The Environmental and Inner-Core Conditions Governing the Intensity of Hurricane Erin (2001)

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ABSTRACT

The evolution of Hurricane Erin (2001) is presented from the perspective of its environmental and inner-core conditions, particularly as they are characterized in the Statistical Hurricane Intensity Prediction Scheme with Microwave Imagery (SHIPS-MI). Erin can be described as having two very distinct periods. The first, which occurred between 1 and 6 September 2001, was characterized by a struggling tropical storm failing to intensify as the result of unfavorable environmental and inner-core conditions. The surrounding environment during this period was dominated by moderate shear and mid- to upper-level dry air, both caused in some part by the presence of a Saharan air layer (SAL). Further intensification was inhibited by the lack of sustained deep convection and latent heating near the low-level center. The authors attribute this in part to negative effects from the SAL. The thermodynamic conditions associated with the SAL were not well sampled by the SHIPS parameters, resulting in substantial overforecasting by both SHIPS and SHIPS-MI. Instead, the hostile conditions surrounding Erin caused its dissipation on 6 September. The second period began on 7 September when Erin re-formed north of the original center. Erin began to pull away from the SAL and moved over 29°C sea surface temperatures, beginning a rapid intensification phase and reaching 105 kt by 1800 UTC 9 September. SHIPS-MI forecasts called for substantial intensification as in the previous period, but this time the model underestimated the rate of intensification. The addition of inner-core characteristics from passive microwave data improved the skill somewhat compared to SHIPS, but still left much room for improvement. For this period, it appears that the increasingly favorable atmospheric conditions caused by Erin moving away from the SAL were not well sampled by SHIPS or SHIPS-MI. As a result, the intensity change forecasts were not able to take into account the more favorable environment.

1. Introduction

Hurricane Erin originated from a tropical depression that formed approximately 1100 km west of the Cape Verde islands on 1800 UTC 1 September 2001 (Fig. 1; Beven et al. 2003). Erin slowly began to intensify, reaching tropical storm strength (maximum sustained wind speed ≥ 35 kt) on 2 September and strengthened to 50 kt by 0600 UTC 3 September. Forecasts from the National Oceanic and Atmospheric Administration’s National Hurricane Center (NOAA/NHC) called for further strengthening, but its intensity gradually decreased over the next 2 days. U.S. Air Force reconnaissance flights on 5 September failed to find a closed circulation and Erin was downgraded to an open wave. On 6 September, a new low-level circulation began to form under convection located to the north of the original center. Erin regained tropical storm strength on 7 September and a period of rapid intensification ensued on 8–9 September that resulted in the storm reaching a peak intensity of 105 kt at 1800 UTC 9 September (Fig. 2a). Erin maintained its category 3 hurricane intensity until 0600 UTC 10 September, before quickly weakening to 80 kt by 0000 UTC September 11. Slow weakening continued for the next several days as Erin began to accelerate off to the north and east. Erin began to take on extratropical characteristics by 14 September, and

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was declared extratropical the next day as it passed near Cape Race, Newfoundland, Canada.

One of the primary objectives of this study is to determine the environmental and inner-core conditions associated with Erin that may have suppressed its intensity during the period 1–5 September, despite intensification being consistently forecast. Changes in these conditions will also be analyzed to determine what factors contributed to Erin’s rapid intensification following its reformation after 6 September. This assessment is made using environmental data from the Statistical Hurricane Intensity Prediction Scheme (SHIPS) developmental sample (DeMaria and Kaplan 1994, 1999; DeMaria et al. 2005). Smaller-scale wind and shear products are available from the University of Wisconsin’s Cooperative Institute for Meteorological Satellite Studies (UW-CIMSS).

Inner-core convective and precipitation characteristics were derived from passive microwave imagery. Passive microwave imagery is sensitive to the precipitation and convective characteristics of tropical cyclones (TCs) from either emission by raindrops (19 GHz) or scattering by graupel and hail (85 GHz). Previous studies have shown that passive microwave brightness temperatures ($T_b$) and/or derived rainfall-rate products have a strong correlation with current and future intensities (Rao and MacArthur 1994; Rodgers et al. 1994; Rodgers and Pierce 1995; Cecil and Zipser 1999; Bankert and Tag 2002). In particular, the 19-Ghz $T_b$ in the inner core of a tropical cyclone have been noted as

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**Fig. 1.** Best track of Hurricane Erin between 1 and 15 Sep 2001 overlaid on MODIS 0.55-μm clear-sky AOT averaged between 3 and 7 Sep. Numbers beside the plotted track represent the days of the month corresponding to the best-track positions at 0000 and 1200 UTC. Thick black lines separate the two primary interest periods (1–6 and 6–11 Sep) of this study. Darker colors for AOT indicate regions of greater aerosol concentrations, which is primarily indicative of dust aerosols below 30°N.
an estimator of inner-core diabatic heating, a key factor associated with the intensification process. The observed lag between increases in inner-core diabatic heating and later intensity changes can be exploited in hurricane intensity forecasting (Steranka et al. 1986).

