from near Erin northward across the central plains states at 0000 UTC 19 August 2007. The northern portion of this trough merged with the prevailing westerlies and moved eastward across Iowa at 1200 UTC. This feature also appeared to be warm-core in character, especially at 1200 UTC when 250-hPa thermal ridging could be ascertained very near the cyclonically curved streamline perturbation.

Using the North American Regional Reanalysis (NARR, see Mesinger et al. 2006) 32-km gridded data set[3], the authors constructed a number of charts that illustrate the degree to which the reinvigorated Erin had a structure consistent with that of a tropical system with warm-core characteristics (Fig. 12). For example, the center of the surface cyclone was associated with a maximum in the precipitable water (PW) field [>60 mm) (Fig. 12a)], in contrast to the typical asymmetry in PW fields for baroclinic and frontal cyclones. The maximum in the PW field also was collocated

[3] Available from NCEP at: http://nomads.ncdc.noaa.gov/data.php?name=access#narr_datasets

with that in the 700-hPa vertical velocity field, and was located ~80 km from a 57 mm PW observed by the 0000 UTC 19 August rawinsonde at Norman (not shown).

Peaks in the θ (Fig. 12b) and surface mass divergence (Fig. 12c) fields were collocated with the center of the surface cyclone at each analysis level, with no evidence of the tilt one would expect of a baroclinic system. Finally, there was no evidence of the transition to baroclinic processes that often characterize tropical systems evolving away from barotropy (Fig. 13). This is consistent with subjective analyses of in situ observations, as on the upper-air charts discussed above.

6. Thermodynamic structure

Soundings and hodographs, both prior to and following the passage of the storm, closely resembled composite soundings for tropical cyclone environments. This was evident in observed soundings for Norman at 0000 UTC and Lamont, OK at 0600 UTC, as well as Rapid Update Cycle (RUC) model soundings sampling the system throughout its passage across western and central Oklahoma (not shown). The Advanced Regional Prediction System (ARPS, after Xue at al. 2000) Data Analysis System (ADAS) sounding at Oklahoma City (OKC) shown in Fig. 14b corresponded very closely to the composites for the right-front quadrants of slow-moving, tornadic tropical systems (Fig. 14a from McCaul 1991).

Strong veering of both the wind and wind shear vectors occurred with height through the lowest 3 km. The environmental lapse rate was nearly moist-adiabatic, accompanied by surface-based CAPE of ~1500 J kg^{-1} (Fig. 14) overnight.

During the ~10 h of Erin's transit over Oklahoma, a blend of surface observations and observed and model soundings (cf. Figs. 9, 11 and 14) depicted wind fields in Erin's Oklahoma stage that generally were strongest near the ground and weakening with height, as is expected for warm-core lows.

7. Reclassification of Erin

Erin's Oklahoma stage, as documented in preceding sections, exhibited many characteristics associated with warm-core systems documented in many studies (e.g., Bosart and Bartlo 1991). The authors believe that the forecasting issues associated with the redevelopment of such systems center on the ingredients that are documented as causative.

