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Evolution of North Atlantic ERA40 tropical cyclone representation

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[1] The evolving representation of Atlantic tropical cyclones (TCs) in the ERA40 reanalysis dataset from 1957 through 2001 is analyzed using metrics of intensity and the three-dimensional cyclone phase space. On average, TC structural representation within the ERA40 has shifted two Saffir-Simpson (SS) categories over the 45 years. Thus, a category three TC during 1957–1971 is comparable in ERA40 representation to a category one during 1988–2001. Further, the ERA40 does not statistically distinguish between category three and four hurricanes within any given tercile. It is also found that less than seven millibars of ERA40 MSLP separate a category one from a five TC, mean ERA40 MSLP does not always decrease with increasing SS category, and not all SS categories are statistically significant with regard to MSLP. It follows that great caution should be exercised when using ERA40 to diagnose long-term trends in TC structure and intensity within the Atlantic. **Citation:** Manning, D. M., and R. E. Hart (2007), Evolution of North Atlantic ERA40 tropical cyclone representation, *Geophys. Res. Lett.*, *34*, L05705, doi:10.1029/2006GL028266.

1. Introduction

[2] The understanding and diagnosis of tropical cyclone (TC) structural evolution has increased tremendously through various satellite-based [*Velden et al.*, 1998; *Klein et al.*, 2000], dropsonde-based [*Franklin et al.*, 2003], and gridded model analysis-based [*Hart*, 2003; *Evans and Hart*, 2003] classifications. This new understanding has brought forward the reanalysis of historical storms in the context of present day understanding [e.g., *Landsea et al.*, 2004]. Such reanalysis is essential not only to update and refine existing datasets such as the National Hurricane Center's best track [*Jarvinen et al.*, 1984; *Neumann et al.*, 1993] (see http://www.nhc.noaa.gov for most recent track information), but also to improve understanding of evolving biases within those same datasets.

[3] One of the many tools available for use during reanalysis is the cyclone phase space (CPS) developed by *Hart* [2003]. The CPS utilizes three individual parameters describing a cyclone's structure to illustrate the evolution of that cyclone. The first parameter (B) measures the storm-motion relative thickness asymmetry of the cyclone to determine its approximate frontal nature. Tropical cyclones (TCs) are typically symmetric with little or no storm-relative thermal gradient across the center, while extra-tropical (or subtropical) cyclones are typically asymmetric and possess a (relatively) strong thermal gradient across the center. The other two parameters are measures of the thermal wind in the lower troposphere ($-V_T^L$) and upper troposphere ($-V_T^U$). As described by *Hart* [2003], these two parameters quantify the warm vs. cold-core magnitude of the cyclone, within each layer, providing a gross sense of how "tropical" or "extratropical" a cyclone is. Using these three parameters, along with minimum MSLP as a measure of surface intensity, it is possible to measure the evolution of TC representation within historical gridded (reanalysis) datasets.

[4] Quantifying variations in TC representation within historical datasets is of utmost importance in light of recent discussions on the role of global warming in trends of TC frequency and intensity [*Emanuel*, 2005; *Webster et al.*, 2006; *Klotzbach*, 2006; *Pielke et al.*, 2006; *Elsner et al.*, 2006]. Intuition would suggest that as observation quality and density improve, TC representation within gridded datasets should also improve. Here, the CPS parameters and MSLP will be used to test the aforementioned hypothesis regarding TC representation within the ECMWF reanalysis data (ERA40) [*Uppala et al.*, 2005], while also acknowledging that evolving dataset biases and long term physical trends may be acting simultaneously. Reanalysis datasets have been used extensively over the past decade, leading to increased insight on climate and climate variability. However, based on the resolution of reanalyses (1.125° in the ERA40), these datasets have yet to be proven as a means for analyzing evolving TC structure over long time periods. To that end, the goal of this study is to determine if the intensity and structural representation of documented TCs in the ERA40 is sufficiently distinct and consistent with best-track estimates to be used for TC trend studies [e.g., *Sriver and Huber*, 2006].