Erin forecasts created from an improved version of SHIPS with Microwave Imagery, labeled SHIPS-MI, were used to aid in the interpretation of the atmospheric conditions affecting Erin’s intensity (Jones et al. 2006). An analysis of SHIPS-MI forecasts for three different tropical cyclone types is presented in the companion paper Jones and Cecil (2007). A similar analysis will be given for Hurricane Erin here, but this work will focus much more heavily on the evolution of the atmospheric and oceanic conditions that govern Erin’s intensity. Various sources of data are used in an attempt to determine whether the conditions represented in the statistical forecast models are a true reflection of what was controlling the intensity of Erin.

The environmental and inner-core data sources are briefly discussed in section 2. Sections 3 and 4 describe in detail the environmental and inner-core characteristics of Erin for two key time periods. The first, occurring between 1 and 5 September 2001, follows Erin from its initial formation to its first dissipation. The second, occurring between 6 and 11 September, follows Erin during its reorganization through its rapid intensification into a major hurricane. Analysis of the SHIPS-MI forecasts for both periods follows in section 5 with final conclusions drawn in section 6.

2. Data

Intensity and location data are taken from postanalysis “best track” files produced by the NHC (Jarvinen et al. 1984). For the purposes of this work, “intensity” is classified as the best-track maximum sustained wind speed. The environmental data for Erin are derived from archived model output at 2° spatial resolution, written to diagnostic files designed for SHIPS training.
The sea surface temperature (SST), in degrees Celsius, along a tropical cyclone’s best track is derived from Reynolds’ SST analyses, which have a 1° spatial resolution and represent values averaged over a 1-week period from buoy and satellite SST measurements (Reynolds and Smith 1994). Best-track and environmental data are sampled at 6-h intervals at 0000, 0600, 1200, and 1800 UTC, respectively. Each environmental parameter is computed at the observation time and for "future" times at 6-h intervals out to 120 h. These are described in much greater detail in the SHIPS references above, and also in Jones and Cecil (2007).

Passive microwave data for Erin were collected from the Special Sensor Microwave Imager (SSM/I; Hollinger et al. 1987), and the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI; Kummerow et al. 1998). Both sensors measure the upwelling microwave radiation emitted from the earth’s surface and atmosphere with radiances then converted into brightness temperature values. Raindrops emit (absorb) radiation over a large portion of the microwave spectrum. Areas of significant rain (>3 mm h⁻¹) appear warmer than the surrounding environment due to the greater emission from raindrops compared to the low-emissivity ocean background at these frequencies. Precipitation ice and large raindrops scatter (in the Mie regime) upwelling radiation at higher frequencies such as 37 and 85 GHz. Increased scattering occurs in areas of large raindrop and/or precipitation ice concentrations, resulting in these areas appearing colder than the surrounding environment. Throughout this study, the 19-GHz $T_b$ data are generally used to assess the magnitude and spatial coverage of rainfall, while 85-GHz $T_b$ data are used as an indicator of the convective activity.

The two microwave parameters used in the Atlantic version of SHIPS-MI are the mean and maximum horizontally polarized 19-GHz $T_b$. The mean parameter is used as a proxy for the intensity of the inner-core (0–100-km radius) precipitation and latent heating, while the maximum $T_b$ serves as a measure of the magnitude of more localized heavy rainfall regions. For a satellite overpass to be used, the tropical cyclone center must be at least 100 km from the edge of the microwave swath and 100 km from land. SHIPS-MI has been updated compared to the version presented in Jones et al. (2006). The primary difference is that SHIPS-MI is now trained on a much larger developmental sample extending back to 1988 and including 2004 data. SHIPS-MI now computes forecasts at 6-h intervals out to 120 h as compared to the 12-hourly, 72-h version previously presented. The Atlantic SHIPS-MI predictors are defined in Table 1.

“Normal” conditions are defined as SHIPS-MI developmental sample means for a particular environmental or inner-core parameter, which are listed in

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Mean</th>
<th>Std dev</th>
<th>Units</th>
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<tr>
<td>MSW0</td>
<td>Initial intensity</td>
<td>55.4</td>
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<td>Previous 12-h intensity change (persistence)</td>
<td>1.9</td>
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<td>Initial intensity times persistence</td>
<td>145.0</td>
<td>638.2</td>
<td>kt²</td>
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<td>EDAY</td>
<td>No. of days from seasonal peak of TC activity</td>
<td>0.6</td>
<td>0.4</td>
<td>days</td>
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<tr>
<td>USPD</td>
<td>Zonal component of TC motion</td>
<td>-3.1</td>
<td>9.8</td>
<td>kt</td>
</tr>
<tr>
<td>POT</td>
<td>Potential (maximum potential intensity derived from along-track SST – initial intensity)</td>
<td>70.7</td>
<td>33.7</td>
<td>kt</td>
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<tr>
<td>POT2</td>
<td>Square of POT</td>
<td>6139.4</td>
<td>4720.0</td>
<td>kt²</td>
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<td>SHRD</td>
<td>200–850-hPa deep-layer vertical wind shear</td>
<td>17.9</td>
<td>9.9</td>
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<td>7.6</td>
<td>5.9</td>
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<td>kt²</td>
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<td>T200</td>
<td>200-hPa temperature</td>
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<td>°C</td>
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<td>EPOS</td>
<td>Theta-e excess between lifted surface parcel and environment, used as a measure of instability</td>
<td>11.4</td>
<td>3.9</td>
<td>°C</td>
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<td>Z850</td>
<td>850-hPa relative vorticity</td>
<td>24.6</td>
<td>56.3</td>
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<td>PSLV</td>
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<td>83.9</td>
<td>hPa</td>
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<td>47.7</td>
<td>9.6</td>
<td>%</td>
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<td>D200</td>
<td>200-hPa divergence</td>
<td>23.9</td>
<td>31.9</td>
<td>10⁻⁵ s⁻¹</td>
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<td>MEANH19</td>
<td>Mean 0–100-km horizontally polarized 19-GHz $T_b$</td>
<td>203.2</td>
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<td>Low-level (700–850 hPa) average relative humidity</td>
<td>60.6</td>
<td>9.7</td>
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<td>SST</td>
<td>Reynolds sea surface temperature</td>
<td>27.2</td>
<td>2.3</td>
<td>°C</td>
</tr>
</tbody>
</table>