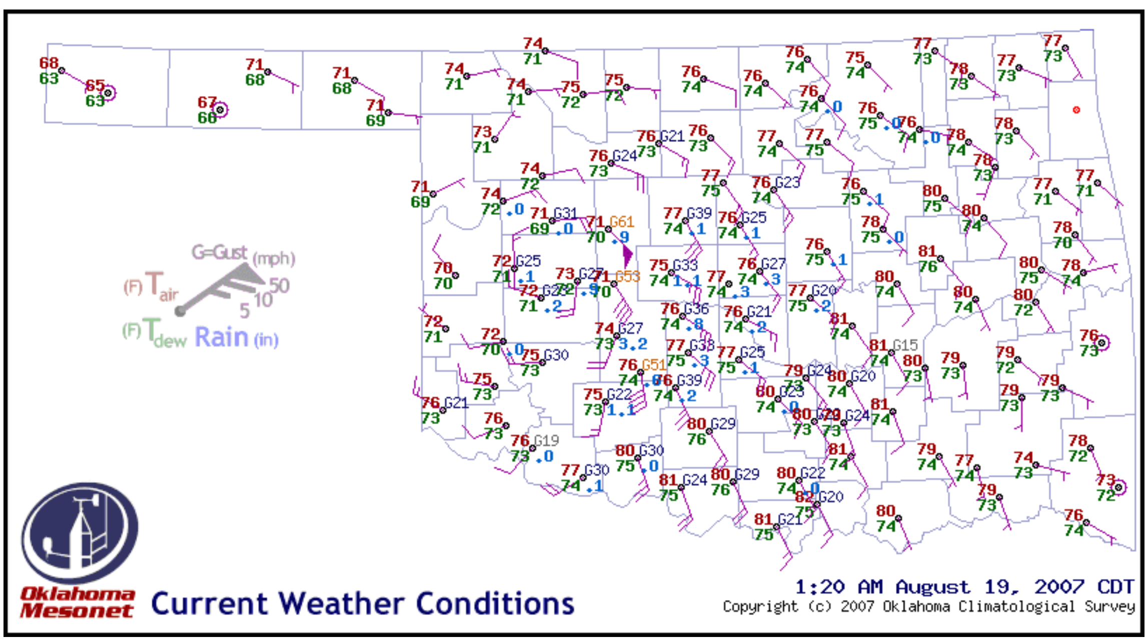

Figure 9. Conventional plot of Oklahoma Mesonet observations at 0620 UTC 19 August 2007. Wind barbs represent gusts in mph per legend, with temperature and dew point values in °F. *Click image to enlarge.*

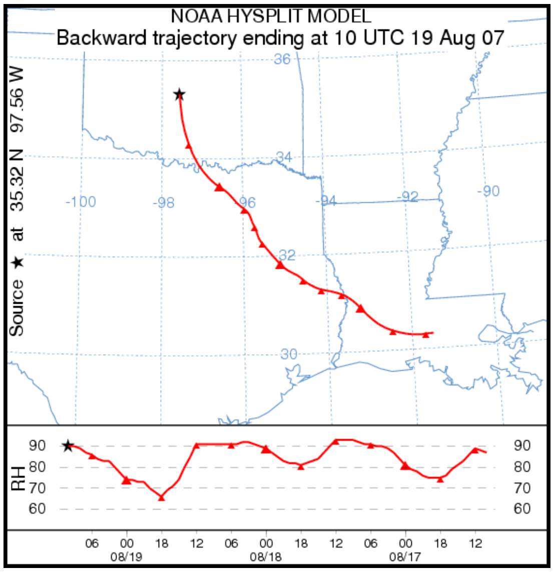

Figure 10. 72 h backward trajectory analysis (tick marks at 6 h intervals) of the 10 m AGL (surface) parcel, ending at the star (Oklahoma City) at 1000 UTC 19 August. The underlying graph, read from right to left, shows relative humidity of the parcel with time following the trajectory, with tick marks corresponding to those on the planar map. Courtesy NOAA. *Click image to enlarge.*

In this case, while the essential tropical nature and history of the disturbance were keys, the attention of forecasters should be drawn to the causes for the warming that reinvigorated the warm core, and not to the geography over which such warming occurred.

The issue of the nomenclature used to characterize this storm, we believe, is now settled. We maintain that the boundary layer, for all practical purposes, was indistinguishable from that over the surface of the Gulf of Mexico, and that the storm did have a warm core aloft as well. As such, we believe that our analyses show that the distinction between the boundary-layer source of the warming responsible for the intensification of this tropical disturbance should not have been a meteorologically relevant criterion in the nomenclature applied to this storm.

Finally, in both Brennan et al. (2009) and Knabb (2008), the issue of how long the reintensified Erin remained at tropical storm strength was raised, alluding to the few hours during which the storm had tropical storm characteristics, as evidenced by strong convection,