2. Methodology

[5] The Atlantic basin was chosen for this study because of the well-documented best track dataset (HURDAT) from

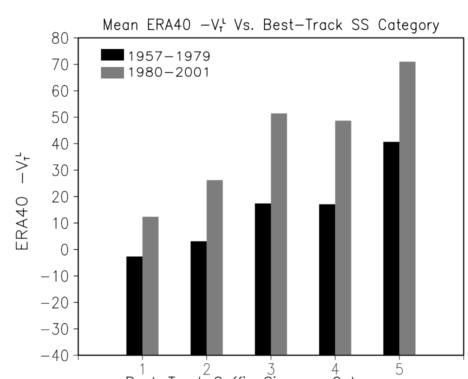

Figure 1. Comparison of the mean $-V_T^L$ for all best track hurricanes within the ERA40 data.

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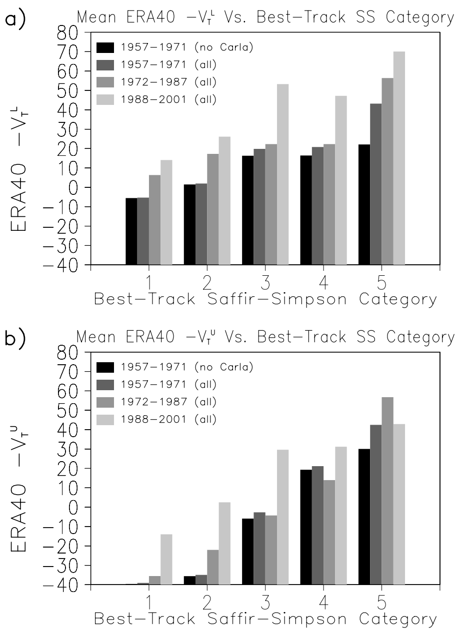

Figure 2. (a) Comparison of the mean $-V_T^L$ for all best track hurricanes within the ERA40 data. Here the data was divided into three equal-length groups based on the relative amount of satellite data assimilated. Note that the first tercile mean changes significantly when Carla is removed from the early period. (b) The same as Figure 2a, but for the upper tropospheric thermal wind ($-V_T^U$).

the National Hurricane Center [*Jarvinen et al.*, 1984; *Neumann et al.*, 1993]. Using the HURDAT data as a guide, all documented TCs from 1957 through 2001 were manually tracked (MSLP minimum) within ERA40 data (except for the first two hurricanes of 1957 which occurred before the start of the ERA40 data). It should be noted that because the TCs were tracked directly within the ERA40 data, the existence of discrepancies between the ERA40 track and the HURDAT track is possible. Since the intensity and structure of the historical representation of cyclones within the ERA40 data is the subject of this study, the tracks were created using the ERA40 cyclones rather than their best track counterparts. Rarely did the ERA40 TC position differ from the best-track position more than one ERA40 grid space (1.125°). From the TC track files created during this process, ERA40 MSLP was recorded, and $-V_T^L$ and $-V_T^U$ were calculated every 6 hours during the TC's existence. Finally, the data was binned by Saffir-Simpson (SS) category and year so that analysis could begin.

[6] Before considering the analysis, it should be noted that only the hurricane stage of each best-track TC was used in this analysis. Further, while some of the ERA40 cyclones likely underwent extratropical transition (ET) before their best track counterparts [*Evans and Hart*, 2003], no attempt was made to correct for those points at which a best track TC may have begun ET in the ERA40. Any resulting contribution to the statistics is argued to be small above SS category one based upon the results of *Evans and Hart* [2003].

Table 1a. P-Values From a Student T-Test Comparing ERA40-Calculated $-V_T^L$ for All SS Categories During the Early Period[a]

SS Cat	2	3	4	5
1	0.1292	**<0.0001**	**0.0003**	**0.0057**
2		**0.0002**	**0.0015**	**0.0099**
3			0.8068	*0.0147*
4				*0.0244*

[a]Early period is 1957–1971 (all storms). Italics and boldface indicate that the differences are statistically significant to 95 and 99%, respectively.

Table 1b. Same as Table 1a, but for the Transitional Period[a]

SS Cat	2	3	4	5
1	0.0534	0.0947	0.1974	**0.0040**
2		0.5261	0.6080	**0.0026**
3			0.9976	*0.0340*
4				*0.0387*

[a]Transitional period is 1972–1987 (all storms).