(DeMaria and Kaplan 1994, 1999; DeMaria et al. 2005). The sea surface temperature (SST), in degrees Celsius, along a tropical cyclone’s best track is derived from Reynolds’s SST analyses, which have a 1° spatial resolution and represent values averaged over a 1-week period from buoy and satellite SST measurements (Reynolds and Smith 1994). Best-track and environmental data are sampled at 6-h intervals at 0000, 0600, 1200, and 1800 UTC, respectively. Each environmental parameter is computed at the observation time and for “future” times at 6-h intervals out to 120 h. These are described in much greater detail in the SHIPS references above, and also in Jones and Cecil (2007).

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TABLE 1. Atlantic SHIPS-MI training sample predictor means and std devs. The first 16 predictors represent those used in operational SHIPS. MEANH19 and MAXH19 replace RHII and D200 in SHIPS-MI. RHLO and SST are not directly included in either model, but are listed here as values of both are discussed in the text.
Table 1. Unless otherwise stated, values for shear, moisture, and SST are those derived from the SHIPS diagnostic file, whose fields are derived from Global Forecasting System (GFS) model analyses. Uncertainty exists as to the exact value of these parameters owing to limitations in model analyses and the spatial averaging process used to derive SHIPS parameters. Discussions of precipitation and convective trends are based on snapshots of passive microwave data available for Erin. Since this encompasses nearly 50 overpasses in total, only selected passive microwave overpasses are shown to highlight the key changes in the inner-core precipitation and/or convective activity. Further information on SHIPS-MI is available in Jones and Cecil (2007).

CIMSS products utilize visible, infrared, and water vapor channels from geostationary meteorological satellites to derive Saharan air layer (SAL) locations and wind information at multiple levels of the troposphere (Velden 1996; Dunion and Velden 2004). The resulting products are available every 3–6 h and have a horizontal spatial resolution of less than 10 km, much higher than for the global numerical weather prediction models or reanalysis data over the same region. Aerosol optical thickness (AOT) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra Earth Observing System satellite are also used to indicate SAL regions (Barnes et al. 1998). The MODIS derives AOT over a clear-sky background using the 0.55-μm channel, with regions of high aerosol concentrations (e.g., dust) having high optical thickness values.

3. Initial organization and dissipation

Erin developed in a region of moderate southwest- to-erly deep layer (850–200 hPa) vertical wind shear (~12 kt) and modestly warm SSTs (~27°C), indicating that conditions were somewhat favorable for tropical cyclone formation and intensification. Above normal low-level (850–700 hPa) atmospheric moisture (RHLO) was also present, coupled with near normal theta-e excess (EPOS), which is used as a proxy for instability in SHIPS, and above normal environmental low-level vorticity (Figs. 2b–d). However, mid- to upper-level (500–300 hPa) humidity (RHHI) was somewhat below normal, and was likely a result of Erin being embedded in an SAL during this phase of its development. The Saharan air layer is a region of midtropospheric dry air and mineral dust originating from the Saharan Desert in Africa (Dunion and Velden 2004). When this air mass is advected over the tropical oceans, it displaces the normally moist atmospheric profile with a much drier one, decreasing the potential for tropical cyclone development. A 1200 UTC 1 September radiosonde from Cape Verde (~1000 km east of Erin) shows evidence of an SAL with very dry air above 600 hPa (Fig. 3). The relative humidity between 600 and 450 hPa is sometimes below 10%.

By 2 September, Geostationary Operational Environmental Satellite (GOES) imagery indicated that Erin was moving into a large and strong SAL region from which it would not emerge for several days (Fig. 4). The degree to which Erin becomes embedded in the SAL is also evident from the AOT data in Fig. 1. These figures indicate that Erin was embedded in a region of high dust aerosol concentration soon after its organization up to 7 September. Evidence of Erin’s prior passage through the SAL was even present on 10 September when very high concentrations of cloud condensation nuclei from dust trapped in the eyewall were measured (Hudson and Simpson 2002).