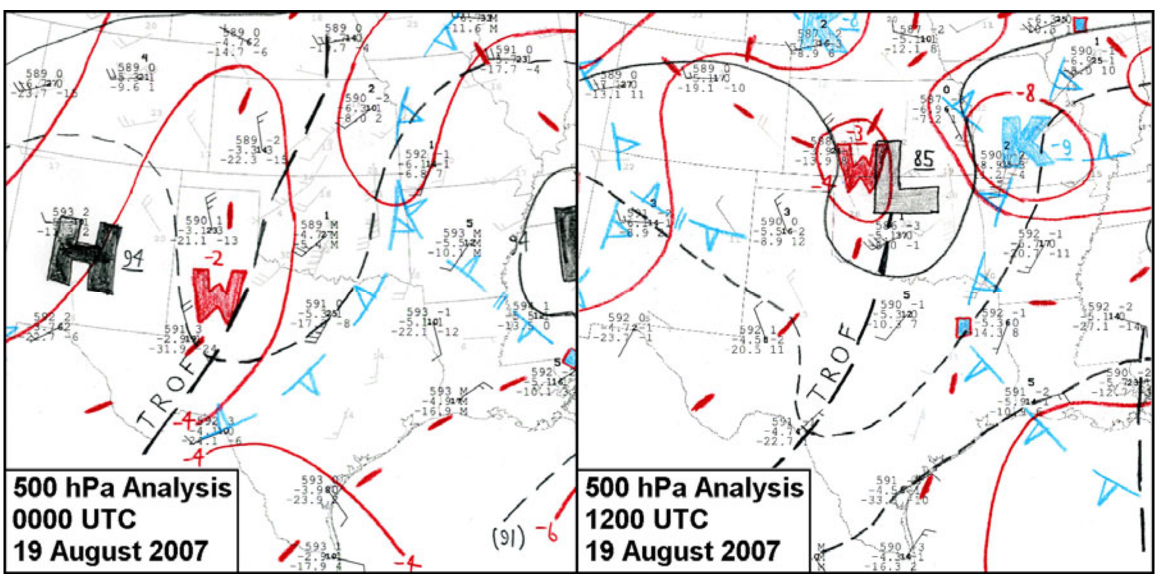

Figure 11. Manual 500-hPa analyses as labeled with conventional rawinsonde station plots, covering south-central U.S. region, 0000 UTC 19 August 2007. Gray-shaded wind plots represent profiler data and WSR-88D velocity-azimuth display (VAD) winds. Solid isohypses drawn at 6 dam intervals, intermediates dashed, height troughs labeled. Isotherms in red at 2º C intervals. Thermal troughs in open blue pips, with minima labeled **K**. *Click image to enlarge.* Click here for complete sets of hand-analyzed, mandatory-level charts for both synoptic times, covering a larger domain over the southern and eastern U.S.

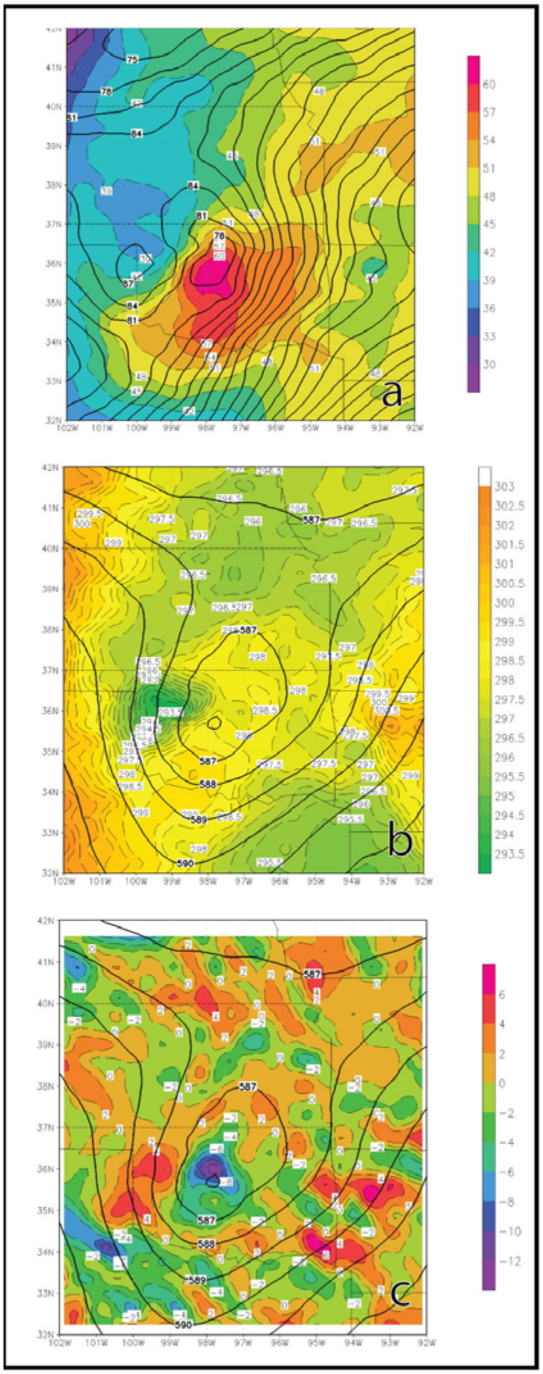

Figure 12. Plots obtained by NCEP Reanalysis for 1200 UTC 19 August 2007 of a) 1000-hPa heights (m) overlain with total precipitable water in the column from the surface to the top of the atmosphere (mm); b) 500-hPa heights (dam) overlain with θ (K); and c) 500-hPa heights (dam) overlain with 1000-hPa divergence ($10^{-5}s^{-1}$). *Click image to enlarge.*

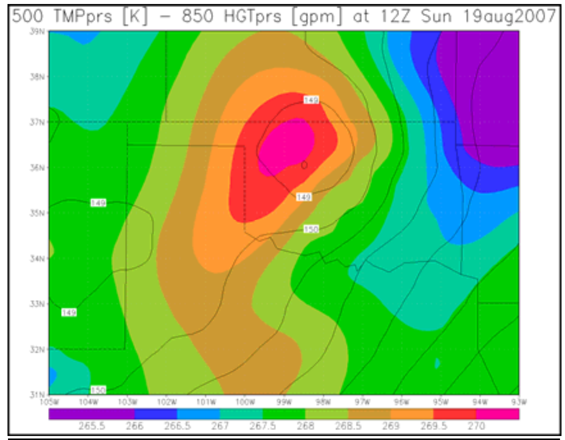

Figure 13. 500-hPa temperatures ($^{\circ}$C) and 850-hPa heights (dam) at 12 UTC 19 August 2007, obtained by NCEP Reanalysis. Note the collocation of the warmest temperatures 500-hPa temperatures with the lowest heights at 850 hPa (and other lower levels, not shown). *Click image to enlarge.*