3. Analysis

[7] The initial stage of analysis was performed by breaking the dataset in half temporally and comparing the two periods. Figure 1 compares the mean values of $-V_T^L$ for each SS category during the two periods. Note that on average there is a two SS category difference between the first and second periods; an SS category five (three) in the earlier period is represented structurally within the ERA40 data roughly the same as an SS category three (one) in the later period. Further, during the early period, the ERA40 TC representation does not contain a low to mid-level warm core ($-V_T^L > 0$) within the CPS until SS category two. Finally, the use of satellite data in the ERA40 assimilation began in the 1970s [*Uppala et al.*, 2005] roughly at the split of these two periods, suggesting that the improving data (with respect to both quality and density) may be a contributing factor to the improved representation over time quantified here.

[8] Further analysis was performed by dividing the data into three groups (terciles) based on the amount of satellite data available. During the early period (1957–1971) no satellite data was available for assimilation, while the transitional period (1972–1987) marked the beginning of satellite data assimilation with only some satellite observations available. By the late period (1988–2001), most frequent assimilation of the satellite observations was underway [*Uppala et al.*, 2005]. The second tercile was also split in two, to acknowledge the rapidly evolving satellite data density throughout the 1980s. These results are discussed later and within the auxiliary material[1].

[9] Evidence of the evolving representation of TCs in the ERA40 data can also be seen in Figures 2a and 2b, displaying the mean values of $-V_T^L$ and $-V_T^U$ for each SS category during the different periods. The first bar in each chart represents the early period, excluding Hurricane Carla (1961), while the other three bars represent the entire early period (including Carla), transitional period, and late period, respectively. Carla was removed from the early

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2006gl028266. Other auxiliary material files are in the html.

Table 1c. Same as Table 1a, but for the Late Period[a]

SS Cat	2	3	4	5
1	**0.0007**	**<0.0001**	**<0.0001**	**<0.0001**
2		**<0.0001**	**<0.0001**	**0.0037**
3			0.2984	0.2661
4				0.1150

[a]Late period is 1988–2001 (all storms).

Table 2b. Same as Table 2a, but for the Transitional Period

SS Cat	2	3	4	5
1	**<0.0001**	0.9913	**0.0030**	**0.0007**
2		**0.0003**	**<0.0001**	**<0.0001**
3			**0.0009**	**<0.0001**
4				0.0802

period to illustrate the extent to which this anomalous TC (whether as a result of ERA40 representation or actual intensity) affects the tercile mean for SS category 5. The following analysis will show statistics when Carla is included; however, the statistics calculated without Carla are available in the auxiliary material.

[10] In Figure 2a, there is on average a two to three SS category difference between the early and late periods with the transitional period falling in between. It should also be noted that the addition of satellite data into the ERA40 assimilation resulted in the representation of a low to mid-level warm core ($-V_T^L > 0$) even in the weakest hurricanes (category one on the SS scale) during the transitional period. Further, a student t-test was done to compare all SS categories to all other SS categories during each of the three periods. The resulting p-values (listed in Tables 1a–1c) reveal that during each period there are at least two pairs of SS categories that are not statistically different ($p > 0.05$) when measured by ERA40 $-V_T^L$. Finally, Figure 2b shows that on average a TC in the ERA40 data does not have an upper level warm core ($-V_T^U > 0$) until it reaches category two intensity during the late period or category four intensity during the early and transitional periods. These analyses all suggest that ERA40 TC representation is highly dependent on the period of occurrence.

[11] As mentioned earlier, there is an observational data density discontinuity during the second tercile that may be reducing the statistical significance of the results in that tercile. Indeed, as shown in the auxiliary material, a noticeable increase in the statistical significance can be seen in the second half of the second tercile. Whereas there were no statistically significant differences during the first half of the period, all but two of the comparisons were statistically significant ($p < 0.05$) during the second half of the period. Such results argue that the representation of TC structure and intensity during the second tercile improves significantly, arguing that observational data density may be an important consideration in long-term trend quantification.

[12] Though analysis has not yet been completed, it is suggested that ERA40 TC representation is also highly dependent on TC size. For example, Hurricane Carla (1961) was an exceptionally large storm with hurricane force winds affecting nearly the entire Texas coast at the time of landfall [*Dunn and Staff*, 1962] and tropical storm force winds extending more than 550 km from the center of circulation [*Licheblau*, 1961]. Carla is the most intense Atlantic TC as represented in the ERA40 data (with an ERA40 minimum MSLP of 981 mb), making it a worthy case of further study.