The use of a theta-e excess (EPOS) between a lifted parcel and its surrounding environment as a measure of “instability” by SHIPS complicates its interpretation with respect to SAL conditions and the favorability of the environment toward tropical cyclone development.
Dry mid- to upper-atmospheric conditions decrease environmental theta-e values, increasing EPOS. While dry air aloft is not necessarily an inhibitor of instability, it does not favor increased instability either. Since SAL conditions are also associated with above normal mid- and upper-tropospheric temperatures (decreasing lapse rates) and an enhanced temperature inversion near 850 hPa, the SAL is generally associated with a region of enhanced stability. Since the vertical gradients of temperature are poorly sampled by the SHIPS parameters, the resulting increase in stability is inadequately measured. The increased midlevel temperatures also act to increase the thermal gradient between it and the cooler air to the south, resulting in the formation of an easterly jet near 700 hPa (Dunion and Velden 2004). This jet acts to increase the shear affecting a tropical cyclone embedded within an SAL. Such shear is not accounted for in the SHIPS parameters, which use the 200–850-hPa shear averaged over a large region.

While above normal low- to midlevel moisture is favorable for the formation of convection, dry middle levels do not favor sustained convection. Midlevel dry air can be entrained into surface-based convective updrafts, leading to evaporative cooling and decreased buoyancy. Midlevel dry air also promotes cold evaporative downdrafts, which can contaminate the boundary layer and lead to the eventual dissipation of the convection (Emanuel 1989; Powell 1990). Sporadic convection may continue, with cycles of boundary layer recovery due to enhanced surface fluxes and boundary layer contamination by the cold downdrafts. This prevents the establishment of sustained inner-core latent heating, inhibiting the formation of a warm core necessary to substantially intensify the system. Overall, the dynamic and thermodynamic conditions surrounding Erin allowed for the possibility of modest organization and intensification, but were not favorable for rapid intensification.

When the pre-Erin African easterly wave was upgraded to a depression at 1800 UTC 1 September, a region of precipitation with embedded convective features was present near and just to the southwest of the center of circulation (Fig. 5). The movement of the storm during this period was in a general west-northwest direction between 14 and 18 kt and was primarily being steered by a midtropospheric ridge to the north. Precipitation intensity and coverage during this phase of development appeared to peak early on 2 September based on passive microwave observations (Fig. 6). During this time, Erin intensified from a 30-kt depression to a 45-kt tropical storm.

The CIMSS deep-layer shear product at 1800 UTC 2 September indicates that Erin was moving from a region of low shear, in which the low-level circulation first developed, to a region of moderate shear (Fig. 7). However, SHIPS deep-layer shear remained near the model mean value (~18 kt), meaning it was unlikely to have a large influence on forecast intensity (Fig. 2c). Despite slowly increasing shear and decreasing cyclonic environmental vorticity (Fig. 2d), Erin intensified to 50 kt by 0600 UTC 3 September before weakening slightly thereafter. With the exception of a brief convective
burst between 1800 UTC 3 September and 0000 UTC 4 September, most significant precipitation was displaced over 100 km down shear from the center (Fig. 8). The intense, but sporadic, nature of the convective bursts indicated that atmospheric instability was present in some form, as indicated by EPOS and despite Erin being surrounded by SAL conditions. In fact, the Cape Verde sounding shows substantial potential instability

![Figure 5](image.png)

**Fig. 5.** F-13 SSM/I overpasses for Erin showing (left) H19 and (right) PCT85 at 2019 UTC 1 Sep 2001. Range rings spaced at 100 km from the interpolated best-track center and the best-track path are overlaid.

![Figure 6](image.png)

**Fig. 6.** Time series of normalized 0–100-km mean and maximum H19 brightness temperatures compared to best-track MSW. Note that mean and maximum H19 brightness temperatures decreased substantially prior to Erin's dissipation on 5 Sep while also increasing prior to the rapid intensification on 8 Sep.
Using a lifted surface parcel, increasing the likelihood of strong convective updrafts (Fig. 3). However, the dry middle- to upper-atmospheric conditions also enhanced the probability of cool, convective downdrafts inhibiting sustained convection.

The degree to which Erin was embedded in the SAL was evident both from MODIS AOT data between 3 and 7 September (Fig. 1) and the GOES-derived SAL product at 0000 UTC 6 September (Fig. 4b). By this time, the increasing shear coupled with the inability of Erin to sustain significant precipitation and convection had led to the dissipation of the low-level circulation.

4. Reorganization and rapid intensification

Erin’s redevelopment occurred late on 6 September, well north of the previous center. It was located nearer to the precipitation and convective maxima that were observed in previous days. By 0000 UTC 7 September, Erin had begun to emerge from the SAL to its south (Figs. 1 and 4b; Halverson et al. 2006). Both lower and upper-level humidity values increased after 6 September as Erin began to move northward away from the SAL region, with a corresponding decrease in EPOS observed during this time (Fig. 2b). Movement had shifted to a northerly to northwesterly direction as Erin reached a weakness in the subtropical ridge. With gradually improving environmental conditions in the form of increasing SSTs (>28°C) and increasing atmospheric moisture (Fig. 2), Erin regained tropical storm strength by 1800 UTC 7 September in association with an increase in near-center precipitation earlier that day (Fig. 6). However, shear again displaced this precipitation well down shear away from the low-level circulation. The southerly deep-layer shear surrounding Erin was evident in the CIMSS shear analysis at 1200 UTC, though its magnitude, as defined by the CIMSS technique, is somewhat less than that reported by SHIPS (12 versus 17 kt; Fig. 9).