as a prime reason why it was not reclassified. Since we are viewing this issue from the perspective of operational forecasters attempting to diagnose the pattern as it was developing, we point out that there is no way to forecast infallibly how long Erin would have remained at tropical storm strength, nor whether the nearly nine hours of explosive convective development would have continued. With the benefit of hindsight, of course, one knows that was just nine hours. However, at the time of the redevelopment, in our opinion, Erin should have been reclassified a tropical storm on the basis of the meteorological ingredients.

8. Conclusions

Erin was not reclassified a tropical storm chiefly because the reintensification to that level was relatively short-lived and presumably was related to a stage in the transition of the storm from a warm-core to a baroclinic system. Yet the storm had pronounced warm-core structure and had developed radar and satellite characteristics of a tropical system.

A09 hypothesized that the widespread flooding and saturated ground observed over Oklahoma during the extended period prior to Erin's arrival provided a continental thermodynamic environment resembling that of

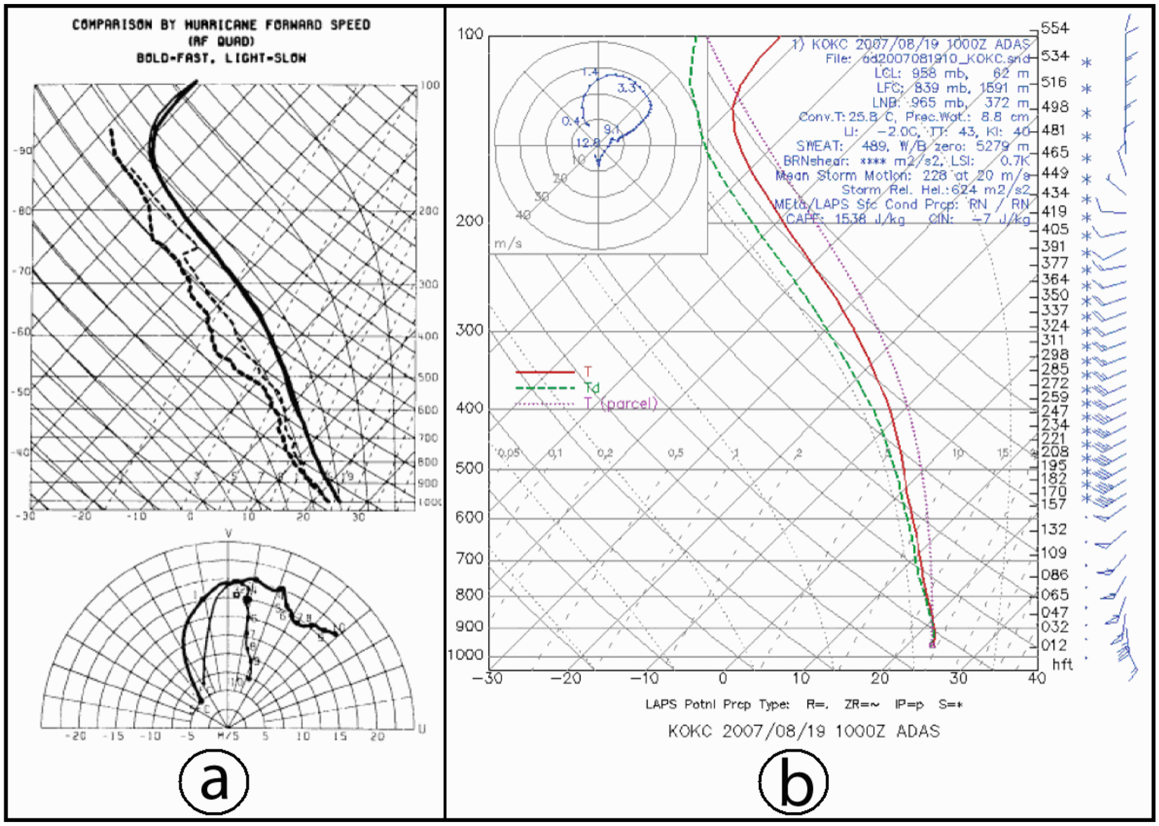

Figure 14. a) Composite soundings and hodographs for right-front quadrant of landfalling tropical systems (from McCaul 1991) (bold—fast moving systems; light—slow moving systems); and b) ADAS sounding and hodograph for KOUN (Norman, OK) at 1000 UTC 19 August 2007. *Click image to enlarge.*

the warm, tropical ocean surface. Additionally, trajectory modeling indicates such an air mass originated upstream from the soaked Oklahoma soil and over the Gulf coastal region of Louisiana and eastern Texas, neither requiring nor experiencing appreciable modification along the way. This contrasts with the earlier, westernmost phase of Erin's Texas track, where initially drier parcels that flowed into Erin may have contributed to its weakened state preceding reintensification. As such, we believe that the combination of these factors favored a period of inland behavior characteristic of an immature but deepening tropical cyclone over water, with latent heat release the main culprit for Erin's redevelopment and marked intensification, further supporting the conclusion of A09 in that regard.