[13] Conversely, consider category five Hurricane Andrew (1992), which was a small storm with hurricane force winds extending less than 50 km from the center of circulation and a tropical storm force wind radius of less than 175 km at the time of peak intensity [*Demuth et al.*, 2006]. Since the ERA40's 1.125° grid cannot adequately resolve such small systems, Andrew is represented as an open wave just prior to Florida landfall which likely explains the poor representation of its warm core. In fact, during the time of peak intensity, Andrew is represented within the ERA40 with a weak cold core ($-V_T^L < 0$).

[14] The magnitudes of $-V_T^L$ and $-V_T^U$ ultimately play a role, although not the sole role, in determining the surface intensity of the TC [*Hart*, 2003]. To ensure that the TC structural evolution is consistent with the TC intensity evolution within the ERA40, further analysis was done using minimum ERA40 MSLP for each SS category. Student t-tests were performed to reveal statistical significance of the MSLP differences (Tables 2a–2c). In each tercile, there are at least two pairs of SS categories that are not statistically significant when MSLP is used for intensity. Additionally, Figure 3 shows that during all periods there is at least one SS category for which MSLP increases with increasing SS category. Finally, less than 7 mb separates an SS category one from five TC in ERA40.

4. Conclusions

[15] It is clear that using the CPS to examine all documented Atlantic TCs within the ERA40 data reveals a strong trend in the structure of the TCs. By subdividing the dataset into three temporal bins that are nearly-uniform in size, further discontinuities in TC structural representation become apparent. TC representation within the ERA40

Table 2a. Same as Table 1a, but for MSLP Rather Than $-V_T^L$

SS Cat	2	3	4	5
1	**0.0009**	0.2432	*0.0455*	**0.0034**
2		**0.0005**	**0.0003**	0.1199
3			0.2510	**<0.0001**
4				**<0.0001**

Table 2c. Same as Table 2a, but for the Late Period

SS Cat	2	3	4	5
1	0.0912	**<0.0001**	**0.0002**	**<0.0001**
2		**<0.0001**	0.0773	**0.0020**
3			*0.0279*	0.1187
4				**0.0082**

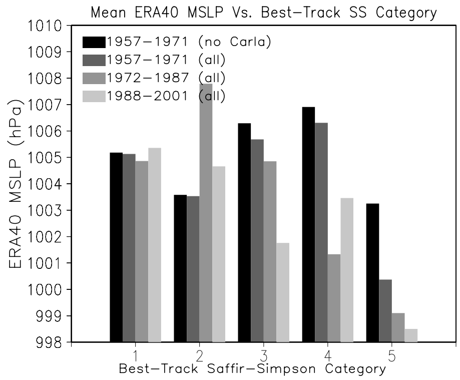

Figure 3. As in Figure 2a, except using MSLP instead of $-V_T^L$.

changes noticeably with time as data availability and quality evolve. This evolution is made clear by the one-to-two SS category difference between each half of the dataset, and the lack of uniform statistical significance in several SS category comparisons in all terciles. Further evidence that the ERA40 should be used with caution when diagnosing long term TC trends was found by examining TC intensity trends within the dataset. Only 5–7 mb of ERA40 mean MSLP separate the five SS categories within all three terciles. Further, the ERA40 does not distinguish between several SS category pairs within any given tercile.

[16] It has been noted that there is considerable uncertainty in the best-track estimates of intensity used here as "verification" [*Landsea et al.*, 2004; *Pielke et al.*, 2006]. Indeed, the statistical significance results found here are an evolving combination of uncertainty in both the "verification" (best-track classification) and the ERA40 representation. Nonetheless, unless all entries in Tables 1a–1c and 2a–2c are boldfaced, it may be difficult to use ERA40 to evaluate long-term trends of TC structure or intensity. In that regard, the results found here provide further insight into the findings of R. Maue and R. Hart (Comment on: "Low frequency variability in globally integrated tropical cyclone power dissipations, submitted to *Geophysical Research Letters*, 2007).

[17] Lastly, it should be noted that the analysis performed here is only for the Atlantic basin and that different ERA40 representation trends exist in the other TC basins.

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