Erin began a period of rapid intensification on 8 September, strengthening from a weak 35-kt tropical storm to a 75-kt category 1 hurricane in just 24 h. During this time, ~15 kt southwesterly shear was still affecting Erin, but the storm was also moving into a region of SSTs that were in excess of 29°C (Fig. 2c). The passive microwave signature of Erin also rapidly improved with a substantial increase in the areal coverage and inten-
sity of precipitation and latent heating in the inner core, especially south of the center, which is indicated by the increase in 0–100-km mean H19 from 206 to 240 K (Fig. 6). An eye also became evident in the microwave imagery at this time (Fig. 10). It is important to note that the increase in inner-core precipitation appears to precede intensification by approximately 12 h (Fig. 6). This lag corresponds well with studies by Steranka et al. (1986) and Rosenthal (1978). Reconnaissance observations at 1930 UTC 8 September also indicated the presence of a large, 93-km-diameter eye. Almost immediately, the eyewall began to contract as is evident from microwave and reconnaissance observations (not shown).

Intensification continued on 9 September with Erin reaching a peak intensity of 105 kt at 1800 UTC, although the inner-core precipitation had decreased slightly over the previous several hours (Fig. 6). Deep-layer shear fell to below 15 kt and remained low for the next 2 days (Fig. 2c), which provided an opportunity for Erin to become better organized. However, Erin began to move over cooler SSTs (~27°C) as it continued to move north (Fig. 2c). This SST decrease corresponded to a 30-kt drop in the maximum potential intensity from 150 to 120 kt. The atmospheric relative humidity and instability also began to decrease as Erin became increasingly embedded in dry air of continental origin (Fig. 4d). The effects of southwesterly shear were still evident as the precipitation maximum was still positioned down shear, northeast of the center (not shown). The eyewall continued to contract throughout the day with reconnaissance aircraft reporting a 56-km-diameter eye at 1810 UTC, near the time of peak intensity. Reconnaissance aircraft also reported a 5°C increase in the temperature difference of the 700-hPa (flight level) eye and the surrounding environmental atmosphere. This indicates that latent heating from the previous day’s precipitation and/or increasing subsidence within the eye had warmed the inner core significantly relative to the environment, which corresponded with the rapid intensification of Erin from a strong tropical storm to a major hurricane. Erin also began an eyewall replacement cycle at this time, which appeared to disrupt the inner-core wind field.

Erin remained a 105-kt major hurricane early on 10 September and began to weaken after 0600 UTC that day. Deep-layer shear remained between 10 and 15 kt, but had shifted to a more southerly direction. As Erin continued to gain latitude, it moved over sub-27°C SSTs while atmospheric moisture and instability (as measured by EPOS) continued to decrease (Fig. 2b). Microwave overpasses between 1000 and 1400 UTC continued to indicate an asymmetric precipitation field with the heaviest rain now positioned to the north and
west of the center (not shown). Despite the lower SSTs and atmospheric moisture that were now affecting the storm, the overall coverage and intensity of the precipitation field had increased on 10 September (Fig. 6).

Erin weakened to 80 kt by 0000 UTC 11 September and maintained this intensity for the next 30 h. Around this time, Erin was picked up by an upper-level trough and began to recurve to the northeast. Southerly shear increased to over 20 kt while SST decreased to near 26°C (Fig. 2c). Organization gradually degraded, with precipitation becoming more offset to the northeast of the center, and the eastern eyewall began to erode as the influence of shear increased. Erin weakened further after 12 September, falling below 70 kt at 0000 UTC 13 September. Microwave observations continued to show an enlargement of the eyewall and an overall decrease in the intensity of inner-core convection and precipitation after 13 September (Fig. 6). Erin continued to slowly weaken, falling below hurricane intensity (65 kt) on 14 September. Around this time, the increasing influence of cooler water, shear, and dry atmospheric conditions led to the onset of extratropical transition, which was complete by 15 September (according to the best track).

5. Forecast analysis

a. 1–6 September

SHIPS-MI forecasts were computed at 6-h intervals out to 120 h (5 days) using coefficients derived from a training sample comprising passive microwave and environmental data between 1988 and 2004. SHIPS-MI forecasts were initiated at the time of a microwave overpass. SHIPS forecasts were created by applying the postanalysis environmental data to the 2005 season operational coefficients, and do not represent forecasts produced in real time during 2001. Where available, SHIPS forecasts do have infrared brightness temperature and oceanic heat content adjustments applied; otherwise, the adjustment was set to zero (DeMaria et al. 2005). Both SHIPS and SHIPS-MI consistently forecasted substantial intensification between 1 and 6 September, leading to large positive errors compared to the best-track intensity (Fig. 11a). Prior to 3 September, SHIPS-MI forecasted greater intensification than did SHIPS due to the convection and precipitation being located over the low-level center. Though Erin quickly intensified from a wave to a 45-kt tropical storm, the longer-term intensification forecast failed to verify.