The authors believe that the classification nomenclature applied to this storm is an important issue. Severe storm forecasters and hurricane forecasters alike need to be aware of the meteorological concerns associated with possible reintensification of tropical systems over land. The issues associated with such systems go beyond those associated with heavy rainfall (i.e., quantitative precipitation forecasting and flash flood guidance) and should include those related to damaging gradient winds away from the core region, severe local storms associated with convective bands, and nearly hurricane strength sustained winds around the eyewall. In short, attention on such storms should remain under tropical forecasting domains, even though conventional wisdom suggests that they are no longer a concern.

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Jeffrey B. Basara):

Initial Review:

Recommendation: Accept with minor revision

General Comments: The authors present a manuscript that documents the warm-core structure associated with the remnants of Tropical Storm Erin. The Erin event was quite unique in that not only did regain tropical storm intensity over land, it gained an intensity greater than observed over water. Overall, the manuscript is well written and the authors thoroughly document their assertion (via results and appropriate citations) that the reintensification of Erin was warm-core in nature. Further, the authors note that the scientific literature provides no firm justification for not classifying the event as tropical in nature and a continuation of the Erin name through its reintensification across Oklahoma. Even so, a number of questions suggested revisions are provided to assist the authors in improving the manuscript prior to formal publication.

Main Comments: The authors have demonstrated through their analyses that the structure of Erin over Oklahoma was warm core in nature, vertically-stacked, and that the low-level air mass was pseudo-tropical in characteristics. However, the confounder regarding Erin is not necessarily its reintensification over Oklahoma, but why it traversed west Texas with little sign of convective redevelopment. To strengthen the arguments provided by the authors, some analysis/discussion should be provided for the period between when Erin made landfall and prior to reintensification. In other words, what was missing in Texas that was suddenly available as Erin traversed Oklahoma? Why did Erin suddenly erupt with significant convection and redevelop low-level tropical characteristics? Can the authors provide insight as to why Erin suddenly weakened over eastern Oklahoma as quickly as it reintensified?

We understand the need for a careful post-analysis of this case, including the issues surrounding the early history of the storm when it crossed the coast into Texas and the reasons why it weakened after it left Oklahoma. However, this manuscript was designed to address one issue and one issue alone, namely, the evidence that suggested that the storm should have been reclassified a tropical storm when it was over Oklahoma, and the subsidiary issue, whether the reasons it was not reclassified as such were correct. Those are the limits we set for ourselves, and we feel we have addressed the issues within those limits.

However, if the editor feels that we should expand the study and include additional analyses, then we will do so.

The authors present a backwards trajectory analysis for the warm sector of the Erin when it is near maximum intensity over Oklahoma. Have the authors (a) constructed similar analyses for other quadrants of the storm and located their source regions and (b) for specific temporal periods along Erin's path (e.g., prior to reintensification, at the onset of intensification, and during its weakening in northeast Oklahoma)? Such analyses might better explain the rapid onset on convection that increased the intensity of Erin?

That's an excellent point; and indeed, they could provide additional insight. While not presented as extra figures at this time due to space considerations, we have constructed HYSPLIT backward trajectories both from other sectors of the Oklahoma phase, and from near the westernmost inland apex of Erin's track over west Texas, during its comparatively weak phase. Those now are summarized in the text. If the reviewers wish, we could add another figure, but haven't yet, given the high figure-to-text ratio already.

The authors provide an assessment of the vertical wind structure via surface observations, upper-air analyses, and soundings to note that wind speed decreased with height consistent with tropical systems. Did the authors examine profiler observations across the region which provides increased spatial and temporal data during the critical phases of Erin's transitions?

Yes, as well as VAD wind profiles. These were reasonably consistent also. In fact, the Purcell profiler fortuitously was well-located for its sampling period, being in the near-southeastern inflow regime, and sampling a portion of the low-level jet, above which winds weakened markedly with height. Vici, by contrast, was rather unrepresentative in our judgment; as it was located farther away and to the NW, and well-removed from the strongest low level pressure gradient and wind fields that could be used to assess near-core vertical kinematic structure. We could insert some brief mention of this if you deem it worthwhile.