To analyze the model performance during the period when Erin was deeply embedded in the SAL with limited sustained inner-core precipitation, the mean absolute error was calculated for only those forecasts originating and occurring between 0000 UTC 3 September and 1200 UTC 6 September (Fig. 12a). The mean absolute error was computed with sub-6-hourly overpasses removed from the sample to eliminate what are essentially duplicate forecasts. For short-term (≤36-h) forecasts, SHIPS-MI outperformed SHIPS, with a maximum improvement of near 5 kt at 24 and 30 h. For forecasts generated after 1200 UTC 4 September, SHIPS-MI generally forecasted less intensification than did SHIPS (Fig. 11a). This was due to a negative contribution from the microwave predictors (Fig. 13a), as most of the convection and precipitation associated
with Erin had become displaced well down shear (e.g., Fig. 8). Neither model accurately forecasted Erin’s dissipation late on 5 September. The overall performance of both SHIPS and SHIPS-MI during this period would be considered poor.

To better determine the physical processes leading to the poor model performance, the contributions from the SHIPS-MI model predictors were broken down into five quasi-independent categories, which include climatology, SST-Potential, shear, (other) environment, and
microwave (Table 2). (A listing of individual predictors, including brief definitions of each, is given in Table 1.) The contribution for a particular category is calculated by summing the individual intensity change forecasts from each predictor within that category (Fig. 13). The average contribution of each category as a function of forecast duration is given in Fig. 14a. This is based on summing the absolute values of the contributions from each category, then dividing the values in Fig. 13 by this sum. Passive microwave terms heavily contributed to the total forecast out to 36 h. Their importance decreased thereafter, as the initial precipitation characteristics have less of an influence on longer-term intensity trends. The contribution from SST-Potential was greatest at 36 h and beyond, its importance increasing with forecast duration. The substantial contribution was a result of a maximum potential intensity (MPI) of ~140 kt from near-normal (~27°–28°C) SSTs, coupled with low initial intensities (~40 kt). (SST was never greater than ±1 standard deviation from the sample mean.) Climatology, primarily in the form of persistence, also contributed a large portion of the 6- and 12-h forecasts. The final two categories, other environment and shear alone, combined to contribute less than 25% at all forecast times. The remaining environmental contribution was primarily the positive contribution from above normal EPOS (Fig. 2b). Recall that Erin was embedded in an SAL during this phase, providing unfavorable conditions for sustained convection (Figs. 1 and 4). However, the positive contribution from EPOS results in an intensification signal being fed into SHIPS-MI.

Shear contributed <10% of the forecast out to 66 h. The model mean deep-layer shear magnitude was 18 kt, with values estimated over Erin being within ±0.5 standard deviations of the sample mean. As a result, the contribution from the shear was small. However, given the degree that the precipitation and convection was being displaced down shear after 3 September, the possibility exists that the shear resulting from the SAL-induced easterly jet was also affecting Erin (Fig. 7), but was unresolved by the shear parameter used here. Recall that the SHIPS shear parameter is a result of an averaging of the wind field over a radius up to 800 km from the center of a tropical cyclone. The large radius smooths out many smaller-scale wind features present in the environment that can affect tropical cyclone intensity. Also, SHIPS uses the difference between the 200- and 850-hPa layers to define the deep-layer shear vector, neglecting the influence of the enhanced 700-hPa jet. It is important to note that the negative influence on the environment from the SAL is not directly taken into account anywhere in SHIPS-MI. Thus, the weakening signal it would likely provide does not show up in the final forecast. (The inclusion of RHHI in SHIPS does little as it is the least significant of the 16 climatological–environmental predictors, and is not suited for capturing dry air below 500 hPa.) The use of an SAL index or satellite-based total precipitable water as a predictor was not tested, but given a sufficient training sample its inclusion might improve forecasts to some degree.

Figure 13a shows the prior 24-h forecast intensity change as a function of date, broken down by physical category and compared against best-track intensity change. For example, at 0000 UTC 3 September, the previous 24-h intensity change had been +15 kt with a corresponding 24-h SHIPS-MI forecast intensity
change of +20 kt. The forecast initialization date and time is 24 h prior to the date and time given for each intensity change value. Clearly evident were the ~10 kt overforecasts produced by SHIPS-MI out to 4 September. No single physical contribution appeared to be responsible for the substantial intensification forecast. Instead, there was a combination of small positive contributions from several marginally favorable conditions. SST-Potential contributes less than 5 kt at 24 h for most forecasts during this phase (Fig. 13a). Shear and climatological predictors (with the exception of persistence) account for very little of the 24-h intensification forecast. The nonshear environmental predictors, led by above normal EPOS, provide 3–5 kt of intensification. The microwave contribution was positive early in the period as a result of the initial inner-core precipitation signature, but quickly became negative (Fig. 13a) as the inner-core precipitation weakened (Fig. 6). For the most part, all oceanic and environmental conditions re-