From a forecasting perspective, Erin posed many challenges as it was never forecast or expected to intensify as rapidly or as strong as it did in Oklahoma. At the same time, the authors point out that such systems should receive consistent "tropical" monitoring whether over water or over land. In all fairness, Erin was highly disorganized for nearly two days before suddenly and unexpectedly reintensifying. How then, in practice, can such monitoring occur for such extremely rare events? Do the authors have specific recommendations to provide as to how this could occur in an operational setting?

We agree, the forecast challenge here would be non-trivial, both from a purely meteorological perspective and from the standpoint of proper products and issuance jurisdiction. We didn't touch on the latter in more extensive detail, because such a discussion (while probably needed in some forum or another) easily could wander off into policy matters that arguably are too tangential with respect to the more meteorologically focused scope of this paper. The end of Section 7 elaborates on this briefly.

[Minor comments omitted...]

REVIEWER B (Christopher W. Landsea):

Initial Review:

Reviewer recommendation: Accept with minor revisions

General Comments: This is a provocative manuscript that makes the case that the inland low associated with the remnants of Erin was a true tropical storm. The authors articulate some important points that are worth publication. There are a few comments included below for the authors to consider. I would suggest that the editors offer Knabb (or Brennan et al.) the opportunity to provide official "Comments on…" either at the same time or shortly after this piece is published in EJSSM.

Substantive Comments:

Page 1: "after apparently dissipating (Figs. 1 and 2) over west Texas and eastern New Mexico". Unless the authors provide evidence to the contrary, the Erin low did remain intact (Knabb 2008) over western Texas.

That's right; and we've changed the wording accordingly to "after weakening considerably".

Pages 2 and 4: The key reason for NHC not officially including the Oklahoma reintensification phase as a tropical cyclone was the very short time scale involved (Knabb 2008 and Brennan et al. 2009). The fact that the reintensification occurred over land was not a factor in NHC's decision (Knabb 2008 and Brennan et al. 2009). Please correct your writeup on both pages 2 and 4 to reflect this.

The reviewer states that the fact that reintensification occurred over land was NOT a factor in NHC's decision not to reclassify Erin as as a tropical storm. Yet, Knabb (2008), referenced by us in the manuscript and the reviewer above, states:

> "…The upper-level forcing was apparently a dominant mechanism, which is in contrast to tropical cyclones that are maintained primarily by extraction of heat energy from the ocean….".

and

> "..A tropical cyclone is defined by NHC as "a warm-core, non-frontal, synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center."…"

In both sentences cited above, the allusion to the role of the ocean in contributing to the factors leading to tropical storm formation appears to be key. It's difficult to ignore that the classification issue did not at least in part relate to the fact that the reintensification occurred over land, rather than the ocean, given the fact that Knabb (2008) specifically implies that development over an ocean is a criterion.

Also, the role of the tropical ocean characteristics in the development of tropical storms and hurricanes is outlined in several places on the NHC website, with several references therein specifically mentioning this (e.g., Gray 1979). For example, according to Holland (2003), referenced on the National Hurricane Center website here (http://www.aoml.noaa.gov/hrd/tcfaq/A1.html):

> "…Each ocean basin has operational criteria for tropical cyclone formation. These must be monitored and appropriate administrative and procedural steps taken when they are reached….."

While we understand that there may not be a stricture forbidding use of the term "tropical storm" for a warm-core disturbance over land, operationally it may be that forecasters' attention is drawn away from such storms if they are NOT over tropical oceans. We believe that the citations above strongly suggest that the lack of underlying ocean surface may have been a concern as applied specifically to Erin's classification; nonetheless, we have reworded those sections a bit.

Page 3: "We maintain that the boundary layer, for all practical purposes, was indistinguishable from that over the surface of the Gulf of Mexico." It may be difficult to back this statement up. Figure 8 shows a substantial cold surface outflow pool in the immediate vicinity of the Erin low. Over the ocean, such cold pools are quickly eroded by sensible heat fluxes from the huge reservoir of very warm waters above the ocean's thermocline. In contrast, over land, such cold pools can be very problematic in allowing continuing maintenance of deep convection, by shutting off the low-level thermodynamical support as there is essentially no sensible heat flux from the shaded, rain-cooled ground. Could it be that this cold pool was one of the reasons, if not the crucial reason, for the very short-term nature of the intensification of this inland low? Please discuss.

Good point. Without trying to get too speculative, brief mention of this possibility as been inserted into the first paragraph of Section 5, since the observational evidence does exist at the surface to support some upscale/mesoscale cold pool development from ~1200 UTC onward.

The discussion of warm core should also reference [former] figures 11 and 13, as these help demonstrate the warm-core structure aloft.