<table>
<thead>
<tr>
<th>Condition</th>
<th>Predictors</th>
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<tbody>
<tr>
<td>Climatology</td>
<td>MSW0, WCG12, VPER, EDAY, USPD</td>
</tr>
<tr>
<td>SST-Potential</td>
<td>POT, POT2</td>
</tr>
<tr>
<td>Shear</td>
<td>SHRD, SHRDLAT, MSWSHRD</td>
</tr>
<tr>
<td>Environmental</td>
<td>T200, EPOS, Z850, PSLV</td>
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<tr>
<td>Microwave</td>
<td>MEANH19, MAXH19</td>
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The microwave contribution in SHIPS-MI is an indirect measure of the environment’s ability to support deep convection. The statistical models represent the thermodynamic conditions as being favorable for intensification, with the shear essentially neutral. But the microwave imagery in Fig. 8 and similar overpasses (not shown) demonstrate that deep convection, widespread precipitation, and associated latent heating were generally lacking near the circulation center. The environment must not have been as favorable as these models suggested. The northeastward displacement of convection in Fig. 7 is suggestive of westerly shear, perhaps the shear found above a low- to midlevel easterly jet associated with the SAL. This would not be resolved by the 200–850-hPa shear parameter averaged over a large region in the model analyses. Still, the presence of an SAL-induced shear can only be inferred, but not directly sampled using the available data. The SAL also typically has extremely dry air, which promotes cold downdrafts contaminating the boundary layer. Dunion et al. (2004) reports examples of the GFS analysis overestimating humidity in the SAL by a factor of 2; dropsonde humidity data were not assimilated into the GFS model.

An example of the importance of passive microwave imagery is given by an individual forecast initialized at 2122 UTC 4 September (Fig. 15) corresponding with a Defense Meteorological Satellite Program (DMSP) F-13 SSM/I overpass shown in Fig. 7. At this time, isolated strong convection was displaced well down shear. Otherwise, there was relatively little inner-core precipitation and latent heating, resulting in a negative contri-
b. 6–11 September

The second phase of Erin’s evolution began with the reformation of the low-level center late on 6 September, followed by rapid intensification on 8–9 September. This period is summarized by SHIPS and SHIPS-MI forecasts between 1200 UTC 6 September and 1200 UTC 10 September (Fig. 11b). The latter date marks the beginning of the final weakening phase following Erin’s peak intensity of 105 kt. Forecasts occurring after this time were not considered so that the focus remains solely on the intensification period. As in the previous period, both models forecast substantial intensification while Erin was only a weak tropical storm (Fig. 11b). Unlike before, Erin substantially intensified at a greater rate than forecast by either SHIPS or SHIPS-MI. For forecasts valid on 9–10 September, SHIPS-MI consistently forecasts a greater rate of intensification than does SHIPS (Fig. 11b), primarily as a result of the positive contribution from the microwave data (Fig. 13b). In some instances, the difference in forecasts was almost 10 kt, giving SHIPS-MI a substantial advantage over SHIPS for all forecasts and resulting in lower mean absolute errors for SHIPS-MI during this period (Fig. 12b). SHIPS-MI did overforecast Erin’s intensity by several knots after it had begun to weaken from its peak of 105 kt (Fig. 11b). Erin’s inner-core precipitation remained vigorous well after its peak intensity occurred, resulting in a strong positive contribution to SHIPS-MI (Fig. 8).

The SST-Potential contribution was similar to that of the previous period (Fig. 13b). The microwave contribution, primarily positive for forecasts originating after 8 September (Fig. 13b), accounts for nearly 20% of the forecast out to 36 h (Fig. 14b). Again, climatology in the form of persistence was very important for 6–12-h forecasts. The shear contribution increased substantially compared to the previous period and also increased substantially with forecast duration (Fig. 14). This increase resulted from a positive shear signal from slightly below normal shear, as well as a much above normal product of shear times latitude (SHRDLAT). The SHRDLAT predictor acts as an offset to SHIPS to reduce the influence of shear on high-latitude tropical cyclones. (The sign of the SHRDLAT coefficient is opposite that of SHR.) Other environmental predictors account for the remainder of the forecast with the most important contributors being below normal theta-e and below normal low-level relative vorticity. The latter was a result of the influence of the weakness in the ridge steering Erin to the north.

The 24-h SHIPS-MI intensity change forecasts for Erin capture both the intensification trend between 8 and 10 September and the slow weakening thereafter (Fig. 13b). The largest difference between the forecast intensity change and the best-track intensity change occurred during the rapid intensification period where SHIPS-MI underforecasts the maximum intensity by over 20 kt. Still, these forecasts represent an improvement over those of the operational SHIPS. The trend of the intensity change forecasts closely follows that of the SST-Potential contribution. Recall that Erin moved into a region of ~29°C SST during the initial stages of rapid intensification. This increased the MPI and kept POT at above normal levels despite the increasing intensity. A small positive signal from shear was also evident, which is a result of the small decrease in shear coupled with an increase in latitude. When SST decreased back to 27°C as Erin reached its peak intensity, POT decreased accordingly, producing a weakening signal in SHIPS-MI forecasts for periods after 10 September (Fig. 13b).

The microwave contribution became positive for forecasts verifying after 9 September, allowing SHIPS-MI to better capture the magnitude of the latter half of the rapid intensification (Figs. 11b and 13b). The microwave contribution remained positive throughout the remainder of the period, as the inner-core precipitation associated with Erin was slow to decrease. Compared to the previous period where Erin failed to intensify beyond tropical storm strength, the environmental contribution for the intensification period was still small, but became increasingly negative. This was a result of the EPOS and the normalized 850-hPa relative vorticity (Z850) parameters falling below normal levels, which in the case of Z850 was nearly two standard deviations below normal (Figs. 2b and 2d). However, this was also the very time when Erin emerged from the SAL, which improved the favorability of the environment to sustain convection and precipitation. Neither SHIPS nor
SHIPS-MI captured Erin’s transition from the suppressing influence of the SAL to a more favorable atmospheric environment on 8 September as it emerged from the SAL.