We have reorganized the material in these sections, and moved some material to different sections, partially to collect our conclusions and present them towards the end, and also to make the arguments on the warm core more cogent.

Most tropical cyclones have a negligible surface warm core. The main warm core is found in the mid and upper troposphere. (And you do show warm core aloft for the low in figures 11 and 13.)

Agreed. Still, it is true that most tropical cyclones have at least an geographically isothermal, somewhat warmer core at the surface.

References for responses to Reviewer:

Brennan, M. J., R. D. Knabb, M. M. Mainelli, and T. B. Kimberlain, 2009: Atlantic hurricane season of 2007. Mon. Wea. Rev., 137, 4061–4088.

Gray, W. M. 1979: Hurricanes: Their formation, structure and likely role in the tropical circulation. Meteorology Over Tropical Oceans, D. B. Shaw, Ed., Roy. Meteor. Soc., James Glaisher House, 155–218.

Holland, G. J., 1993: Ready reckoner. Global guide to tropical cyclone forecasting, WMO/TC–No. 560, Rep. TCP-31, World Meteorological Organization; Geneva, Switzerland.

Knabb, R. D., 2008, cited 2009: Tropical cyclone report: Tropical Storm Erin (AL052007), 15–17 August 2007. [Available online at http://www.nhc.noaa.gov/pdf/TCR-AL052007_Erin.pdf.]

References:

Atlantic Hurricane Season of 2007
Michael J. Brennan, Richard D. Knabb, Michelle Mainelli, and Todd B. Kimberlain
Monthly Weather Review
Volume 137, Issue 12 (December 2009) pp. 4061–4088
DOI: 10.1175/2009MWR2995.1

[Minor comments omitted...]

Second review:

Recommendation: Accept.

REVIEWER C (Michael J. Brennan):

Initial Review:

Recommendation: Accept with minor revisions.

General Comments: The authors present observational evidence that Erin developed a warm-core structure as it re-intensified over Oklahoma on 18-19 August 2007. Additionally, the authors assert that Erin should have been classified as a tropical cyclone both operationally and in post-storm analysis by the National Hurricane Center. While much of the evidence and results shown by the authors has already been published in the literature, particularly by Arndt et al. (2009), the evidence and results here compliment and build upon that previous work.

I have a few points I would like to see addressed before the manuscript is accepted, but most of the revisions are relatively minor.

Major Comments:

1. End of page 3 and end of section 2 on Page 4: Here the authors assert that Erin should have been classified as a tropical cyclone both operationally and in post-analysis by NHC. However, these comments are made prior to the presentation of any supporting evidence by the authors. I have no problem with the authors stating their opinion about this issue, but I think it should be done in the "Conclusions" section, or at least after the supporting evidence of Erin's structure and re-intensification process are presented.

We agree. On the basis of the reviewer's comments, we have substantially revised the manuscript, and created a separate section in which these issues are addressed.

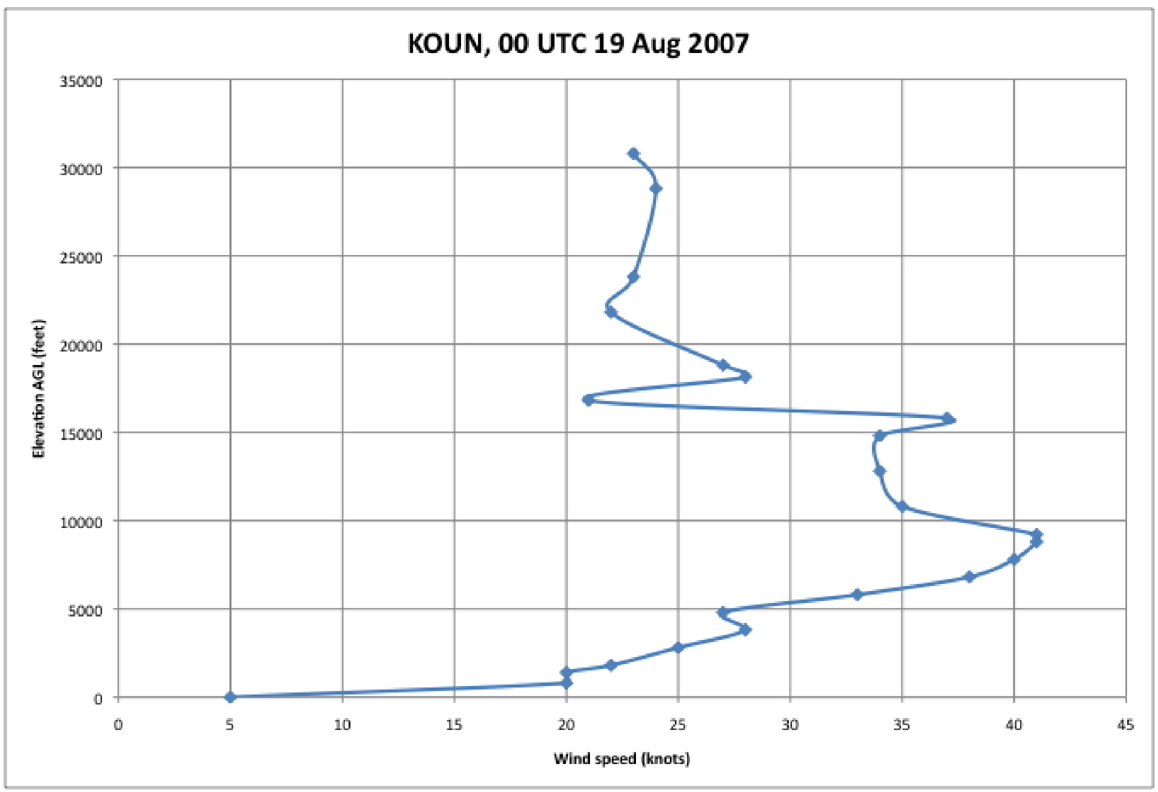
2. Page 3, [former] 6th line of final paragraph: The authors state that "…the boundary layer…was indistinguishable from that over the surface of the Gulf of Mexico…". While the boundary layer over Oklahoma was warm and moist, it would better make the authors' point if they compared near-surface