The positive impact of the inclusion of passive microwave imagery into SHIPS was evident in a forecast initialized at 1600 UTC 8 September while Erin was in the process of rapid intensification (Figs. 10 and 16). The 0–100-km mean H19 $T_b$ was 229 K, 25 K above the model mean (Table 1). The total microwave contribution added 5 kt to the 24–36-h forecasts compared to those of SHIPS, better capturing (but still underestimating) the true rate of intensification. Also note that this 5-kt improvement is in addition to the positive contribution from the infrared adjustment included in SHIPS, but not in SHIPS-MI. The actual contribution from the microwave terms in SHIPS-MI was ~8 kt (Fig. 13b). Both models also accurately forecast weakening after 10 September as the result of the movement over cooler SSTs.

6. Conclusions

The intensity of Erin during the first half of its life cycle was primarily governed by wind shear and atmospheric thermodynamic conditions. The circulation initially organized in a region of relatively low shear during a convective burst event. Shear rapidly increased as a result of both synoptic conditions and the influence of the SAL, displacing precipitation and convection down shear from the center. Despite the surrounding SAL, the low-level moisture (below the SAL inversion) was well above normal. This produced substantial potential instability, which appears to have been realized by the strong convective bursts. While the environment was favorable for the onset of convection, the dry mid- to upper-tropospheric conditions were also favorable for the formation of cold downdrafts. This, combined with shear, continually cut off convective updrafts from the surface moisture, preventing sustained convection from occurring and leading to the eventual dissipation of the low-level circulation.

The primary inhibitors of intensification between 1 and 5 September appear to be the SAL and vertical wind shear, with the shear possibly being enhanced by the SAL. Erin emerged from the SAL on 7 September, allowing increased inner-core precipitation and further development of a warm core. Coupled with an increase in SST, steady intensification began. Precipitation finally became sustained around the low-level circulation on 8 September, marking the beginning of a period of rapid intensification to a 105-kt hurricane by 1800 UTC 9 September. The latter half of the rapid intensification period was also aided by a small decrease in shear and the formation and contraction of a well-defined eyewall. Intensification halted at 105 kt as Erin began to move over colder SSTs and underwent an eyewall replacement cycle. By 0000 UTC 11 September, the eyewall cycle was complete, and the effect of cooler water and limited convective activity led to weakening. Weakening continued at a gradual pace until Erin underwent a transition to an extratropical system on 14–15 September.

SHIPS and SHIPS-MI incorrectly forecast substantial intensification soon after the initial consolidation of the low-level circulation on 1 September. Once shear had increased and the inner-core organization decreased, SHIPS-MI forecast little short-term intensification after 3 September, but failed to dissipate Erin. No single physical signal appeared responsible, but a combination of marginally favorable conditions produced a strong intensification forecast. The dry middle-level conditions and the enhanced shear associated with the SAL are not accounted for in SHIPS-MI. However, the inclusion of RHHI in SHIPS did not improve the forecast significantly. Future research may focus on adding a predictor derived from the CIMSS SAL index or total precipitable water into SHIPS, using knowledge gained from a larger sample of tropical cyclones affected by SAL conditions.

After the low-level center re-formed on 7 September, SHIPS-MI again forecast substantial intensification as a result of the lower shear and warmer SSTs ahead of Erin. The positive contribution from the increasing precipitation correctly forecast greater intensification than
did SHIPS between 8 and 10 September. Both accurately captured the halt to rapid intensification and the onset of weakening on 10 September, which was primarily due to the negative contribution from decreasing SSTs.

Inner-core latent heating within tropical cyclones is often a response to the conditions in the environment, such as SST, shear, moisture content, etc., which SHIPS is designed to characterize. If SHIPS mischaracterizes these conditions (e.g., underestimating shear or overestimating instability), the microwave contribution should partially correct for this error as the microwave characterization of latent heating is indirectly a measure of the environment’s ability to support precipitation and convection. If SHIPS conditions are generally unfavorable (favorable), but there is (is not) abundant inner-core precipitation, then the environmental terms within SHIPS must be mischaracterizing, or completely missing, some key atmospheric or oceanic condition.

While the microwave predictors were able to provide an indirect indication of the negative impacts of the environment surrounding Erin, the lack of a more direct measurement is one of the primary factors leading to the dramatic overforecasts observed prior to 6 September. The accuracy of the atmospheric moisture content within the GFS analysis has been questioned and may substantially overestimate the moisture content in SAL regions, artificially making Erin’s environment appear more favorable for intensification (Dunion et al. 2004). The theta-e predictor, used as a proxy for instability by SHIPS, also misrepresents the favorability of the environment in cases such as this. For this example, it consistently gave the false impression that the thermodynamic characteristics surrounding Erin were favorable prior to 6 September and unfavorable thereafter although the opposite appears to be true. While certain physical categories such as SST and (to a lesser extent) shear appear to have been adequately described within SHIPS and SHIPS-MI, atmospheric thermodynamic conditions were poorly represented and failed to distinguish the unfavorable initial environment from the more favorable environment later.

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REFERENCES


Powell, M. D., 1990: Boundary layer structure and dynamics in