potential temperature or equivalent potential temperature over some area of the northwestern Gulf, perhaps along the track of Erin, and central Oklahoma.

Some trajectories we ran (but didn't show as figures) emanated from that part of the Gulf through which Erin passed, from about the same time to shortly afterward. Discussion of those has been added at the behest of another reviewer. If the reviewers wish, we could add another figure to that effect, though we didn't do so for now due to space considerations and the already rather large number of figures for such a short paper. Automated mesoanalyses of surface theta-e yield comparable values in both air masses as well, but of course with differences in the geometry of the parameter field.

3. Page 5, [former] final sentence and caption for Figure 9: The authors state that the wind fields were stronger near the ground and weakened with height, while referencing Figure 9, which only shows surface winds. This would be better shown with an observed sounding or profile of VAD wind retrievals from a WSR-88D along the path of Erin early on 19 August. They could also reference the ADAS analyzed sounding in Figure 14. However, the upper-air data shown in the supplement to Figure 11 at 1200 UTC 19 August and in the ADAS sounding in Figure 14 show that the strongest winds were found near the 700¬mb level, not at the top of the boundary layer, as would be expected in a mature TC.

This is an interesting point and a correct observation. We have made some changes to the text to reflect that the wind profile, while consistent with what is expected for a warm-core low, is not quite what has been observed for tropical systems over the ocean. We do point out that defining a boundary layer in a sounding during a period of active convection is difficult (and, in the case, the KOUN sounding at 12 UTC is truncated) and probably different for a case over the continent. We have attached the wind speed profile at 0000 UTC 17 August, although, of course, this was at a time when the system was in southwest Oklahoma and NW Texas, and not centered at KOUN. At least this shows that the wind speeds at that time decreased from about 5000 feet AGL to the upper troposphere.



[Minor comments omitted...]

Second review:

Recommendation: Accept with minor revision.

General Comments: In this revision, the authors have addressed all of the major comments I had on the previous version of the manuscript. However, some of the minor changes the authors said were made did not make it into the revised version of the manuscript that I reviewed (see below). After reading the revised manuscript closely, I have a few additional points I would like the authors to address or clarify. Finally, the manuscript could be tightened up further with a careful reading by the authors to correct awkward or informal wording in several places. If these changes are made to the satisfaction of the editor, this manuscript will be acceptable for publication.

The authors apologize for missing some of the minor comments. All of these have been addressed either by rewording or revising the manuscript. We have responded to all comments below.

Thanks for your help in our quest for publishing this study.

Major Comments:

1. From my previous review, minor comments 3, 7, 8, and 9 were not fixed in the revised manuscript.

We agree. These have been fixed.

2. Page 1, top of 2nd column, end of section 2 on page 4, and page 8: According to Brennan et al. (2009) and Knabb (2008), the stated reason for Erin not being classified as a tropical cyclone over Oklahoma had more to do with the temporal duration of the organized deep convection associated with the system, not the duration of its re-intensification.

This is a fair statement. We have revised the text accordingly. However, we hasten to point out that exact nature of the temporal duration is not defined by NHC. We believe that once the intensification exceeded a reasonable few hours (~6 hr, for example), then any caution with respect to this issue should have been "thrown to the winds." In this case, the explosive convection and the reintensifcation was into its tenth hour before it abated or reversed.

3. It might also be helpful to include NHC's definition of a tropical cyclone (or refer readers to it).

We made this insertion, as a footnote.

[Minor comments omitted...]